An Interim Assessment of the AEAP's Emissions Characterization and Near-Field Interactions Elements

ISBN
978-0-309-05846-9

28 pages
6 x 9
PAPERBACK (1997)

Panel on Atmospheric Effects of Aviation, National Research Council

An Interim Assessment of AEAP's Emissions Characterization and Near-Field Interactions Elements

Panel on Atmospheric Effects of Aviation

Board on Atmospheric Sciences and Climate

Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Support for this project was provided by the National Aeronautics and Space Administration under grant NASW-4938 order no. 109. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the above-mentioned agency.

International Standard Book Number 0-309-05846-5

Additional copies of this report are available from:
National Academy Press
2101 Constitution Ave., NW
Box 285
Washington, DC 20055
800-624-6242
202-334-3313 (in the Washington, D.C. metropolitan area)

Printed in the United States of America

PANEL ON ATMOSPHERIC EFFECTS OF AVIATION

ALBERT J. KAEHN, Jr. (*Chair*), Brigadier General, U.S. Air Force, retired
*DONALD W. BAHR, retired (formerly with General Electric Aircraft Engines)
JACK G. CALVERT, National Center for Atmospheric Research, Boulder, Colorado
ANTONY D. CLARKE, University of Hawaii, Honolulu
*WILLIAM E. COOPER, Michigan State University, East Lansing
DIETER H. EHHALT, Institut für Atmosphärische Chemie, Jülich, Germany
CLAIRE GRANIER, Université Paris, France; National Oceanic and Atmospheric Administration and Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado
*EDWARD GREITZER, Massachusetts Institute of Technology, Cambridge
JAMES R. HOLTON, University of Washington, Seattle
HAROLD S. JOHNSTON, University of California, Berkeley
*KONRAD MAUERSBERGER, Max-Planck-Institut für Kernphysik, Heidelberg, Germany
MICHAEL OPPENHEIMER, Environmental Defense Fund, New York, New York
RUTH A. RECK, Argonne National Laboratory, Illinois
W. GEORGE N. SLINN, Cascade Scientific Research Corporation, Richland, Washington
KNUT H. STAMNES, University of Alaska, Fairbanks
YUK L. YUNG, California Institute of Technology, Pasadena

Staff

WILLIAM A. SPRIGG, Director
ELLEN F. RICE, Program Officer
DORIS BOUADJEMI, Administrative Assistant

---

*Members of the Emissions working group

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ERIC J. BARRON (*Co-Chair*), Pennsylvania State University, University Park
JAMES R. MAHONEY (*Co-Chair*), International Technology Corporation, Torrance, California
SUSAN K. AVERY, CIRES, University of Colorado, Boulder
PETER M. BANKS, ERIM, Ann Arbor, Michigan
LANCE F. BOSART, State University of New York, Albany
FRANCO EINAUDI, NASA Goddard Space Flight Center, Greenbelt, Maryland
MARVIN A. GELLER, State University of New York, Stony Brook
DONALD M. HUNTEN, University of Arizona, Tucson
CHARLES E. KOLB, Aerodyne Research, Inc., Billerica, Massachusetts
WITOLD F. KRAJEWSKI, The University of Iowa, Iowa City
THOMAS J. LENNON, Sonalysts, Inc., Alexandria, Virginia
MARK R. SCHOEBERL, NASA Goddard Space Flight Center, Greenbelt, Maryland
ROBERT J. SERAFIN, National Center for Atmospheric Research, Boulder, Colorado
JOANNE SIMPSON, NASA Goddard Space Flight Center, Greenbelt, Maryland
NIEN DAK SZE, Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts

Staff

WILLIAM A. SPRIGG, Director
LOWELL SMITH, Senior Program Officer
H. FRANK EDEN, Senior Program Officer
DAVID H. SLADE, Senior Program Officer
ELLEN F. RICE, Reports Officer
DORIS BOUADJEMI, Administrative Assistant
KELLY NORSINGLE, Senior Project Assistant
TENECIA A. BROWN, Project Assistant

