

CONSIDERATIONS OF HIGH ALTITUDE EMISSIONS

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SUMMARY

Since the early 1970s, various concerns (sometimes conflicting) have been expressed about the possibility of adverse environmental effects of stratospheric exhaust emissions from aircraft. This paper describes the status of the Federal Aviation Administration's High Altitude Pollution Program, which was instituted in 1976 to develop the detailed quantitative information needed to judge whether or not regulatory action to limit such emissions would be necessary. The complexities of this question and the nature and magnitude of uncertainties still present in our scientific understanding of the potential interactions between aircraft exhaust emissions and stratospheric ozone and climate are reviewed. The direction and scope of future Federal and international activities are described.

INTRODUCTION

About 1970, questions concerning the environmental consequences of high altitude aircraft emissions from a fleet of civil supersonic transport aircraft (SSTs) were first raised. Since that time, we have seen two major studies completed (refs. 1 and 2), both of which included the conclusion that a large fleet of SSTs carried with it the likelihood of significant ozone reduction from a stratospheric accumulation of aircraft engine exhaust-oxides of nitrogen. In addition, both reports claimed that qualitatively similar effects could be expected to result from stratospheric flight of subsonic aircraft, though the lower altitudes associated with subsonic flight made the effects correspondingly less severe on a "per aircraft" basis.

Specifically, Figure 1 depicts the estimates of the Department of Transportation's Climatic Impact Assessment Program (CIAP) (ref. 1). It can be seen that, according to this now-outdated estimate, it would have been reasonable to assume that an economically viable fleet of SSTs — say a production run of several hundred aircraft — would be required to have lower oxides of nitrogen emission in order to be environmentally acceptable. Upon reflection, it is also seen that Figure 1 implied a potential problem for large fleet subsonic aircraft which cruise in the 40 to 45,000 ft. region (about 13.5 km). The contemporary report of the National Academy of Sciences estimated somewhat more serious effects from similar aircraft, by about a factor of two.

Both of these reports carried with them the caveat that our understanding of this complex atmospheric science problem was not perfect, and gave estimates of uncertainty associated with their predictions of ozone destruction. These uncertainty estimates are reproduced in Table 1 (ref. 2, p. 17; ref. 1, p. xvi, p. 29), where "subsonic aircraft" are taken to be similar to today's modern 4-engine wide-bodied transport.

Both reports called for additional study and suggested an immediate start on a plan for developing appropriate international regulation to avoid undesirable environmental effects. In the United States, the Federal Aviation Administration is the agency responsible for civil aircraft regulation, and it has established the High Altitude Pollution Program (HAPP) (ref. 3). The purpose of this program is to quantitatively determine the requirements for reduced cruise-altitude exhaust emissions and, in conjunction with appropriate Federal and international agencies, to ensure that, if necessary, appropriate regulatory action is taken to avoid environmental degradation.

HIGH ALTITUDE POLLUTION PROGRAM

HAPP was organized in the recognition that the uncertainties described by the previous studies could not be ignored if the Federal government was to develop an appropriate regulatory policy with regard to high altitude flight by either supersonic- or subsonic-cruising aircraft. Simply stated, we are not now in a position to predict with reasonable certainty the environmental effects of high altitude flight. To reduce these uncertainties to a tolerable level, the HAPP effort has been planned to carry out studies and analyses in a variety of disciplines:

Engines and Fuels	Assessment
Laboratory Measurements	Regulation
Field Measurements	Monitoring
Models	

We recognize, and believe it important for others to do so, that this program cannot be carried out in isolation. HAPP depends on a number of other Federal agencies to carry out their own presently-planned mission-oriented programs which are expected to provide important information for our analysis. Specifically, though not a complete list, there are important related efforts in the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, Department of Defense, Energy Research and Development Administration, National Science Foundation and Environmental Protection Agency. In addition, contributing activities are ongoing or planned in a number of foreign countries, including the United Kingdom, France, Canada, Belgium, Japan, Germany, Australia, and the Soviet Union. Finally, international bodies including the International Civil Aviation Organization, World Meteorological Organization, World Health Organization, United Nations Environment Programme, and others are also contributing valuable information. Activity on such a broad front must be continued if we are to be able to reach timely conclusions on the need for, type of, and timing of any regulations which might

be necessary to ensure protection from adverse environmental consequences of high altitude flight. The following paragraphs are devoted to a brief description of the four major technical elements of HAPP.

