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NASA/CP—1999-208918

Workshop on Aerosols and Particulates From Aircraft Gas Turbine Engines

Proceedings of a conference held at Ohio Aerospace Institute
and sponsored by NASA Glenn Research Center
Cleveland, Ohio
July 29–30, 1997

National Aeronautics and
Space Administration

Glenn Research Center

June 1999

We apologize for being so late in publishing this workshop conference. Please note that the intent is to print the content as it was presented at the conference and any recent editing/updates do not include the knowledge learned between then and now.

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FOREWORD

The Workshop on Aerosols and Particulates from Aircraft Gas Turbine Engines was held on July 29-30, 1997 at the NASA Lewis Research Center in Cleveland, Ohio. Participants consisted of approximately 100 United States citizens representing gas turbine industries, government agencies and the academic world. An attendance list is included in the proceedings. Their expertise included engine and airframe design, combustion processes and kinetics, atmospheric science, fuels, flight operations and instrumentation.

Although much work has been accomplished quantifying particulates from gas turbine engines, and reported as SAE Smoke Number, comparatively little is known regarding their characterization and formation mechanisms. With growing climatological concerns regarding the potential effects of aerosols and particulates on cloud formation this area has been identified as an emerging research field. The purpose of this workshop was to begin to address these issues in a systematic manner. Specifically, the objective was to evolve the elements of a prioritized program plan for the measurement and characterization of particulates, aerosol precursors and aerosols from aero gas turbine combustors and engines.

The workshop was conducted in three phases:

- Phase I consisted of a series of relevant presentations. Authorship credit is listed with each paper in these proceedings
- Phase II consisted of segregating attendees by their areas of expertise into three working groups consisting of trace chemistry, instrumentation and venues/procedures. The working groups employed participative discussions to achieve consensus in identifying and prioritizing areas of greatest concern
- Phase III consisted of working groups presenting their results to all attendees. This was followed by general discussions on each topic.

Subsequently, workshop results were incorporated by NASA into a research program in support of the High Speed Research and the Advanced Subsonic Programs.

Richard W. Niedzwiecki
NASA Glenn Research Center

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EXECUTIVE SUMMARY

Frederick Dryer
Princeton University
Princeton, New Jersey

and

Richard Niedzwiecki
NASA Glenn Research Center
Cleveland, Ohio

Sulfur issues with regard to atmospheric effects of aircraft emissions of aerosol and particulates have been discussed in detail in several recent reports (e.g., Albritton et al., 1996; Friedl et al., 1997). The National Research Council (NRC) Panel on Atmospheric Effects of Aviation (PAEAN) has recently reviewed the Emissions Characterization and Near-Field Interactions Elements of the Atmospheric Effects of Aviation Project (AEAP) research plan to appraise the projects results and to suggest how to best reduce remaining uncertainties in the assessment. (report to be issued, 1997). The lack of sulfur oxides effects on emissions from engines, and the dilemma that atmospheric plume data apparently show that SO_2 oxidation by OH in the aircraft wake is not the dominant source of condensed sulfate have motivated the NRC to recommend that prioritization of emissions characterization by the Engine Exhaust Trace Chemistry (EETC) Committee (Miake-Lye, 1992) characterization of sulfur oxides emissions be updated accordingly. This prioritization was originally developed to address issues associated with the Atmospheric Effects of Stratospheric Aircraft (AESA), was updated to include the Subsonic Assessment (SASS) at the inception of the program. Sulfur oxides characterization had been given a lower priority in that report, since the importance of aerosols to climatic effects had not been expected to be so closely coupled to emissions issues at the exit plane of the engine and the near-field production of aerosols. The recommendations of the NRC were to raise SO_x emissions characterization to a high priority, and to perform characterization studies on full scale engines characteristic of recent and imminent additions to the fleet.

The chair of the EETC committee (F.L. Dryer, Princeton) and NASA-Lewis recently organized a workshop (Niedzwiecki and Dryer, 1997) in response to the suggestions of the NRC and to develop consensus among experts in the field as to important issues and venues to be considered. The charges to the workshop were to:

- Reconsider the prioritizations of engine trace constituents for assessing impacts of aircraft, including the species to be measured, and the accuracy with which measurements are needed for addressing the AEAP assessments.
- Review and update both extractive and insitu measurement techniques for achieving the characterization needs.
- Determine the best venues and venue characteristics for performing the necessary measurements.

The general consensus of the workshop concurred that better characterization of SO_x and particulate emissions for a wider variety of engines are needed. The major points of agreement with regard to NRC recommendations were:

- Consign a higher priority to particulate and aerosol research (designated as SO_2, SO_3, OH).

- Refine instrumentation techniques to measure aerosols and aerosol precursors.
- Test actual commercial engines - as new as possible.
- Military engines are a good choice of test venue if commercial engines are not available.
- Perform piggyback tests where possible - request aid from our advisory committees to obtain engine venues.
- Validate NO_x, CO and THC emission concentrations under cruise conditions -- develop correlations for performing this.

However, participants believed that the recommendations of the NRC panel need to be further augmented to give the community an appropriate level of understanding of aerosol and aerosol precursor production and fate in aero-propulsion engines. While characterization of engine emissions of SO_2, SO_3 and OH are central to addressing aerosol/particulate effects, other constituents also impact the aerosol/particulate problem. These include particulate matter emitted from the aircraft, consisting of soot (carbon non-volatile), soot precursor components and PAH (non-volatiles), metals and silica emissions, and nitric acid.

Interpretations of recent measurements and current modeling studies indicate that growth of aerosol precursors occurs in the engine hot section downstream of the combustor. Hot section turbine cooling air appears to play a major role in defining aerosol precursors at the exit plane of the engine. The production is also related to the initial conditions entering the hot section, i.e. combustor emissions themselves. These characteristics suggest that the production of aerosol precursors is engine/hot section design dependent. Modeling of hot-section and nozzle interactions, including the detailed chemical kinetic and cooling air issues were concluded to be critical to understanding particulate/aerosol engine emissions characteristics, interpreting specific engine measurements, correlating emissions measurements across engine types, generating accurate predictions of emissions from future engine designs, and defining emission control parameters and strategies. Modeling will require further development and validation of modeling tools and validated kinetic/transport information on sulfur oxides kinetics and interactions with combustion products and other emissions species, including gas phase and heterogeneous components. Fundamental program elements involving both numerical modeling and fundamental experimental efforts were concluded to be important to meeting these needs. Determining appropriate hot section initial conditions was also viewed as essential, both in modeling the hot section/nozzle interactions, and in providing best estimates of the calculated nozzle exit plane parameters for input to modeling the near-field interactions down stream.

Engine tests are critically important to defining aerosol/particulate precursor issues. However, engine test venues remain very expensive and difficult to access. A typical test, piggybacked upon engine development testing costs approximately $500K. A dedicated engine test would cost more than an order of magnitude more. Manufacturers are (understandably) reluctant in making available their newest commercial engines. Thus rig tests on combustors and hot sections, which are much lower cost and readily available on a weekly basis, are essential to obtaining aerosol/particulate precursor data and technology base. In test rigs, flow, operational, and fuel parameter issues can be varied in a systematic manner to understand the non-linear fluid dynamic, chemical kinetic, and heat transfer issues in the presence of real-flow conditions. Given successful development of modeling

tools, data from combustor rigs can be used to determine impacts of engine design parameters prior to development of full-scale prototypes, and engine design differences among various engine designs and classes can be fully assessed. Specific engine tests to accomplish this task will be inordinately costly and thus are likely to yield results in only a small number of engine classes and for limited engine operating envelope conditions.

Workshop Organization:

Prof. Dryer, the co-chair of the workshop, opened the discussions with a brief review of the relationships of the High Speed Research (HSR) and the Advanced Subsonic Technology (AST) programs, and the missions of the AEAP and its sub-elements, the AESA and SASS projects. A brief history of the efforts of the EETC Committee, which Prof. Dryer chairs, was then given, including a review of the committee's purpose, and goals. Recommendations of the EETC Committee prior to recent technical revelations concerning the importance sulfur and aerosol/particulate emissions on both subsonic and high speed propulsion impacts on upper tropospheric and stratospheric ozone and upper tropospheric climatic issues were reviewed, and a synopsis of evidence supporting and questions concerning the role(s) of aerosol/particulates was presented.

A brief discussion of how sulfur oxidation kinetics interactions in the hot-section and nozzle play a role in the formation of aerosol precursors was given by Dr. Dryer, and the present deficiencies in validated sulfur oxidation kinetics were summarized. Mr. R. Niedzwiecki then reviewed the present programmatic issues addressing aerosol particulate testing in engines, and also added some discussion as to the relationship of the present needs to those likely to develop in consideration of the recent discussion of proposed EPA $PM_{2.5}$ emissions regulations and impacts in the vicinity of airports. Dr. R. Miake-Lye gave a description of the current status of the emissions measurement activities at both the engine exit plane and the aircraft near-field plume which led to the statement of problem. Dr. R. Kawa then reviewed the potential climate impact issues which point to a need for more definitive understanding of the aerosol/particulate and aerosol precursor problems.

To apprise workshop participants of other pertinent background, the following five technical overviews were presented:

- UMR MASS and Smoke Number - P Whitefield, D. Hagen, University of Missouri, Rolla
- Airborne Observations of Aircraft Aerosol Emissions - B. Anderson, NASA LaRC
- Data Correlation on Soot Emissions - H. Lilenfeld, Boeing
- Engine Test and Measurements - C. C. Wey, NASA LeRC
- Engine Hot Section Modeling - I. Waitz, S. Lukachko, MIT

To assist in developing a research plan, and to update the present EETC considerations with regard to aerosol/particulate issues, the workshop participants were then charged with addressing the following matters:

- Measurement Priorities-
    - What Should be measured?

    - What are the measurement requirements which should be met to best impact assessment needs?
- Measurement Techniques-
    - What Techniques are available?
    - What is the status (research or applied tools?) of the techniques?
    - What developments are needed to support measurements?
- Measurement Venues-
    - What in-flight measurements are needed? What venues are available?
    - What engine tests are needed? What venues are available?
    - Are sub-element tests (combustor development rig, sector, etc.) desirable? If yes, what are the venues?
    - Are fundamental theoretical, experimental, and/or computational efforts needed for understanding, correlating, and/or applying results?

The Workshop participants were then accordingly divided into three plan/working groups to consider the above problems. The working groups were:

- Trace Chemistry
- Instrumentation
- Sampling Procedures and Venues

Participants were encouraged to participate in the group(s) of specific interest to them, and the co-chairs worked in all three groups to assist in coordination. Additionally, the co-chairs of each group made presentations to all workshop participants describing the initial directions of inquiry after about five hours of deliberations. After an additional six hours of discussions, the group chairs presented summary overviews of their discussions for critical comment and coordination by all workshop participants. Following discussions and suggestions from the participants, summary reports of each working group were prepared by the group chairs. These summaries were reviewed by the respective working group chairs and the final summary reports and materials from each of these group are presented here.

Richard Niedzwiecki
NASA Glenn Research Center
Cleveland, Ohio

and

Frederick L. Dryer
Princeton University
Princeton, New Jersey

HSRP - High Speed Research Program
-developing new technologies of high speed aircraft propulsion (LPP- lean, premixed, pre-vaporized, RQL- rich-quench-lean designs).

AESA - Atmospheric Effects of Stratospheric Aircraft
-assessing primarily ozone perturbations effects of future high speed aircraft on primarily the 18-22 km region of the stratosphere.

SASS - Subsonic Assessment Program
-assess ozone perturbation effects as well as radiative (climatic) impact of subsonic aircraft emissions from both ozone layer/greenhouse effects and aerosol/cloud cloud scattering.

AEAP - Atmospheric Effects of Aircraft Project
-coordinating program for AESA and SASS projects.

Engine Exhaust Trace Chemistry (EETC) Committee (1992)

F. Dryer (Chair)
J. Facey, NASA-Hq
D. Fahey, NOAA
A. Hansen, LBNL
D. Hagen, U.Missouri, Rolla
P. Heberling, GE Aircraft Engines
R. Howard, AEDC
C. Jacimowski, NASA-Langley
H. Lilenfeld, McDonnell Douglas
S. Langhoff, NASA-Ames
R. Lohman, Pratt & Whitney
N. Marchionna, Stirling Thermal Motors Inc.
R. Miake-Lye Aerodyne Research Inc.
R. Niedwziecki, NASA-LeRC
R. Oliver, IDA
R. Pueschel, NASA-Ames
C.C. Wey, ARL/NASA-Le-RC
P. Whitfield, U Missouri, Rolla
J. Wormhoudt, Aerodyne Research Inc.

Engine Exhaust Trace Chemistry (EETC) Committee

Purpose:

(1992) -
Provide guidance and recommendations to HSRP/AESA in developing a future engine emissions measurement and assessment programs.

(1993)-
Provide guidance and recommendations on modifications/new issues raised by added consideration of SASS program, coordinated with AESA through the AEAP.

Engine Exhaust Trace Chemistry (EETC) Committee

Committee Charges:

-Prioritize engine trace constituents for assessing impacts of aircraft.
-Assess both extractive and insitu measurement techniques.
-Determine best venues for performing the necessary measurements

Engine Exhaust Trace Chemistry (EETC) Committee

-Prioritize engine trace constituents for assessing impacts of HSCT's:

•Those which directly impact ozone chemistry:

- **NO, NO_2, HNO_3, NO_y**

•Those which affect wake/plume chemical condensation phenomena:

- **total particulate mass,** size distribution, reactivity, SO_2/SO_3, H_2SO_4, OH, NMHC

•Those which might serve as design optimization indicators in engine development.

- CO_2

Sulfur Content of Jet Fuels

Current Regulation: SO_2 $EI_{reg} < 6$ g/kg-fuel

- Actual amount is typically a factor of ten less than current regulation.

- Eventual fuel sulfur content?
It's difficult to make it universally zero.

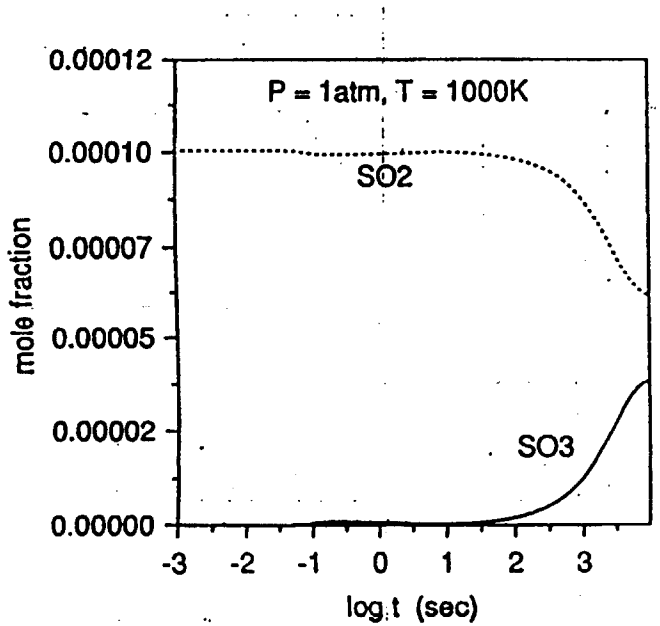
SO_x AND NO_x REACTIONS

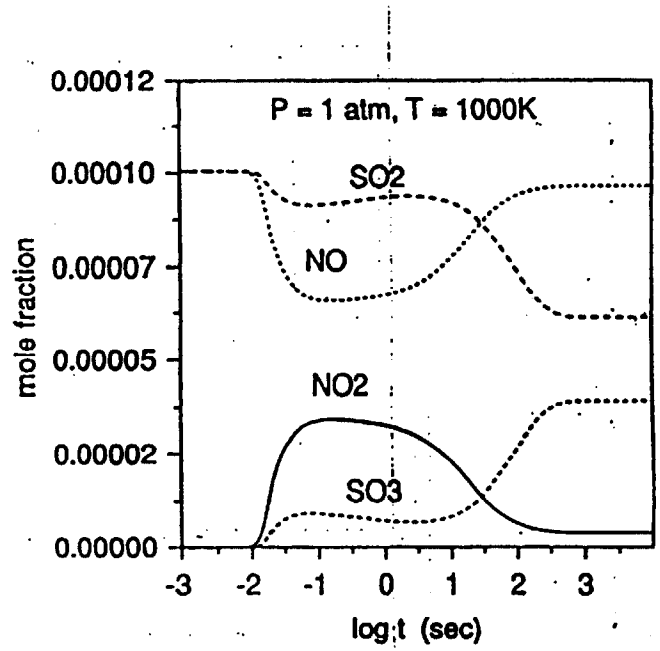
$$SO_2 + O + M \rightarrow SO_3 + M$$
$$SO_3 + HO_2 \rightarrow HSO_3 + O_2$$
$$HSO_3 + M \rightarrow SO_2 + OH + M$$

$$O + HO_2 \rightarrow O_2 + OH$$

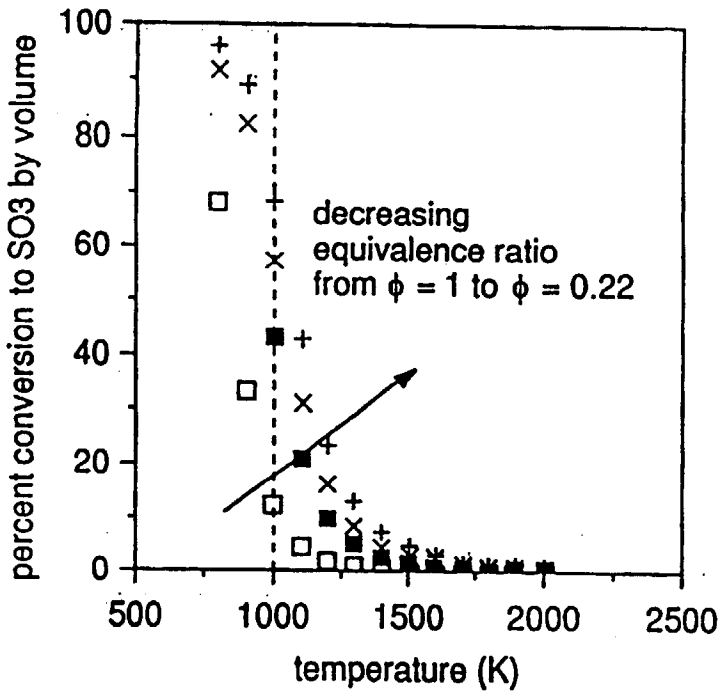
$$NO + HO_2 \rightarrow NO_2 + OH$$
$$NO_2 + H \rightarrow NO + OH$$

$$H + HO_2 \rightarrow OH + OH$$

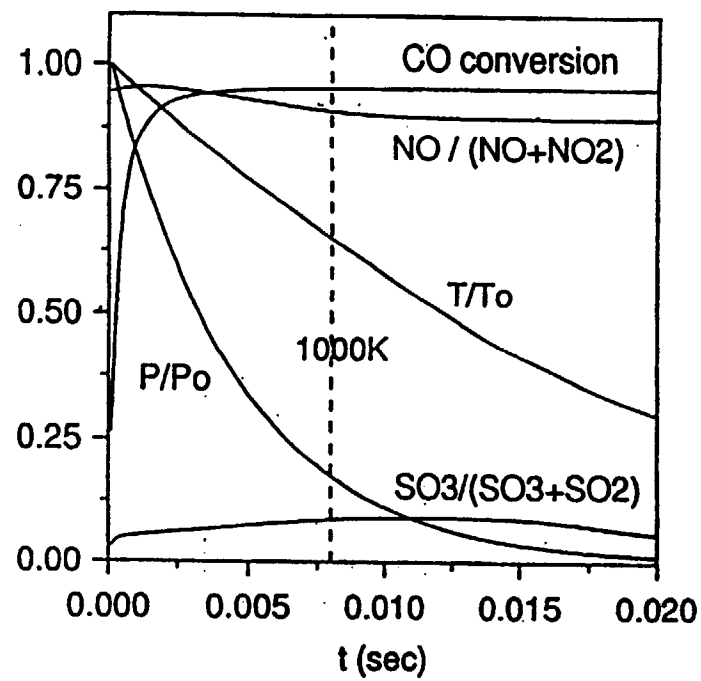

P = 1atm, T = 1000K
SO2
SO3
mole fraction
0.00012
0.00010
0.00007
0.00005
0.00002
0.00000
-3
-2
-1
0
1
2
3
log t (sec)


P = 1 atm, T = 1000K
SO2
NO
NO2
SO3
mole fraction
0.00012
0.00010
0.00007
0.00005
0.00002
0.00000
-3
-2
-1
0
1
2
3
log t (sec)

SO_3 / SO_2 RATIO



from Brown et al., Geophysical Research Letters, 23, 3603, 1996



isentropic expansion
To = 1500K
Po = 10 atm

Organization of Workshop

This Afternoon-

-Charge to Working Groups

Sol Gorland, LeRC

-NASA Preliminary Plan/Working Group Expectations

- Trace Chemistry
- Instrumentation
- Procedures/Venues

-Working Group Deliberations

Tomorrow-

-Continuing Deliberations, Summary Report Development

Organization of Workshop

This Morning -

- Background

- Problem Definition

  R. Niedzwiecki, LeRC

- Engine/Near Field A/P Issues

  R. Miake-Lye, ARI, Inc.

- Climatology Issues

  S. Baughcum, Boeing

- What we know (don't know) now

- Smoke Number/MASS Results

  P. Whitefield/D. Hagen, UMR

- Flight Measurements

  W. Grose/B. Anderson, LaRC

- Data Correlation

  H. Lilenfield, MDC

- Engine Test Venues and Measurements

  C. Wey, LeRC

- Engine Hot-Section Modeling

  Ian Waitz, MIT

Organization of Workshop

This Afternoon -

- Charge to Working Groups
  Sol Gorland, LeRC

- NASA Preliminary Plan/Working Group Ecpectations
  - Trace Chemistry
  - Instrumentation
  - Procedures/Venues

- Working Group Deliberations

Tomorrow -

- Continuing Deliberations, Summary Report Development

Workshop Objective

Develop a program plan for the measurement and characterization of particulates, aerosol precursors, from aircraft gas turbine combustors and engines.

Issues:

- Measurement Priorities
  - What should be measured?
  - Priorities?
  - Measurement requirements?
- Measurement Techniques
  - What techniques are available?
  - What needs to be developed?
- Measurement Venues
  - In flight?
  - Engine Tests?
  - Combustor Tests? (sector? rig?)
- Fundamentals for understanding/ translating/applying results.

Motivation

Inflight plume measurements (1995) behind Concorde indicate high particulate/aerosol loading in near wake.

- Result is indicative of a high of sulfur oxide conversion to sulfate, and data suggest that the dominant cause of conversion is not oxidation by OH.
- Mechanism for the observed degree of conversion is not yet fully rationalized. Increases in sulfate aerosol surface area in lower stratosphere may result in ozone depletion, and impact is maximized if the formation is in the near-wake/exhaust plume.
- Uncertainties in predicting impact of HSCT fleet result.

Motivation
(continued)

-Direct Relevance of high degree of SO_2 Oxidation unknown.

- Results suggest that SO_2, SO_3, OH, and additional aerosol/particulate (soot) characterizations in various venues, particularly behind aircraft engines are needed.

- Present work suggests that emission characteristics at the engine exit plane may differ from those at the combustor exit.

    -Hot section chemistry, fluid mechanics, cooling, and geometry can effect changes.

    -Chemical oxidative interactions of sulfur leading to sulfates are not well-characterized presently.

Richard W. Niedzwiecki
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Cleveland, Ohio

OUR OBJECTIVES

EVOLVE A PROGRAM PLAN FOR THE MEASUREMENT AND CHARACTERIZATION OF PARTICULATES, AEROSOL PRECURSORS AND AEROSOLS FROM AERO GAS TURBINE COMBUSTORS AND ENGINES

- Characterize particulates and aerosols from jet engines
- Develop a data base for the above - current & new engine emphasis
- Develop a field instrument & techniques for measurement of particulates & aerosols

FOCAL POINTS:

- Technology needs
- Intrusive & non-intrusive instrumentation development
- Test venues, procedures & special requirements

Technology Plan continued

- Assemble preliminary plan and hold industry workshop.
  - Trace chemistry committee chair
  - Restrict attendance for more candid discussions?
  - Hold in Spring/Summer of 1997

Engine Exhaust Constituents

- Gaseous: CO, CO_2, H_2O, NOx, THC
- Particles:
  - Solids: Particulates
  - Liquids: Aerosols
- Status
  - We do a good job measuring gaseous
  - We do a poor job with particles
    - New need
    - Smoke number inadequate

Particles - Solids and Vapors

Particulates:

- Carbon based: THC, Sulfur, NOy, etc. on surface
- Relatively nonreactive - (hydrophobic)
- Several microns to 0.1 um
- Exist at high/low temps
- Formed in combustor

Aerosols:

- Non-carbon based
- Reactive
- Acids and combustion fragments - H_2SO_4, HNO_3, THC, etc.
- Smaller than particulates

Particle Source

Particulates:

- Source - combustion
- Control by leaner burning, lower pressure, high temperature, high combustion efficiency, staged (axial) burning
- Smoke meter only current measurement - inadequate

Aerosols:

- Source - Engine hot section, combination of combustion and exhaust gas
- Control by removing sulfur from fuel; reducing NOx, high combustion efficiency - Other control measures?
- No validated technique to measure from engine exhaust.

Particle Quantification Needs Particulates and Aerosols

- Particle size and size distribution
- Total mass
- Characterization - What are its constituents?
- Range .001 to 1 + microns
- Reactivity:
  - Climate: nucleation potential
  - Constituents (health and air quality)
    - Make-up
    - Mutagenic and carcinogenic effects
    - Long-term health effects

Particle Concerns

- Climate change - high altitude cloud formation changing the albedo of the earth.
- Local air quality - acid rain, smog (airports)
- Health - breathing problems - ingestion of particles and retention in lungs
  - Mutagenticity and carcinogenicity of particles-long term effects.

$\Downarrow$

We do not know what is in jet engine exhausts

Regulatory Problem

- EPA regulates particle concentrations on a local (state and county) basis -2X severity in congress.
- A/C operations not currently regulated locally but on a federal basis.
- EPA, environmentalists, local government wants to bring A/C within regulations applicable to all other polluters ---- eg. California Control Board.
- We do not even know what exists in jet engine exhaust besides smoke number (S.N.)
  - S.N. measures large particles only (see FAA memo)
- EPA regulates particle concentrations on a local (state and county) basis - 2X severity in congress
  - Small particles of concern
  - No validated method of obtaining required particle data exists - University of Missouri/Rolla may come closest with MASS unit.

Technical Considerations

Data Bases

- AEDC Engine tests
- Williams Engine tests, LeRC
- F-100 Engine Tests, planned LeRC
- Flight measurements from AEAP
- Combustor Tests
  - LDI - LeRC, University of Missouri/Rolla
  - RQL - UTRC/University of Missouri/Rolla

Conclusion

- Data Base inadequate for determining aviation impact
- Need to expand - weight to modern and future "cleaner" engines

Reduction Strategies

Particulate

- Uniform/Lean burning
- Increasing pressures and combustion inefficiency-increase levels
- Is LPP the ultimate low?
- Can be measured in combustor rigs and engines

Aerosols

- Eliminate sulfur from fuel - big problems
- Reduce NOx
- Any other strategies? - unknown
- Could aerosol effects be minimized by inerting the compounds?
- Do not exist in combustor exhaust - exist downstream of engine exit nozzle
- Do precursors exist in combustor exhausts?
- Can we remove combustor exhaust heat to aerosol forming regimes?

Technology Plan Continued

- Easy Environmental answer - eliminate sulfur from fuel
  - Do study to determine cost, infrastructure, supply (worldwide) storage impacts - airframe manufacturer
  - Do study/Exp. to determine impact of sulfur - free fuels on air craft fuel system, - engine manufacturer
  - self lubricating pump
  - How low is allowable
- Apply above to as many venues as possible to obtain industry data-base.
  - In-house - particle measures for all tests
  - AST, HSR, other contract results
  - Capitalize on any available engine tests.
  - Team with DOD in joint ventures to characterize particles
- Provide basis for a future A/C regulation

AEREA

European Commission

Global Atmospheric Effects of Aviation

Report of the Proceedings of the S mposium

Virginia Beach, Virginia USA

15-19 April 1996

PNEU

UNEP

OMM

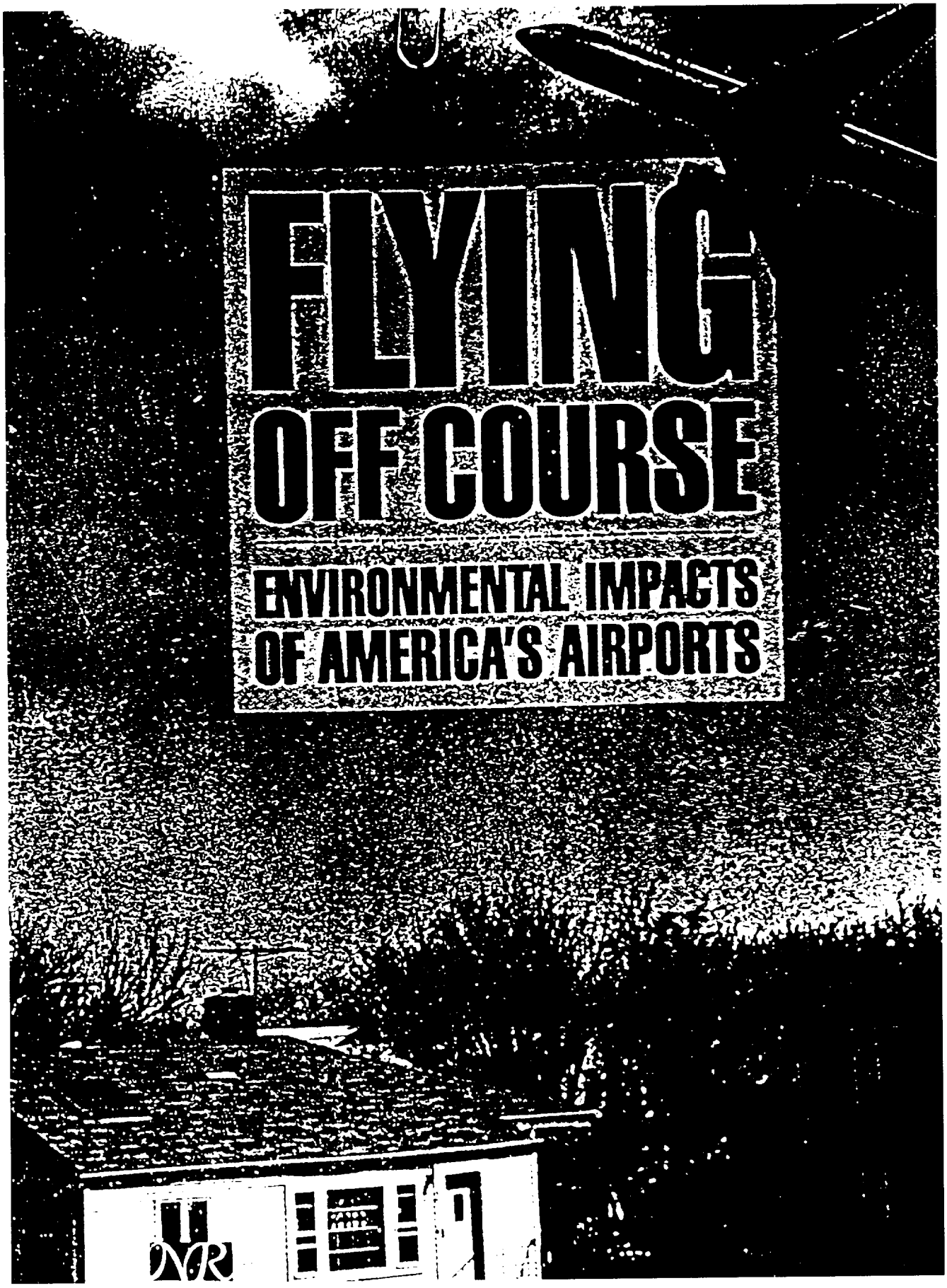
WMO

Status of National Aviation Assessments

- The national assessments also indicate that NO_x emissions are presently similar (i.e., equivalent radiative forcing) to CO_2 in climate importance.
- Potential implementation of advanced NO_x reduction technology, along with the short atmospheric residence time for this pollutant, could decrease future concerns with this pollutant.
- However, the level of confidence in the global assessment of this species contribution to climate change is low; and uncertainty regarding the natural and human sources of NO_x in the upper troposphere and lower stratosphere is especially high.

Status of National Aviation Assessments

- Studies of the effects of aerosol and particulate have only recently begun, the level of confidence in the related assessment is very low, and does not yet provide even qualitative guidance.
- Uncertainty regarding natural and human sources of cloud nuclei is high, but estimates of radiative forcing from indirect effects (i.e., "cloudiness") of aircraft aerosol and particulate emissions indicate the impact may be similar to that from CO_2 or even larger.


FLYING
OFF COURSE
ENVIRONMENTAL IMPACTS
OF AMERICA'S AIRPORTS

What our critics say -- National Resources Defense Council

"While the Clean Air Act Amendments of 1990 effectively targeted motor vehicles and industrial sources for emissions reductions, it left state and local officials essentially unable to control air pollution from an airport's planes"

"Airports are not regulated in the same way as other comparably large air pollution sources. Although aircraft engine prototypes have to meed certain emissions standards, neither airports nor airlines are held accountable for total ground level aircraft emissions".

"Although significant environmental impacts were common to most of the airports in our survey, the regulatory fraoework currently in place to address these impacts is inadequate. □ecvause aviation is the fastest growing mode of transportation in the United States, these failings must be addressed."

"Recommendations -- Treat airport generated emissions in the same manner as emissions from other large sources and include them in state air pollution plans" ....."Conduct further study and require additional reporting of toxic aircraft emissions"

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 51

[FRL-]

Interim Implementation Policy on New or Revised Ozone and Particulate Matter (PM) National Ambient Air Quality Standards (NAAQS)

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice of Proposed Policy (NPP).

SUMMARY: This notice is to propose a policy regarding interim implementation requirements for ozone and PM air pollution control during the time period following promulgation of new or revised NAAQS. Elsewhere in today's Federal Register, EPA is proposing these NAAQS. The policy as proposed is intended to ensure momentum is maintained by the States in the current program while moving toward developing their plans for implementing the new NAAQS. An explanation and structure of the Federal Advisory Committee Act (FACA) Subcommittee for Ozone, PM and Regional Haze Implementation Programs (Subcommittee) is provided under SUPPLEMENTARY INFORMATION.