COMMISSION ON GEOSCIENCES, ENVIRONMENT, AND RESOURCES

GEORGE M. HORNBERGER (*Chair*), University of Virginia, Charlottesville
PATRICK R. ATKINS, Aluminum Company of America, Pittsburgh, Pennsylvania
JAMES P. BRUCE, Canadian Climate Program Board, Ottawa, Ontario
WILLIAM L. FISHER, University of Texas, Austin
JERRY F. FRANKLIN, University of Washington, Seattle
THOMAS E. GRAEDEL, Yale University, New Haven, Connecticut
DEBRA S. KNOPMAN, Progressive Foundation, Washington, D.C.
KAI N. LEE, Williams College, Williamstown, Massachusetts
PERRY L. McCARTY, Stanford University, California
JUDITH E. McDOWELL, Woods Hole Oceanographic Institution, Massachusetts
RICHARD A. MESERVE, Covington & Burling, Washington, D.C.
S. GEORGE PHILANDER, Princeton University, New Jersey
RAYMOND A. PRICE, Queen's University at Kingston, Ontario
THOMAS C. SCHELLING, University of Maryland, College Park
ELLEN K. SILBERGELD, University of Maryland Medical School, Baltimore
VICTORIA J. TSCHINKEL, Landers and Parsons, Tallahassee, Florida
E-AN ZEN, University of Maryland, College Park

Staff

STEPHEN RATTIEN, Executive Director
STEPHEN D. PARKER, Associate Executive Director
MORGAN GOPNIK, Assistant Executive Director
GREGORY SYMMES, Reports Officer
JEANETTE SPOON, Acting Administrative Officer
SANDI FITZPATRICK, Administrative Associate
MARQUITA SMITH, Administrative Assistant/Technology Analyst

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Preface

This interim assessment is a product of the NRC Panel on the Atmospheric Effects of Aviation (PAEAN). PAEAN consists of sixteen people selected to provide expertise in relevant fields that include field observations, laboratory chemistry, atmospheric dynamics and modeling, aircraft combustors, climate, and public policy. The charge from its NASA sponsor, the Atmospheric Effects of Aviation Project (AEAP), is to provide assessment of and guidance to AEAP by evaluating the appropriateness of the AEA project's research plan, appraising the project-sponsored results relative to the current state of scientific knowledge, identifying key scientific uncertainties, and suggesting research activities likely to reduce those uncertainties.

AEAP has six primary elements: Global Modeling, Atmospheric Observations, Laboratory Studies, Operational Scenarios, Near-Field Interactions, and Emissions Characterization. This report examines the last two project elements, which are both exhaust-related. Emissions Characterization is determining the constituents discharged under cruise operating conditions for current and future engines, and Near-Field Interactions is exploring how chemical, dynamic, or physical processes in aircraft wakes can alter these constituents. The effects of the current subsonic fleet are of great concern at present, and the Emissions Characterization and Near-Field Interactions project elements are vital to assessing those effects correctly. This interim report reviews the two elements and recommends some changes in emphasis.

PAEAN has met three times as a panel, and each of its working groups—supersonic/stratospheric, subsonic/tropospheric, and emissions—has met on its own. The emissions group put together the initial draft of this document, and we thank them for their efforts. We appreciate the skill and perseverance of our staff officer and editor, Ellen Rice, and the administrative support of Doris Bouadjemi. Last, we are grateful to the many people, both those involved with AEAP and those outside it, who through briefings and reports kept us apprised of these two elements of the project and related work.

Albert J. Kaehn, Jr.
PAEAN Chair

Contents

Executive Summary

The objective of NASA's Atmospheric Effects of Aviation Project (AEAP) is to develop scientific bases for assessing atmospheric impacts of the exhaust emissions discharged by fleets of subsonic and supersonic civil aircraft. Emissions Characterization (Element 9.6 of AEAP) is tasked with determining the constituents discharged under cruise operating conditions for current and future subsonic-transport engines as well as ultra-low-emission future supersonic-transport engines. Near-Field Interactions (Element 9.5) explores how chemical, dynamic, or physical processes in aircraft wakes can alter these constituents. This interim assessment reviews the status of these elements, and suggests some change in priorities within each one.