Engines and Fuels

The major objective of our activity in the field of engines and fuels is to provide an accurate technical data base of aircraft exhaust emissions for the worldwide fleet of aircraft expected to be operating at high altitudes over the next few decades. As shown in the following list, this is not the simplest of tasks:

Engine Emission Characteristics	Fleet Forecast
Fuels Characteristics	Operational Characteristics
Projected Changes	



Atmospheric Emissions Data Base

First, we must accumulate an accurate data base on the characteristic emissions of all types of aircraft engines, the characteristics of fuels that are expected to be burned, and the associated changes in these parameters that are expected to result from new engine technology and possible new sources of hydrocarbon fuels. Next, we must develop — as part of the FAA's continuing work on aviation forecasting — a reasonably accurate forecast of global aviation use over the next few decades: How many hours will be spent, at what cruise altitudes, by what types of aircraft? Third, we must develop an accurate picture of real-world operational influences on aircraft emission rates, since oxides of nitrogen emissions especially are affected by variations in cruise altitude, power setting, flight speed, and aircraft gross weight. Finally, all these factors are combined to result in the desired end product: an accurate forecast of the emissions of the world's aircraft fleet, resolved into about 1 km high by 10° wide latitude shells, from about 6 km altitude upward to about 20 km.

We would be remiss if we did not acknowledge the importance to our effort of the fine work presently carried out at NASA's Lewis Research Center. We strongly support and encourage continuation of those efforts.

Laboratory Measurements

The major objective of work carried out in our laboratory measurements program area is to provide an accurate data base on important stratospheric chemical reaction rates for use in atmospheric models. This work includes considerations of heterogeneous chemical reactions (i.e., those between species in different physical phases, like gas-particle interactions) and phase equilibria of demonstrated importance to better understanding the impact of aviation. In addition, we envision the probable need for a limited amount of work directed at obtaining better spectroscopic data, both for use in the

photochemistry part of atmospheric models and for the identification of trace constituents in the atmosphere through field measurements. The following list explicitly shows our planned activities in this program area:

Chemical Data Evaluation
Photolytic Quantum Yields
Gas-Phase Reactions
Molecular Spectroscopy
Heterogeneous Processes
Experimental Simulations
New Technique Development

We intend to continue support of the Chemical Kinetics Data Evaluation Project at the National Bureau of Standards. This effort, jointly funded by us and NASA's Upper Atmospheric Research Office, has proven particularly useful in providing an unbiased assessment of the best estimate of the accuracy with which important chemical reaction rate data are known. In FY 1976, for the first time, our support of this activity was broadened to permit NBS to include consideration of reaction rates of importance in the formation of oxides of nitrogen in high temperature combustion systems.

One other project in the planning stage deserves mention, and that is our recognition of the need to contribute at least partial support to development of new measurement techniques which show promise of enabling actual measurement of previously estimated chemical reaction rates on atmospheric species of importance to aviation. Noteworthy in this area is our expressed desire to join forces with the staff of the Atmospheric Science Division at Langley Research Center to support development of tunable diode lasers by a new diode-fabrication process. Availability of such devices, we are convinced, would be invaluable in certain key areas where measurements have been previously beyond reach.