DATES: Written comments on this proposal must be received by [60 days from publication of today's notice].

ADDRESSES: Comments. Comments on this proposal should be submitted (in duplicate if possible) to the Air and Radiation Docket and Information Center, 401 M Street, SW, Washington, DC 20460, Attention Docket Number A-95-38.

Docket. The public docket for this action is available for public inspection and copying between 8:00 a.m. and 5:30

DRAFT DOCUMENT

REGULATORY IMPACT ANALYSIS

FOR

PROPOSED

PARTICULATE MATTER

NATIONAL AMBIENT AIR QUALITY STANDARD

Prepared by:

Innovative Strategies and Economics Group
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U.S. EPA
Research Triangle Park, N.C.

December 1996

SCIENCE
RESEARCH
DEVELOPMENT

PREPRINT

EUROPEAN SCIENTIFIC ASSESSMENT OF THE ATMOSPHERIC EFFECTS OF AIRCRAFT EMISSIONS.

ENVIRONMENT AND CLIMATE PROGRAMME

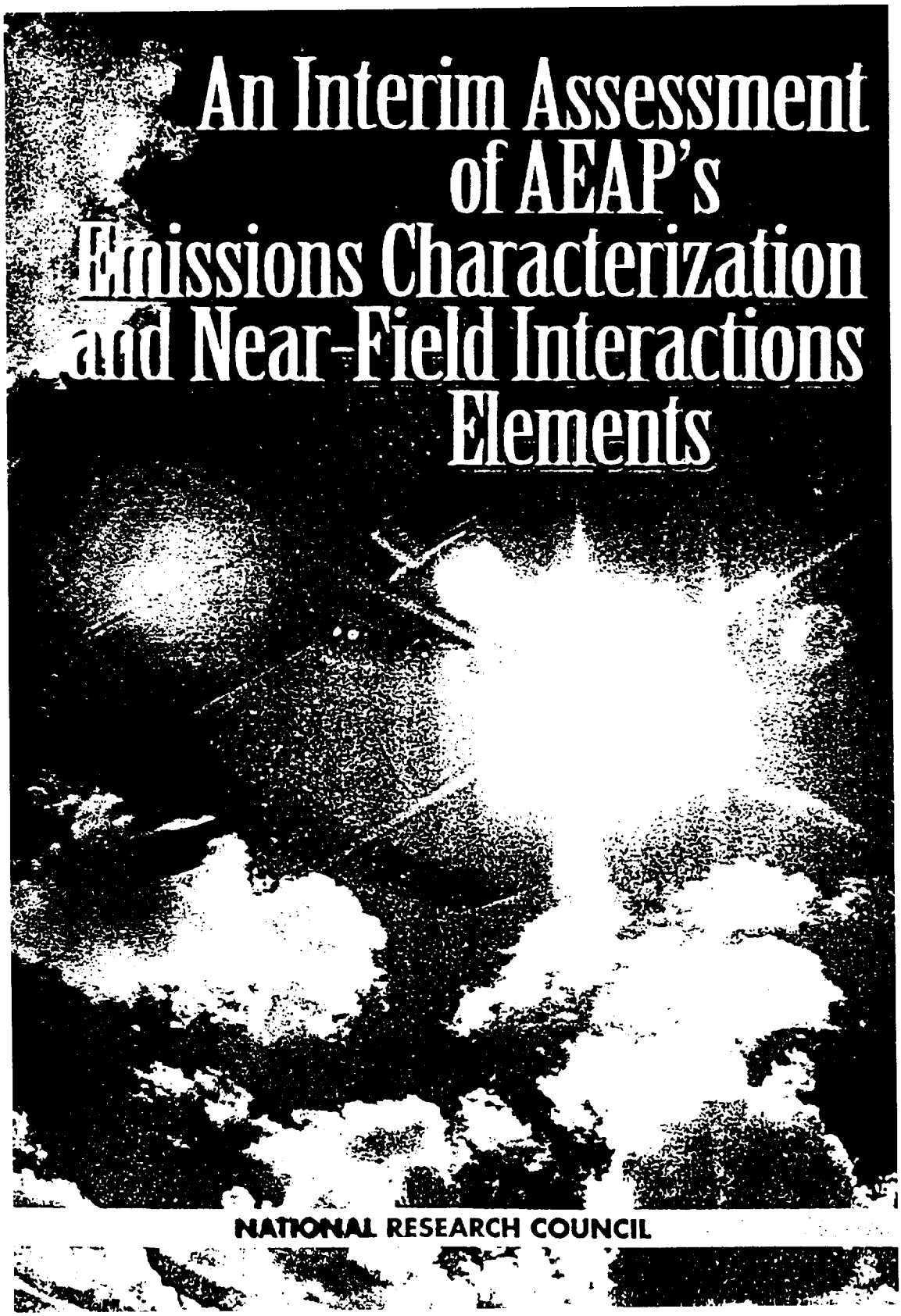
JULY 1997

European Commission Report

"The release by aircraft engines of solid particles or liquid aerosols in the atmosphere (sulphates, soot) Coupled to the release of water could affect the radiative balance in the vicinity of the tropopause. In addition to their direct radiative effect, and their role in cloud formation, these particles may enhance significantly the importance of heterogeneous chemistry and could lead to ozone depletion in the lower stratosphere."

Recent studies "indicate that the smoke number, and therefore the SAE method only reflects the number density of the relatively insignificant numbers of large particles, whole not accurately accounting for the total number of particles emitted."

"Results indicate that sea level static engine test measurements should not be used to represent the altitude particle emissions from an engine. While there are prediction equations for calculation of gaseous emissions at altitude conditions from sea level data, such relationships have not yet been entablished for particulates."


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

PANEL ON ATMOSPHERIC EFFECTS OF AVIATION

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NRC REVIEW

RECOMMENDATIONS -- TRACE CHEMISTRY

- o Raise particulate & aerosol research needs to top priority level
- o Emphasize altitude engine testing
- o Develop & verify advanced diagnostic techniques for measurement of aerosols and particulates
- o Characterizaton required for both subsonic and supersonic aircraft -- Concorde measurements cited for unexpectedly high levels
- o Focus on newer engines to extent possible - new entries in the fleet and demonstrator engines from AST & HSR program

CONCLUSIONS

O PARTICULATE & AEROSOL EMITTANTS ARE A NEW SERIOUS CONCERN WHICH HAVE DRAWN THE ATTENTION OF ENVIRONMENTAL GROUPS, THE EPA, EUROPEAN AND U.S. SCIENTISTSAND THE NAS/NRC

O BOTH CLIMATOLOGICAL AND HEALTH CONCERNS HAVE BEEN RAISED

O AN INADEQUATE DATA BASE EXISTS REGARDING THESE EMITTANTS

- CURRENT SAE SMOKE NUMBER IS INADEQUATE FOR DETAILING CONSTITUENTS

O EXISTING DATA EMPHASIZES OLDER ENGINES AND AIRCRAFT -- NOT REPRESENTATIVE OF ADVANCED AND FUTURE FLEET

O VERIFIED ADVANCED INSTRUMENTATION AND DATA-TAKING TECHNIQUES REQUIRED

STATEMENT OF PROBLEM: ENGINE AND NEAR-FIELD; AEROSOL AND PARTICULATE

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Motivation and context: The primary objective of NASA's Atmospheric Effects of Aviation Project (AEAP) is to assess the global impact of emissions deposited in the atmosphere from commercial aviation operating at cruise altitudes. Historically, the global implications of aircraft emissions have not been the subject of legislative regulation as have near-airport impacts, so the measurements to quantify these high altitude emissions are not a standard part of engine certification and are generally are not available. Thus, a significant component of AEAP is to characterize the cruise emissions from the commercial fleet.

In the first years of AEAP, planning and prioritizing of the species and measurement techniques were carried out [EETC Committee report] to establish the direction of the emissions characterization element of AEAP. The current status of the activity to date is that CO_2, H_2O, and NO_x have been well characterized. These primary combustion products and the pollutant emissions that have been the focus of many global studies to data have been measured with multiple techniques [AEDC Report] and at multiple venues, including in-flight [Fahey et al, DLR's POLINAT, SUCCESS]. In addition to these gaseous emissions, non-volatile (soot) particle number densities and particle size data are now available for many engines [UMR references] and multiple measurement venues, as well.

From these efforts, primary emissions can be quantified with reasonable accuracy for the existing commercial fleet and projections for these emissions can be made for future technologies. On the other hand, modeling and in-flight measurements have raised questions about other emissions which have yet to be fully characterized. For NO_x emissions, the conversion to non-NO_x NO_y (HONO, HNO_3) has not been quantified. Based on chemical kinetics calculations, this conversion is expected to be modest and global modeling results suggest that, for such modest conversions, the global effects are predicted to be small.

A more uncertain situation holds for sulfur emissions. The degree of SO_2 oxidation to SO_3 and H_2SO_4 also has not been quantified for many situations and has implications for aerosol formation as discussed below. Further, the state of emitted aerosols needs characterization beyond the number densities and size distributions to understand how emitted aerosol may affect contrail and cloud formation. More specifically, when, where, and how does soot become condensation nuclei (CN) capable of condensing water vapor? In order to fully understand how these questions affect the global atmosphere, chemical and physical processes that are occurring in the near-field of the airplane's wake and, indeed, with in the engine itself need to be understood.

Problem: With the current level of engine emission characterization, ***aerosol properties, aerosol precursor gases, and aerosol formation processes are not sufficiently well***

understood to make a reliable global impact assessment. Advances in our understanding are required in the following areas:

- SO_3: Sulfur emission speciation; to understand SO_2 oxidation and aerosol formation
- Soot: Activation for condensation nucleation processes; coagulation with soot, sulfate aerosol, and ambient CN
- Radicals: Which are active in post-combustor sections of engine (rates and mechanisms)? Which are emitted at nozzle exit?
- HCs: Do unburned hydrocarbons have any role in aerosol formation?

SO_x Effects: Modeling studies of the stratosphere (Weisenstein et al., 1996; Danilin et al., 1997) indicate that the chemical and physical state of sulfur emissions are important for understanding their global impact. When aircraft sulfur emissions are deposited in the atmosphere as many small sulfate aerosols, the additional surface area and associated heterogeneous reactions reduce the NO_x induced ozone depletion. At the same time, ozone depletion is increased due to heterogeneous processing on sulfate aerosol that shifts Cl_y and Br_y to ClO and BrO, respectively, and shifts HO_x to OH. The net effect of SO_x emissions is a decrease in ozone which may be more important than that due to NO_x emissions alone.

Recently measurements have been made in the troposphere (SUCCESS campaign, GRL 1997 special issue, POLINAT). Volatile (H_2SO_4) aerosols are the most numerous condensation nuclei close to the airplane, however their connection to contrail and cloud formation processes are still very uncertain. In what way do these volatile aerosol emission interact with soot and other (such as entrained ambient) particulates and what are the properties of the aircraft particulates as they are left for atmospheric dispersal?

SO_x Puzzle: Modeling and limited engine experimental data suggest SO_x is emitted mostly as SO_2. However, in-flight experiments indicate >10% has condensed as H_2SO_4 [Fahey et al., 1995] within 100m of emission [Anderson et al., 1997; Miake-Lye et al., 1997]. Could the model results and few measurements be missing SO_x emissions leaving the engine as SO_3/ H_2SO_4? If so, what new kinetic rates or mechanisms are needed to explain this additional oxidation? On the other hand, if the models and measurements are correct that most of the sulfur emissions are SO_2, how is SO_2 being oxidized immediately after emission to account for the numerous volatile aerosol? What non-linear and/or heterogeneous mechanism can be identified that could oxidize the SO_2 fast enough?

Soot Emissions: What does aviation contribute to atmospheric background of black carbon aerosol? Measurements in the upper troposphere have sampled soot emissions that have been attributed to aircraft exhaust, but how do the numerous 20-40 nm particles that are measured at the engine exhaust [Hagen presentation, Lilenfeld presentation, UMR references] end up contributing to the larger sized particle in the ambient background? Indeed, what is the particle size distribution due to aircraft exhaust that is deposited in the atmosphere? Perhaps most important, does aviation soot have unique contrail or cloud formation properties and what makes soot capable of condensing water?

The activation of soot by trace species in the exhaust has been suggested as one means of their chemical activation. Which species are responsible for this activation? SO_x has been proposed as a likely candidate but are SO_x emissions sufficient and are they necessary? Does activation occur during soot formation (which occurs in the combustor), at high T (in the combustor and/or turbine), or at low T (chemical activation, coagulation after emission)?

Intra-Engine Processes: What oxidation of important pollutant emissions (NO_x, SO_x) occurs inside the engine? In order to understand these processes, flowfield/chemistry coupling effects need to be accounted for [Waitz presentation, Lukachko et al., 1997]. The temperatures and pressures encountered in the post-combustor engine hot sections span a range between combustion conditions and atmospheric conditions where existing experimental results are lacking. Thus there are limitations of the applicability of existing rates for mechanisms which are included in models and it is not clear whether a complete kinetic mechanisms has been assembled for this intermediate regime.

Central to understanding the evolution of emissions within the engine is to identify which radicals drive intra-engine oxidation. When intra-engine processes are sufficiently well understood, both the emissions and the remaining oxidative radicals, available for subsequent reactions in the external exhaust flow, can be quantified. Such results will provide a more complete exhaust characterization for calculated estimates of continued exhaust evolution by near-field models and for eventual deposition in the global atmosphere. In addition, a reliable intra-engine model will provide a predictive capability for engines for which a full set of emissions measurements do not exist, including new technology engines which may be still under development.

Requirements: The full characterization of aircraft emissions for use in a global assessment will require several additional types of data. A better understanding of SO_x, NO_y ,and HO_x emissions is necessary. In particular, the speciation of SO_x at emission is least understood, so initial measurements here are most important. The uncertainties in our understanding of SO_x emissions suggest that NO_y speciation, in particular emissions of HONO and HNO_3, has not been determined quantitatively either. Thus, measurements of SO_x, NO_y ,and HO_x at the engine exit would constrain our uncertainties in gas phase kinetics in several dimensions. Such results, in concert with measurements of radical levels (O, OH, ...) at the high pressure turbine entrance, could be used directly in developing a better, more complete mechanism for post-combustor hot sections. Beyond the gaseous emissions, our understanding of soot activation is incomplete, and basic laboratory data combined with relevant engine test results are needed to determine the properties of aircraft particulate emissions so that they too can be included in a global assessment. Finally, a predictive capability is needed to extend engine measurement results to related cycles and technology that is being considered for implementation in the future, as global assessments attempt to predict the future state of the atmosphere.

Motivation and context

Objective: Assess global impact of aviation emissions at altitude.

→ Characterize cruise emissions

Status: CO_2, H_2O, and NO_x have been well characterized.

Measured with multiple techniques at multiple venues, including in-flight.

Non-volatile (soot) particle number densities, particle size data available for many engines, multiple venues.

- NOx conversion to non-NO_x NO_y (HONO, HNO_3)? Conversion modest, global effects small.
- SO_2 oxidation to SO_3, H_2SO_4?
- When, where, how does soot become condensation nuclei (CN)?
- Raises near-field (and engine) chemistry issues.

Problem

Cannot quantify aerosol properties or precursors and aerosol formation sufficiently to make global impact assessment.

SO_3: Speciation–to understand SO_2 oxidation, aerosol formation

Soot: Activation for condensation nucleation processes, coagulation with soot, sulfate aerosol, ambient CN

Radicals: Which are active in post-combustor sections of engine (rates and mechanisms)? Which are emitted at nozzle exit?

HCs: Any role in aerosol formation?

SO_x Effects

Stratosphere (Weisenstein et al., 1996; Danilin et al., 1997)

- Sulfate aerosol reduces NO_x effect on ozone depletion.
- Sulfate aerosol shifts Cl_y, Br_y to ClO, BrO; HO_x to OH.
- Net effect: SO_x, emissions may be more important than NO_x.

Troposphere (SUCCESS campaign, GRL 1997 special issue)

- Volatile (H_2SO_4) aerosol are dominant close to airplane
- Connection to contrail and cloud formation process very uncertain.

Interaction with soot and other particulates?

SO_x Puzzle

Modeling and limited engine experimental data suggest SO_x emitted as SO_2.

In-flight experiments indicate >10% condensed as H_2SO_4 (Fahey et al., 1995) within 100m of emission (Anderson et al., 1997; Miake-Lye et al., 1997).

- Leaving engine as SO_3/H_2SO_4? What new kinetic rates or mechanisms are needed to explain?

  or

- Oxidizing immediately after emission? What (non-linear, heterogeneous?) mechanism can oxidize fast enough?

Soot Emissions

What does aviation contribute to atmospheric background?

- What is particle size distribution deposited in the atmosphere?
- Does aviation soot have unique contrail or cloud formation properties?

What makes soot capable of condensing water?

- Chemical activation? By what? (SO_x sufficient? necessary?)
- Does activation occur during soot formation (combustor), at high T (in combustor/turbine), or at low T (chemical activation, coagulation)?

Intra-Engine Processes

- What oxidation (SO_x, NO_x) occurs inside engine?
  - Flowfield/chemistry coupling effects.
  - Limitations of existing rates (mechanisms).
  - Which radicals drive intra-engine oxidation? Which are emitted into exhaust for external reactions
- Provide complete calculated estimates for near-field models.
- Develop predictive capability for unmeasured engines, new technology.

Requirements

- SO_x speciation; NO_x +HONO, HNO_3; OH at engine exit.
- Better, more complete mechanism for post-combustor hot sections.
- Radical levels (O, OH, ...) at HP turbine entrance, nozzle exit.
- Soot activation, (basic laboratory data, engine test results).
- Predictive capability to extend results to related cycles, technology.

POTENTIAL CLIMATE IMPACTS OF ENGINE PARTICLE EMISSIONS

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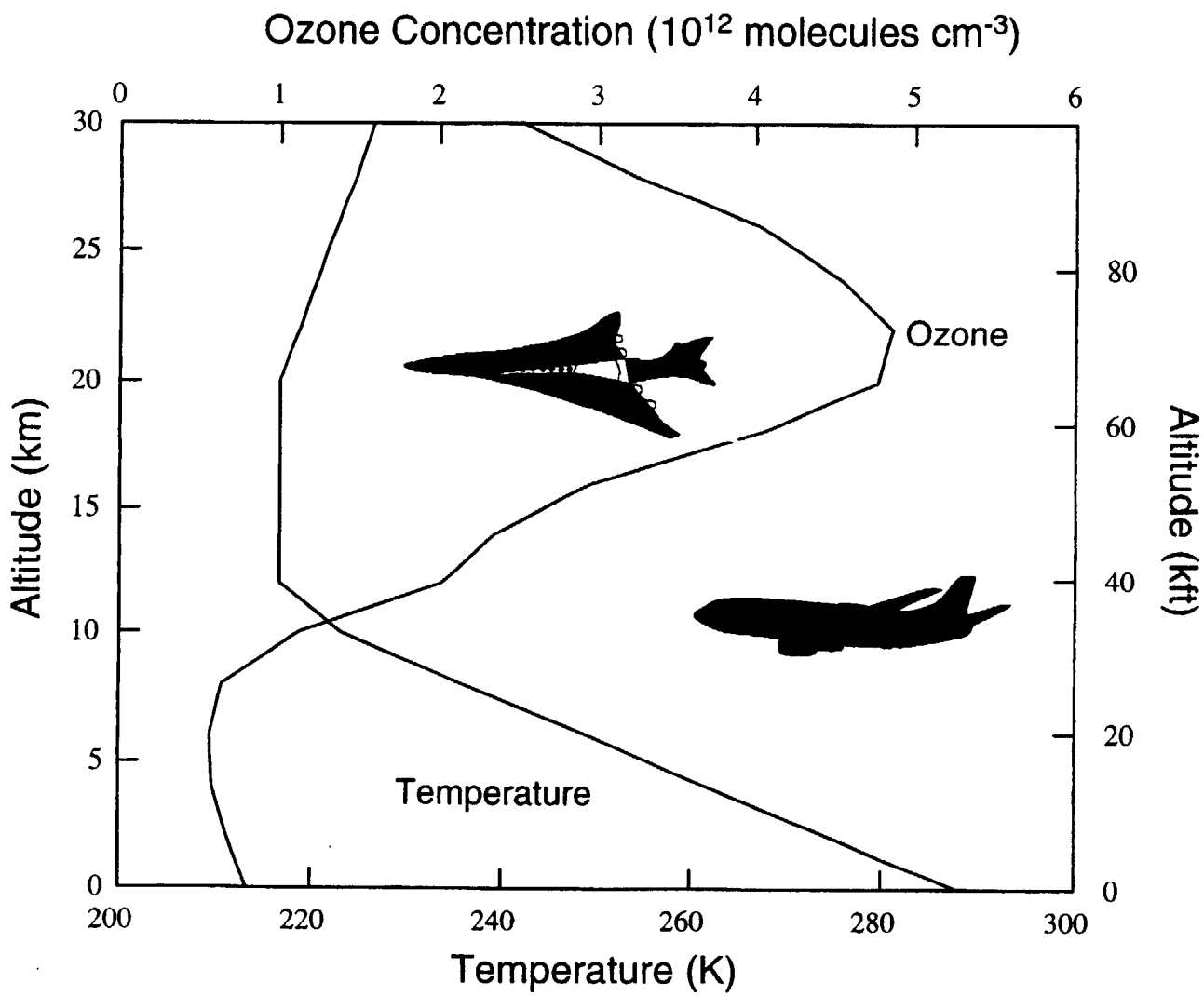
Solid (soot) and liquid (presumed sulfate) particle emissions from aircraft engines may have serious impacts on the atmosphere. While the direct radiative impact of these particles is expected to be small relative to those from natural sources (Atmospheric Effects of Subsonic Aircraft: Interim Assessment of the Advanced Subsonic Technology Program, NASA Ref. Pub. 1400, 1997), their indirect effects on atmospheric chemistry and cloud formation may have a significant impact. The potential impacts of primary concern are the increase of sulfate surface area and accelerated heterogeneous chemical reactions, and the potential for either modified soot or sulfate particles to serve as cloud nuclei which would change the frequency or radiative characteristics of clouds. Volatile (sulfate) particle concentrations measured behind the Concorde aircraft in flight in the stratosphere were much higher than expected from near-field model calculations of particle formation and growth. Global model calculations constrained by these data calculate a greater level of stratospheric ozone depletion from the proposed HSCT fleet than those without particle emission. Soot particles have also been proposed as important in heterogeneous chemistry but this remains to be substantiated. Aircraft volatile particle production in the troposphere has been shown by measurements to depend strongly on fuel sulfur content. Sulfate particles of sufficient size are known to provide a good nucleating surface for cloud growth. Although pure carbon soot is hydrophobic, the solid particle surface may incorporate more suitable nucleating sites. The non-volatile (soot) particles also tend to occupy the large end of aircraft particle size spectra. Quantitative connection between aircraft particle emissions and cloud modification has not been established yet, however, even small changes in cloud amount or properties could have a significant effect on the radiative balance of the atmosphere.

http://hyperion.gsfc.nasa.gov/AEAP/AEAP.html

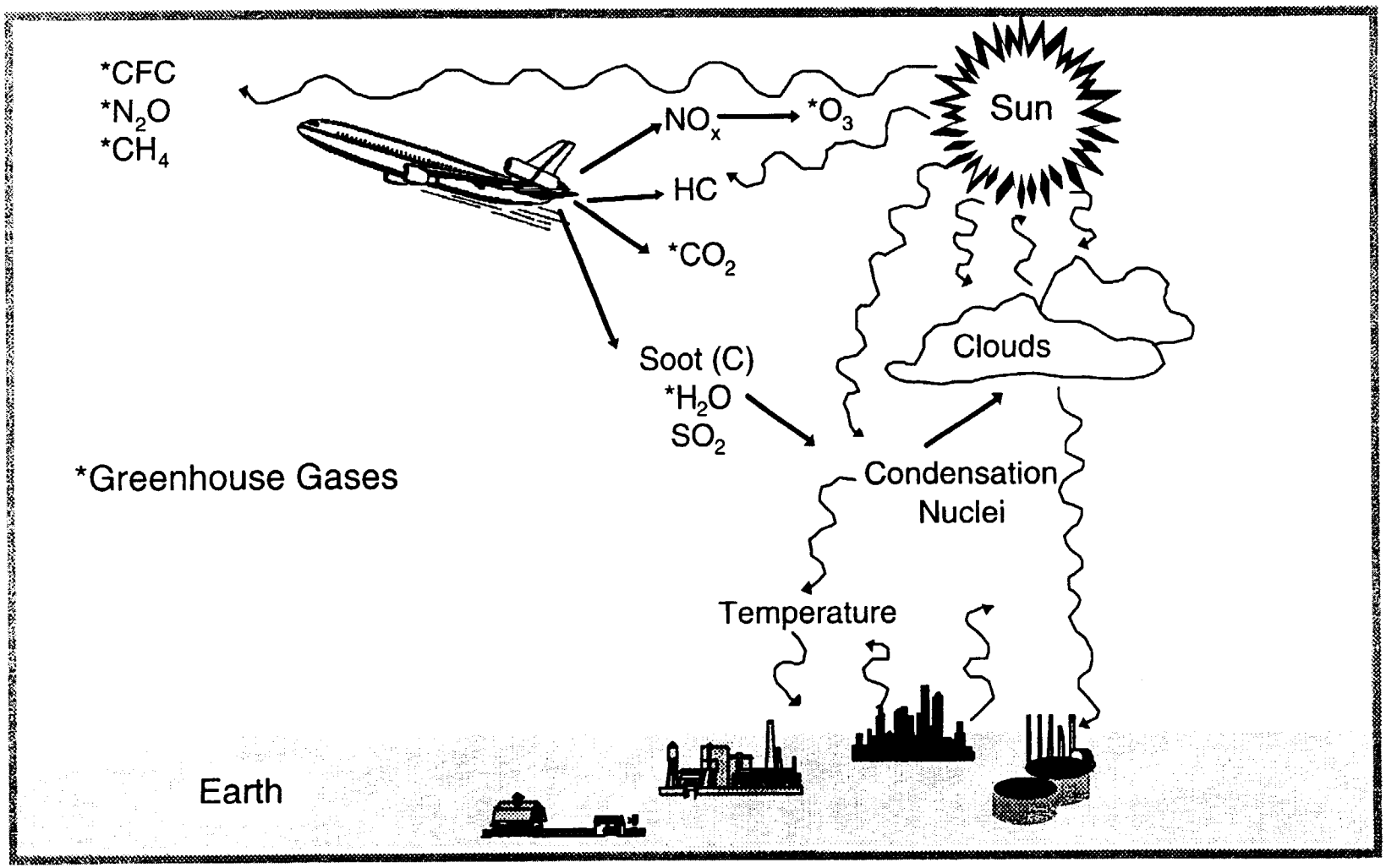
AEAP Mission



AESA

SASS

CLIMATE EFFECTS OF EMISSIONS

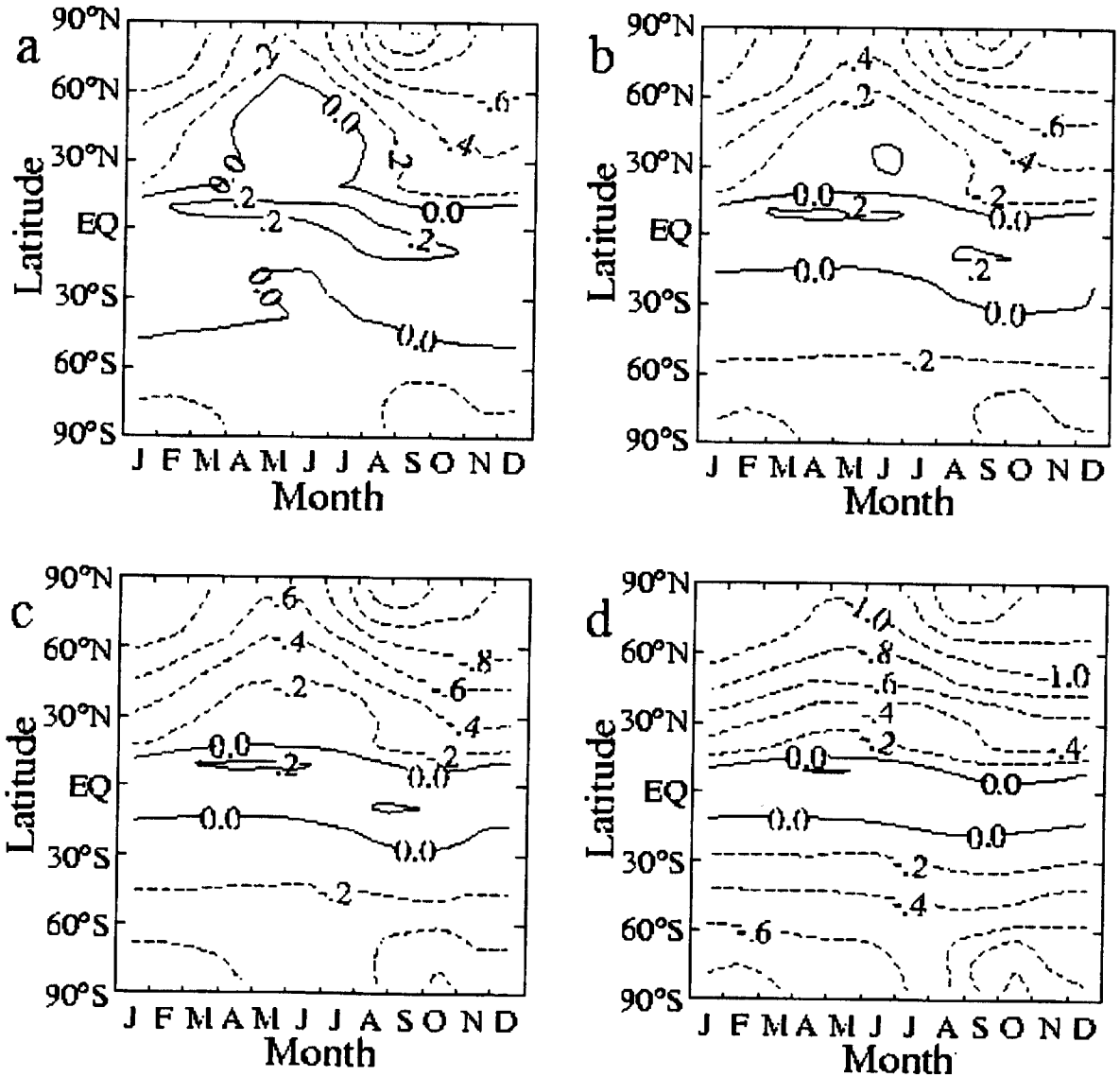


SASS Assessment (Friedl et al., 1997)

Emittant	Impact	Impact Estimate (Global Ave.)	Uncertainty
NO_x	O_3 Column	+ 0.1 % (+0.3% ave., over 30°-60°N)	±0.5%, NO_x sources poorly quantified
	Direct Radiative Forcing	+0.001 W m^{-2}	small
	Indirect Rad. Forcing	+ 0.01 W m^{-2}	±0.05 W m^{-2}, NO_x sources poorly quantified
CO_2	O_3 Column	negligible	small
	Direct Radiative Forcing	+ 0.0003 W m^{-2} (+0.0067 W m^{-2} over last 30 years)	±0.0001 W m^{-2}, mainly due to model uncertainties
Hydrocarbons	O_3 Column	small	small
	Direct Radiative Forcing	negligible	small
	Indirect Rad. Forcing	negligible	small
CO	O_3 Column	small	small
	Direct Radiative Forcing	negligible	small
	Indirect Rad. Forcing	negligible	small

SASS Assessment (cont.)

Emittant	Impact	Impact Estimate (Global Ave.)	Uncertainty
H_2O	O_3 Column	small	large, depends on PSC details
	Direct Radiative Forcing	significant, sign uncertain	large, radiative transfer properties of contrails poorly known
	Indirect Rad. Forcing	potentially significant	moderate, depends on involvement in PSC/O_3 process and/or in plume processes that result in CCN and IN
Sulfur	O_3 Column	small	large, sources inadequately defined, size distribution poorly known
	Direct Radiative Forcing	+0.0001 W m^{-2}	moderate, sources inadequately defined, size distribution poorly known
	Indirect Rad. Forcing	potentially significant	large, interaction with aircraft soot and role as CCN/IN poorly defined
Soot	O_3 Column	small	small
	Direct Radiative Forcing	+ 0.003 W m^{-2}	moderate, size distribution and single particle albedo uncertain
	Indirect Rad. Forcing	unknown	large, depends on # that are coated with sulfur and act as CCN or IN



Percent change in column ozone due to emissions from HSCT Aircraft with EI(NOx)=5. Panel (a) Shows results with no SO2 emission. Panels (b)-(d) include SO2 emission as (b) 100% gas, (c) 90% gas and 10% particles, and (d) 100% particles [Weisenstein et al., GRL, 1996].