The discussion of the Emissions Characterization element examines the selection of the constituents to be measured, the venue for conducting the measurements, and the methods of obtaining the measurements. The panel recommends that measurements of SO_2, SO_3, and OH be given a higher priority, and that methods for measuring these constituents and characterizing soot particulate be refined. Also recommended is increased emphasis on testing actual subsonic engines (preferably engine models recently introduced into operational service), rather than relying heavily on combustor test rigs. Tests of an advanced military supersonic aircraft engine are recommended to assess the degree of SO_x oxidation.

For the Near-Field Interactions element, the development of analytical models and the current measurement activities are reviewed. The panel recommends that the completion of at least preliminary versions of plume and wake models be given top priority so that their integration to form a suite can begin soon; corollary to this is a recommendation for prompt dissemination of flight-test datasets.

Introduction

The overall objective of the NASA Atmospheric Effects of Aviation Project (AEAP) is to develop scientific bases for assessing atmospheric impacts of the exhaust emissions discharged during cruise operations by fleets of subsonic and supersonic civil aircraft. The AEAP is comprised of two major entities, the Subsonic Assessment (SASS) project and the Atmospheric Effects of Supersonic Aircraft (AESA) project. The SASS project is being conducted under the auspices of NASA's Advanced Subsonic Technology Program (ASTP), and the AESA project under those of NASA's High-Speed Research Program (HSRP). Because of their shared focus on environmental impact, program management of these two assessment efforts has been consolidated into an overall program, the AEAP.

The purpose of the SASS project is to assess the possible impacts of both current and future fleets of subsonic civil transport aircraft. At cruise altitudes these aircraft operate in the upper troposphere and the lower stratosphere. The AESA project, on the other hand, is designed to assess the impacts of a potential future fleet of high-speed civil transports (HSCTs). These supersonic aircraft are expected to feature the use of advanced aircraft and engine technology being evolved in the NASA HSRP. Their cruise operations will take place at mid-stratospheric altitudes (in the range of 16 to 20 km).

The AESA project, which was initiated first, has been in progress for about six years. Its current status is summarized in *1995 Scientific Assessment of the Atmospheric Effects of Stratospheric Aircraft* (Stolarski et al., 1995). The SASS project was started in 1994. Its current status is summarized in *Atmospheric*

Effects of Aviation: First Report of the Subsonic Assessment Project (Thompson et al., 1996).

Among the six primary elements of the AEAP are Emissions Characterization (Element 9.6) and Near-Field Interactions (Element 9.5). The objective of the Emissions Characterization effort is to determine the exhaust-emission constituents and levels discharged at cruise operating conditions by current-technology subsonic-transport aircraft engines, projected future advanced-technology subsonic engines, and projected advanced-technology supersonic-transport engines equipped with ultra-low-emission combustors. The objective of the Near-Field Interactions effort is to determine whether and how fluid dynamic, chemical, and/or physical processes in aircraft wakes can alter the engine-emission constituents or their deposition altitude.

The NRC's Panel on Atmospheric Effects of Aviation (PAEAN) was requested to evaluate the appropriateness of AEAP's research plan, appraise the project's results, and suggest how best to reduce the remaining uncertainties. (An earlier panel did the same for the AESA project (NRC, 1994).) This report accordingly provides an interim assessment of the NASA Emissions Characterization and Near-Field Interactions efforts conducted to date, as summarized in the two publications mentioned earlier. It is intended to aid in detailed planning of the future work of these two AEAP elements. A second PAEAN report, *Interim Review of the Subsonic Assessment Project: Management, Science, and Goals* (NRC, 1997), makes recommendations for the SASS component. A third report, dealing with AESA, is in process.

Emissions Characterization

The Emissions Characterization element encompasses a wide range of research activities. In addition to a variety of combustor-rig and engine-emission measurement activities, extensive efforts are being conducted to develop advanced emission-measurement methods and associated computational fluid dynamics (CFD) analytical models.