Field Measurements

Perhaps it goes without saying that actual measurement of atmospheric species concentrations forms a necessary part of HAPP. Unfortunately, the nature of these projects renders them expensive. Our major objective in this program area is to build upon the existing stratospheric composition data base to make it more accurate and meaningful, concentrating, of course, on species important to developing a better understanding of aircraft impact. More specifically, better knowledge is needed of the concentration of gaseous compounds in the oxides of nitrogen and water "families" in their spatial distribution, diurnal and seasonal variation, and sources and sinks. Major planned projects are as follows:

NO-NO₂-N₂O₅-O₃ Measurements
NO-NO₂-N₂O₅-HNO₃-O₃ Measurements
"Tracers" of Atmospheric Motions
Rainout/Washout Measurements
Critical Data Analysis
Instrument Development

As can be seen, our emphasis is heavily on simultaneous, in-situ measurements of photochemically-related species. We are long past the point where a single stratospheric measurement of a species like nitric oxide is of value. It is now generally recognized that significant improvement in our understanding will only come from a series of coordinated measurements of the complete oxides of nitrogen family, for example. The same is largely true for similar atmospheric science questions, like that surrounding the continued use of fluorocarbons.

It is perhaps worth noting that one of our currently-funded projects involves critical analyses of measurement data. This represents an initial modest effort modeled after the chemical kinetics data evaluation work of NBS mentioned earlier. Here, our main objective is to attempt to eliminate some of the unexplained variability in reported atmospheric measurements by a detailed review including consideration of such normally-ignored factors as prevailing local meteorology, corrections for method of sensor-altitude reporting, possible bias arising from choice of measurement technique, etc. We expect this initial step will pave the way for development of a methodology which will permit substantially more meaningful incorporation of such data into atmospheric models by those less skilled in interpretation than in their use.

Atmospheric Models

It would be desirable to actually observe and quantitatively measure any atmospheric effects which might arise from high altitude aircraft exhaust, but it is not practical to do so, since the effects at present are far too small to be directly detected. Thus, to provide the information upon which future designs should be based, it is necessary to use predictive atmospheric models. The objective of our work in this program area is to maintain and continually update our capability to synthesize the information available from the best atmospheric models to analyze and predict the environmental effects from high altitude aircraft emissions. The project areas included are as follows:

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|----------------------------|-------------------------|
| 1-Dimensional | Thermal-Radiation |
| 2-Dimensional | Chemical Kinetics |
| 3-Dimensional | Sensitivity Studies |
| Theoretical Considerations | Meteorological Analysis |

This program area includes, in addition to the expected use of one-, two- and three-dimensional atmospheric transport models (with and without coupled chemical kinetics and thermal-radiation calculations), three investigations which deserve further examination.

FAA values sensitivity studies highly. By carefully combing through a model to ascertain which input parameters or assumed relationships (like chemical reaction rates, etc.) have the greatest impact on the model results, we can develop a good idea of the relative importance of the uncertainties in these factors. Thus, this approach provides a unique management tool in our problem-oriented study: we are able to rank order the priorities in our

research support, and are better able to plan a program where the expenditure of research funds is closely tied to optimum return — a corresponding improvement in the reduction of uncertainty in the model's output.

A second point we should explain more fully is the part called "meteorological analyses." It is clear to us that, since the debate on the effects of high altitude flight began, there has been generally insufficient attention paid to fundamental meteorology. Atmospheric contaminants like nitric oxide are moved about by air motions and, for the high altitude flight problem, these motions are quite critical. The tropopause region, which separates the stratosphere from the troposphere, is exceedingly complex from the meteorological viewpoint. Transport in and from this region—either upward to the stratosphere, which produces enhanced effects on ozone, or downward to the troposphere, where the substances are rapidly removed from the atmosphere—is poorly understood. We intend to focus attention on developing a much better understanding of this so-called stratosphere-troposphere exchange. Meteorology of the tropopause region is an area of much greater significance to understanding aircraft effects than to questions about the stratospheric effects of fertilizers or fluorocarbons, substances which are not directly injected into this region. The region of interest, between about 10 and 25 km, is dominated by transport effects rather than chemical/photochemical processes.