UMR MOBILE AEROSOL SAMPLING FACILITY AND SMOKE METER

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Rolla, Missouri

PARTICULATE PROPERTIES

Concentration

Size distribution (Area, Volume)

Emission Index

Volatility

Hydration

Morphology

Composition

CONDITION VARIABLES

Altitude

T3

P3

Fuel composition

RECENT CAMPAIGNS

AIRBORNE SAMPLING

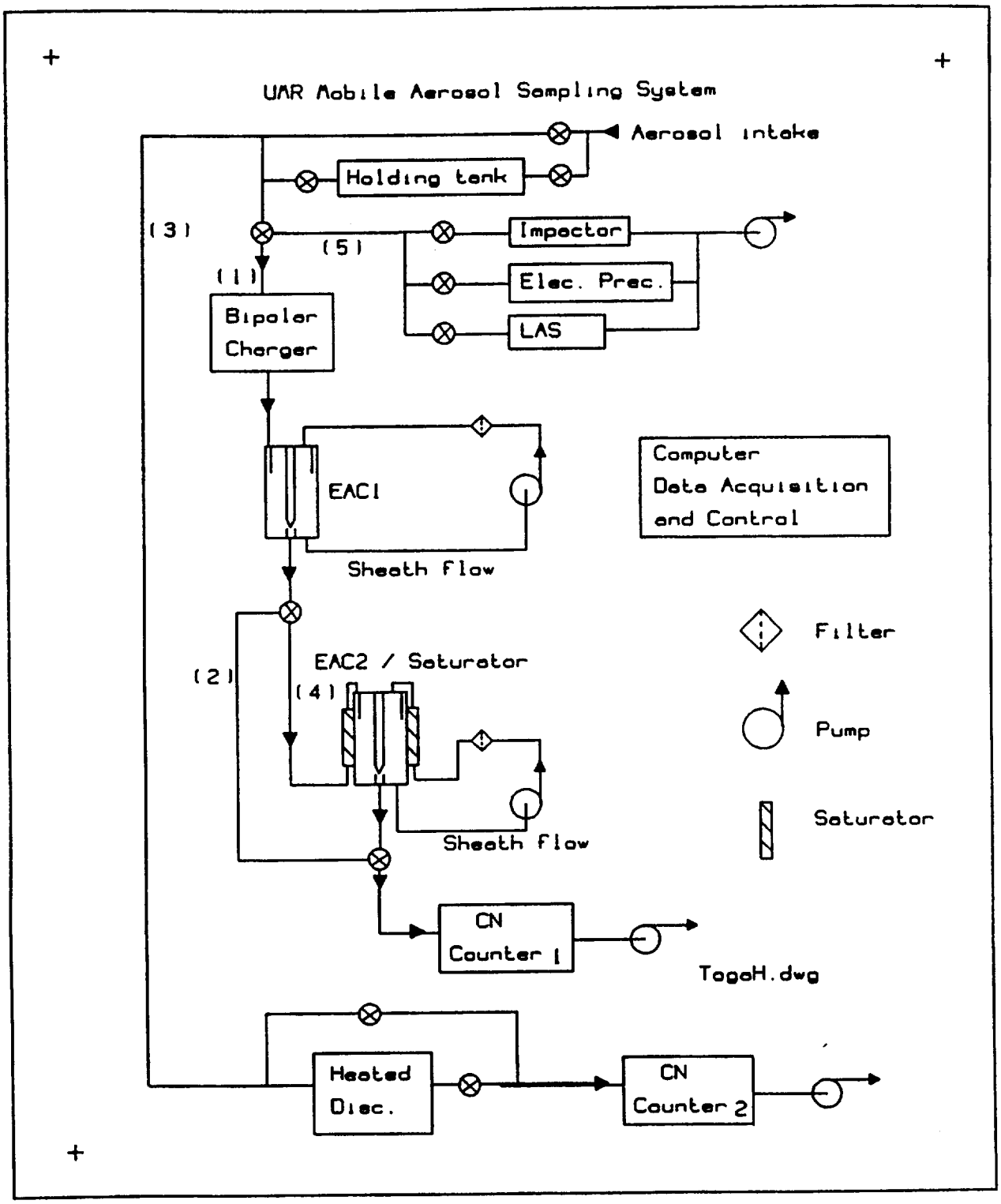
NCAR Sabreliner
DLR plume chasing
POLINAT
NASA Project SUCCESS
AF RISO

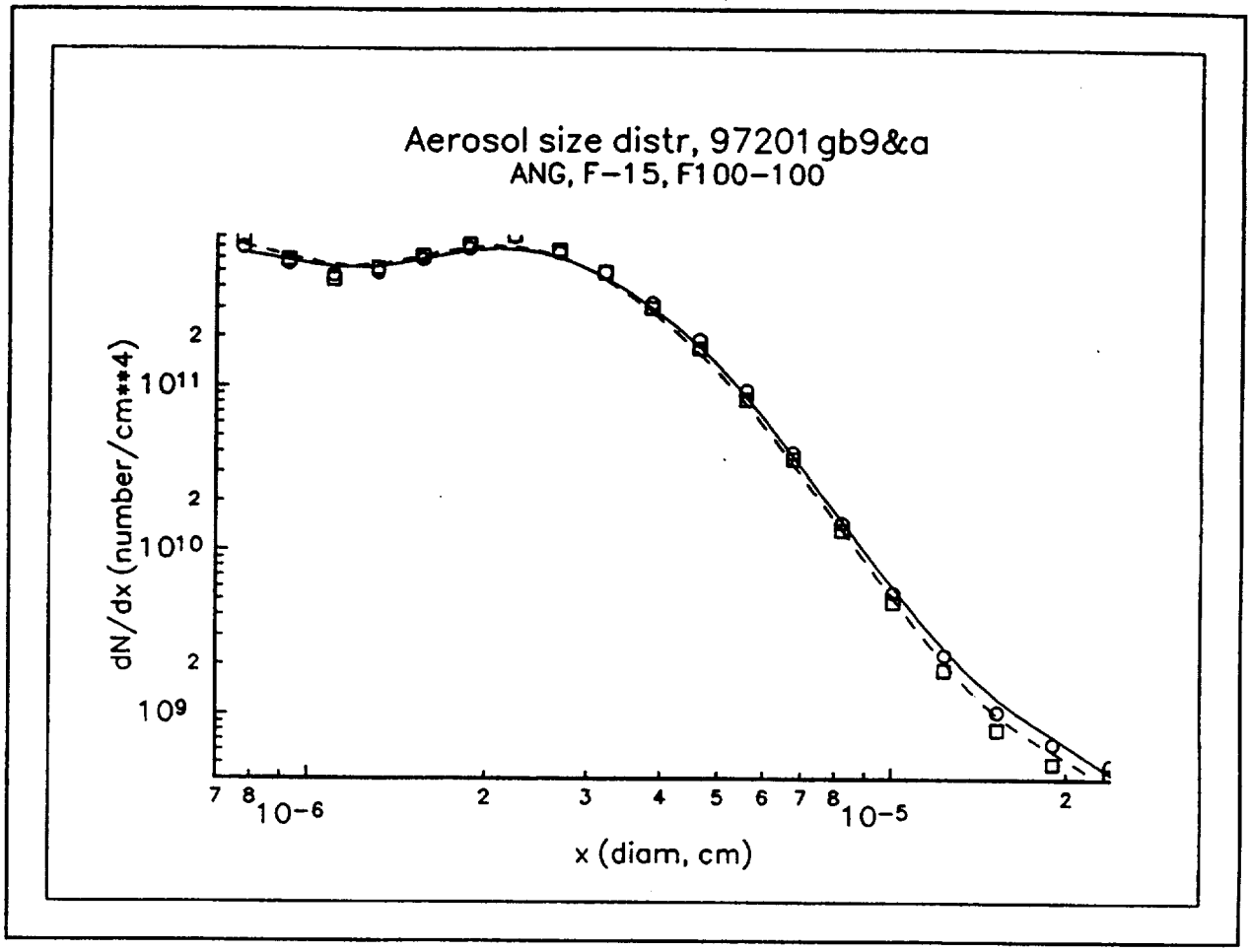
GROUND TEST SAMPLING

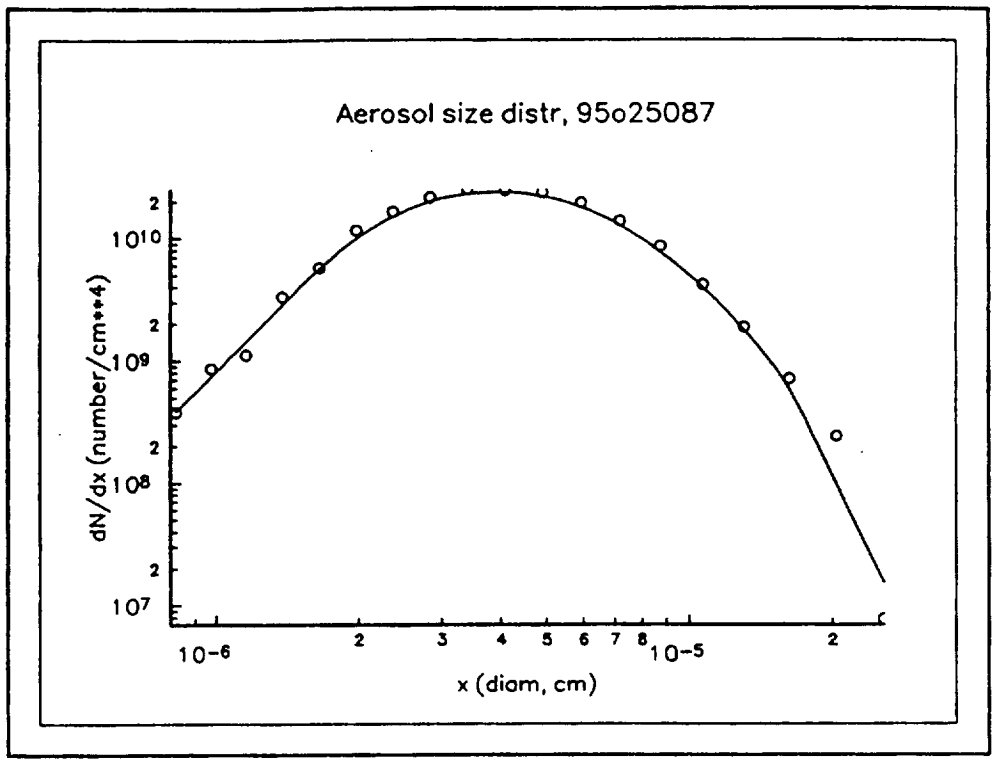
McDD Hush House
Pratt & Whitney
AEDC (altitude chamber)
ATTAS ground test
Concorde engine test
NASA Langley (B737, B757, T38)
NASA Lewis
AFNG F15 JP8+100

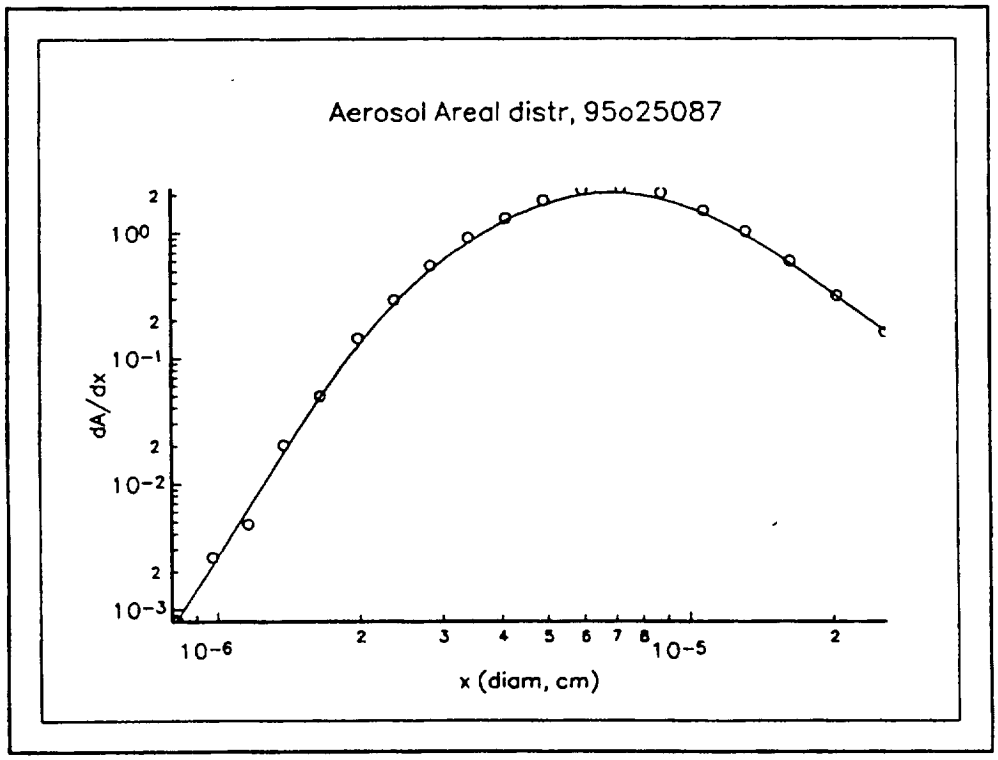
OTHER

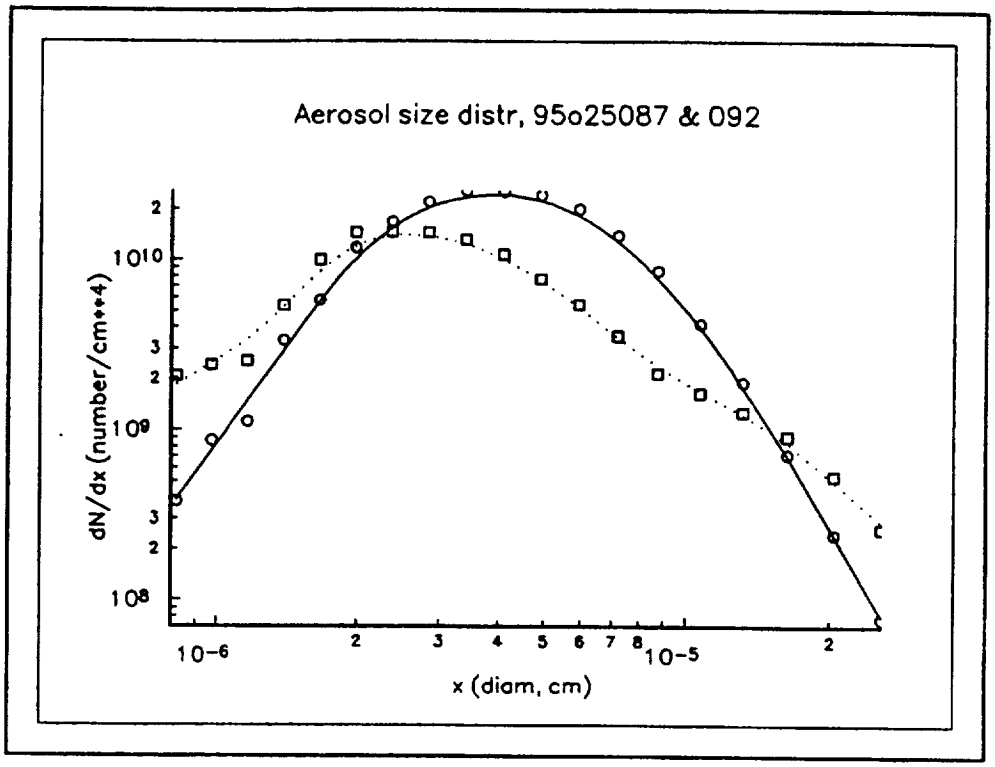
AF Phillips Laboratory
WPAFB Fuel formulation/Ptl formation

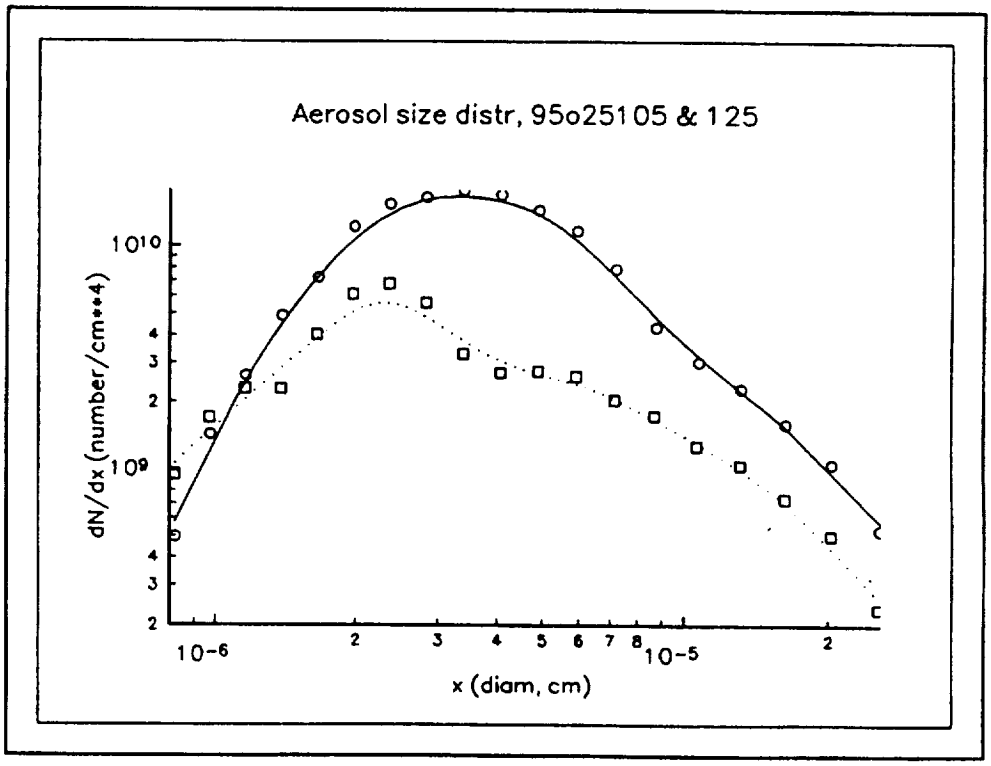

UAR Mobile Aerosol Sampling System
Aerosol intake
Holding tank
(3)
(5)
Impactor
(1)
Elec. Prec.
Bipolar Charger
LAS
EAC1
Computer Data Acquisition and Control
Sheath Flow
Filter
EAC2 / Saturator
(2)
(4)
Pump
Saturator
Sheath Flow
CN Counter 1
TogoH.dwg
Heated Disc.
CN Counter 2

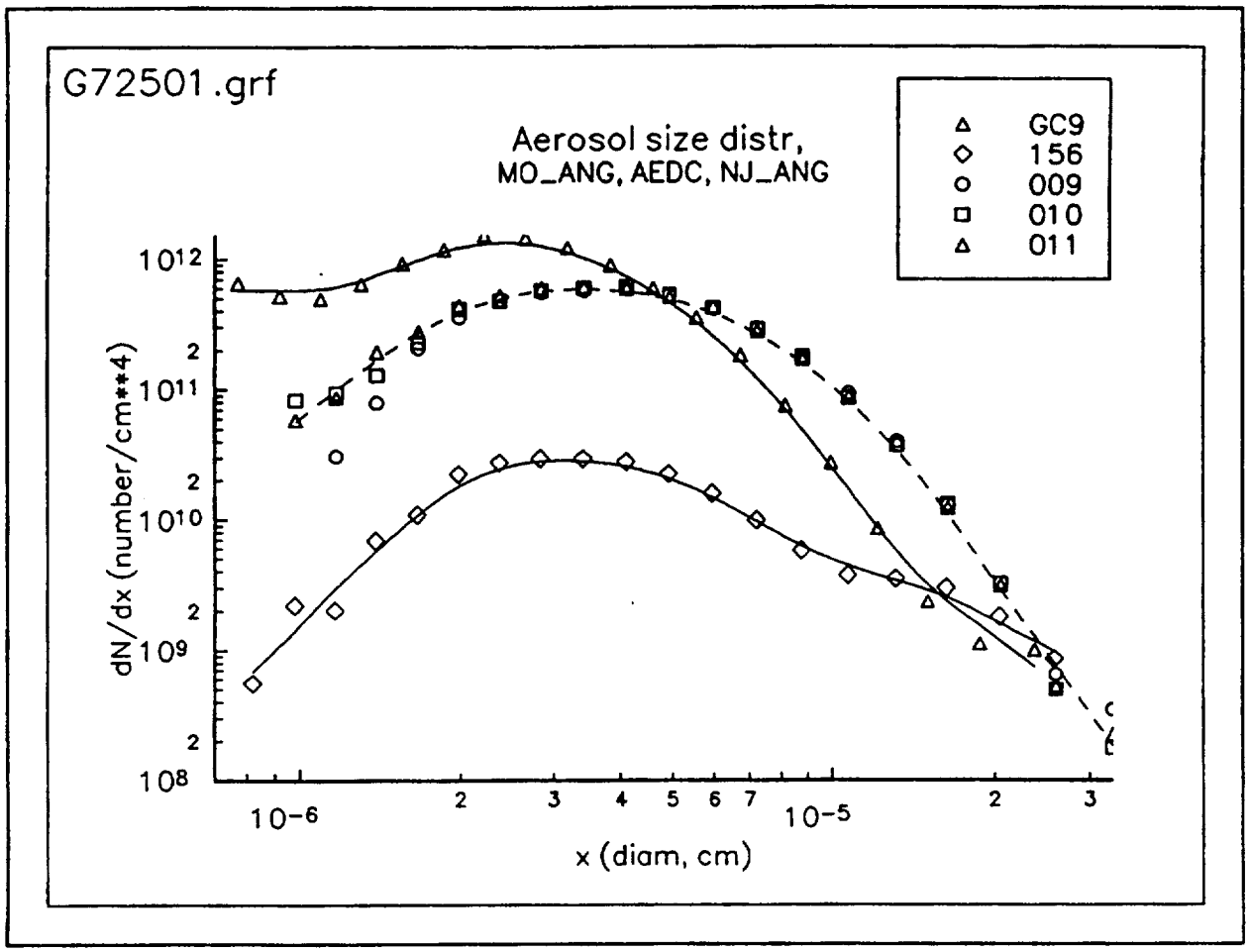

Aerosol size distr, 97201gb9&a
ANG, F-15, F100-100
dN/dx (number/cm**4)
2
10^11
2
10^10
2
10^9
7 8 10^-6 2 3 4 5 6 7 8 10^-5 2
x (diam, cm)


Aerosol size distr, 95o25087
dN/dx (number/cm**4)
2
10^10
2
10^9
2
10^8
2
10^7
10^-6
2
3
4
5
6
7
8
10^-5
2
x (diam, cm)

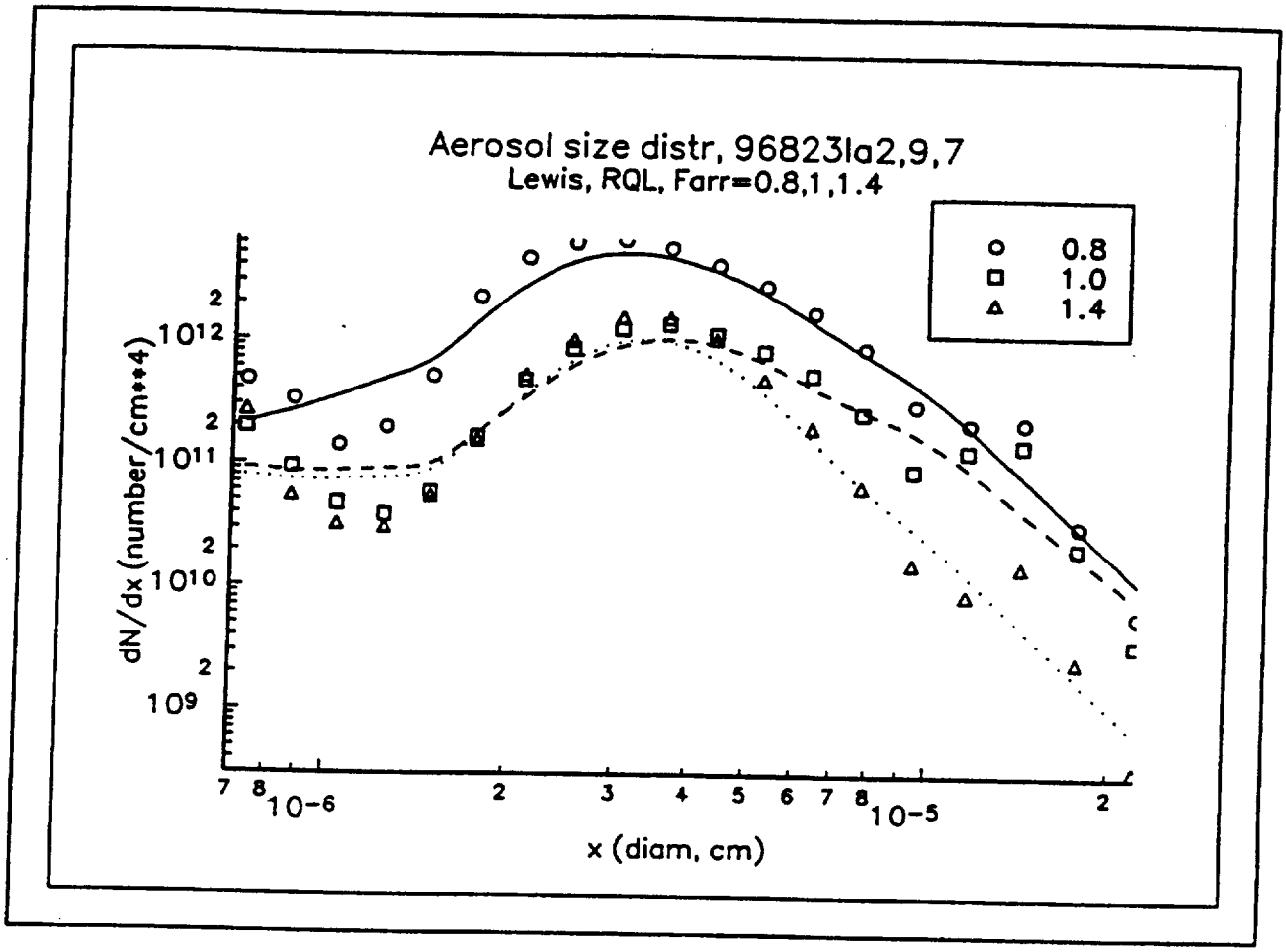

Aerosol Areal distr, 95o25087
dA/dx
2
10^0
2
10^-1
2
10^-2
2
10^-3
10^-6
2
3
4
5
6
7
8
10^-5
2
x (diam, cm)

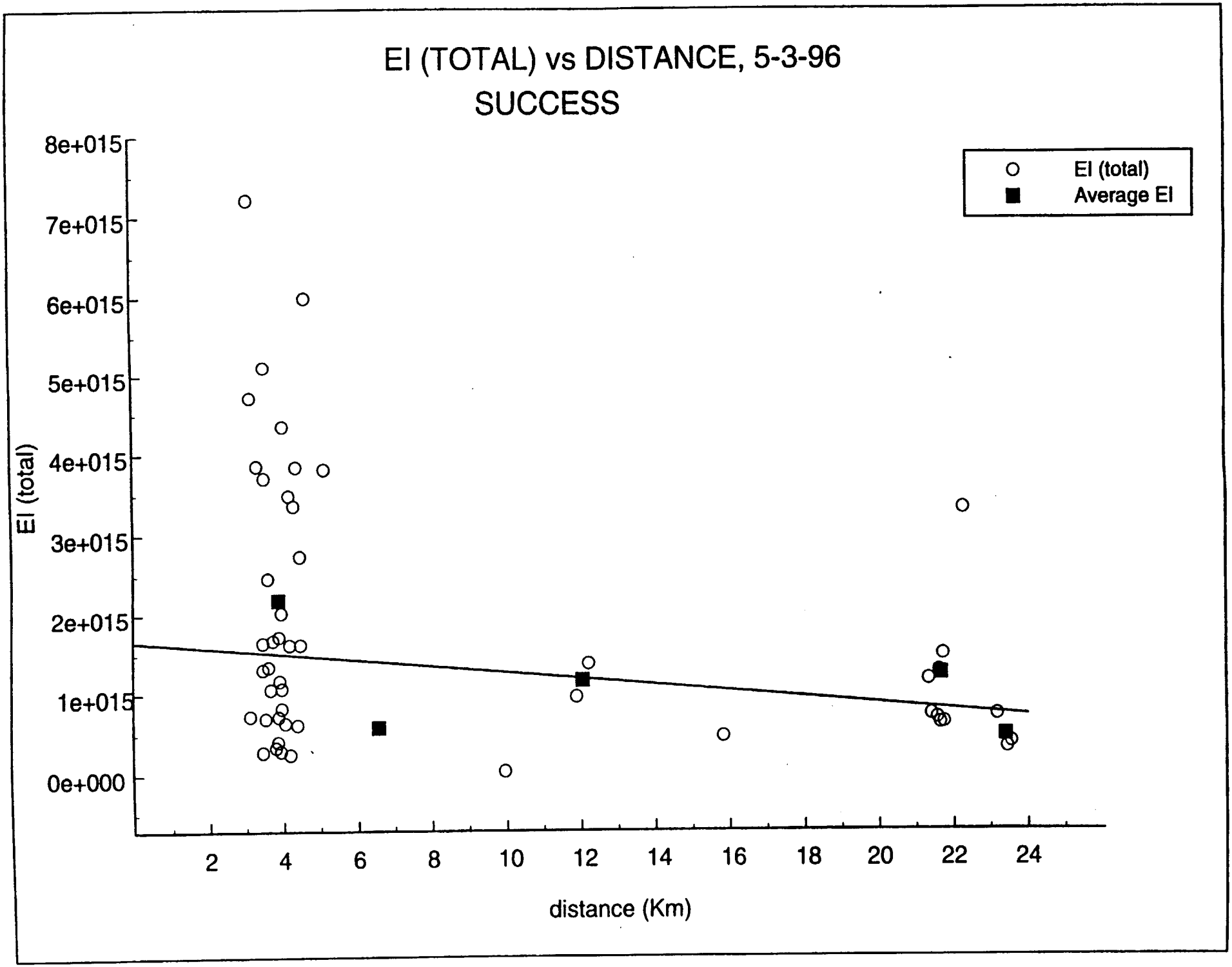

Aerosol size distr, 95o25087 & 092
dN/dx (number/cm**4)
x (diam, cm)

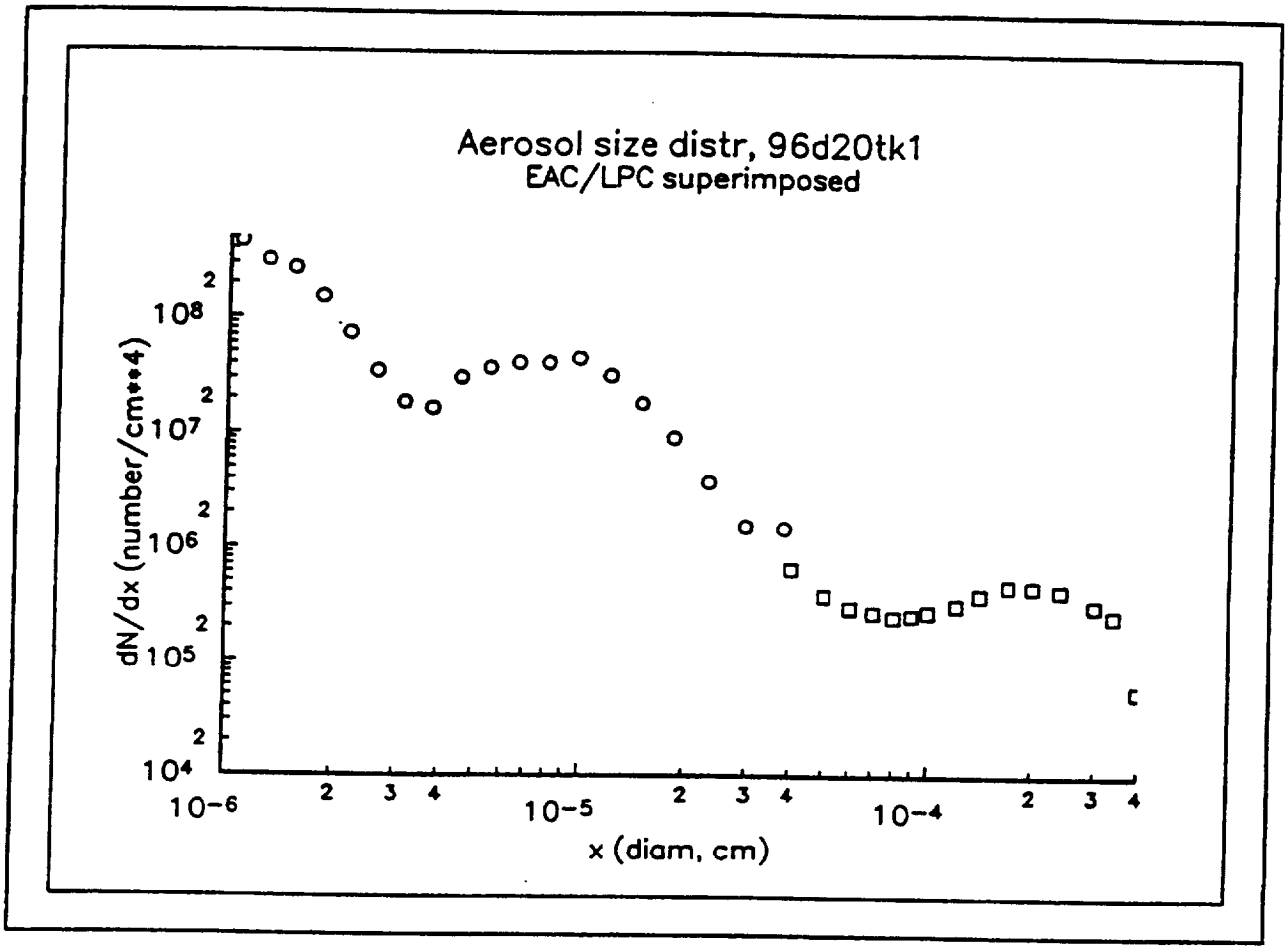

Aerosol size distr, 95o25105 & 125
dN/dx (number/cm**4)
x (diam, cm)



MO_ANG, F100-100, gc9, 76%
AEDC run 156, T3=733K, Alt=3.1 km (SLS), Time=14:57:00
MO_ANG, F100-220, 009,010,011, 80%


Aerosol size distr, 96823la2,9,7
Lewis, RQL, Farr=0.8,1,1.4
0.8
1.0
1.4
dN/dx (number/cm**4)
x (diam, cm)


EI (TOTAL) vs DISTANCE, 5-3-96
SUCCESS
EI (total)
Average EI
8e+015
7e+015
6e+015
5e+015
4e+015
3e+015
2e+015
1e+015
0e+000
EI (total)
2
4
6
8
10
12
14
16
18
20
22
24
distance (Km)


Aerosol size distr, 96d20tk1
EAC/LPC superimposed
dN/dx (number/cm**4)
10^8
10^7
10^6
10^5
10^4
2
10^-6
10^-5
10^-4
3
4
x (diam, cm)

SMOKE METER

The Smoke Meter attempts to measure the particulate emission in the jet engine exhaust flow.

Several known volumes of exhaust are passed through a filter. Any change in the observed optical reflectance of the filter can be correlated to the quantity of particulate matter in the exhaust.

The Smoke Number derived from the optical reflectance and flow rate information is the industry standard for particulate emission in jet exhaust.