As of the end of fiscal year 1996, approximately 68 percent of the funding allocated to this element had been expended or committed. The work planned for Emissions Characterization is scheduled to be completed during fiscal year 2001. The funding available for the remaining five years is not large, considering the breadth of activities and the magnitude of test efforts—on the order of $1.91 M. The three key considerations in the execution of the work scope of this element are the prioritization of the engine-exhaust constituents to be measured, the selection of venues for conducting these measurements, and the selection of measurement methods.

EMISSION CONSTITUENTS TO BE MEASURED

A prioritization of the constituents to be measured was initially generated in 1992 as a part of the AESA project. This prioritization effort was carried out by a committee of experts, the Engine Exhaust Trace Chemistry Committee (EETCC), that was specifically established to guide and support the work being conducted within this research area. The results of the EETCC's prioritization efforts are summarized in *Engine Trace Constituent Measurements Recommended for the Assessment of the Atmospheric Effects of Stratospheric Aircraft* (Miake-Lye et al., 1992). A summary version of the prioritized listing contained in that report is presented in Table 1. At the start of the SASS project in 1994, the EETCC determined that this AESA prioritization was also applicable to the new project's emission-characterization efforts.

But in light of the recently obtained in-flight measurements of the composi-

TABLE 1 Summary of 1992 EETCC Priorities for Engine Emissions to be Measured

First Priority	Second Priority	Low Priority
NO_x	SO_2	H_2O
Soot particulate	SO_3/H_2SO_4	HO_2/H_2O_2
	OH	CH_4
	HNO_3	Non-methane hydrocarbons
	Total hydrocarbons	CO
	CO_2	Cl
		Metal oxides

tion of the plume of a Concorde aircraft, as described in a paper by Fahey et al. (1995) and in NASA's AESA report (Stolarski et al., 1995), some adjustments of this prioritized listing may now be needed. The particulate-emission measurements obtained in these in-flight tests indicate a high degree of sulfur dioxide (SO_2) oxidation to condensed sulfate. This finding is surprising, especially because the data suggest that SO_2 oxidation by hydroxyl radicals (OH) is not the dominant cause of the conversion. The 1995 AESA report states that a mechanism that rationalizes the observed degree of SO_2 oxidation has yet to be identified. The report also notes that increases in sulfate-aerosol surface area in the lower stratosphere may result in ozone depletion, and that this impact is maximized if the sulfate is formed within the exhaust plume. These effects are cited as sources of uncertainties in predicting the impacts of HSCT fleets on the ozone column. (The topic is also discussed in PAEAN's recently published report on SASS (NRC, 1997).)

NASA's Concorde measurements are of considerable significance in that they are the first in-flight measurements made behind a supersonic aircraft. It is of especial importance that the measured nitrogen oxides (NO_x) emission indices are in good agreement with those obtained previously in emission tests of a Concorde aircraft engine (Olympus) conducted in an altitude test cell. However, any specific inferences concerning the SO_2 oxidation characteristics observed in these tests must be tempered by the fact that the Olympus engines that power the Concorde aircraft embody old technology (circa 1965). The future HSCT engine is likely to have a very different thermodynamic cycle, and thus very different exhaust-gas characteristics and compositions. In particular, the NO_x and soot-particulate emission levels of such an engine are expected to be considerably different from those of the Olympus engine.

Accordingly, the direct relevance of the high degree of SO_2 oxidation observed in the in-flight tests is unknown. Nevertheless, in view of the significant atmospheric impacts that could result from such high conversion rates, an improved understanding is needed of the chemical and particulate formation processes that occur in engine exhaust plumes, particularly in the near field. These mechanisms are being investigated in other elements of AEAP. As an important contribution to this understanding, however, additional engine tests (described below) are needed to determine the degrees of SO_2 oxidation that occur within engines. Such information is necessary as the starting point for studies to determine the degrees of SO_2 oxidation that can occur at various stages within the plume. Some data relevant to this question will also be forthcoming from ongoing U.S. and European flight-measurement projects.