Finally, we will conduct several studies of a theoretical nature to better understand the limits within which predictive models can be reasonably relied upon. To cite one example of this type of problem, most are aware that the so-called "eddy diffusion coefficient" employed as the transport mechanism in a one-dimensional model is generally derived by inversion of the global-average vertical distribution of mixing ratio obtained for a reliable "tracer" of atmospheric motion, such as methane (see ref. 4). In performing this inversion, care must be taken to include proper considerations of all significant atmospheric sources and sinks of the tracer to avoid misinterpreting, for example, a chemical loss process as more rapid than atmospheric transport. What is not generally recognized is the implication of the acknowledged fact that this approach does not explicitly decouple the chemistry from the transport (ref. 5). Rather, in using the model, one assumes that the calculated chemical changes — for example, in ozone — do not significantly affect the previously-assumed formulation of atmospheric transport. But what happens when new data indicate the need for a modification of one of the parameters that went into the original derivation of the eddy diffusion coefficient? Clearly, the old calculation is now invalid, but what implication does this have for its continued use? Such is typical of the as-yet-unresolved questions we will attempt to answer.

PROGRAM STATUS

The preceding paragraphs have briefly reviewed four of the major areas of study in the FAA High Altitude Pollution Program. The program has been underway for about a year now, and is planned to continue for another seven, unless we can develop reliable answers in a shorter time. In the next few months, we will complete and release a major report on this program. The

report will summarize the status of our current understanding of the environmental effects, discuss the immediacy of the need for regulatory action directed at ensuring reduced levels of cruise-altitude exhaust emissions, and detail plans for further work in the program. Two other reports will also be shortly available as a result of our contracted studies. The first, developed under contract with the Institute for Defense Analyses, Arlington, VA., will provide a relatively comprehensive state-of-the-art summary and comparison of reports which have treated these subjects over the last several years. Major points of agreement and difference will be noted and expanded upon. The second, developed for HAPP by Lawrence Livermore Laboratory of the Energy Research and Development Administration, will summarize the first year of their participation in the program — the major activity in our atmospheric modeling program area. Of particular interest is their work in developing a better understanding of the uncertainties in our present knowledge.

Obviously, the contents of these not-yet-completed reports cannot be summarized here. We can point to some of the areas which will be discussed in them, however.

Uncertainty Studies

We have developed information which indicates that the uncertainties in the aircraft/ozone-reduction relationship estimated by both the CIAP and National Academy of Sciences studies, and summarized above in Table I, reflected a significant overestimate of the accuracy of their predictions. Specifically, it is likely that the estimates of SST effects on ozone were overestimated by perhaps an order of magnitude or more. This should not be confused with the uncertainty previously placed on those estimates — a factor of two to three. These differences arise principally from three new factors: improved understanding of the rates at which important chemical reactions proceed in the stratosphere, especially those involving the oxides of nitrogen; similarly improved data on reactions involving water-derived species; consideration of the interactions between aircraft-produced oxides of nitrogen and fluorocarbon-produced oxides of chlorine.

Subsonic Aircraft Effects

Both the previously-cited studies extrapolated results obtained from models developed primarily for evaluation of 20 km cruise-altitude effects to regions well below that altitude, to include consideration of subsonic aircraft as well. Both correctly pointed to difficulties inherent in estimating transport characteristics in this difficult region, which was implicitly the reason for assigning much higher uncertainty—a factor of ten—to projections of ozone reduction from subsonic aircraft flight in the upper troposphere and lower stratosphere. Neither study, however, contemplated that secondary effects in the models' treatment of ozone-producing chemistry—effects which were known at the time (ref. 6) — would have a significant impact on their findings.

Our study to date indicates the likelihood, in part owing to our including ozone-producing reactions in model calculations, that previous estimates of the effects of subsonic aircraft on ozone are seriously in error, to the point where it is now reasonable to project an increase in ozone for many—if not all—of these flights.