Questions:

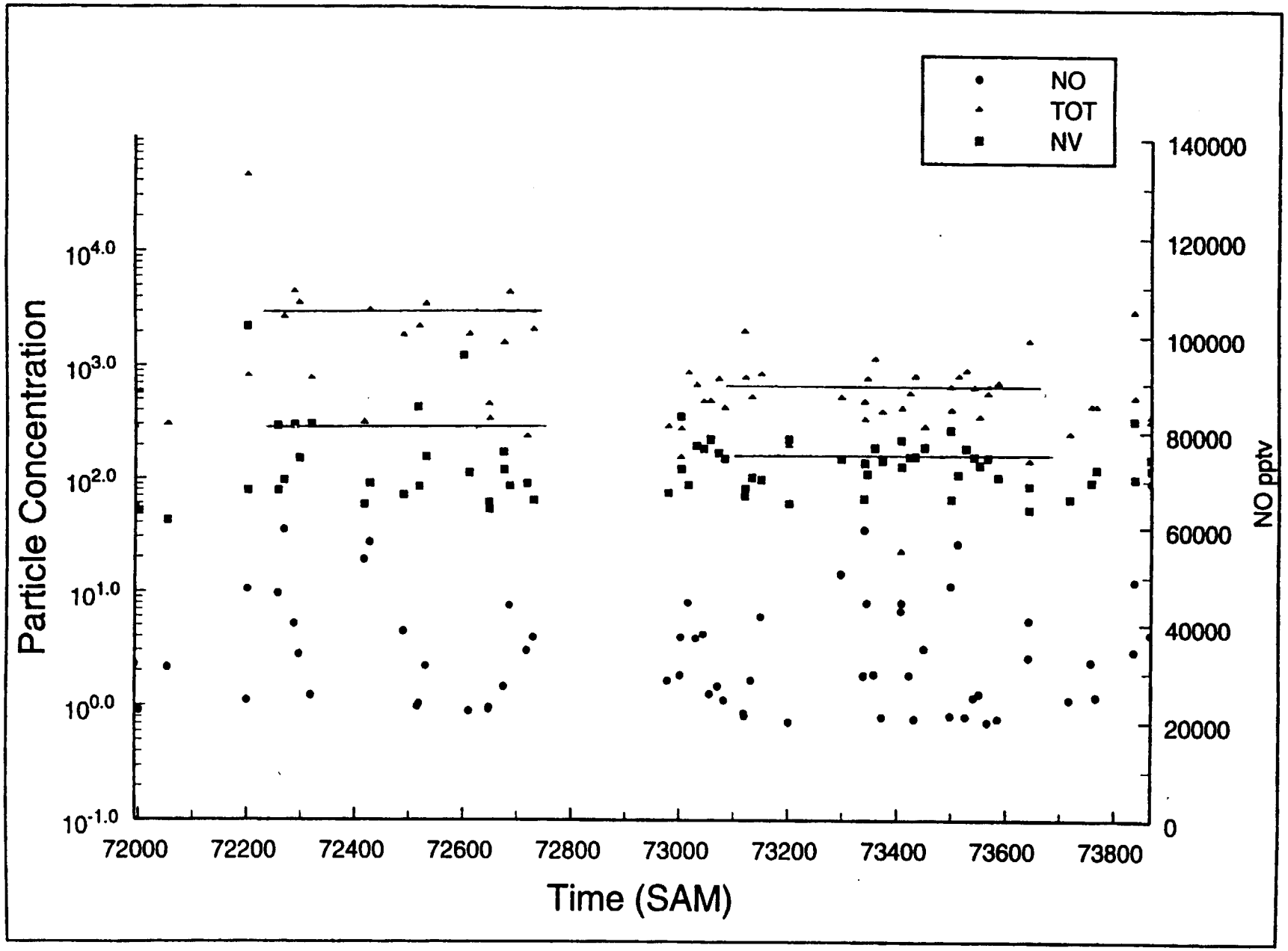
1. Does the filter collect all particles, including those of atmosphericaly significant diameters (< 100nm) ?

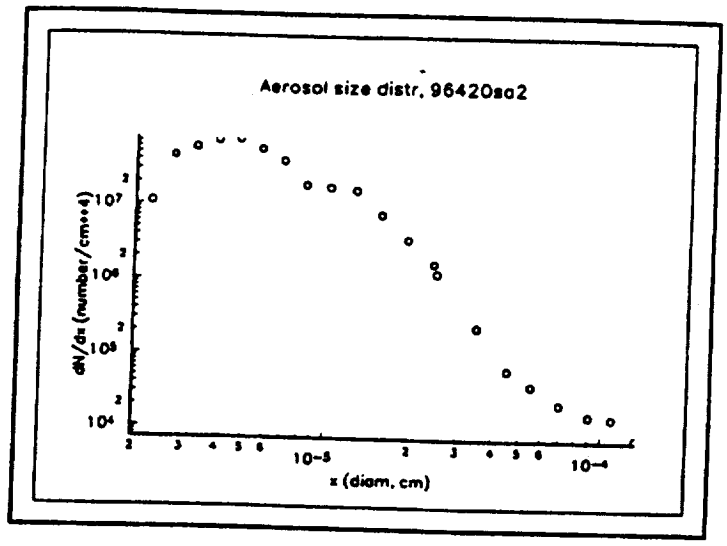
2. If so, does the derived Smoke Number accurately represent the presence of the atmospherically significant particles?

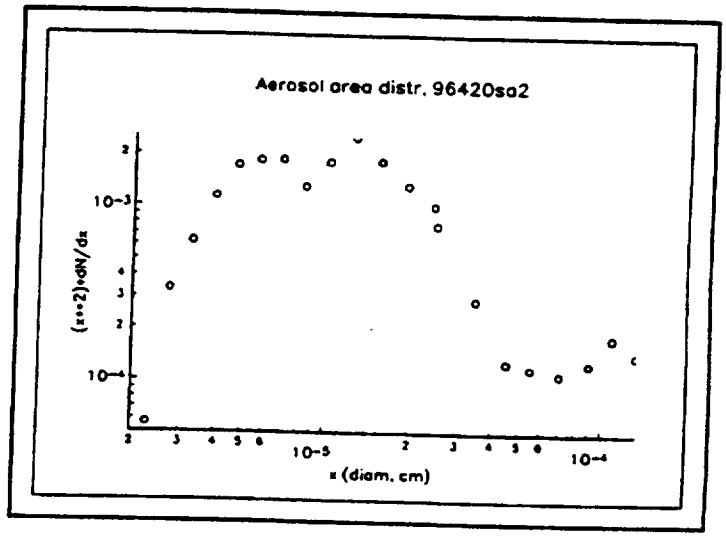
3. Can any correlations be drawn between Smoke Number data and the data aquired using the MASS methodology?

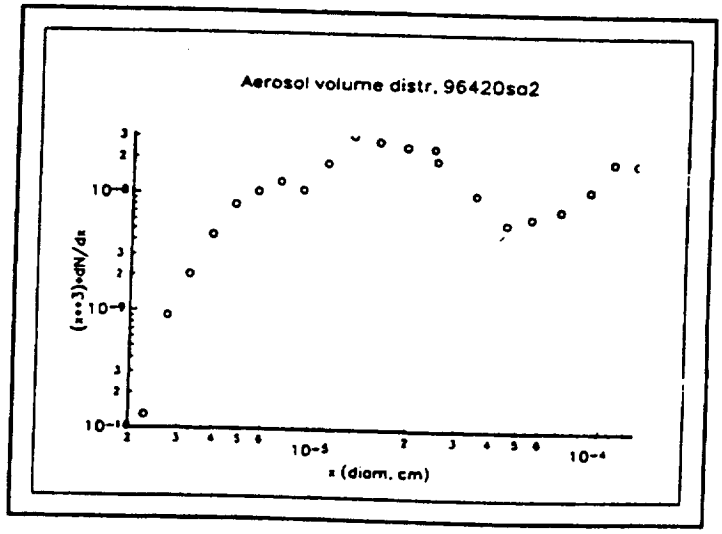
757 Plume Encounters

SUCCESS 3 May 1996




Aerosol size distr. 96420sa2
dN/dx (number/cm**4)
x (diam. cm)


Aerosol area distr. 96420sa2
(x**2)*dN/dx
x (diam. cm)


Aerosol volume distr. 96420sa2
(x**3)*dN/dx
x (diam. cm)

Millipore Fine Particle Transmission Studies

Particle Diameter	%Transmission
10nm	0.868
50nm	0.004
100nm	0.002
150nm	0.000
200nm	0.000

Smoke Number Analysis

Total Smoke Number

Sample Time(s)Smoke Index
159.22
2513.35
5018.15
10030.33

Smoke Number==>14.68

Impactor Smoke Number

Sample Time(s)Smoke Index
152.72
259.22
5012.29
10014.88

Smoke Number==>8.34

Particle Size (nm)	Number Collected	Smoke Index	Extrapolated Smoke Number	Total Aerosol Surface Area (cm^2)	Total Aerosol Mass (g)
53	1E+09	0	0	8.8e-6	7.8e-8
78	1E+09	2.27	0	1.9e-5	2.5e-7
116	1E+08	20.57	0	4.9e-6	9.6e-8
143	1E+08	24.14	2.64	7.5e-6	1.8e-7
223	1E+08	57.34	40.38	1.8e-5	6.8e-7

CONCLUSIONS

1. The Smoke Meter filter does collect all particles.

2. However, atmospherically significant particles, the most numerous in typical jet engine exhaust, do not contribute to the Smoke Number in a measurable fashion.

3. The Smoke Number is largely a result of the few large diameter particles emitted from jet engines.

4. In the recently reported AEDC test, an altitude chamber test of an advanced current engine, the measured Smoke Numbers were 0 for all operating conditions; whereas the mean emission index for atmospherically significant particles was measured to be 1E13 particles/kg fuel.

5. Recent studies have demonstrated a relationship between Smoke Number and particulate emisssion index for older engine technologies. (Representative of the current subsonic commercial fleet.).

Test/date /sponsor	Meas Suite	Source	Major Results & Conclusions Reporting Status
MDC GE404 Mar 92 MDAE	TCN/SD/HYD	HH/F18	proof of principle studies log normal distribution peak dia. <100nm typ.[CN]=10^5 - 10^7 cm^{-3} **AIAA 95-0111 Reno Jan. 1995**
UTRC Aug '94 NASA-AEA	TCN/SD/HYD	Early RQL res rig	log normal distribution peak dia. <100nm typ.[part] > 10^7 cm^{-3} SMF - negligible **NASA-AEA Workshop Virginia Beach 1995.**
POLINAT 1 Nov '94 NASA-AEA DLR UMR	TCN/SD/HYD	Multi-FLIGHT	Aircraft/Engines characterized in flight: B747 - CF6-80C2B1F B747 - JT9D-7A (3 NFS) B747 - CF6-50E2 (2 NFS) B747 - JT9D-7J B747 - CF1-50E2 DC10 - CF6-50C EA34 - CFM56-5C2 EI(CN)= 10^{14}-10^{16} /kg fuel Large volatile component Junge type distribution SMF decreases with plume age Direct evidence of GTPC during plume propagation
POLINAT 1 Jun '95 NASA-AEA DLR UMR	TCN/NVCN/SD /HYD	Multi-FLIGHT	Detailed results and conclusions given in: **European Commission Report - EUR 16978 Pollution from Aircraft Emissions in the North Atlantic Flight Corridor (POLINAT)** **ISBN 92-827-8569-6 & associated publications**

DLR Sulf2 Jul '95 UMR	TCN/NVCN/SD /HYD	GT ATTAS*	Particulate concentrations very high, increase with increasing fuel sulfur content. Size distributions demonstrate multi-modality but relative shape independent of fuel sulfur
Concorde Aug '95 UMR	TCN/NVCN/SD /HYD	GT Olympus	Largest EI(CN) measured to date 10^{17} - 10^{19}/kg fuel Junge type distributions, huge volatile component. **Proc. of the Int. Coll. on the Impact of Aircraft Emissions Upon the Atmosphere, vol I pp119-124 Paris October 1996**
AEDC Oct '95 NASA-AEA	TCN/NVCN/SD	ASC AdvCCT	Mean EI(CN) calculated from all measurements is 2.2 0.7E13, associated mean mass-based EI(soot) is 0.012 0.001. No strong correlation between EI(CN) and thrust, alt or T3 and P3. Appears to be a correlation between combustion efficiency and EI(CN) obsrved in the ground idle data points, where elevated EI(CN), CO and UHC are recorded. EI(CN) measured are small compared with those measured for commercial fleet. Correlates well with SN = 0 reported in this study. Typ.SD's log-normal and peak in the vacinity of 20-40 nm diameter. The volatile component of the aerosol is measured to be small and in most cases negligable. **Experimental Characterization of Gas Turbine Emissions at Simulated Flight Altitude Conditions. Ed. Robert Howard, AEDC TR-96-3 June 1996.**

SNIFF Feb '96 NASA-AEA	TCN/NVCN/SD	GT B737 B757 T-38	log normal distribution peak dia. <100nm typ.[part] > 10^7 cm^{-3} SMF - negligible Significant diference in EI(CN) between L&R engines of B737, consistent with Langley LIDAR measurements. **NASA-AEA Workshop Virginia Beach 1997.**
DLR Sulf3 Mar '96 UMR	TCN/NVCN	GT & FL ATTAS AB300	First particulate sampling <100m separation in flight with fuel sulfur content varying between 6 and 2700ppm. NVCN did not vary as a function of [Sulf]. **Near field measurements on contrail properties from fuels with different sulfur content.** JGR in press Jul'97
SUCCESS May '96 NASA-AEA UMR	TCN/NVCN/SD LAS/HYD/CFX	RB-211 FL	Significant increase in EI(CN) with increasing fuel sulfur content From 2-10km separation between B757 & DC8 EI(CN) decreases with increasing separation distance **2 GRL's submitted Jun 97:** **a. Particle concentration characterization for jet engine emissions under cruise conditions.** **b. Particulate sizing and emission indices for a jet engine exhaust sampled at cruise.**
LeRC-PSL1 Jun '96 NASA-AEA UMR	TCN/NVCN/SD /HYD/SEM	ASC	currently subject to a non-disclosure agreement.
LeRC-FT Sep '96 NASA-AEA UMR	TCN/NVCN/SD /HYD/SEM	RQL FT LDI FT	currently subject to a non-disclosure agreement.

MO-ANG Feb '97 MDAE	TCN/NVCN/SD /LPC/SEM	GT F100 -100	log-normal distributions peak dia. <100nm EI(CN) comparable to commercial fleet, increases with thrust in 60-80% range **Report due Jan 98 following 2nd phase of study with +100 fuel additive.**
WPAFB Fuels Current AFOSR UMR	TCN/NVCN/SD /LPC/SEM	Lab WSR TVComb.	Work in progress **Report on first phase due Dec 1997**
NJ-ANG Jun '97 NASA-AEA UMR	TCN/NVCN/SD /LPC/SEM	GT F100 -220	log-normal distributions peak dia. <100nm EI(CN) comparable to commercial fleet, no strong dependence on thrust
LeRC-PSL2 Current NASA-AEA UMR	TCN/NVCN/SD /LPC/SEM	ASC F100 -220	Measurements Aug/Sep 97
POLINAT2- SONEX Sep '97 NASA-AEA DLR UMR	TCN/NVCN/SD HYD/LPC/SEM		Measurements Sep/Oct 97

AIRBORNE OBSERVATIONS OF AEROSOL EMISSIONS FROM F-16 AIRCRAFT

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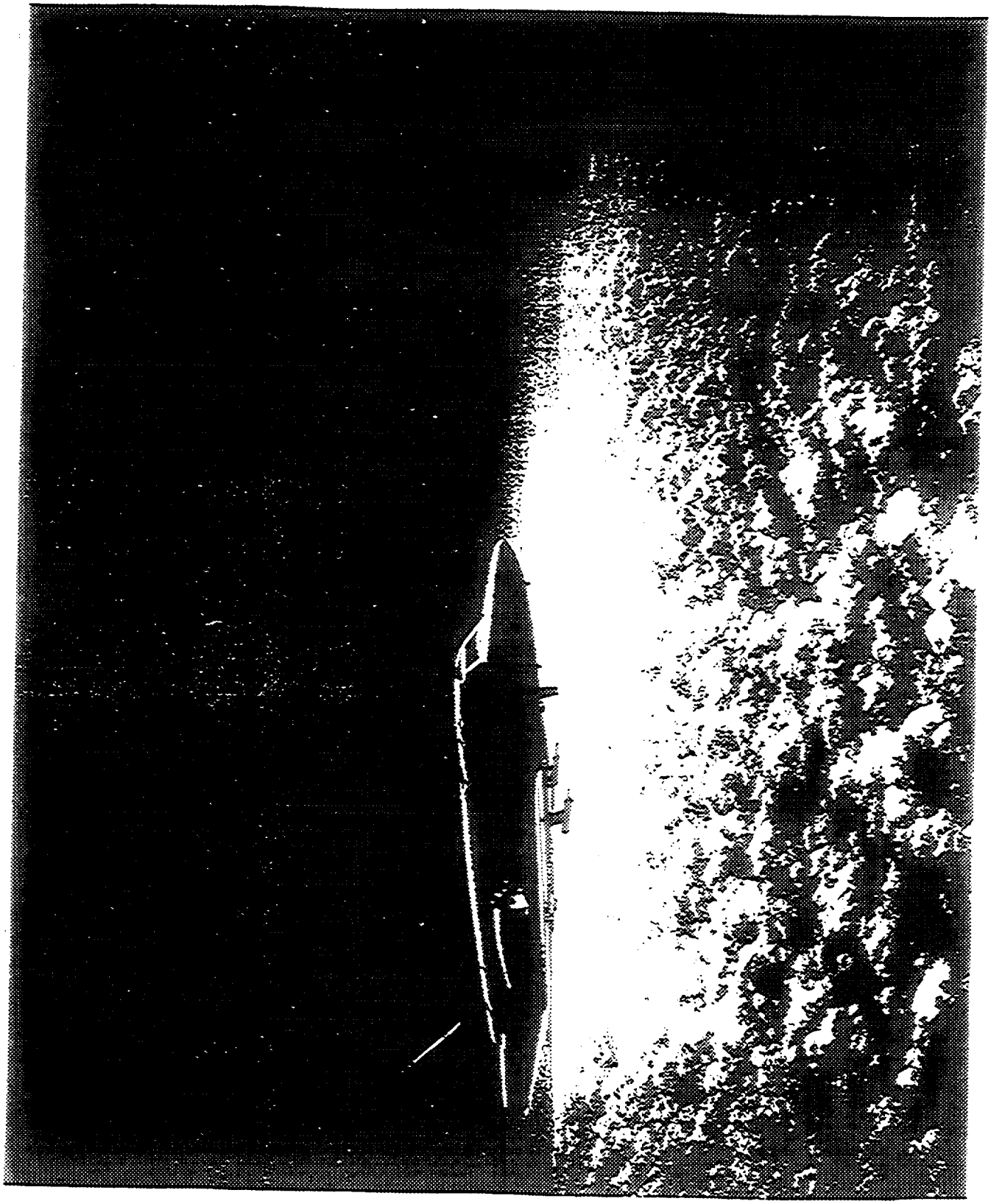
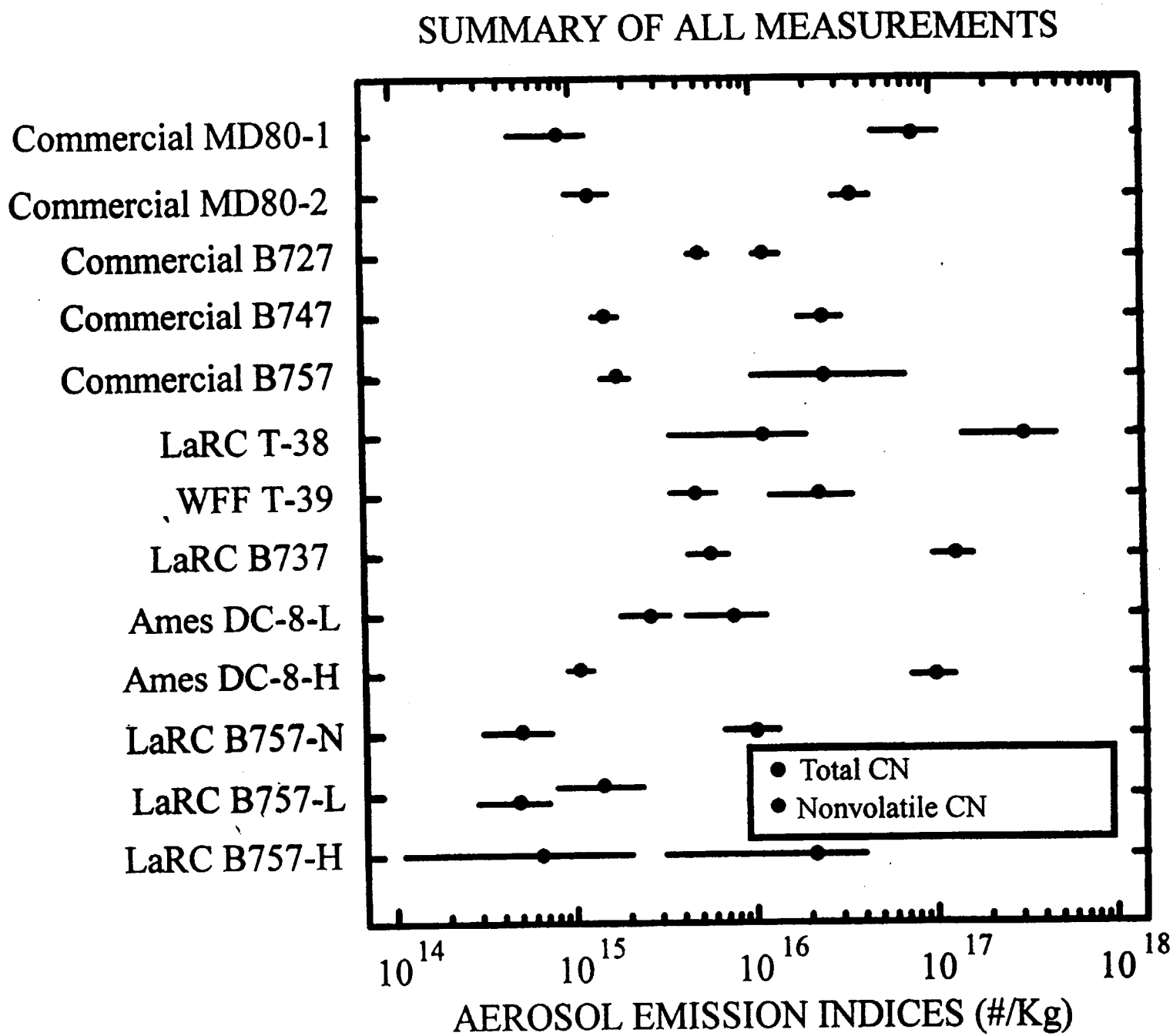
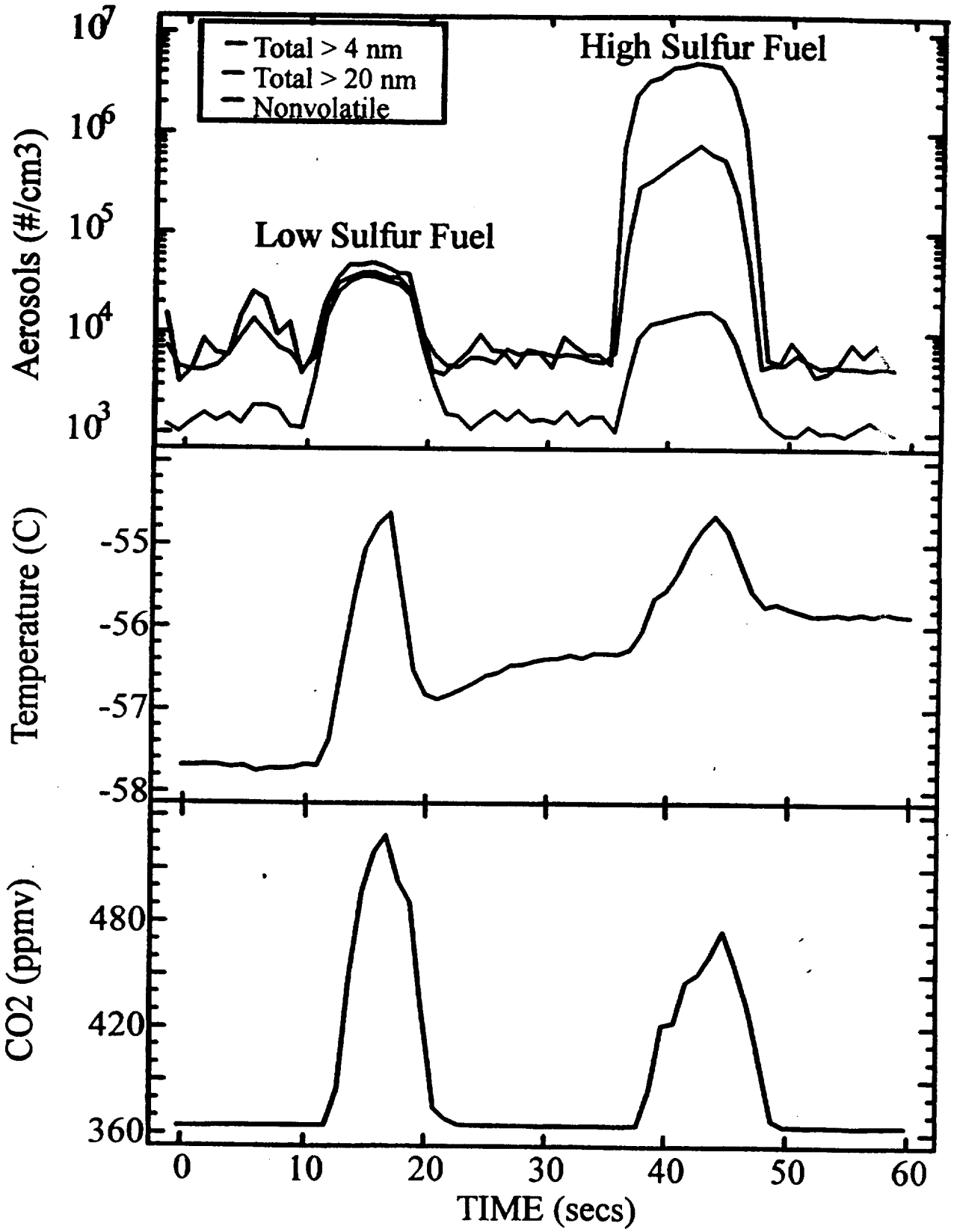
NASA Langley Research Center
Hampton, Virginia

We presented results from the SASS Near-Field Interactions Flight (SNIF-III) Experiment which was conducted during May and June 1997 in collaboration with the Vermont and New Jersey Air National Guard Units. The project objectives were to quantify the fraction of fuel sulfur converted to S(VI) species by jet engines and to gain a better understanding of particle formation and growth processes within aircraft wakes. Size and volatility segregated aerosol measurements along with sulfur species measurements were recorded in the exhaust of F-16 aircraft equipped with F-100 engines burning fuels with a range of fuel S concentrations at different altitudes and engine power settings. A total of 10 missions were flown in which F-16 exhaust plumes were sampled by an instrumented T-39 Sabreliner aircraft. On six of the flights, measurements were obtained behind the same two aircraft, one burning standard JP-8 fuel and the other either ~28 ppm or 1100 ppm S fuel or an equal mixture of the two (~560 ppm S). A pair of flights was conducted for each fuel mixture, one at 30,000 ft altitude and the other starting at 35,000 ft and climbing to higher altitudes if contrail conditions were not encountered at the initial flight level. On each flight, the F-16s were operated at two power settings, ~80% and full military power. Exhaust emissions were sampled behind both aircraft at each flight level, power setting, and fuel S concentration at an initial aircraft separation of 30 m, gradually widening to ~3 km.

Analyses of the aerosol data in the cases where fuel S was varied suggest results were consistent with observations from project SUCCESS, i.e., a significant fraction of the fuel S was oxidized to form S(VI) species and volatile particle emission indices (EIs) in comparably aged plumes exhibited a nonlinear dependence upon the fuel S concentration. For the high sulfur fuel, volatile particle EIs in 10-second-old-plumes were 2 to 3 x 10^{17} kg^{-1} fuel burned and exhibited no obvious trend with engine power setting or flight altitude. In contrast, ~8-fold fewer particles were observed in similarly aged plumes from the same aircraft burning fuel with 560 ppm S content and EIs of $< 1 \times 10^{15}$ kg^{-1} fuel burned were observed in the 28 ppm S fuel case. Moreover, data recorded as a function of plume age indicates that formation and growth of the volatile particles proceeds more slowly as the fuel S level is reduced. For example, ultrafine particle concentrations appear to stabilize within 5 seconds after emission in the 1100 ppm S cases but are still increasing in 20-second old plumes produced from burning the 560 ppm S fuel.




SUMMARY OF ALL MEASUREMENTS
Commercial MD80-1
Commercial MD80-2
Commercial B727
Commercial B747
Commercial B757
LaRC T-38
WFF T-39
LaRC B737
Ames DC-8-L
Ames DC-8-H
LaRC B757-N
LaRC B757-L
LaRC B757-H
Total CN
Nonvolatile CN
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
AEROSOL EMISSION INDICES (#/Kg)


Total > 4 nm
Total > 20 nm
Nonvolatile
High Sulfur Fuel
Low Sulfur Fuel
Aerosols (#/cm3)
10^7
10^6
10^5
10^4
10^3
Temperature (C)
-55
-56
-57
-58
CO2 (ppmv)
480
420
360
0
10
20
30
40
50
60
TIME (secs)

T-39 Instrument Payload

Parameter	Response	Precision
CO2	10 Hz	0.1 ppm
Tdew	.2 Hz	1 deg
T	20 Hz	0.1 deg
u, v, w	10 Hz	0.5 m/s
P, alt	10 Hz	0.1 mb, 10 m
Total CN > 4 nm	2 Hz	10 %
Total CN > 15 nm	2 Hz	10 %
Total CN > 23 nm	2 Hz	10 %
Nonvolatile CN > 4 nm	2 Hz	10 %
Nonvolatile CN >15 nm	2 Hz	10 %
Aerosol Size 0.1 to 3.0 um	10 Hz	20 %

SO2, H2SO4, HNO3, HONO: Impactor Grids

Source Aircraft

Test/Warm-up Flights

Air Force C-5A Galaxy

Wallops C-130 (2 flights)

Wallops BE-200 King Air (2 flights)

Langley B-737-100 (2 flights)

Aircraft with F-100 Series 220 Engines

Vermont Air National Guard F-16s
5 different aircraft, 2 flights
JP-8+100 fuel

New Jersey Air National Guard F-16s
4 different aircraft, 8 flights
5 different fuel mixtures

SNIF-III Experiment Test Matrix

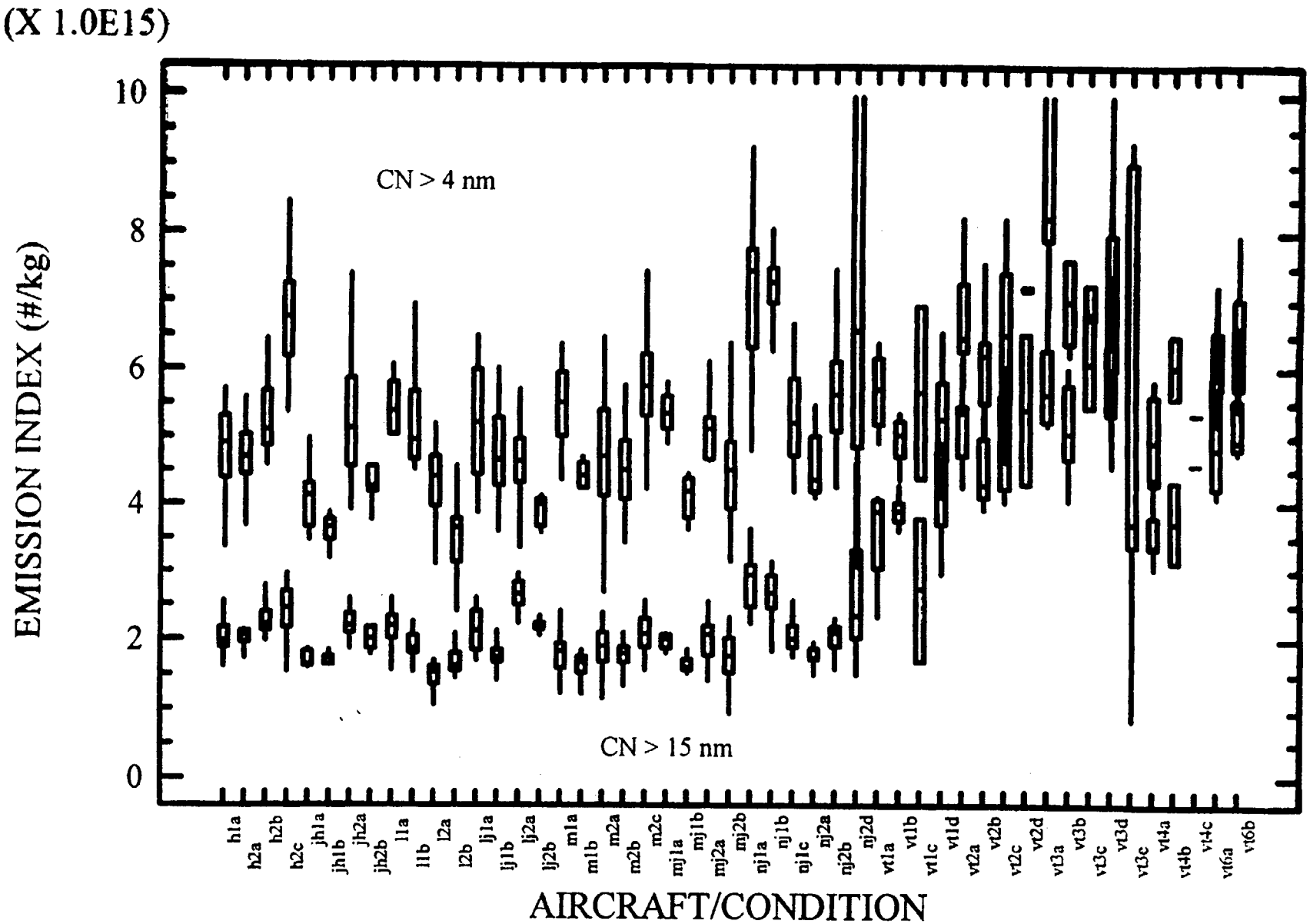
Fuel Sulfur	Low	Medium	High
Environmental parameters	T, P, Q (altitude)	T, Q, P (altitude)	T, Q, P (altitude)
Aircraft Parameters	power	power	power
Plume Age 30 meters + + + + + + 2 km			