Some changes to the EETCC's prioritization are thus recommended. Measurements of the SO_2 and SO_3 (sulfur trioxide) emission levels of engines should be changed from second priority to first. Also, because of its importance in near-field chemistry, consideration should be given to a higher priority for OH measurements. In the AESA-related testing, these measurements should be obtained with engines that are more representative of the eventual HSCT aircraft engine. Supersonic military aircraft engines are suitable candidates, being fairly similar in design and operating features to the currently proposed HSCT engine.

VENUES FOR CONDUCTING EMISSION MEASUREMENTS

A second issue of major importance in the execution of the Emission Characterization element is the selection of venues for conducting measurements. Engine tests, made either during flight or in altitude test cells, are preferred. Because of the high costs of such testing, however, considerable reliance on combustor-rig tests of various kinds is currently featured in the planned work of this element.

While attractive from a cost standpoint, the use of combustor-rig tests for the acquisition of emission data does have some significant limitations. Obtaining representative samples at the combustor-exit plane with gas-extraction methods is difficult because most current subsonic engines have large radial and circumferential concentration and temperature gradients. With non-intrusive measurement techniques, obtaining optical access to the combustor-exit gas flow is usually difficult because of adverse geometries and hostile environments. Also, in the case of some constituents, concentrations measured at the combustor-exit plane may not be representative of those existing at the engine-exit plane. This is certainly true for highly reactive species, such as OH, and may also be true for several other species, such as soot particulate, SO_2, SO_3, and hydrocarbons.

To resolve these latter shortcomings, analytical models need to be used to quantify any chemical changes occurring in the combustion gas as it flows from the combustor-exit plane to the engine-exit plane. The development and validation of such highly complex, sophisticated 2-D and 3-D computational fluid dynamics models are formidable undertakings. The models being developed as part of this AEAP activity are still some way from usable. An assessment of the progress and expected results of these efforts will be made when additional information on their status is available.

In the case of soot particulate, obtaining accurate measurements of total mass, size distribution, and other characteristics at the combustor-exit plane is especially difficult with existing gas-sampling techniques. The combustion-gas pressures at the sampling plane are quite high (from several to tens of atmospheres). Before the characteristics of the sampled particulate matter can be measured, the pressure of the sample of gas must be reduced to essentially one atmosphere. Completing this pressure reduction without simultaneously altering some of the particulate characteristics is a challenge that has not yet been fully met.

For these reasons, and given the limited remaining budget for this AEAP element, an increased emphasis on engine testing at cruise-altitude operating conditions and a corresponding decreased reliance on combustor-rig testing are recommended for the present. In view of the funding limitations of this element, aggressive efforts to seek out and capitalize on opportunities for conducting such testing on a piggyback basis—taking advantage of other experiments to add emissions instrumentation—are strongly encouraged. To the extent possible, these tests should be patterned after the excellent engine-test program conducted as a part of this element during 1995 at the Arnold Engineering Development Center (AEDC) at Arnold Air Force Base. In this extensive test series, gaseous and particulate emission data were obtained in piggybacked tests of a modern engine at both sea-level and altitude operating conditions. The large array of extracted-gas-sample and non-intrusive measurement methods used in conducting these tests, together with the test findings, are described in Howard et al. (1996).

Additional tests are needed to further quantify the emission characteristics of current-technology subsonic engines. These tests should preferably involve civil subsonic engines, especially newer models recently introduced into operational service. The latter engines will power the bulk of the subsonic aircraft fleet in service for at least the next three decades. Although more advanced subsonic engines will be gradually introduced, it is probably premature at this time to speculate on what their NO_x and other emission characteristics might be. The degrees of emission abatement that will have to be incorporated into the combustors of these future engines will, in fact, be in large part determined by the SASS project's assessments. These SASS findings will not be available until 2002, at the earliest. For these reasons, the planned rig testing of candidate Advanced Subsonic Technology Program combustors should be relegated to second-priority status.