Effect of Including Fluorocarbons

The recently-completed National Academy of Sciences Study (1976) on the effects of fluorocarbons (Freons) on stratospheric ozone documented the direct and indirect (through reactions with water vapor-derived species) coupling of the reactions of oxides of nitrogen and fluorocarbon-derived chlorine-containing species. Implicit in their analysis is the fact that these later results have a major impact on the earlier calculations of aircraft effects. Unfortunately, this was not explicitly treated by the academy, and the task of such a synthesis is left to others. What can be said now is that the effect of fluorocarbons already released into the atmosphere is to reduce the ozone-destruction potential of a unit injection of oxides of nitrogen by aircraft. (Indeed, this is one of the reasons that earlier estimates of aircraft effects were too high, as mentioned above.) At the same time, this factor adds a major complication to analyses of future fleet effects, since the amount of stratospheric chlorine must now be forecast, in addition to the size of the aircraft fleet.

CONCLUDING REMARKS

Considerations of high altitude emissions effects must form an important part of designing environmentally-compatible advanced generations of aircraft. The Federal Aviation Administration has acknowledged its responsibility to provide the guidance required by government-industry teams working toward the goal of improving the quality of service rendered by the nation's air transportation system. FAA has made a major, long-term commitment to this end by establishing and conducting the High Altitude Pollution Program, fully supported by the Secretary of Transportation. Results of this effort to date substantiate the need for this activity, by demonstrating the inaccurate and qualitative nature of previous efforts. It is important to recognize, however, that the preliminary findings described earlier are necessarily tentative in nature, and require further refinement and documentation before they can form a sufficiently reliable basis for policy formulation. We appreciate and will continue to rely heavily upon cooperation with other government- and industry-sponsored efforts to achieve our goal.

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TABLE I.- CIAP AND NAS UNCERTAINTY ESTIMATES

Ozone Reduction In Northern Hemisphere

Percent Per 100 Aircraft
(1974 Engine Emissions Assumed)

	NAS Estimate	Uncertainty Factor	CIAP Estimate	Uncertainty Factor
Subsonic (~ 11 km)	0.02	± 10	0.014	-10;+2
Subsonic (13.5 km)	0.2	± 10	0.079	-10;+2
Supersonic (16.5 km)	0.7	± 3	0.39	-3.3;+1.5
Supersonic (~ 19 km)	3	± 2	1.74	-3.3;+1.5

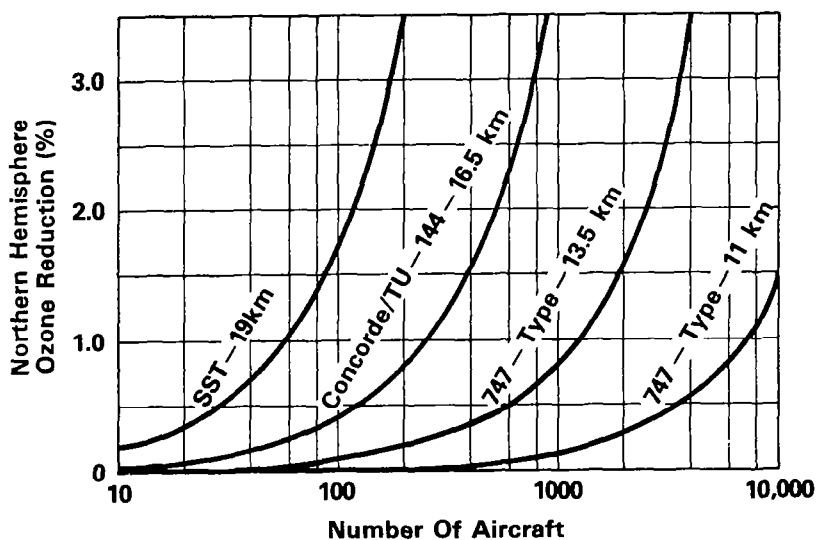


Figure 1.- CIAP - estimated ozone reduction.