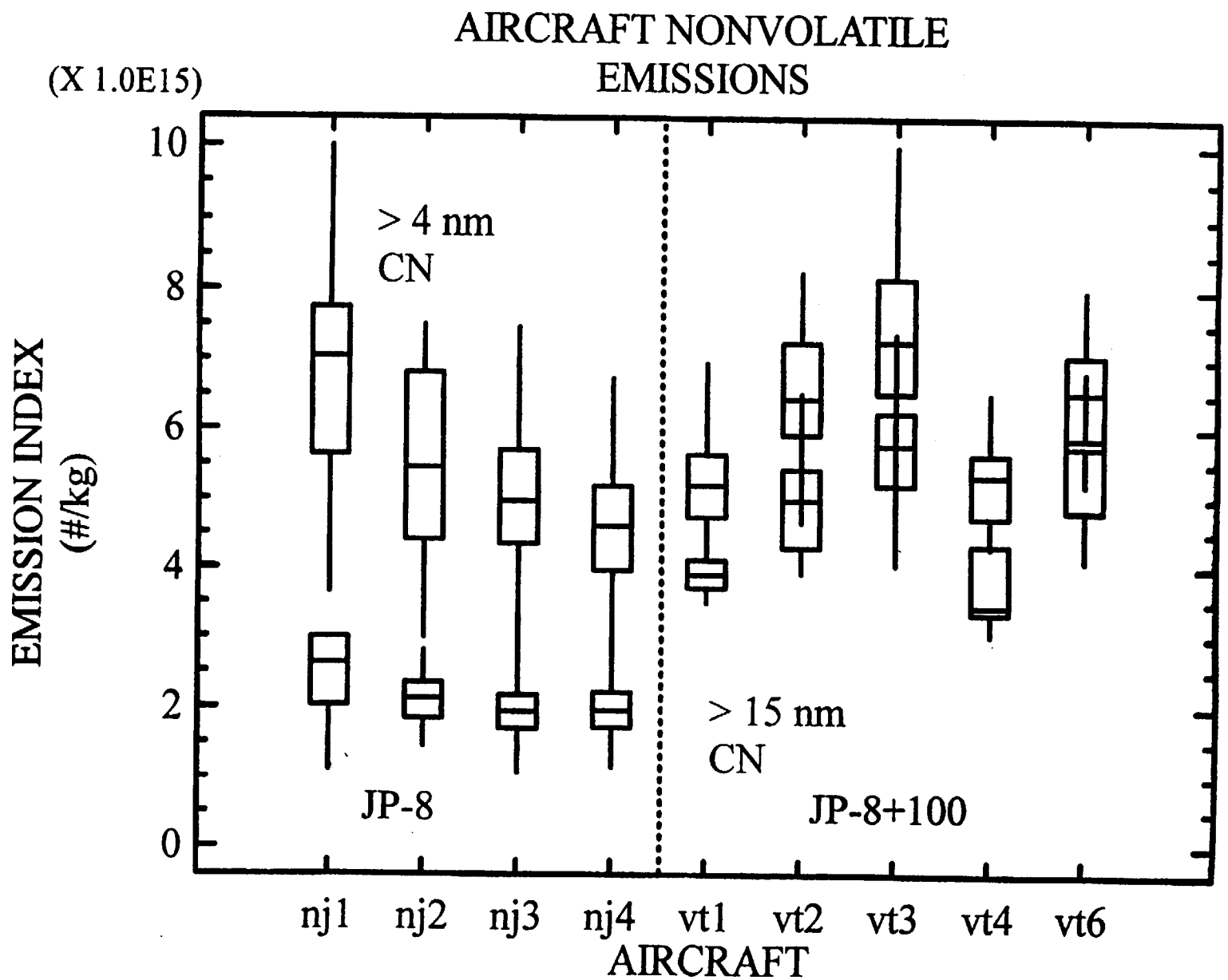
SNIF-III Test Matrix for Individual Fuel

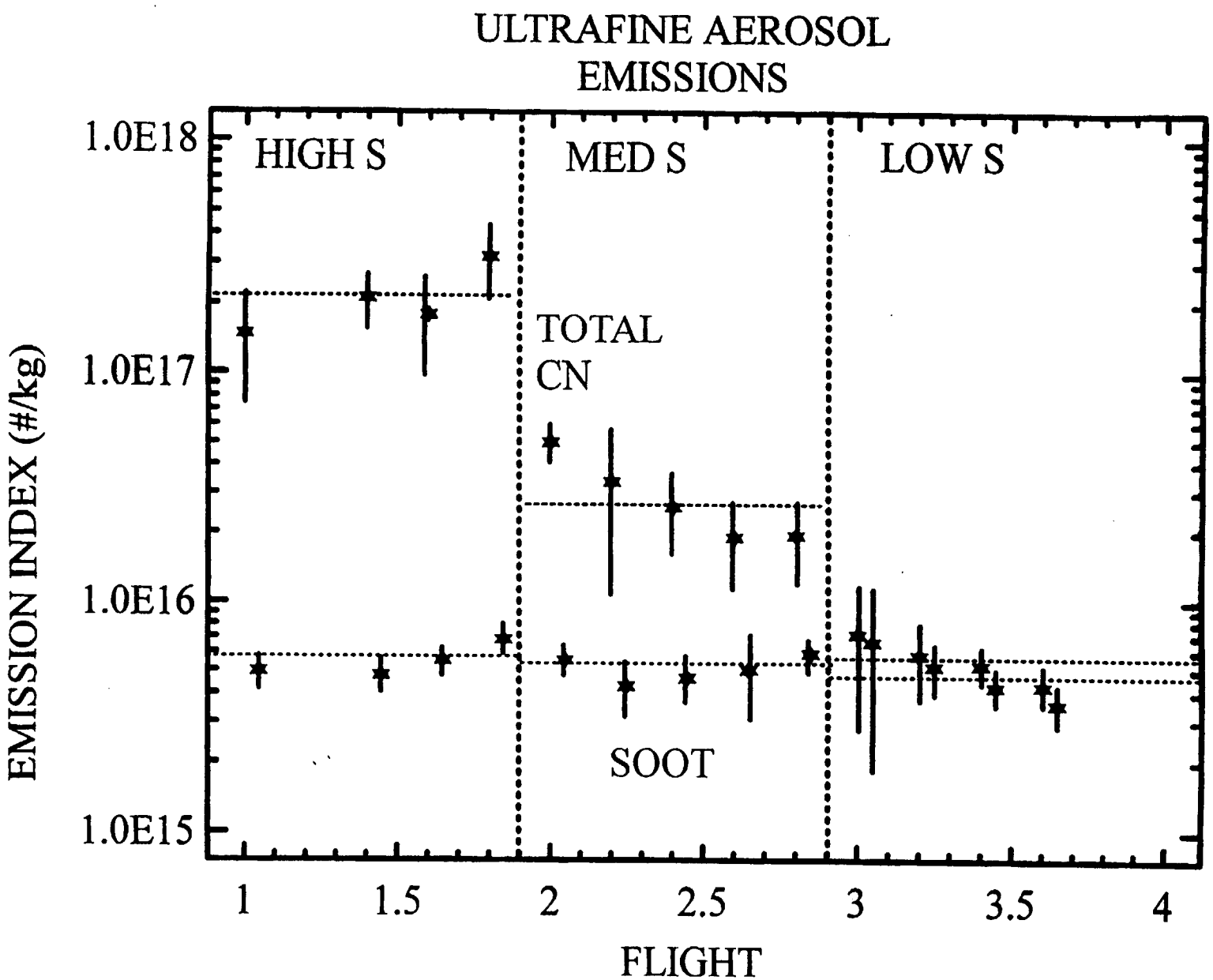
SNIF-III Test Matrix for Individual Fuels

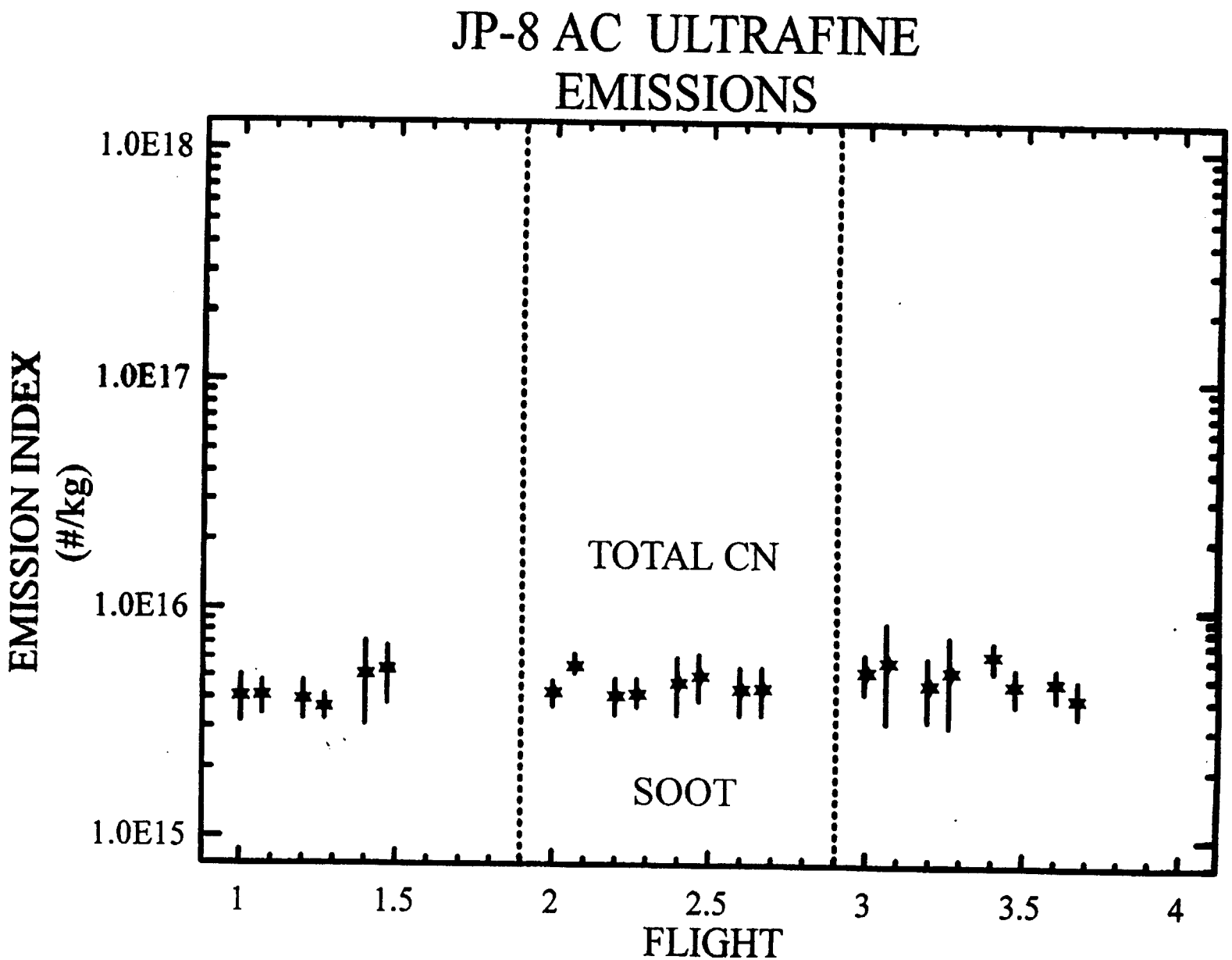
Altitude	30 kft		35 kft		Con Alt
Power Setting	78%	88%	78%	85%	85%
Separation Distance	30 m	30 m	30 m	30 m	30 m
	200 m	200 m	200 m	200 m	200 m
	400 m	400m	400 m	400 m	400 m
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	2000 m	2000 m	2000 m	2000 m	2000 m

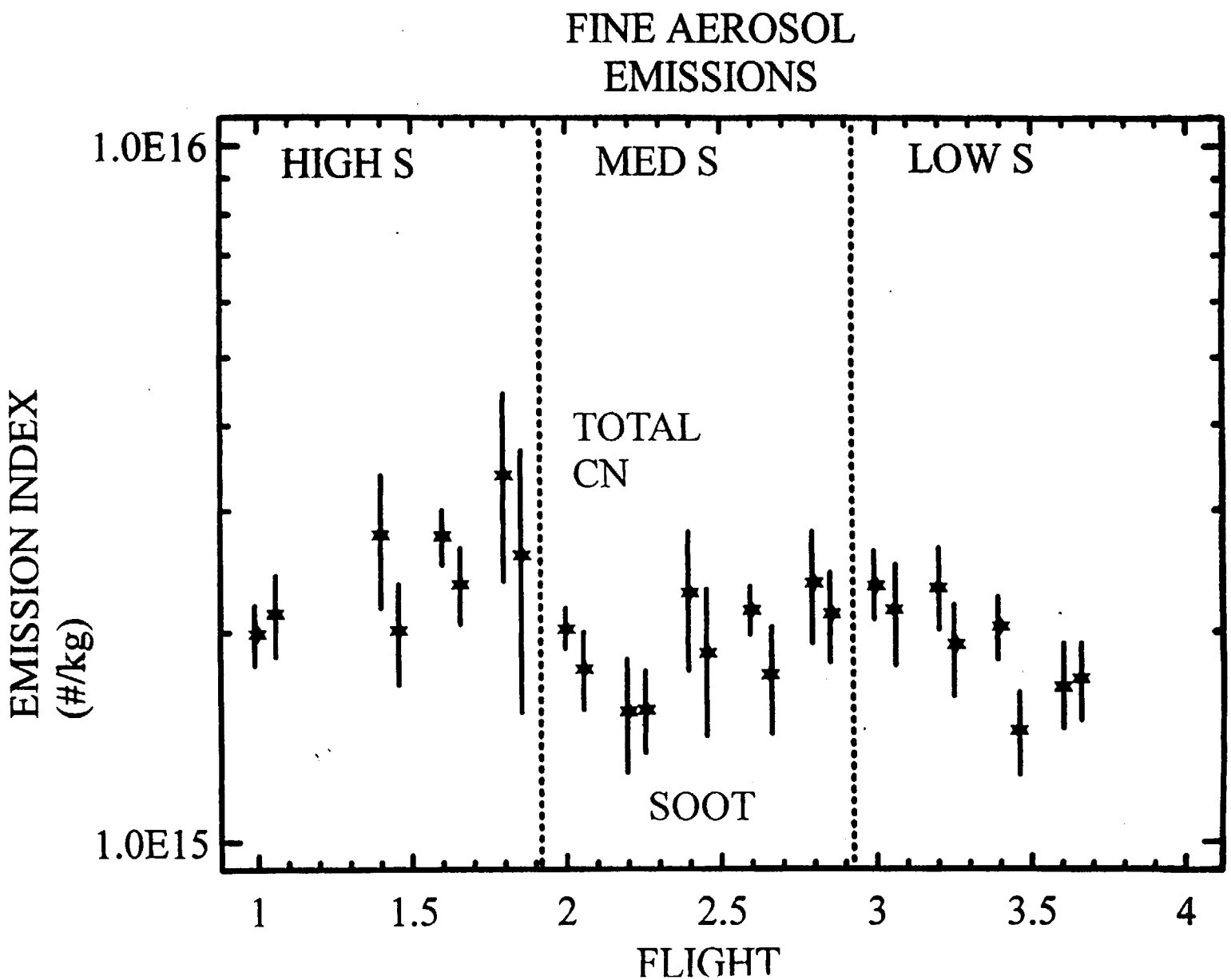
NONVOLATILE AEROSOL EMISSIONS



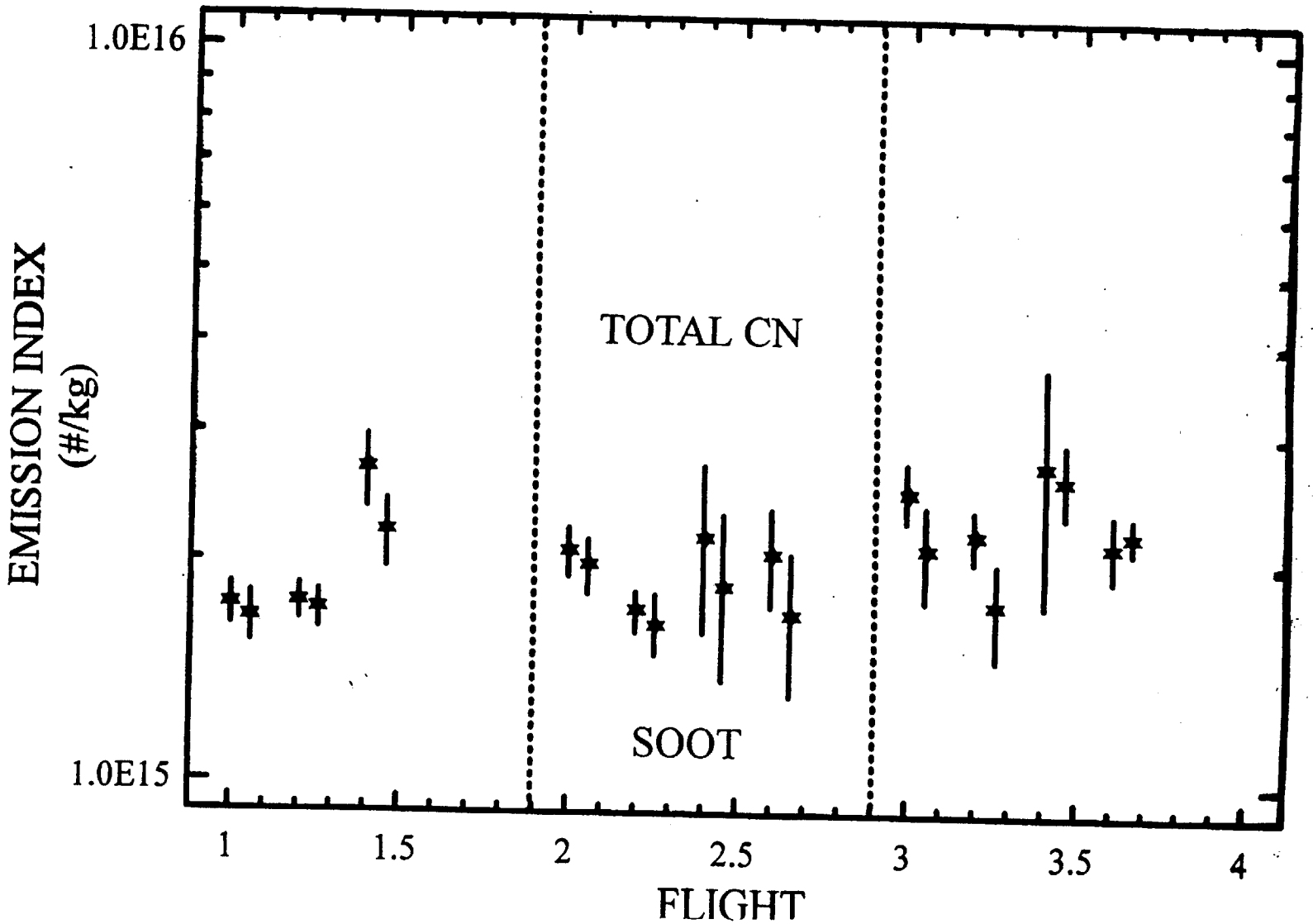

AIRCRAFT NONVOLATILE
EMISSIONS
(X 1.0E15)
EMISSION INDEX
(#/kg)
10
8
6
4
2
0
> 4 nm
CN
> 15 nm
CN
JP-8
JP-8+100
nj1
nj2
nj3
nj4
vt1
vt2
vt3
vt4
vt6
AIRCRAFT


ULTRAFINE AEROSOL
EMISSIONS
HIGH S
MED S
LOW S
TOTAL
CN
SOOT
1.0E18
1.0E17
1.0E16
1.0E15
EMISSION INDEX (#/kg)
1
1.5
2
2.5
3
3.5
4
FLIGHT

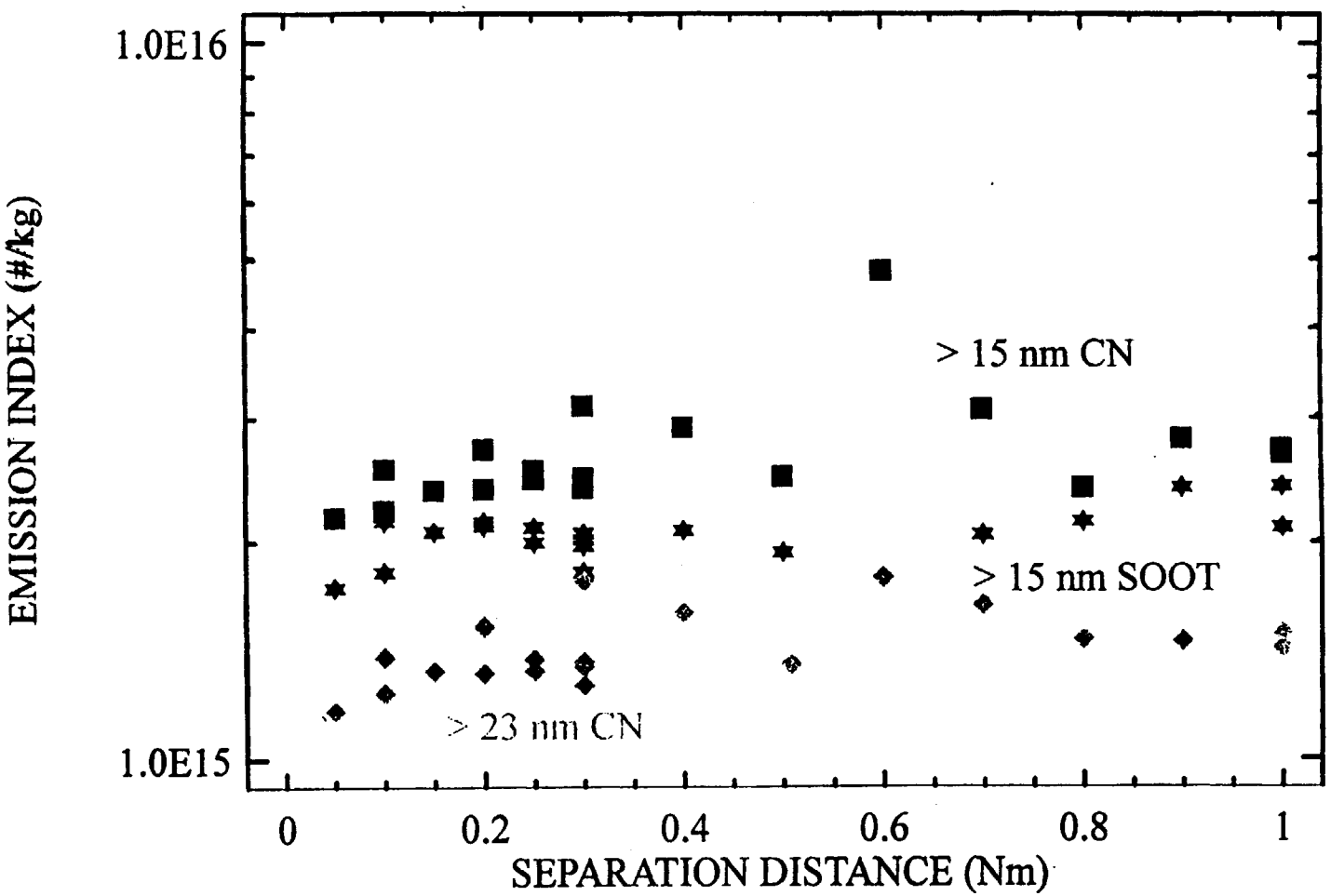

JP-8 AC ULTRAFINE EMISSIONS
EMISSION INDEX (#/kg)
1.0E18
1.0E17
1.0E16
1.0E15
TOTAL CN
SOOT
1
1.5
2
2.5
3
3.5
4
FLIGHT

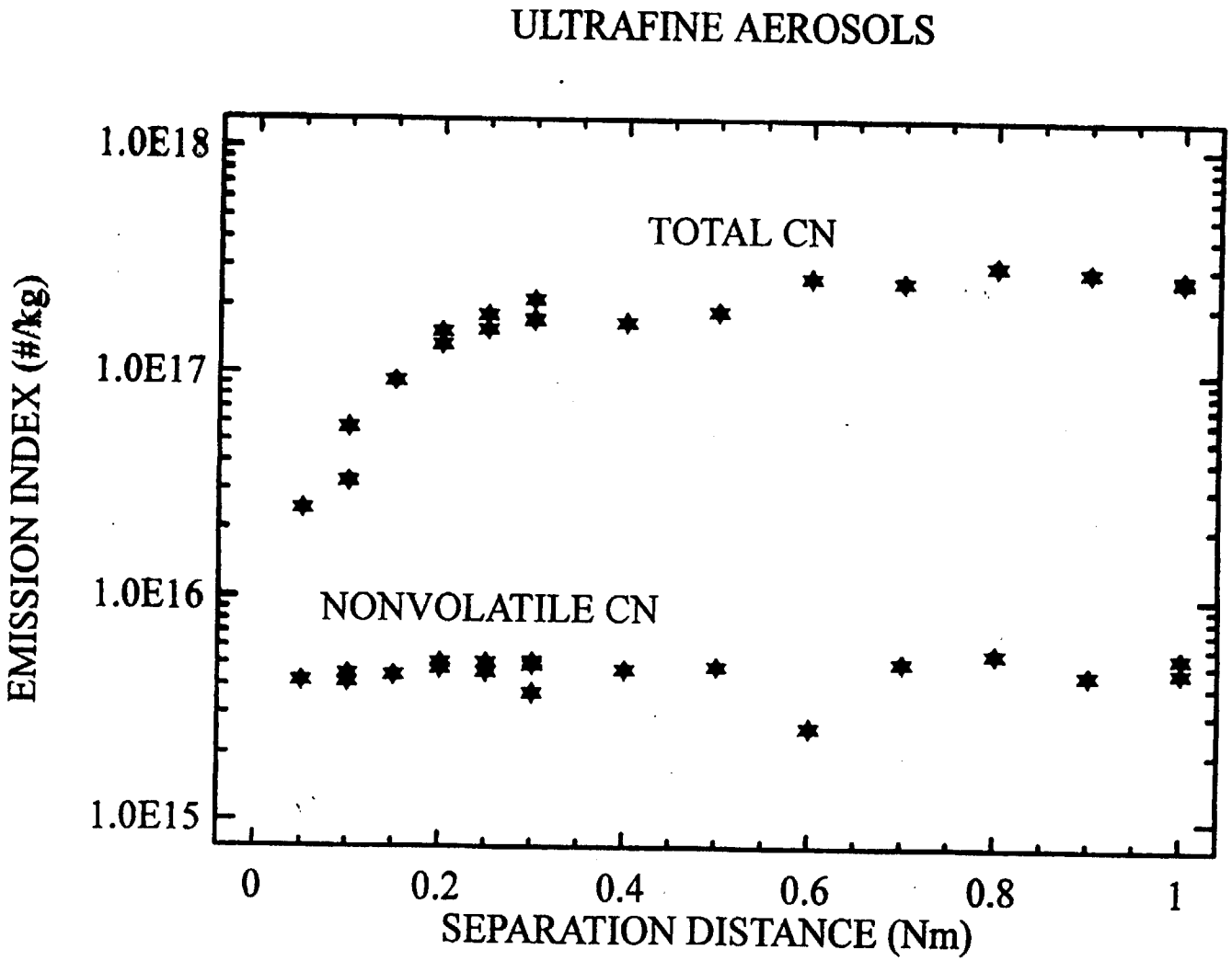

FINE AEROSOL
EMISSIONS
HIGH S
MED S
LOW S
TOTAL
CN
SOOT
1.0E16
1.0E15
EMISSION INDEX
(#/kg)
1
1.5
2
2.5
3
3.5
4
FLIGHT

JP-8 AC FINE EMISSIONS



FINE AEROSOL EMISSIONS




ULTRAFINE AEROSOLS
TOTAL CN
NONVOLATILE CN
EMISSION INDEX (#/kg)
1.0E18
1.0E17
1.0E16
1.0E15
0
0.2
0.4
0.6
0.8
1
SEPARATION DISTANCE (Nm)

Preliminary Observations

- F-100s emit ~6 x 10^{15} particles > 4 nm at typical cruise conditions.
- F-100s burning JP-8 + 100 tend to emit larger particles than those burning standard JP-8.
- Ti and Si aerosols are present in aircraft exhaust plumes.
- The concentration of fuel sulfur controls the emission of volatile particles by aircraft.
- Volatile aerosols are typically < 15 nm in size and their number densities vary non-linearly with fuel S concentration.
- Nonvolatile particles are present early in plume and the number > 4 nm in diameter increase 10 fold in the first 5 seconds after emission.

Some Remaining Questions

- What is the size distribution of the volatile aerosols and how does this change in time? What is the equilibrium concentration of particles in aged aircraft plumes?

- What factors control new particle formation? Why is process apparently non-linear with fuel S? What fraction of H2SO4 is deposited on soot particles?

- What fraction of the CN in aged aircraft plumes are active as IN and CCN?

- Are substantial #s of Ti and Si particles generated by aircraft?

- Does the fraction of fuel S oxidized to S(VI) vary substantially between engines?

- Would contrails form if [fuel sulfur] = 0?

WORKSHOP ON AEROSOLS AND PARTICULATES FROM AIRCRAFT GAS TURBINE ENGINES

Harvey V. Lilenfeld
McDonnell Douglas Corporation
St. Louis, Missouri

Prior to 1990, the major source of measurements on particulate emissions from aircraft utilized the measurement of 'smoke numbers'. This technique was developed to quantify the light scattering properties of engine exhaust, but is not directly applicable for modeling of the effects of engine particulates on the atmosphere. The data base for particulate emissions from aircraft flying in the atmosphere has increased dramatically in the last few years due to the implementation of equipment capable of measuring particle number densities, size distributions, hydration properties and emission indices. This equipment was developed to quantify engine exhaust emissions because of concerns of the environmental impact of supersonic and subsonic aircraft.

This paper reports on the status of the data base obtained from these measurements and reports on the correlations currently being used to characterize the current and future fleets of aircraft flying in the troposphere and stratosphere.

As a result of project Pollinet, a European campaign to measure the effects of emissions of subsonic aircraft, a number of particle emission indices were measured by workers from the University of Missouri Rolla and their associates. These results for particle emission indices (particles/kg fuel burned) for both total particles and non-volatile particles (particles remaining after volatile particles are removed by heating to 170C) are correlated for a number of aircraft/engine combinations flight at 300 hft. The agreement among engine types for non-volatile particles (assumed to be predominantly soot) is generally good (within 20%) with a range among the aircraft intercepted of $2x10^{14}$ - $2x10^{15}$ particles/Kg fuel. These data were also correlated with smoke numbers optained from the ICAO data base.

Work-in-progress data base correlations are described for an assortment size distributions obtained from measurements on the ground, in the air and in altitude chambers taken during the NASA sponsored projects SNIF and SUCCESS.

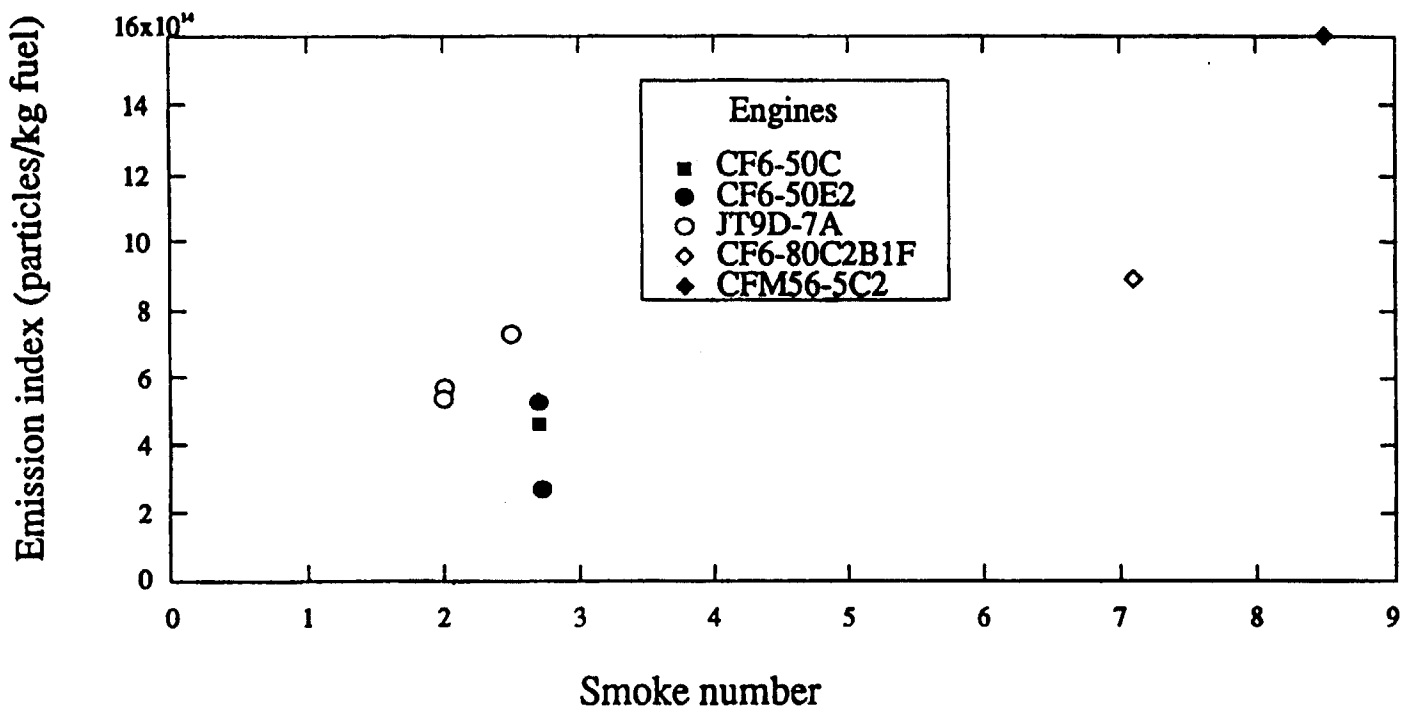
Interesting measurements of a NASA owned 737 aircraft with JT8 engines and a 757 aircraft with RB-211-535C engines are described. The 757 aircraft is of interest because of the difference seen for particles emissions between the port and starboard engines. This case is interest because it is very atypical for results to vary this much between engines of the same type.

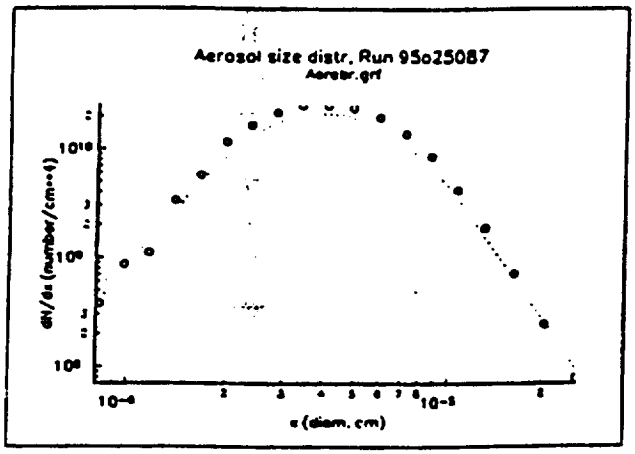
Measurements of emission indices on the ground and in the air for the 757 aircraft are compared. In addition, measurements of this aircraft by several groups are compared.