In the case of the AESA-related activities of this element, primary reliance on engine testing is also recommended. While no HSCT engine prototypes exist at this time, a demonstrator engine equipped with an ultra-low-NO_x combustor will be tested during the 2001–2002 time period as part of the HSRP. The specific purpose of this demonstrator-engine test effort is to evaluate a version of the ultra-low-NO_x combustor concept that is being evolved in the HSRP. This engine-test series should provide an excellent opportunity to obtain a quantitative determination of the future HSCT aircraft engine's emission characteristics at cruise.

Prior to this dedicated-demonstrator test, engine tests to assess the degrees of SO_x oxidation occurring within engines should be conducted. For this purpose, piggybacked tests of an advanced military supersonic aircraft engine are recommended.

METHODS OF OBTAINING EMISSION MEASUREMENTS

The third key issue is the selection of measurement methods for use in the engine and combustor-rig tests. For some constituents (such as NO_x, CO_2, CO, hydrocarbons, and soot particulates), extractive sampling and analysis methods are well developed. Accordingly, in any given engine or combustor test series, the concentrations of these constituents can be readily quantified. These measured concentrations can then be used to calculate emission-index (grams per kilogram of fuel) values, using known engine fuel–air ratio data. For other constituents (such as SO_2 and SO_3), well-established techniques for analyzing extracted-gas samples are not available. For the most part, non-intrusive methods of determining exhaust-gas constituent concentrations are still in the research stage. For these reasons, as a part of the work scope of this AEAP element, efforts have been made to develop improved extracted-gas sample-analysis methods, as well as new and/or improved non-intrusive analysis methods. Excellent progress has been made in both areas. Along with a standard suite of extracted-gas sample-analysis methods, these new and/or improved measurement methods were deployed in the above-described AEDC engine test series, with good success.

Further improved and/or new methods for measuring emitted levels of soot particulates, OH, SO_2, and SO_3 at the engine exhaust-nozzle exit plane are still needed, as they are for characterizing the particulates. Intensified efforts to meet these needs are recommended. In the case of soot-particulate characterization, refinement and validation of the methods evolved to date in this AEAP element should receive greater emphasis. In the case of OH-concentration measurement, further refinement of the UV-absorption method currently being developed by AEAP would be desirable. And for measuring SO_2 and SO_3 concentrations, suitable new extracted-gas sample-analysis methods and/or non-intrusive sampling and analysis methods are needed. For instance, tunable-diode-laser absorption spectroscopy should be sensitive enough to determine SO_3 (which is so reactive a non-intrusive method is needed) and SO_2 concentrations, via a multiple-pass optical system set up to sample across the engine-exit plane. Efforts to evolve and refine the hydrocarbon-speciation methods currently being pursued as a part of the work scope of this AEAP element should also continue. In all cases, emphasis should be focused on measurements at the engine-exit plane, rather than at the combustor-exit plane.

Near-Field Interactions Element

The Near-Field Interactions element encompasses a broad range of analytical model-development and measurement activities. The prime objective of the measurements is to provide the detailed test data needed to assess the accuracy and completeness of the models. The combined goal of the modeling and measurement efforts is to describe and quantify the chemical and physical processes that occur in HSCT and subsonic-aircraft wakes during cruise operations. These processes occur in three identifiable regimes: engine exhaust-plume, wake-vortex, and vortex-breakup/wake-dispersion. The last regime, which typically extends to a distance of more than 20 km behind the aircraft in the case of subsonic civil transports, is where the engine exhaust gases or their chemical derivatives are mixed into the background atmosphere.

Through fiscal year 1996, approximately 53 percent of the funding allocated to this AEAP element has been expended or committed. The work planned for Near-Field Interactions is scheduled to be completed during fiscal year 2001. The funding available for the remaining five years of this element is on the order of $3.55 M.

ANALYTICAL MODEL DEVELOPMENT ACTIVITIES

A set of computer models is being developed to describe the fluid dynamic, chemical, and condensation processes that occur in each of the three exhaust-flow/atmospheric-mixing regimes behind the aircraft. As a part of the AESA project, some models of the regimes closest to the engine-exit plane were evolved. Models of the wake-dispersion regime (20 or more km behind the engine) are currently being developed. Also, as a result of the findings of the Concorde aircraft far-wake sampling experiment conducted with the NASA ER-2 aircraft, modeling efforts are being initiated to describe the particulate-formation processes that occur in aircraft wakes.

To date, progress in validating any of these models has been constrained by a lack of available suitable datasets on near-field interactions. The capabilities and accuracy of these models are thus not well established at this time.

Aggressive efforts to expedite the development and validation of this suite of computer models are recommended. At least first-cut versions of these individual models are required so that the important effort of integrating them can be initiated. Because of the complexity of these individual models and their likely interdependence, the integration task can be expected to be a challenging undertaking, possibly involving several iterations, before emissions can be "tracked" from the exhaust-plume through the wake-vortex into the wake-dispersion regime of the model suite.

MEASUREMENT ACTIVITIES

Flight-test programs to acquire near-field interaction measurements are in progress. One such program involves the use of the NASA Sabreliner as the airborne platform. Another involves participation in the AEAP Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS), which employs a DC-8 aircraft as the platform. Other aircraft platforms, including participation in the use of the NASA ER-2 aircraft, are being considered for use in future flight-test campaigns. The overall intent of these campaigns is to acquire quantitative measurements of the parameters shown in Table 2.

The variety and sophistication of the instrumentation suites being used, or being considered for use, in these campaigns should enable them ultimately to yield extensive, high-quality datasets. These datasets are expected to be valuable for testing and validating the various analytical models that are currently being developed. Once successful measurements have been made, the promptest possible dissemination of the datasets to the interested modelers is recommended, both to expedite the execution of the individual model development and validation tasks and to permit the modeling community to identify possible additional test-data needs.

TABLE 2 Near-Field Observables, by Region

Exhaust Plume	Wake Vortex	Vortex Breakup and Wake Dispersion
NO_x emission index (NO_x/CO_2)	All measurements in exhaust-plume column *plus:*	All measurements in wake-vortex column *plus:*
SO_x emission index (SO_x/CO_2)	H_2SO_4/H_2O condensation nuclei (number density, size distribution)	Photochemistry of exhaust-rich region
NO_y speciation (NO, NO_2, HONO, HNO_3)	Contrail droplet properties (number density, size distribution, composition)	Particulate evolution
SO_x speciation (SO_2, SO_3, H_2SO_4, $H_2SO_4 \cdot nH_2O$)	Contrail volume/shape	
HO_x speciation (OH, HO_2, H_2O_2)	Vorticity	
Soot-particulate properties (number density, size distribution, hydration)	Turbulence scale	
Gas-temperature profiles		
Exhaust-concentration profiles		

Recommendations

On the basis of the issues raised in this report, the panel recommends continued or increased emphasis by AEAP on the areas noted below.

EMISSIONS CHARACTERIZATION

1. Some revisions are recommended to the existing prioritization of the engine emissions to be measured. Specifically, measurements of SO_2, SO_3, and OH levels should be changed from second to first priority.

2. An increased emphasis on conducting tests of civil subsonic engines at cruise-altitude operating conditions, and a corresponding decreased reliance on combustor-rig testing, are recommended. Aggressive efforts to seek out and capitalize on opportunities for conducting such tests on a piggyback basis are strongly encouraged. To the extent possible, these tests should involve engine models that have been recently introduced into operational service. One important product of such tests should be validated procedures for calculating NO_x, CO, and hydrocarbon emission indices at cruise by adjusting the emission-index values contained in the International Civil Aviation Organization (ICAO) emissions database. This extensive database contains emission-index data, acquired at sea-level operating conditions, for a large number of in-service engines. In the case of the HSCT engine-emission-characterization effort, prime reliance should be placed on the planned tests of the demonstrator engine that will embody the ultra-low-NO_x combustor concept. This test series is a planned task of the HSRP. Prior to this dedicated-demonstrator test, engine tests at cruise-altitude operating conditions to assess the degrees of SO_x oxidation occurring within engines should

be conducted. For this purpose, piggybacked tests of an advanced military supersonic aircraft engine are recommended.