Measurements taken on the ground and in flight for military aircraft flying with F100 engines are compared. The older version of the F100 engine (F100-100 servies) appears to have a greater emissions than the later (F100-200) model at high thrust settings. The emissions from both of these older engines is more than an order of magnitude greater than the emissions from a modern engine. These results indicate the improvements made by industry of the past several decades on particulate emissions.

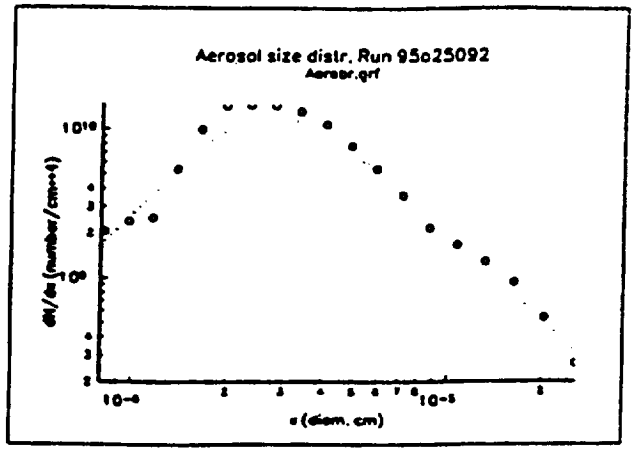
The size distributions of particles emitted from these aircraft appear to change somewhat as a function of thrust setting. Size distributions among the engine models (F100-100 vs F100-200) are compared but the differences noted may represent different operating conditions as well as differences among engine models.

Date	Time UTC	Plane	Engine	Level hft	press hPa	T °C	Fuel t/hr	EI Total (kg fuel^{-1})	EI Non-Volatile (kg fuel^{-1})
30 Jun 95	13:30	B747	CF6-80C2B1F	370	216.6	-59	8.4		8.9×10^{14}
30 Jun 95	13:53	B747	JT9D-7A	326	266.9	-47	13.6		3.3×10^{14}
30 Jun 95	14:32	B747	JT9D-7A	330	262.0	-47	12.0		5.4×10^{14}
3 Jul 95	13:50	B747	CF6-50E2	350	238.4	-51	12.0	5.8×10^{15}	2.7×10^{14}
3 Jul 95	14:25	DC10	CF6-50C	330	262.0	-46.5	13.13	4.5×10^{15}	4.6×10^{14}
3 Jul 95	14:50	B747	JT9D-7J	330	262.0	-46	7.35	9.9×10^{15}	4.5×10^{14}
3 Jul 95	15:30	B747	JT9D-7A	330	262.0	-47		8.1×10^{14}	5.7×10^{14}
5 Jul 95	2:28	B747	CF6-50E2	350	238.4	-51	10.4	1.8×10^{15}	5.3×10^{14}
5 Jul 95	3:28	EA34	CFM56-5C2	350	238.4	-51	6.0	2.9×10^{16}	1.6×10^{15}

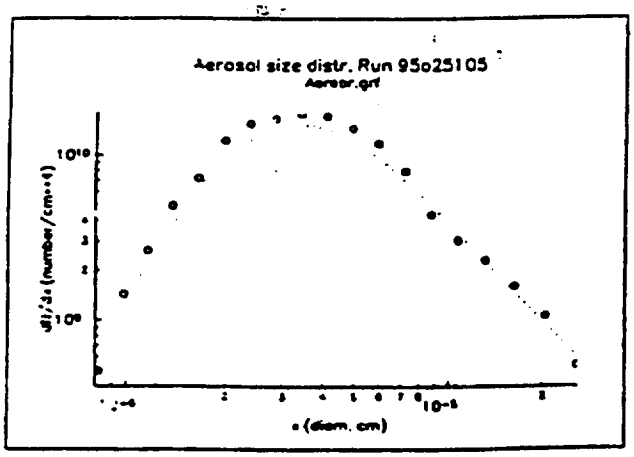

Emission index (particles/kg fuel)
16x10¹⁴
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
Smoke number
Engines
CF6-50C
CF6-50E2
JT9D-7A
CF6-80C2B1F
CFM56-5C2



+ 9.1 km pla = 860

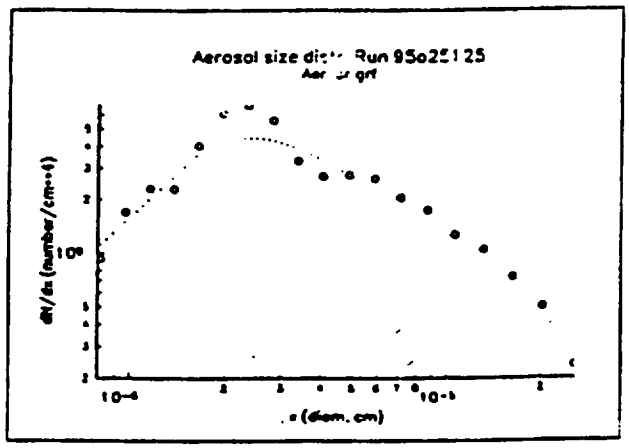


9.1 km pla = 750



12.2 km

T3 = 727 K

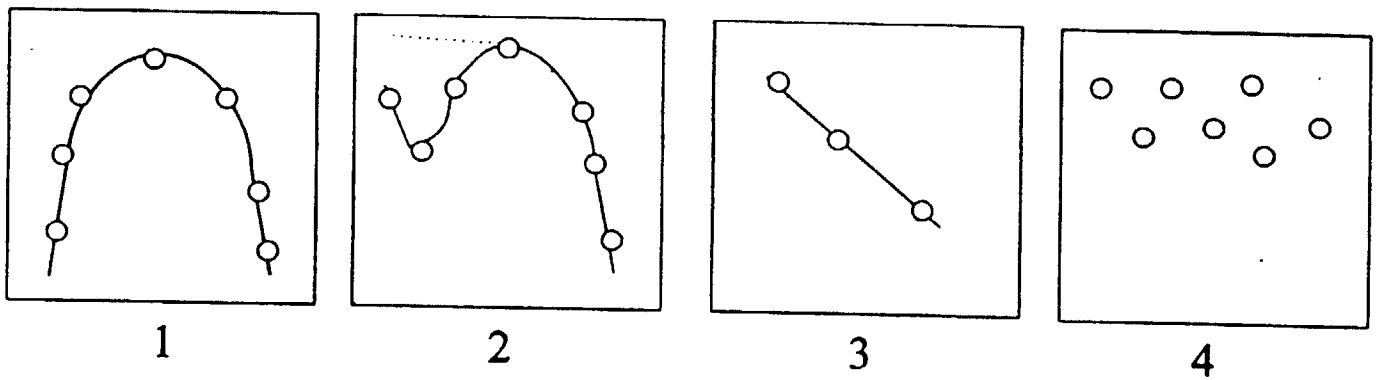


12.2 km

T3 = 665 K

Database Correlations

1) Characterize each distribution according to shape.



2) Determine fraction of distribution with diameters >100 nm.

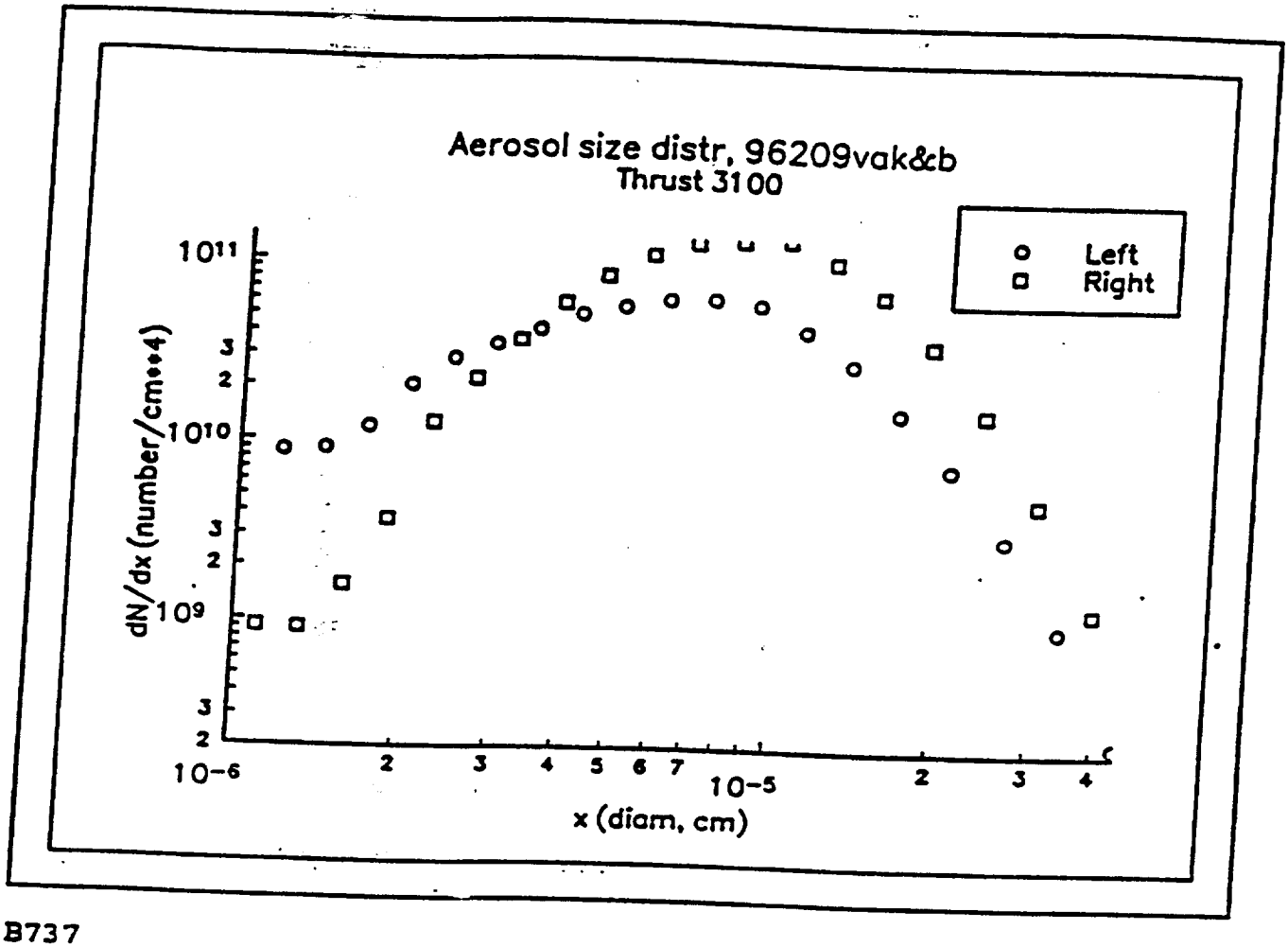
3) For types 1 and 2 determine the number of nodes

4) For types 1 and 2 determine the peak size and $l_{10\%}$ and $r_{10\%}$ (the left and right 10% widths)

5) Calculate areal mean diameter

6) Calculate volume mean diameter

Name	Shape	Fraction	# Modes	Left 10% (nm)	Peak1 (num/cm^4)	Peak2 (num/cm^4)	Peak3 (num/cm^4)	Right 10% (nm)	Slope
1	1	0.065	1	0	1.8E+10	0	0	190	0
2	1	0.086	1	0	1.8E+10	0	0	190	0
9	1	0.0013	1	0	6.00E+10	0	0	70	0
10	1	0.006	1	0	6E+10	0	0	70	0
12	1		1	0	5.00E+10	0	0	70	0
13	1		1	0	5.00E+10	0	0	70	0
21	1		1	0	6.00E+10	0	0	70	0
26	2		1	0	9.00E+11	0	0	180	0
27	2		1	0	9.00E+11	0	0	180	0
29	2		1	0	2.00E+10	0	0	70	0
39	2		2	0	3.00E+09	4.00E+11	0	200	0
51	1		1	0	3.00E+10	0	0	120	0
56	1		1	9	3.00E+10	0	0	90	0
57	1		1	9	3.00E+10	0	0	90	0
59	1		1	9	3.00E+10	0	0	90	0
64	1		1	15	1.00E+11	0	0	0	0
69	1		1	0	2.50E+10	0	0	200	0
76	1		1	10	2.00E+10	0	0	100	0
77	1		1	10	2.00E+10	0	0	100	0
79	1		1	15	2.00E+10	0	0	180	0
82	1		1	14	2.00E+10	0	0	140	0
87	1		1	14	2.00E+10	0	0	140	0
92	1		1	0	1.00E+10	0	0	150	0
93	1		1	0	1.00E+10	0	0	150	0
95	1		1	0	1.00E+10	0	0	100	0
105	1		1	11	1.7E+10	0	0	160	0
106	1		1	11	1.1E+10	0	0	160	0
108	1		1	10	3.1E+10	0	0	150	0
113	1		1	10	2.2E+10	0	0	130	0
118	1		1	16	1.5E+10	0	0	0	0
119	1		1	16	1.5E+10	0	0	0	0
125	1		1	0	6E+09	0	0	0	0
130	1		1	0	4E+09	0	0	150	0
135	1		2	0	6.00E+06	5.00E+06	0	0	0
138	1		1	9.5	8E+08	0	0	80	0
143	1		1	9.5	2.5E+09	0	0	80	0
151	2		1	0	5E+10	0	0	120	0
156	1		1	13	2.8E+10	0	0	150	0
157	1		1	13	2.8E+10	0	0	150	0
162	1		1	14	3.5E+10	0	0	140	0
163	1		1	14	3.5E+10	0	0	140	0
169	1		1	17	1.50E+10	0	0	0	0
172	1		1	11	1E+12	0	0	120	0
175	1		1	9	4E+10	0	0	85	0
176	1		1	9	4E+10	0	0	85	0
178	1		1	10	3.5E+10	0	0	160	0
179	1		1	10	3.5E+10	0	0	160	0
183	1		1	0	1.5E+09	0	0	90	0
188	1		1	0	9E+10	0	0	100	0
193	1		1	11	6.5E+10	0	0	95	0
196	1		1	13	1.7E+10	0	0	0	0


Aerosol size distr, 96209vak&b
Thrust 3100
Left
Right
dN/dx (number/cm**4)
x (diam, cm)

B737

737 JT8

lbs fuel/hr	E.I. (Total particles) part/kg fuel	E. I. (Nonvolatile Particles) part/kg fuel
1200 right	4.30×10^{15}	1.73×10^{15}
2400 right	4.79×10^{15}	1.97×10^{15}
3100 right	8.77×10^{15}	3.69×10^{15}
1200 left	3.40×10^{15}	1.37×10^{15}
2400 left	3.69×10^{15}	1.52×10^{15}
3100 left`	3.76×10^{15}	1.58×10^{15}

757 RB211-535C

lb fuel /hr	E.I. (Total particles) part/kg fuel	E.I. (Nonvolatile particles) part/kg fuel
3100 right	8.1×10^{12}	6.6×10^{12}
3100 left	1.1×10^{13}	1.1×10^{13}
3800 right	1.3×10^{13}	1.1×10^{13}
3800 left	1.2×10^{13}	9.1×10^{12}

Total Particle Concentration from 757 flight

	B. Anderson[1]	R. F. Pueschel et. al.[2]	D. Hagen et. al.[3]
High Sulfur	$3x10^{15}$-$5x10^{16}$	1-$1.6x10^{16}$	$1.4x10^{15}$-$5.1x10^{15}$
Low Sulfur	$8x10^{14}$-$3x10^{15}$	2.1-$3.5x10^{15}$	$1.5x10^{14}$-$1.9x10^{15}$

1. In NASA Reference Publication 1400 Atmospheric Effects of Subsonic Aircraft: Interim Assessment Report of the Advance Subsonic Technology Program R. R. Friedl ed. Godard Space Flight Center Greenbelt Md. 20771 1997

2. R.F. Pueschel et. al. Sulfuric acid and Soot Particle Formation in Aircraft Exhaust - GRL - submitted

3. D. Hagen et. al. Particulate sizing and emission indices for a jet engine exhaust sampled at cruise - GRL submitted

Non-Volatile Particle Concentration from 757 Flight

	B. Anderson [1]	D. Hagen et. al. [2]
High Sulfur	$1x10^{14}$-$2x10^{13}$	$5x10^{13}$-$5.5x10^{14}$
Low Sulfur	$3x10^{14}$-$8x10^{14}$	$1x10^{13}$-$5.5x10^{14}$

1. In NASA Reference Publication 1400 Atmospheric Effects of Subsonic Aircraft: Interim Assessment Report of the Advance Subsonic Technology Program R. R. Friedl ed. Godard Space Flight Center Greenbelt Md. 20771 1997

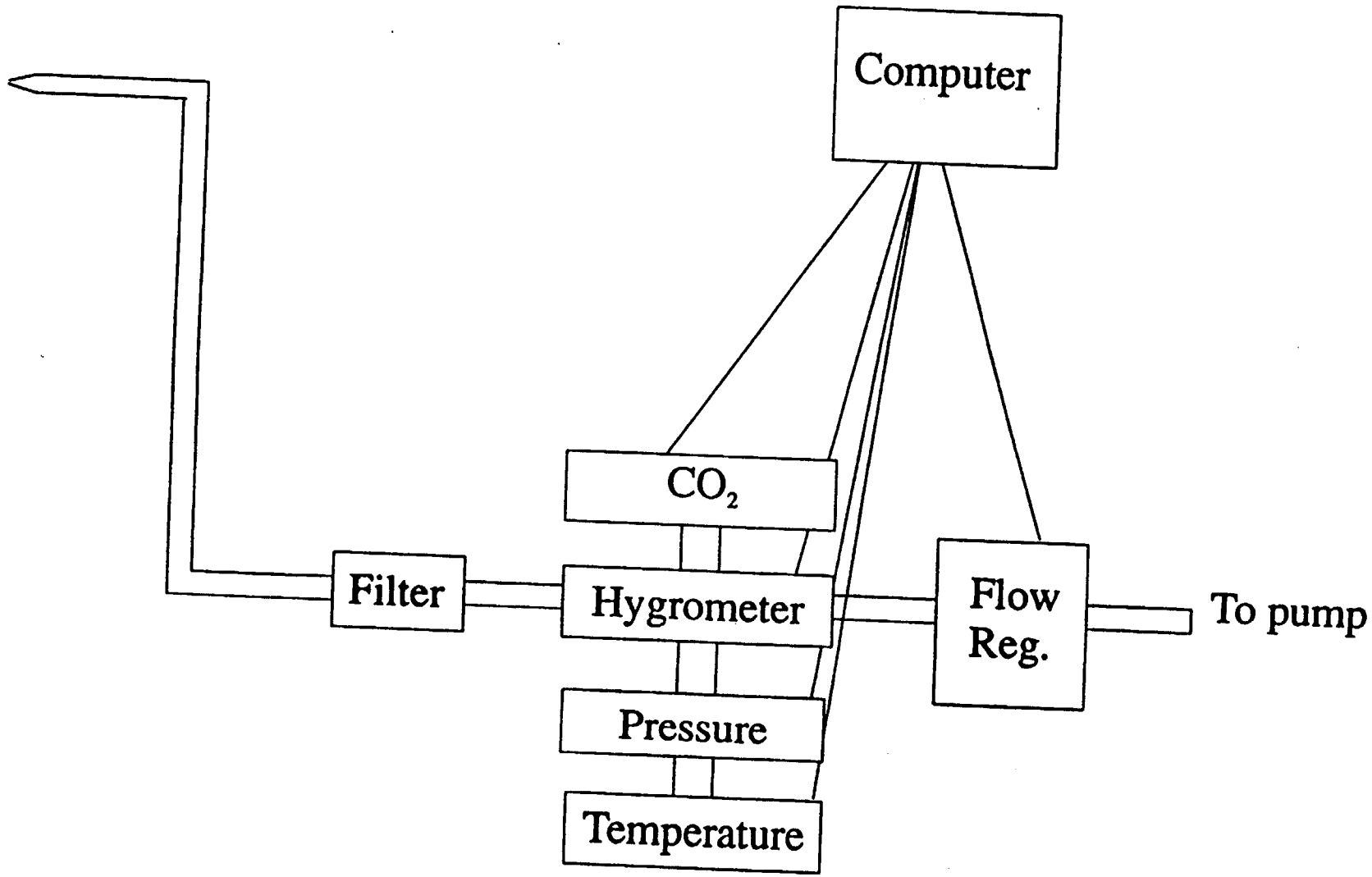
2. D. Hagen et. al. Particulate sizing and emission indices for a jet engine exhaust sampled at cruise - GRL submitted