3. Intensification of current efforts to develop or refine methods for adequately measuring SO_2, SO_3, and OH concentrations, as well as soot-particulate characteristics, is recommended. In all cases, emphasis should be focused on measurements at the engine-exit plane, rather than at the combustor-exit plane.

NEAR-FIELD INTERACTIONS

1. Aggressive efforts to complete at least first-cut versions of the three plume and wake models are recommended, so that the integration of these models into a set can be initiated.

2. The promptest possible dissemination of the various flight-test datasets to the interested modelers is recommended, so as to expedite individual model development and validation tasks and to permit identification of possible needs for additional data.

References

Fahey, D.W., E.R. Keim, K.A. Boering, C.A. Brock, J.C. Wilson, H.H. Jonsson, S. Anthony, T.F. Hanisco, P.O. Wennberg, R.C. Miake-Lye, R.J. Salawitch, N. Louisnard, E.L. Woodbridge, R.S. Gao, S.G. Donnelly, R.C. Wamsley, L.A. Del Negro, S. Solomon, B.C. Daube, S.C. Wofsy, C.R. Webster, R.D. May, K.K. Kelly, M. Loewenstein, J.R. Podolske, and K.R. Chan. 1995. Emissions measurements of the Concorde supersonic aircraft in the lower stratosphere. Science 270, 70-74.

Howard, R.P., R.S. Hiers, Jr., P.D. Whitefield, D.E. Hagen, J.C. Wormhoudt, R.C. Miake-Lye, and R. Strange. 1996. Experimental Characterization of Gas Turbine Emissions at Simulated Flight Altitude Conditions. Technical Report AEDC-TR-96-3, USAF Arnold Engineering Development Center, Arnold AFB, Tennessee.

Miake-Lye, R.C., W.J. Dodds, D.W. Fahey, C.E. Kolb, and S.R. Langhoff. 1992. Engine Trace Constituent Measurements Recommended for the Assessment of the Atmospheric Effects of Stratospheric Aircraft. Report ARI-RR-947, Aerodyne Research, Inc., Billerica, Mass.

National Research Council (NRC). 1994. Atmospheric Effects of Stratospheric Aircraft: An Evaluation of NASA's Interim Assessment. Panel on Atmospheric Effects of Stratospheric Aircraft, National Academy Press, Washington, D.C.

NRC. 1997. Interim Review of the Subsonic Assessment Project: Management, Science, and Goals. Panel on Atmospheric Effects of Aviation, National Academy Press, Washington, D.C.

Stolarski, R.S., S.L. Baughcum, W.H. Brune, A.R. Douglass, D.W. Fahey, R.F. Friedl, S.C. Liu, R.A. Plumb, L.R. Poole, H.L. Wesoky, and D.R. Worsnop. 1995. 1995 Scientific Assessment of the Atmospheric Effects of Stratospheric Aircraft. NASA Reference Publication 1381, National Aeronautics and Space Administration, Washington, D.C.

Thompson, A.M., R.R. Friedl, and H.L. Wesoky (eds.). 1996. Atmospheric Effects of Aviation: First Report of the Subsonic Assessment Project. Reference Publication 1385, National Aeronautics and Space Administration, Washington, D.C.

Acronyms and Other Abbreviations

AEAP	Atmospheric Effects of Aviation Project
AEDC	Arnold Engineering Development Center
AESA	Atmospheric Effects of Stratospheric Aircraft (project)
ASTP	Advanced Subsonic Technology Program
CFD	Computational fluid dynamics
EETCC	Engine Exhaust Trace Chemistry Committee
HSCT	High-speed civil transport
HSRP	High-Speed Research Program
ICAO	International Civil Aviation Organization
NASA	National Aeronautics and Space Administration
PAEAN	Panel on Atmospheric Effects of Aviation
SASS	Subsonic Assessment (project)
SUCCESS	Subsonic Aircraft: Contrail and Cloud Effects Special Study
UV	Ultraviolet