Methodology for ground testing F100 engines

Record Engine Numbers
Record Tail Numbers

Place probe 1 meter from exhaust on centerline

For each run record :
Thrust (%)
FTIT
Fuel flow
Nozzle Opening



Gas Phase Detection System

Changes to F100 Engines affecting soot emissions

F100-100

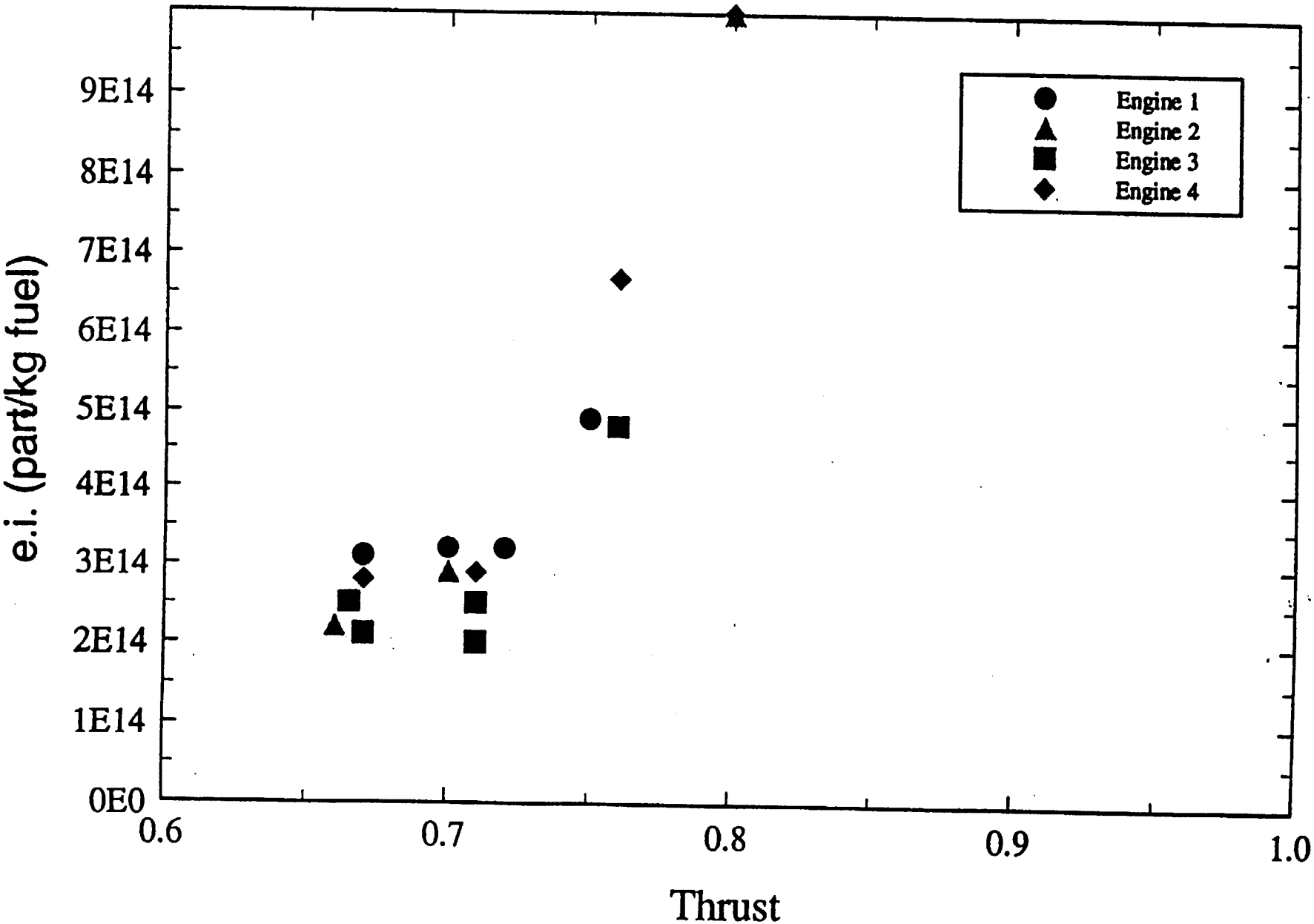
F100-220

1. Imporved axial swirler
2. Added more air

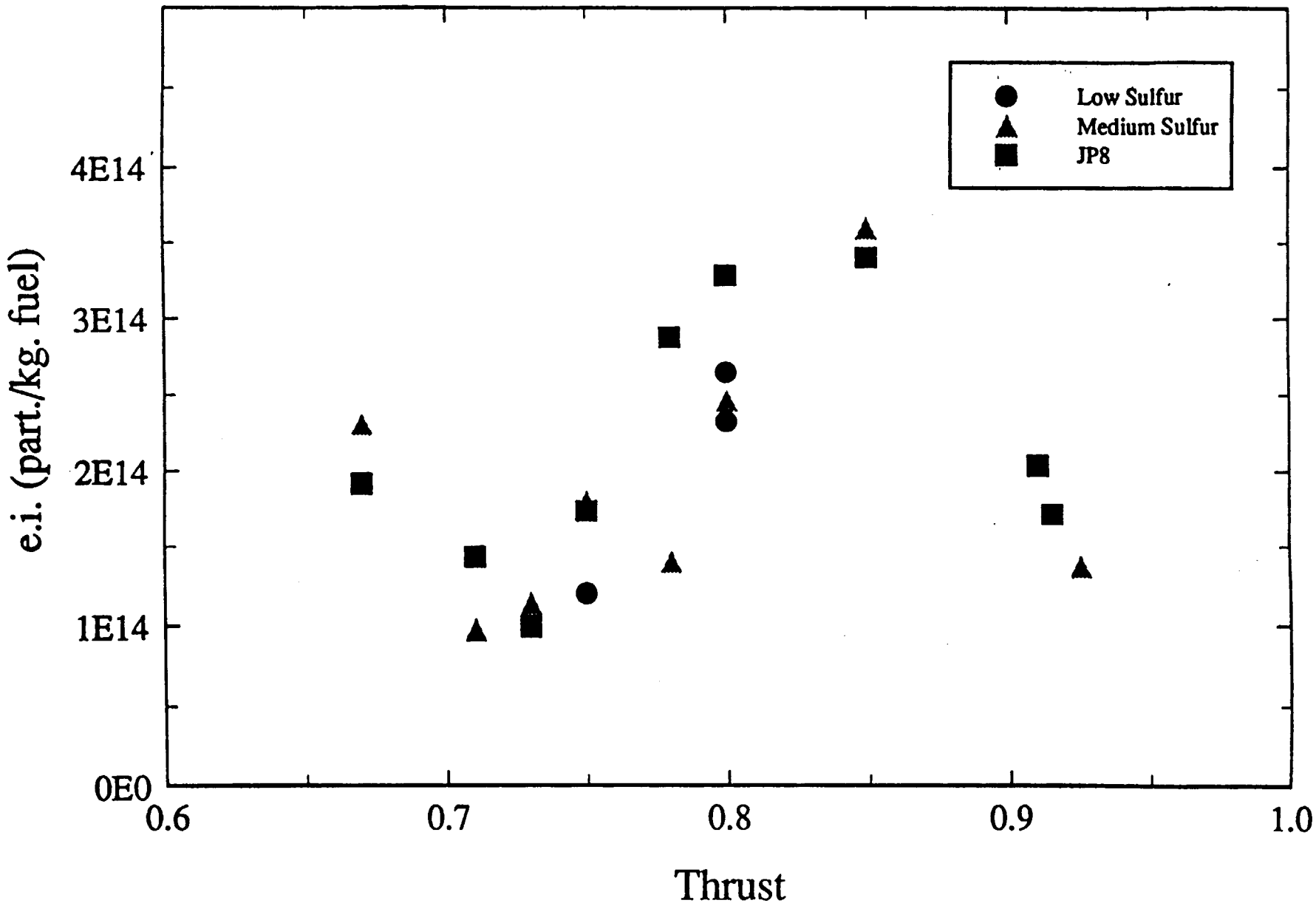
F100-229

High sheer swirler

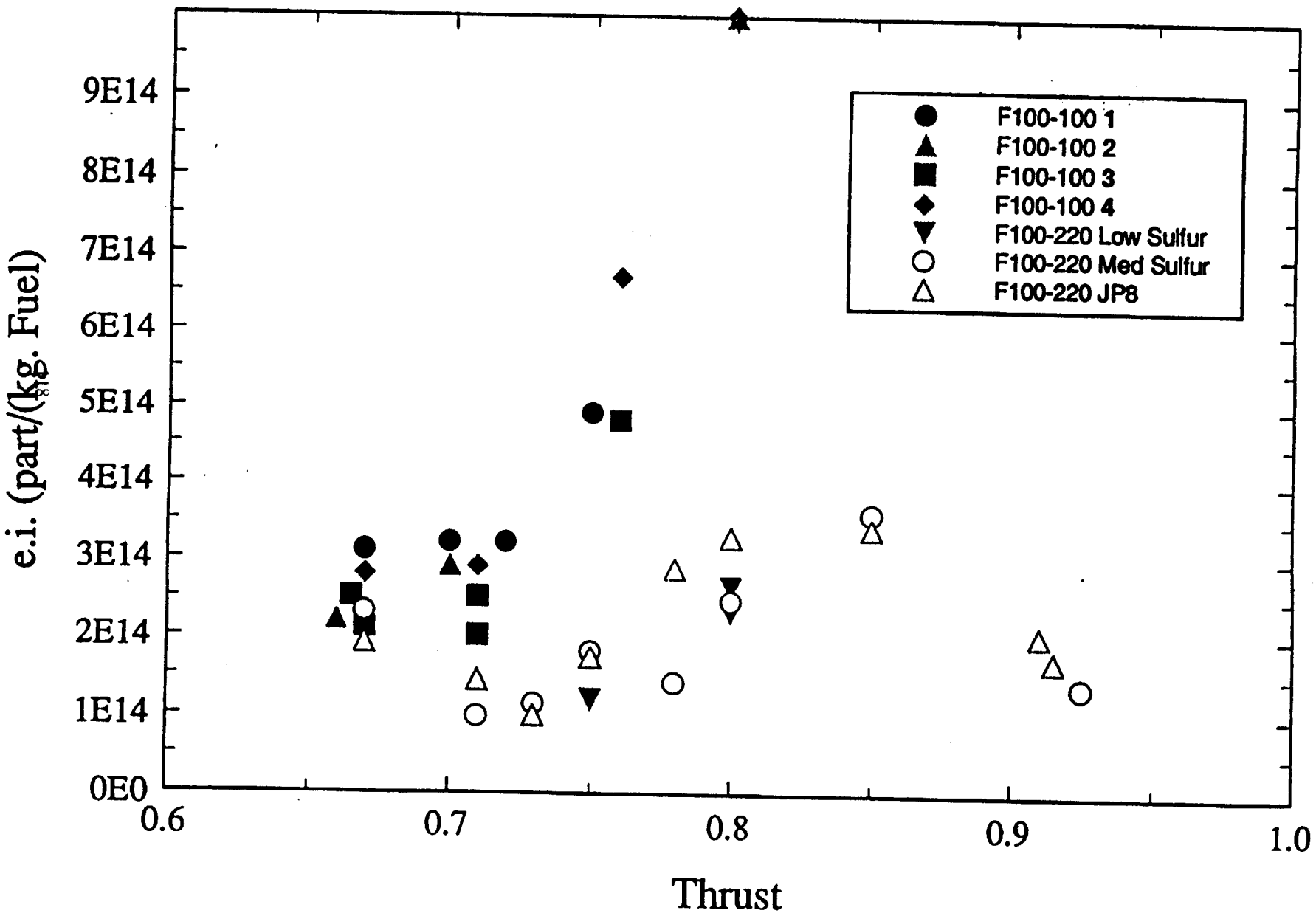
Emission indices for 4 F100-100 engines

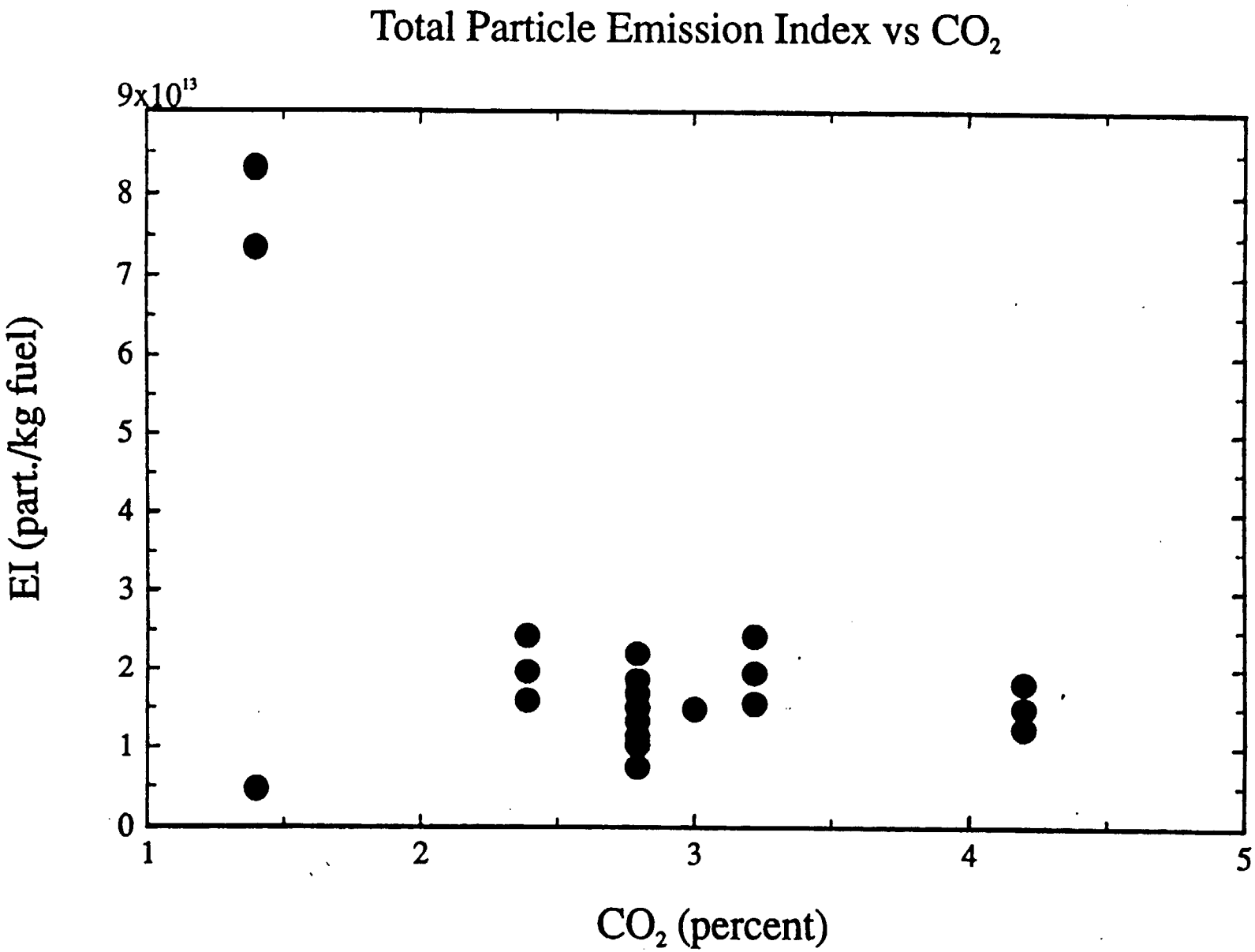


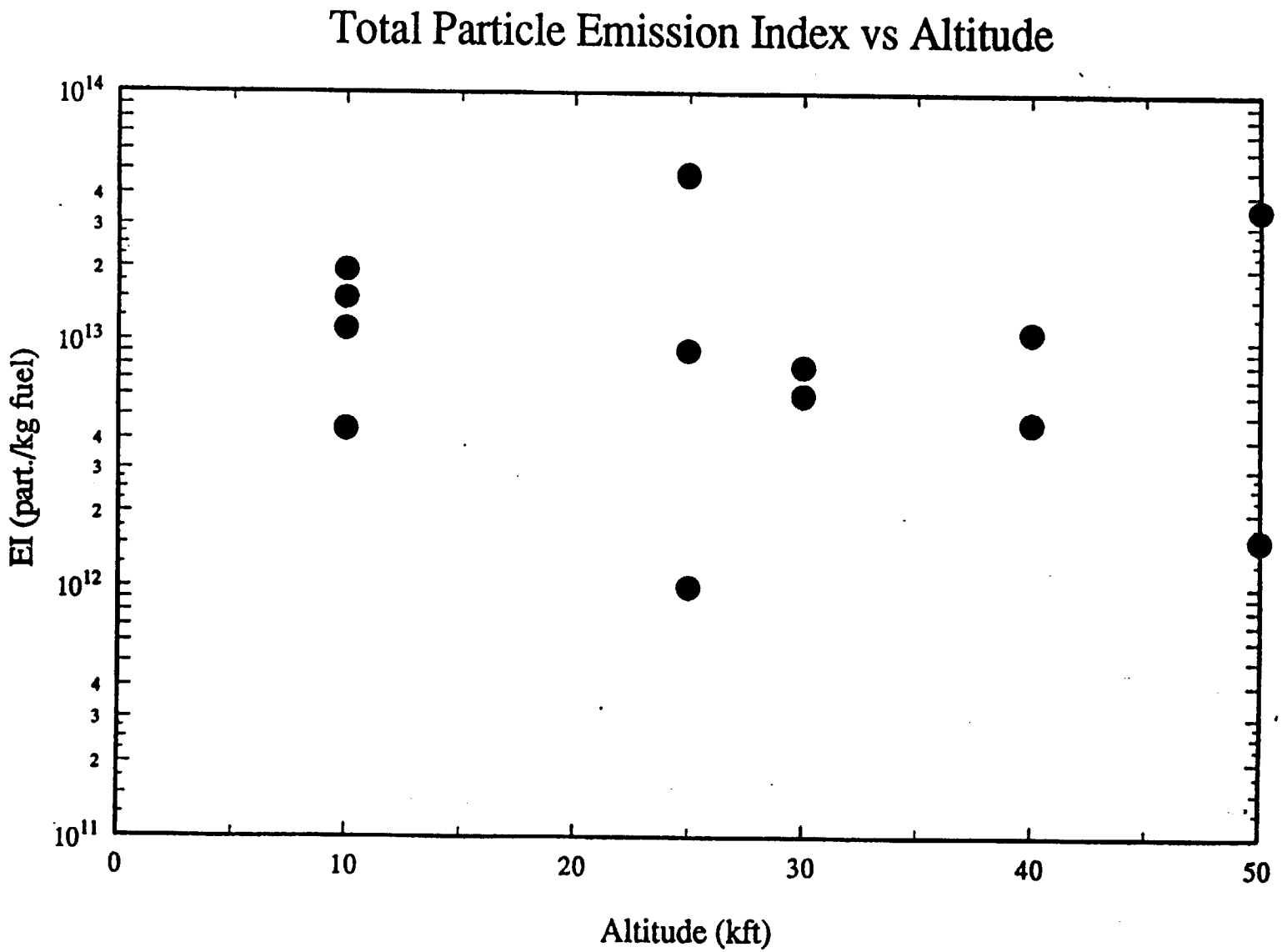
Emisson indices for 2 F100-220 engines

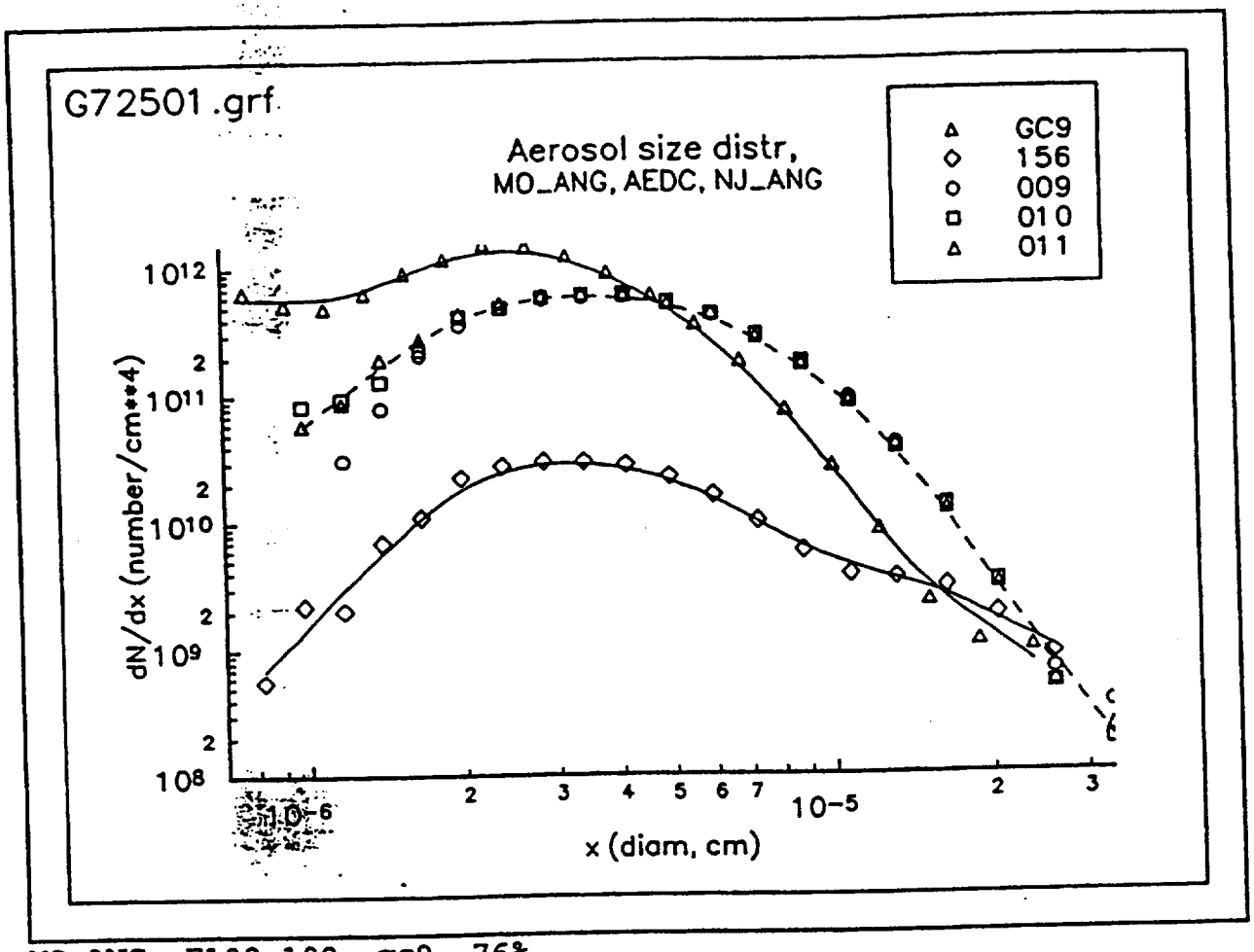


Comparison of F100-100 and F100-220 series engines




Total Particle Emission Index vs CO_2
$9x10^{13}$
8
7
6
5
4
3
2
1
0
EI (part./kg fuel)
1
2
3
4
5
CO_2 (percent)


Total Particle Emission Index vs Altitude
EI (part./kg fuel)
10^{14}
4
3
2
10^{13}
4
3
2
10^{12}
4
3
2
10^{11}
0
10
20
30
40
50
Altitude (kft)



MO_ANG, F100-100, gc9, 76%
AEDC run 156, T3=733K, Alt=3.1 km (SLS), Time=14:57:00
MO_ANG, F100-220, 009,010,011, 80%

ENGINE TEST AND MEASUREMENTS

Chowen Chou Wey
NASA Glenn Research Center
Cleveland, Ohio

Although the importance of aerosols and their precursors are now well recognized, the characterization of current subsonic engines for these emissions is far from complete. Furthermore, since the relationship of engine operating parameters to aerosol emissions is not known, extrapolation to untested and unbuilt engines necessarily remains highly uncertain.

1997 NASA LeRC engine test, as well as the parallel 1997 NASA LaRC flight measurement, attempts to address both issues by expanding measurements of aerosols and aerosol precursors with fuels containing different levels of fuel sulfur content. The specific objective of the 1997 engine test is to obtain a database of sulfur oxides emissions as well as the non-volatile particulate emission properties as a function of fuel sulfur and engine operating conditions.

Four diagnostic systems, extractive and non-intrusive (optical), will be assembled for the gaseous and particulate emissions characterization measurements study. NASA is responsible for the extractive gaseous emissions measurement system which contains an array of analyzers dedicated to examining the concentrations of specific gases (NO, NO_x, CO, CO_2, O_2, THC, SO_2) and the smoke number. University of Missouri-Rolla uses the Mobile Aerosol Sampling System to measure aerosol/particulate total concentration, size distribution, volatility and hydration property. Air Force Research Laboratory uses the Chemical Ionization Mass Spectrometer to measure SO_2, SO_3/H_2SO_4, and HNO_3. Aerodyne Research, Inc. uses Infrared Tunable Diode Laser system to measure SO_2, SO_3, NO, H_2O, and CO_2.

Objectives

- Quantify engine gaseous and particulate emittants under sea-level and altitude conditions

- Verify, if possible, ICAO probe sampling procedures with independent non-intrusive sampling methods

- Determine NO, NO_2 pressure effects with changes in altitude

Measurement Techniques

- Gaseous - Extractive Gas Sampling
  - NO, NO_x: chemiluminescence (AEDC)
  - CO, CO_2: nondispersive IR analyzers (AEDC)
  - O_2: paramagnetic analyzer (AEDC)
  - THC: flame ionization detector (AEDC)
  - CO_2 : IR absorption (MDC)
- Gaseous - Optical Non-Intrusive
  - NO, OH: UV laser absorption (Sverdrup/AEDC)
  - NO, NO_2, CO_2, H_2O: tunable diode laser absorption (ARI)
- Particulate - Extractive Gas Sampling
  - Smoke number - SAE smoke meter (Sverdrup/AEDC)
  - Total concentration, size distribution, hydration properties: mobile aerosol sampling system (UMR)

Test Matrix

- Set point idle
- 25,000 ft at three inlet temperature
- 30,000 ft at three inlet temperature
- 40,000 ft at three inlet temperature
- 50,000 ft at three inlet temperature
- Sea-Level-Static -- ground idle 36%, 41%, 55%, and MIL PLA

Summary of Results

- All NOx data agreed within uncertainties of respective instruments
- Each optical measurement system produced precise and repeatable spectral data and predicted overall trends
- NOx levels agreed with prior engine test data -- where prior data available
- All CO_2 data agreed
- Particulate data showed that this is a very clean engine and there is no strong correlation between emission index and thrust, altitude, or combustor inlet temperature
- The results represent the first database of its kind to provide particulate characterization i.e. total and non-volatile concentration, total and non-volatile aerosol size distribution, and hydration property (soluble mass fraction) for a cruise simulation

Objectives

- Expand data base of engine gaseous and particulate emissions under sea-level and altitude conditions to small size engine
- Compare probe and non-intrusive measurements for NO, NO_2, CO_2
- Define particulate characteristics
- Obtain data for correlation of NOx from ground test to altitude conditions
- Define EPAP type parameter for G.A. engine

Measurement Techniques

- Gaseous - Extractive Gas Sampling
  - NO, NOx: chemiluminescence (LeRC)
  - CO, CO_2: nondispersive IR analyzers (LeRC)
  - O_2: paramagnetic analyzer (LeRC)
  - THC: flame ionization detector (LeRC)
- Gaseous - Optical Non-Intrusive
  - NO, NO_2, CO_2, H_2O: tunable diode laser absorption (ARI)
- Particulate - Extractive Gas Sampling
  - Smoke number - SAE smoke meter (LeRC)
  - Total concentration, size distribution, hydration property: mobile aerosol sampling system (UMR)
  - Total concentration, size distribution: particle analyzer (LeRC)

Test Matrix

- 10,000 ft at two inlet temperature
- 15,000 ft at five inlet temperature
- 25,000 ft at four inlet temperature
- 30,000 ft at two inlet temperature
- 40,000 ft at four inlet temperature
- 50,000 ft at four inlet temperature
- 65,000 ft at two inlet temperature
- Sea-Level-Static at six inlet temperature

Summary of Results

- All NOx data agreed within uncertainties of respective instruments
- Optical measurement system produced precise and repeatable spectral data and predicted overall trends
- Particulate data showed that this is a clean engine and there is correlation between emission index and thrust, altitude, or combustor inlet temperature
- The results expand the database of its kind to small size engine

Objectives

- Quantify engine gaseous and particulate emittants, including SO_2, SO_3/H_2SO_4 for the first time, under sea-level and altitude conditions for different jet fuels

- Define the effects of fuel sulfur level on SO_2, SO_3/H_2SO_4 and particulate characteristics

- Compare probe and non-intrusive measurements for NO, NO_2, CO_2, SO_2, SO_3

- Data to be used as a comparative baseline with flight measurements

Measurement Techniques

- Gaseous - Extractive Gas Sampling
  - NO, NOx: chemiluminescence (LeRC)
  - CO, CO_2: nondispersive IR analyzers (LeRC)
  - O_2: paramagnetic analyzer (LeRC)
  - THC: flame ionization detector (LeRC)
  - SO2: UV Fluorescence (LeRC)
  - SO_2, SO_3/H_2SO_4: mass spectrometer (AF/PL)
- Gaseous - Optical Non-Intrusive
  - NO, NO_2, CO_2, H_2O, SO_2, SO_3: tunable diode laser absorption (ARI)
- Particulate - Extractive Gas Sampling
  - Smoke number - SAE smoke meter (LeRC)
  - Total concentration, size distribution, hydration property: mobile aerosol sampling system (UMR)

Test Plan

- Simulated Altitude
  - 30,000 ft at five inlet temperature
  - 40,000 ft at five inlet temperature
  - 55,000 ft at four inlet temperature
  - Sea-Level-Static at six inlet temperature
  - Higher altitude ?
- Fuel
  - Low Sulfur Jet A with anti-corrosion additive
  - High Sulfur Jet A with anti-corrosion additive
  - JP8+100
  - Medium Sulfur Jet A ?

HOT SECTION MODELING

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MIT Aero-Environmental Research Laboratory
Cambridge, Massachusetts

and

Richard C. Miake-Lye, Robert C. Brown,
and Mark R. Anderson
Aerodyne Research Inc.
Billerica, Massachusetts

Many aircraft engine exhaust species that may perturb the atmosphere exist in trace amounts. These species can be transformed by chemical reaction within the engine prior to emission into the atmosphere. To better understand the role of intra-engine processes in determining the final composition of engine exhaust, a flow-chemistry model was developed over the last three years through a collaboration between the Massachusetts Institute of Technology (MIT) and Aerodyne Research, Inc. (ARI). This computational approach was used to investigate chemical processes that occur through the turbine and exhaust nozzle by simulating the post-combustor flow path over a range of physical representations, from simplified, homogenous cases to situations that incorporate complex fluid mechanics more typical of a modern aircraft turbine.

Using a chemistry model that includes HO_x, NO_y, SO_x, and CO_x reactions developed through the work of Robert C. Brown of ARI and Fred L. Dryer of Princeton University, several 1-D parametric analyses were conducted for the entire turbine and exhaust nozzle flowpath of a typical advanced subsonic engine to understand the effects of important flow and chemistry variations on species evolution in general, and the development of volatile aerosol precursors in particular. These studies highlighted the sensitivity of exhaust composition to the trace species concentrations specified at the combustor exit, mass addition within the turbine, and combustor exit temperature. Representative 2-D, single turbine blade row simulations were also performed to determine the potential impact of flow nonuniformities that cannot be captured directly or modeled simply through 1-D analyses. Temperature nonuniformities that result from the use of an internal blade cooling strategy were investigated and revealed a significant impact in SO_x chemistry. Comparisons of 1-D approximations to the 2-D turbine solutions were then carried out to help determine the extent to which current 1-D modeling capabilities can resolve changes in chemical composition. The results call into question the validity of 1-

D averaged flow analysis for the highly-nonuniform, unsteady flow fields of the turbine and exhaust nozzle.

Suggestions for future work to be carried out within the AEAP include:

1. Conduct complementary numerical analyses and laboratory and/or engine test cell experiments both to acquire data regarding trace species emissions, and to provide a mechanism for validating numerical tools.
2. Develop valid kinetic models for trace species chemistry within the intra-engine environment (combustor dilution zone, turbine, and exhaust nozzle).
3. Perform numerical investigations to identify and understand key fluid mechanical effects in 1-D, 2-D and 3-D turbine and nozzle geometries.
4. Improve computational mechanics and code usability to allow more realistic situations to be modeled, both for understanding the relevant physics and chemistry, and for supporting flight and ground-based engine tests.
5. Develop accurate, simplified models of intra-engine trace chemical processes that may be used in lieu of complex three-dimensional, multi-blade row simulations, to provide estimates of the trace emissions constituents of current and future engines.
6. Extend the range of intra-engine chemsitry modeling to include the combustor, both for defining relevant inputs for turbine and nozzle modeling efforts, and for discovering possible impacts of combustion processes on volatile aerosol formation.

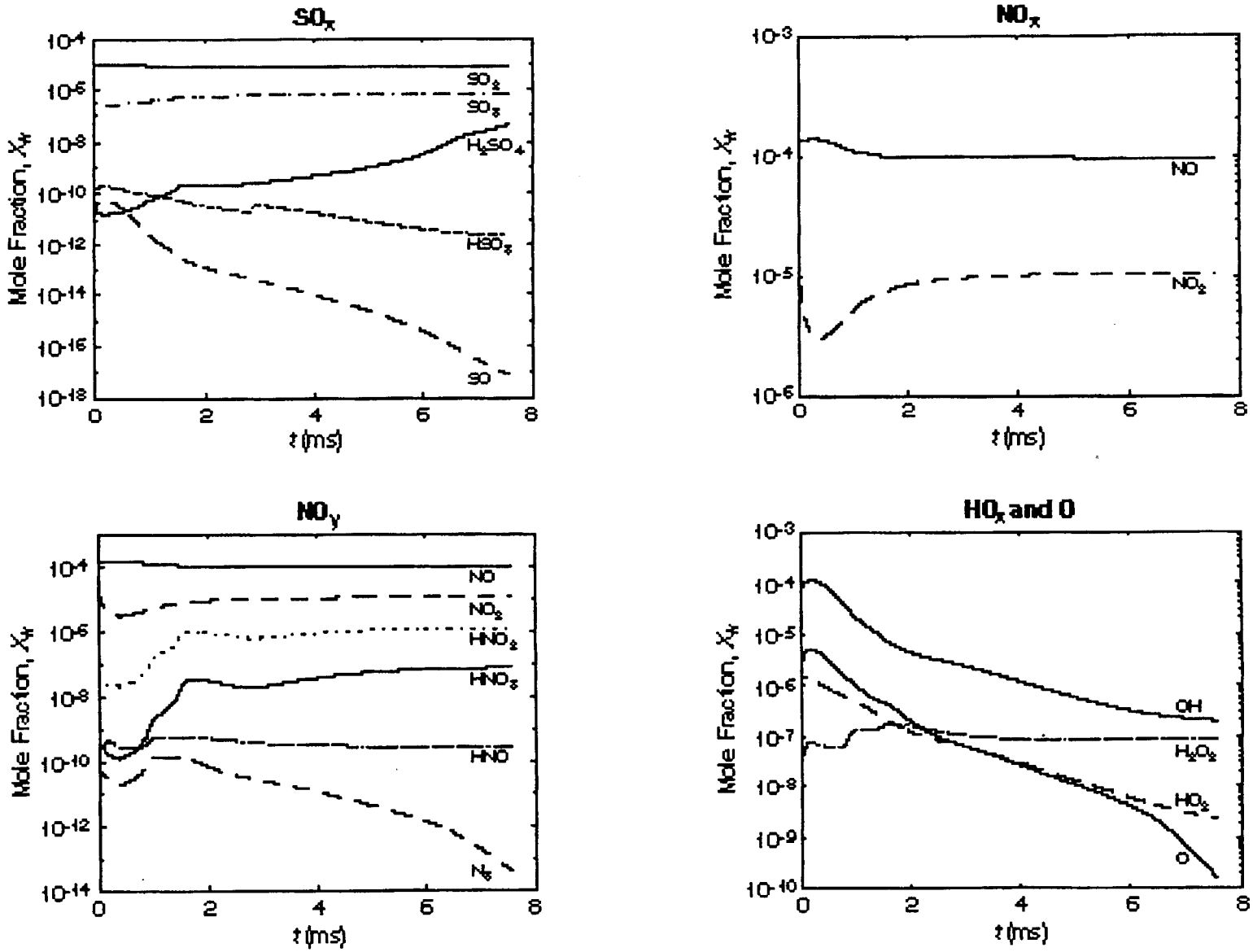
Outline of Presentation

- Current status of turbine and exhaust nozzle flow-chemistry modeling
- Future research directions / needs
  - Investigate aerosol precursor turbine flow field effects
  - Develop valid kinetic models for intra-engine environment
  - Improve computational capabilities
  - Continue validation of numerical tools
  - Develop accurate simplified models of intra-engine processes
  - Measure / model trace species chemistry in combustor

Requirements for Hot Section Modeling

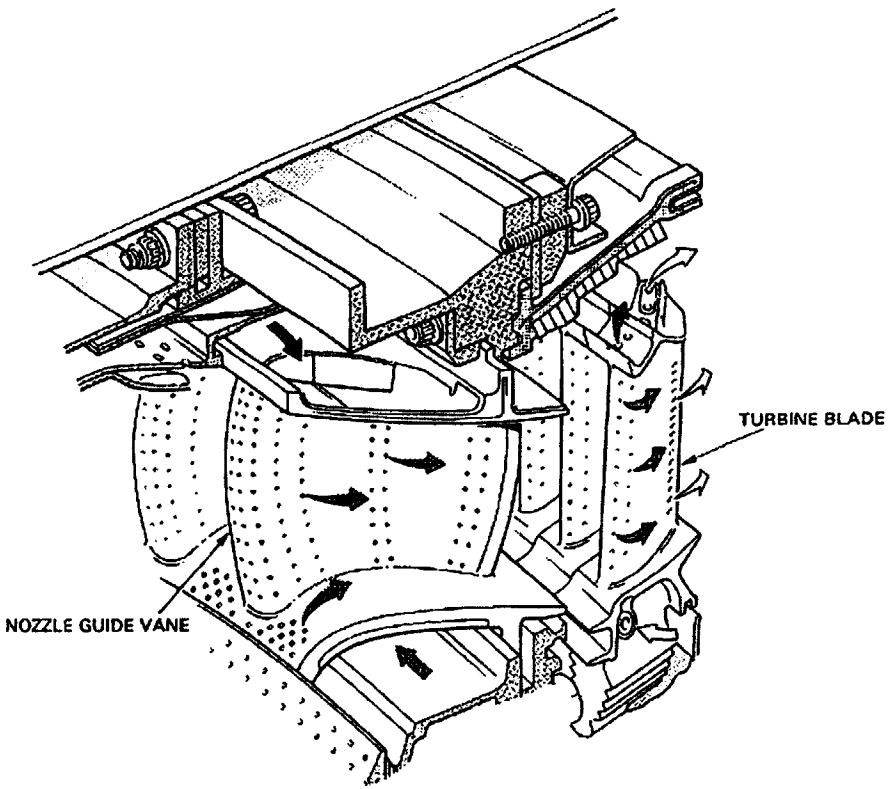
- Significant atmospheric effects dependent on details of trace species chemistry
  - e.g. NO_y-NO_x, SO_x, HO_x: concentrations range from 0.0001 - 0.1 ppmv
- Evolution of many trace species poorly understood
- Trace species undergo considerable change through turbine and exhaust nozzle
- Turbine and exhaust nozzle flow and chemistry are complex and pose many theoretical / modeling challenges
- All previous research treated turbine and nozzle as either:
  - infinitely thin: combustor exit speciation = nozzle exit speciation
  - 1-D: kinetic change through averaged temperature, pressure, velocities based on minimal interpolation between combustor and nozzle

Turbine and Exhaust Nozzle Chemistry



Turbine Chemistry Modeling Challenges

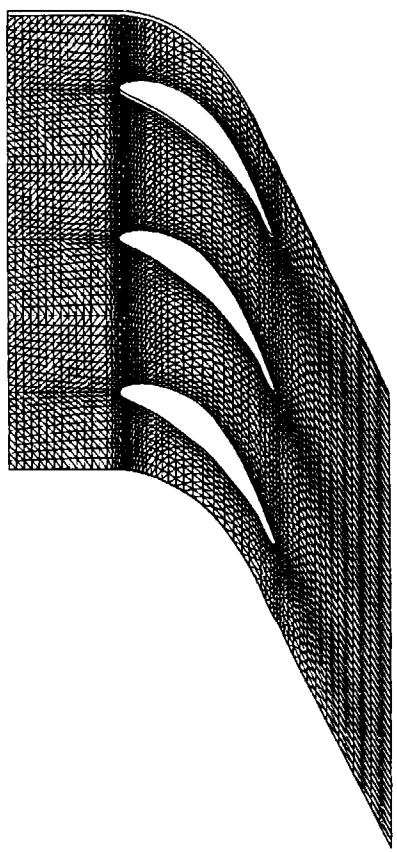
- Complex, 3-D, unsteady flow field
- Multiple stages
- Complex inlet and boundary conditions
- 25+ species, 70+ passive chemical reactions
- Small concentrations (ppm to ppt) can result in significant atmospheric impact



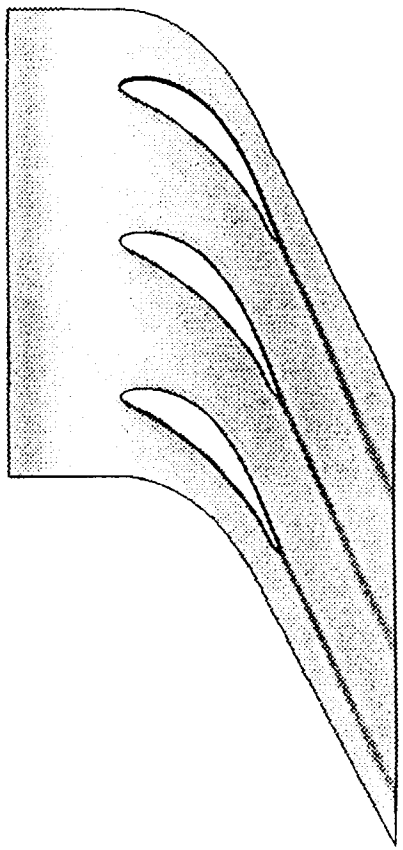
Source: Adapted from Rolls-Royce, 1986

Useful Modeling Tool Developed

- First 1-D, 2-D, 3-D modeling tool for turbine and nozzle chemistry developed
- Limited numerical validation
  - self-consistency
- Limited applications
  - kinetics, geometry, and flow conditions
- Computationally intensive



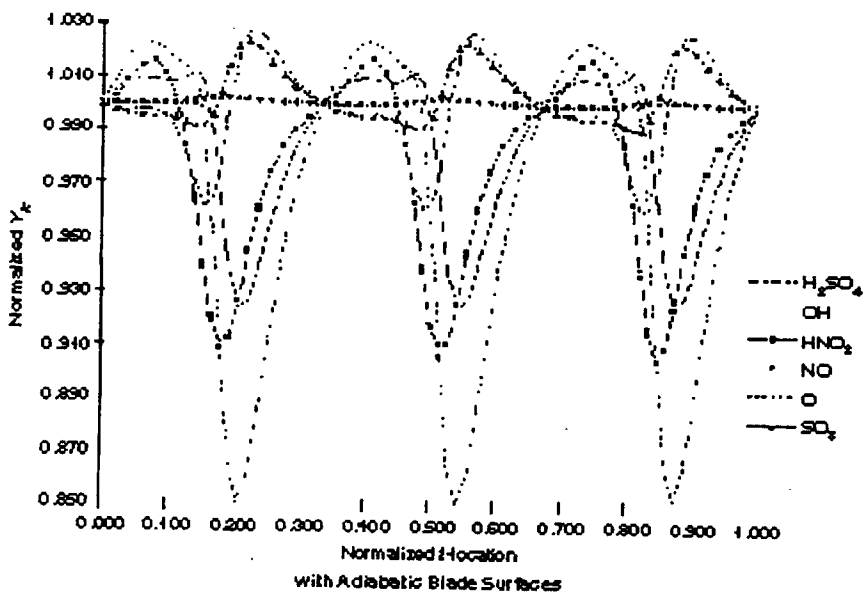
2-D Grid

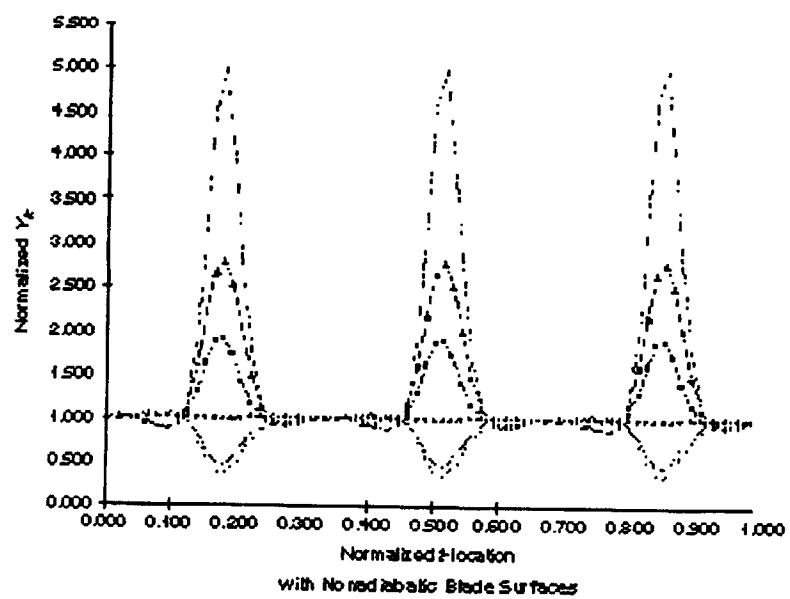


OH Distribution

Current Status of Understanding

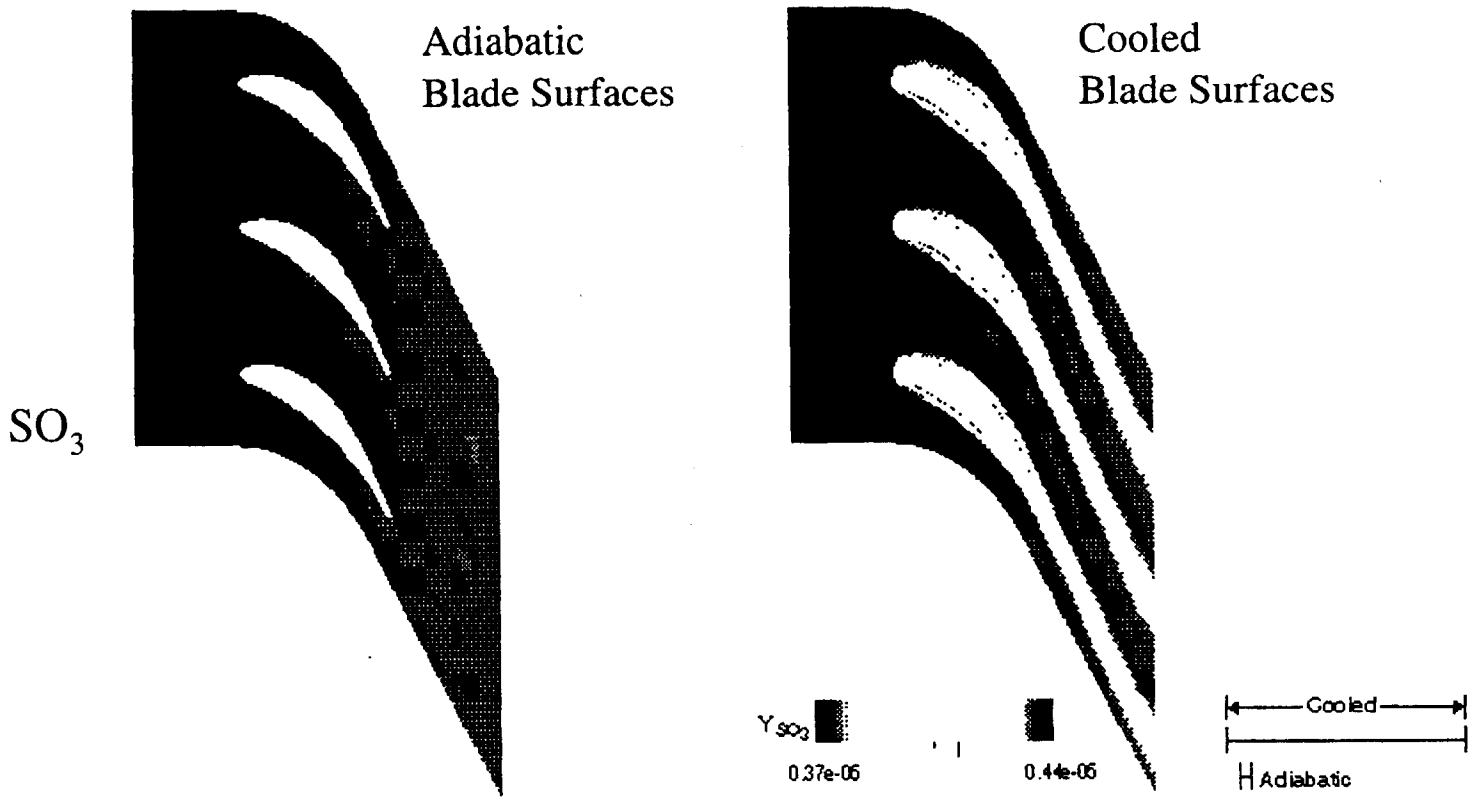
- Results suggest 1-D modeling <u>insufficient</u> to accurately capture some trace species evolution
  - Errors of two orders of magnitude observed for some species over single blade row
  - 2-D / 3-D fluid mechanical effects play critical role





Current Status of Understanding

- Temperature gradients associated with blade cooling possible enhance SO_2 to SO_3 oxidation
- For first time, strong role for turbine in pollution formation /control suggested



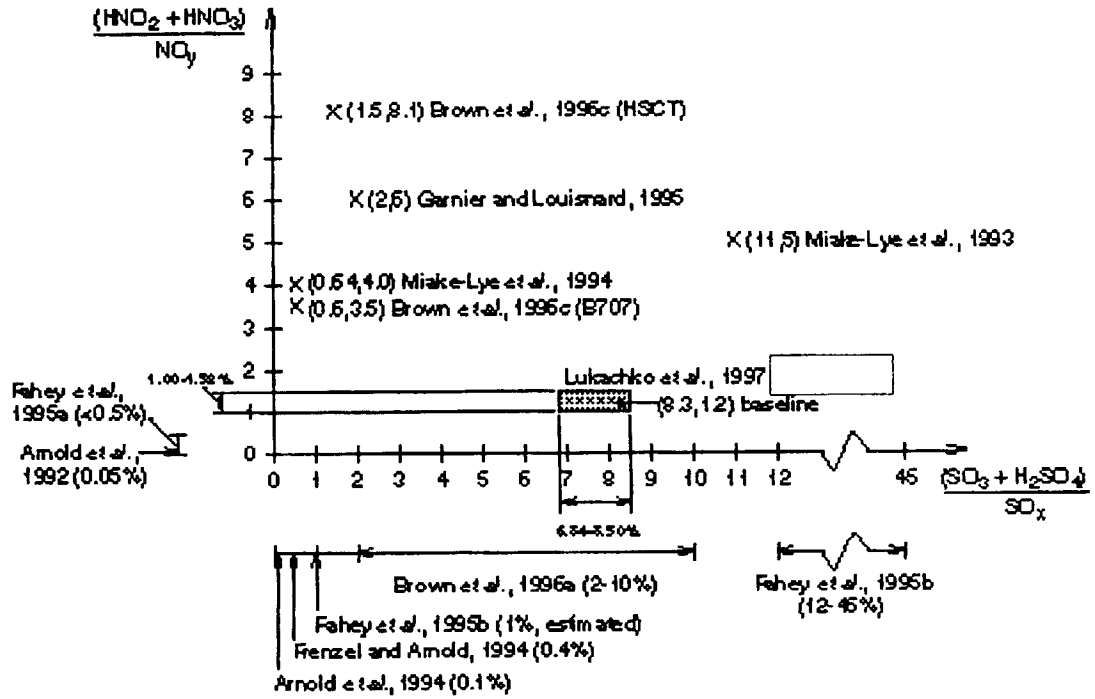
Future Research Directions / Needs

Issue 1.

Investigate aerosol precursor turbine flow field effects.

Flow Field Effects and Aerosol Precursor Chemistry

- Large number of fine aerosols observed
  - may have significant atmospheric effects
- Predictions and measurements vary widely
  - plume / wake models do not indicate extensive oxidation
  - 1-D models for turbine and exhaust nozzle indicate limited oxidation



- 2-D / 3-D models suggest more oxidation—temperature gradients
  - one specific geometry, cycle, temperature, reaction set for limited phenomena
- Understanding of aerosol precursor chemistry far from what required for assessments

Flow Field Effects and Aerosol Precursor Chemistry

- Objectives
  - continue to evaluate effects of fluid mechanical phenomena on the evolution of SO_x, NO_y, and HO_x chemistry
  - isolate important phenomena and requirements for adequate modeling of entire chemical scheme—interactions among chemical families important
  - analyze ground level and *in-situ* exhaust data
- Approach
  - evolve 2-D / 3-D calculations to encompass wider diversity of flow situations and geometrical specifications
    - implement well-resolved 2-D / 3-D single blade-row flow-chemistry calculations
    - conduct multiple blade row calculations
    - incorporate unsteady effects via boundary conditions
  - conduct further single parameter or combined 1-D calculations to investigate influences of additional averaged-flow perturbations
    - cooling flows, different cycles (technology) , operational effects, blade-row - resolved profiles

Future Research Directions / Needs

Issue 2.

Develop valid kinetic models for intra-engine environment.

Development of Valid Kinetic Models

- Kinetic models are not validated
  - range of temperatures and pressures in turbine and exhaust nozzle large
  - range of parameters unfamiliar to both combustion and atmospheric chemistry
    - alternative rate parameters for reactions in current mechanism
  - some important oxidation routes may not be included
    - sulfur oxidation via SO_4 intermediary (ARI)
    - SO_2, NO_y uptake on soot particles (ARI)
    - combustor exit ionic concentrations persist through engine (ARI)
    - alternative sulfur, carbon mechanisms (Dryer, Princeton)
    - catalysis on hot engine surfaces, trace metals in exhaust
- Trace species sensitive to boundary conditions as well as local temperatures and pressures
  - sensitivities and thus results will change with different models

Development of Kinetic Models

- Objectives
  - produce and evaluate several viable kinetic models using mechanisms validated for proper ranges
  - evaluate and recommend set of species, gaseous reactions, and heterogeneous processes for standard model
- Approach
  - perform analyses of reaction influence coefficients at various points in flow field for 1-D and/or 2-D/3-D calculations
  - implement sensitivity analyses for rate parameters
  - conduct computational experiments to confirm influential reactions
  - conduct validations using experimental-computational comparisons for simple cases via CNEWT
    - 1-D reactor (Dryer) and/or 2-D/3-D single blade-row geometries
  - laboratory experimental support to fill gaps in knowledge base

Future Research Directions / Needs

Issue 3.

Improve computational capabilities of numerical tools.

Improved Computational Capabilities

- Expensive, complex 3-D multiple blade row calculations may be required to simulate relevant fluid / chemical effects
  - without chemistry, 3-D single blade row approachable using coarse, Euler-type grid
  - with chemistry, 3-D single blade row unmanageable without efficiency, capacity boosts
- Potential integration with engine design support systems (*e.g.* NPSS) requires improved interface and code structure
- Additional capabilities required to evaluate range of possible fluid phenomena and chemical mechanisms

Current Implementations	Calculation Statistics
IBM RISC-based Power Servers (AIX)	>70% cpu time spent on chemistry
DEC Alpha Servers (OSF-1, Digital UNIX)	typically 40-150 MB for 2-D turbine grid
SGI Iris and Indigo II workstations (IRIX)	25 sec/iteration on Alpha Server 2100/275
HP workstations (HP-UX)	typically 4000-6000 iterations to converge

Improved Computational Capabilities

- Objectives
  - establish means through which to conduct calculations at next level of detail (3-D steady, 2-D multiple blade row)
  - respond to needs of various customers in engineering and scientific communities
- Approach
  - update algorithms for efficiency, improve code structure for modularity
  - implement parallelization
    - parallelizing compilers, code structural changes—message passing routines
    - parallelize nodal chemistry calculation first, fluid routines if required
  - add / improve several current capabilities, establish best practice uses
    - higher order boundary conditions, assumptions for constants
    - integrate improved unstructured grid generator
  - incorporate uncertainty analysis techniques
  - improve documentation and implement a basic UI/GUI

Future Research Directions / Needs

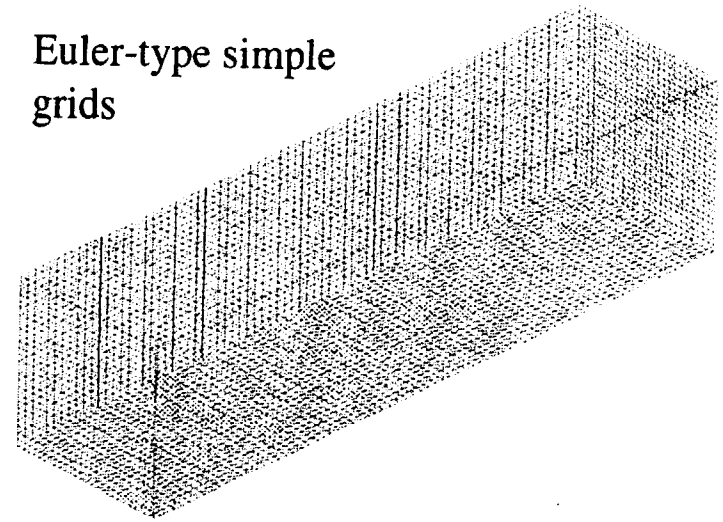
Issue 4.

Continue validation of numerical tools.

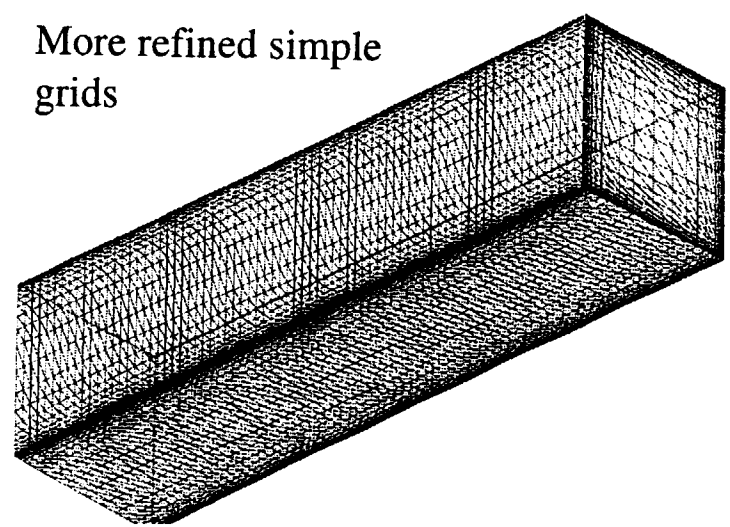
Validation of Numerical Tools

- Validation has consisted of limited self-consistency checks
  - using simple geometries in order to simplify flow situations to well understood cases
- No experimental comparisons have been made to validate code in practical situations
  - availability of experimental information limited
  - code useful for analyzing trends, predictive capabilities not assessed
- Only basic understanding of code accuracy limitations and relation to application-oriented accuracy requirements

Euler-type simple grids



More refined simple grids



Validation of Numerical Tools

- Objectives
  - continue validation to gain better understanding of code accuracy
  - analyze requirements as they relate to assessment needs for downstream modelers, for useful design decisions
- Approach
  - continue self-consistency checks using simple geometries
    - assure basic functions operate satisfactorily
    - identify needs for algorithmic improvement
  - conduct comparisons of computational results to experimental results to address predictive needs
    - 1-D reactor (Dryer) and/or 2-D/3-D single blade-row laboratory setups
    - information from combustor rig and full-scale engine tests (ground , altitude condition), preferably with cycle information and relevant 1-D, 2-D, and/or 3-D geometrical data for post-combustor flow path
  - use 1-D results as input to representative plume/wake calculation

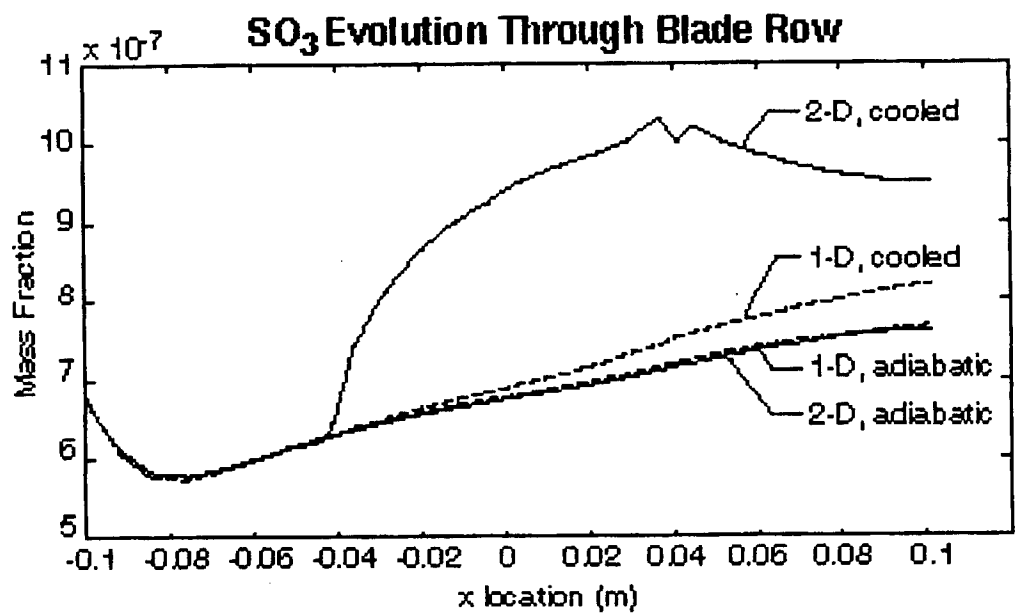
Future Research Directions / Needs

Issue 5.

Develop accurate simplified models of intra-engine processes.

Development of Accurate Simplified Models

- Results have indicated that 1-D models are insufficient in current form to adequately predict all chemical changes



- 3-D solutions are not universally attainable because of limited computational resources
- Practical applications of computational models may require simplifications and computational approximations

Development of Accurate Simplified Models

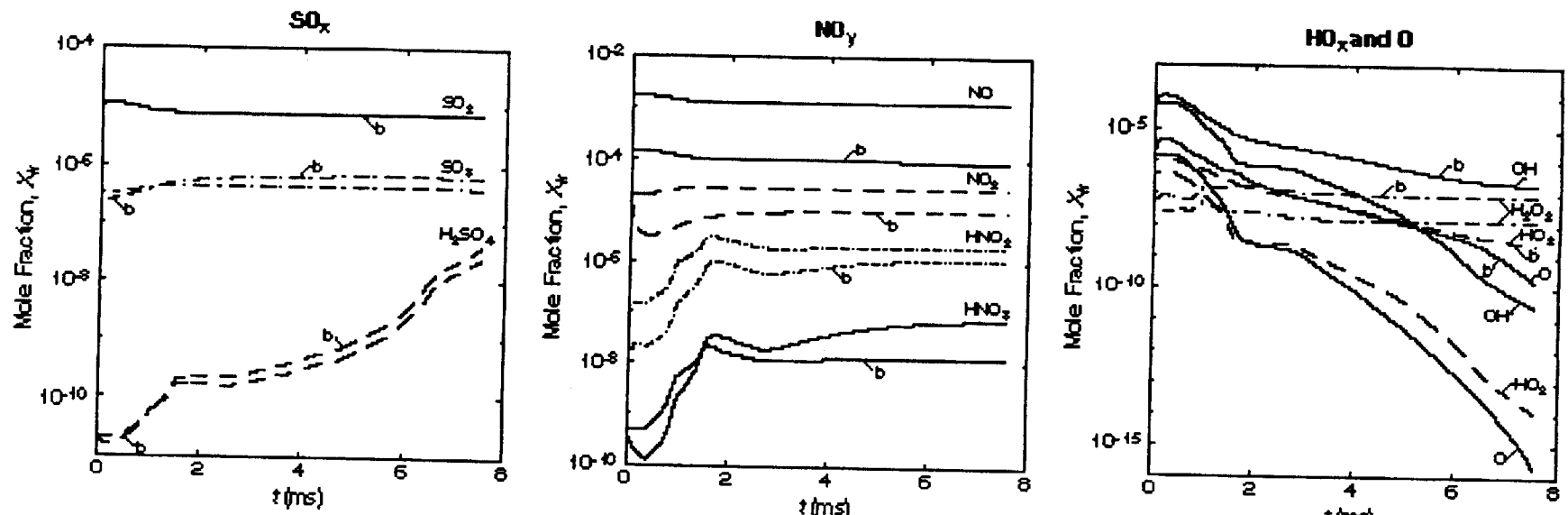
- Objective
  - determine whether or not simplified 1-D and / or 2-D models can be developed that simulate 3-D complex turbine flows
  - organize possible simplifications towards possible integration with current NPSS strategies
- Approach
  - many of same steps required of further investigations of turbine flow-field effects also apply here
    - evolve 2-D / 3-D calculations to encompass wider diversity of flow situations and geometrical specifications
    - conduct further single parameter or combined 1-D calculations to investigate influences of additional averaged-flow perturbations
  - extra steps: incorporating experimental data and integrating information available via higher-order simulations into lower-order simulations
    - novel averaging techniques, empirical corrections, theoretical simplifications

Future Research Directions / Needs

Issue 6.

Measure / model trace species chemistry in combustor.

Understanding Trace Species in Combustor



Note: b = baseline evolution

- Solutions obtained sensitive to initializations
  - particularly to equilibrium or nonequilibrium concentration assumptions
- Present combustor exit initializations ad hoc
  - no current understanding of combustor trace species at combustor exit
  - based on assumptions about emission indices, fuel content, important species
  - first-order estimates not internally consistent

Understanding Trace Species in Combustor

- Objectives
  - understand content and distribution of species at combustor exit plane to allow accurate turbine simulation, especially for trace species
  - investigate early sulfur, nitrogen oxidation potential within combustor dilution zones
- Approach
  - obtain experimental and / or CFD information for combustor exit plane
    - temperature, pressure, velocity, species distributions
    - measurements from simple reactors and / or complete combustor rig at combustor exit plane
  - formulate mechanistic basis for inlet / initial conditions
    - based on combustor calculation—simplified or complex CFD—for combustor exit plane results
    - CFD must incorporate trace species for full extent of combustor
  - possible support with development of intra-engine diagnostic instrumentation for trace species (ARI)

Research on Intra-Engine Chemistry: Future Directions Summary

- Aircraft atmospheric effects in general, turbine/nozzle role in particular, growing in importance
  - *e.g.* sulfur issue
  - only one research effort worldwide addressing these issues
- Developed first capability for 1-D, 2-D, 3-D numerical modeling of chemistry in turbine and nozzle
  - only preliminary applications thus far
  - important for understanding results from future measurement campaigns
  - results to date suggest <u>many</u> critical areas for future work

CHARGE TO WORKING GROUPS

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TRACE CHEMISTRY

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PHILLIP WHITEFIELD

INSTRUMENTATION

MICHELLE ZALLER

RICHARD MIAKE-LYE

VENUES & PROCEDURES

PETER PACHLHOFER

ROBERT HOWARD

INTEGRATE SPECIAL NEEDS

PROBES & PLUMBING

STANDARDIZATION

PIGGYBACKING

Trace Chemistry

Krishnan Radhakrishnan

Phillip Whitefield

Instrumentation

Michelle Zaller

Richard Miake-Lye

Venues & Procedures

Peter Pachlhofer

Robert Howard

Industry Perspective On Instrumentation

Richard Strange

Species and Concentrations

Michelle Zaller

The Aerosol Precursor Problem

Richard Miake-Lye

MicroFine Particle Analysis and Generation

David Pui

Absorption Spectroscopy

Daniel Oh

Emission Spectroscopy

Michael Winter

SO_3

Trace Chemistry

Krishnan Radhakrishnan

Phillip Whitefield

Instrumentation

Michelle Zaller

Richard Miake-Lye

Venues & Procedures

Peter Pachlhofer

Robert Howard

Soot

INTERACTIONS:

O HO_X C_XH_Y NO_X

The spin-forbidden dissociation–recombination reaction $SO_3 \rightleftharpoons SO_2 + O$

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(Received 17 October 1978)

Rate constants for the spin-forbidden dissociation process $SO_3 + Ar \rightarrow SO_2 + O + Ar$ have been measured in shock waves between 1700 and 2500 K. The results are compared with data on the low temperature (200–400 K) recombination reaction. The analysis in terms of unimolecular reaction rate theory allows for a determination of the threshold energy of the reaction.

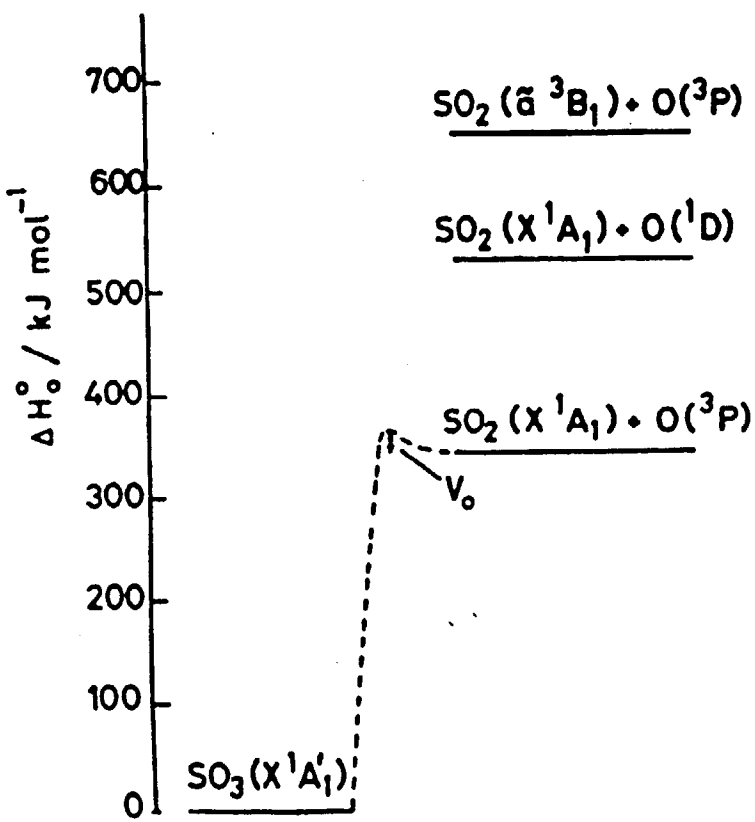
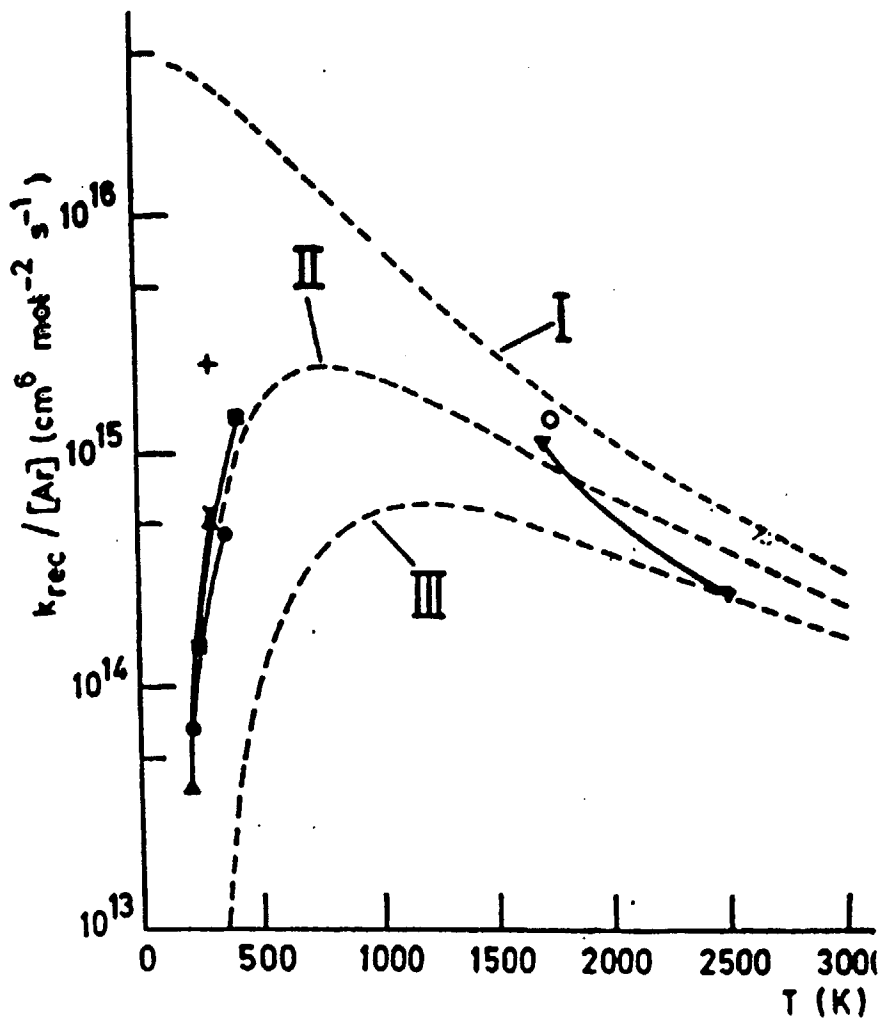


FIG. 1. Energy diagram for the $SO_3 \rightleftharpoons SO_2 + O$ system.



Trace Chemistry

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Robert Howard

IMMEDIATE

Near Term

LONG TERM

Is A Jet Engine The Best Place To Study What Goes On In A Jet Engine?

$$S_{FUEL} \rightarrow SO_2 \rightarrow SO_3 \rightarrow H_2SO_4$$

$$S_{FUEL} \xrightarrow{\quad ? \quad} H_2SO_4$$

AEROSOLS & PRECURSORS

SPECIES

REACTIONS AND RATES

THERMOCHEMISTRY AND TRANSPORT

TRACE CHEMISTRY

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The goals of the trace chemistry group were to identify the processes relevant to aerosol and aerosol precursor formation occurring within aircraft gas turbine engines; that is, within the combustor, turbine, and nozzle. The topics of discussion focused on whether the chemistry of aerosol formation is homogeneous or heterogeneous; what species are important for aerosol and aerosol precursor formation; what modeling/theoretical activities to pursue; what experiments to carry out that both support modeling activities and elucidate fundamental processes; and the role of particulates in aerosol and aerosol precursor formation.

The consensus of the group was that attention should be focused on SO_2, SO_3, and aerosols. Of immediate concern is the measurement of the concentration of the species SO_3, SO_2, H_2SO_4, OH, HO_2, H_2O_2, O, NO, NO_2, HONO, HNO_3, CO, and CO_2 and particulates in various engines, both those currently in use and those in development. The recommendation was that concentration measurements should be made at both the combustor exit and the engine exit. At each location the above species were classified into one of four categories of decreasing importance, Priority I through IV, as follows:

Combustor Exit:
- Priority I species - SO_3:SO_2 ratio, SO_3, SO_2, and particulates;
- Priority II species - OH and O;
- Priority III species - NO and NO_2;
- Priority IV species - CO and CO_2.

Engine Exit:
- Priority I species - SO_3:SO_2 ratio, SO_3, SO_2, H_2SO_4, and particulates;
- Priority II species - OH, HO_2, H_2O_2, and O;
- Priority III species - NO, NO_2, HONO, and HNO_3;
- Priority IV species - CO and CO_2.

Table I summarizes the anticipated concentration range of each of these species. For particulate matter, the quantities of interest are the number density, size distribution, and composition. In order to provide data for validating multidimensional reacting flow models, it would be desirable to make 2-D, time-resolved measurements of the concentrations of the above species and, in addition, of the pressure, temperature, and velocity. A near term goal of the experimental program should be to confirm the nonlinear effects of sulfur speciation, and if present, to provide an explanation for them. It is also desirable to examine if the particulate matter retains any sulfur. The recommendation is to examine the effects on SO_X production of variations in fuel-bound sulfur and aromatic content (which may affect the amount of particulates formed). These experiments should help us to understand if there is a coupling

between particulate formation and SO_x concentration. Similarly, any coupling with NO_x can be examined either by introducing NO_x into the combustion air or by using fuel-bound nitrogen.

Also of immediate urgency is the need to establish and validate a detailed mechanism for sulfur oxidation/aerosol formation, whose chemistry is concluded to be homogeneous, because there is not enough surface area for heterogeneous effects. It is envisaged that this work will involve both experimental and theoretical programs. The experimental work will require, in addition to the measurements described above, fundamental studies in devices such as flow reactors and shock tubes. Complementing this effort should be modeling and theoretical activities. One impediment to the successful modeling of sulfur oxidation is the lack of reliable data for thermodynamic and transport properties for several species, such as aqueous nitric acid, sulfur oxides, and sulfuric acid. Quantum mechanical calculations are recommended as a convenient means of deriving values for these properties. Such calculations would also help establish rate constants for several important reactions for which experimental measurements are inherently fraught with uncertainty. Efforts to implement sufficiently detailed chemistry into computational fluid dynamic codes should be continued. Zero- and one-dimensional flow models are also useful vehicles for elucidating the minimal set of species and reactions that must be included in two- and three-dimensional modeling studies.

INSTRUMENTATION WORKING GROUP SUMMARY

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The Instrumentation Working Group compiled a summary of measurement techniques applicable to gas turbine engine aerosol precursors and particulates. An assessment was made of the limits, accuracy, applicability, and technology readiness of the various techniques. These are summarized in Table I. Despite advances made in emissions characterization of aircraft engines, uncertainties still exist in the mechanisms by which aerosols and particulates are produced in the near-field engine exhaust. To adequately assess current understanding of the formation of sulfuric acid aerosols in the exhaust plumes of gas turbine engines, measurements are required to determine the degree and importance of sulfur oxidation in the turbine and at the engine exit. Ideally, concentrations of all sulfur species would be acquired, with emphasis on SO_2 and SO_3.

Numerous options exist for extractive and non-extractive measurement of SO_2 at the engine exit, most of which are well developed (see Table I). SO_2 measurements should be performed first to place an upper bound on the percentage of SO_2 oxidation. If extractive and non-extractive techniques indicate that a large amount of the fuel sulfur is not detected as SO_2, then efforts are needed to improve techniques for SO_3 measurements. Based on the preliminary results of recent F-100 engine tests conducted at NASA Lewis Research Center, for which about 75% of the fuel sulfur was measured as SO_2, additional work will be required to account for the fuel sulfur in the engine exhaust. CI-MS measurements need to be pursued, although a careful assessment needs to be made of the sampling line impact on the extracted sample composition. Efforts should also be placed on implementing non-intrusive techniques and extending their capabilities by maximizing exhaust coverage for line-of-sight measurements, as well as development of 2-D techniques, where feasible.

Recommendations were made to continue engine exit and combustor measurements of particulates. Particulate measurements should include particle size distribution, mass fraction, hydration properties, and volatile fraction. These measurements have already been made using extractive sampling from gas turbine combustor rigs and engine exhausts, so numerous refinements have been made to commercial instruments that measure particulate size distribution and number density. However, methods to ensure that unaltered samples are obtained need to be developed. Particulate speciation was also assigned a high priority for quantifying the fractions of carbon soot, PAH, refractory materials, metals, sulfates, and nitrates. Determination of carbon soot morphology was given a lower priority than the particulate speciation.

High priority was also placed on performing a comparison of particle sizing instruments. Concern was expressed by the workshop attendees who routinely make particulate measurements about the variation in number density measured during in-flight tests by different instruments. In some cases, measurements performed by different groups of researchers during the same flight tests showed an order of magnitude variation. The University of Minnesota offered to host a comparison test, but the logistics of getting several groups and sets of equipment together at the same place and time were agreed to be difficult. An alternative would be to send a particle generator to the various laboratories, if schedule conflicts prohibit a common test location and time.

Second priority was assigned to measuring concentrations of odd hydrogen and oxidizing species. Since OH, HO_2, H_2O_2, and O are extremely reactive, non-extractive measurements are recommended. A combination of absorption and fluorescence is anticipated to be effective for OH measurements in the combustor and at the engine exit. Extractive measurements of HO_2 have been made in the stratosphere, where the ambient level of OH is relatively low. Use of techniques that convert HO_2 to OH for combustor and engine exit measurements needs to be evaluated, since the ratio of HO_2/OH may be 1% or less at both the combustor and engine exit. CI-MS might be a viable option for H_2O_2, subject to sampling line conversion issues. However, H_2O_2 is a low priority oxidizing

species in the combustor and at the engine exit, since it is calculated to be present in concentrations of 0.1% or less of the OH mole fraction at the engine exit [Miake-Lye et al, 1992]. Atomic oxygen may be present at levels from 2-10% of OH in the combustor, but is expected to be negligible at the engine exit. The two candidates for atomic oxygen measurements are REMPI and LIF. Both of these have been performed in atmospheric pressure laboratory burners, but need to be proven under gas turbine combustor exit conditions.

Particulate measurement by simultaneous extractive and non-extractive techniques was given equal priority to the oxidizer measurements. Concern was expressed over the ability of typical ground test sampling lines to deliver an unaltered sample to a remotely located instrument, and it was suggested that the sampling probe and line losses be checked out by attempting measurements using an optical or non-extractive technique immediately upstream of the sampling probe. This is a possible application for LII as a check on the volume fraction of soot. Optical measurements of size distribution are not well developed for ultrafine particles less than about 20 nm in diameter, so a non-extractive technique for particulate size distribution cannot be recommended without further development.

Carbon dioxide measurements need to be made to complement other extractive measurement techniques. Although total engine CO_2 emissions can be calculated based on fuel consumption, carbon dioxide measurements enable conversion of other species concentrations to emission indices. Carbon monoxide, which acts as a sink for oxidizing species, should be measured using non-extractive techniques. CO can be rapidly converted to CO_2 in extractive probes, and a comparison between extractive and non-extractive measurements should be performed. Development of non-extractive techniques would help to assess the degree of CO conversion, and might be needed to improve the concentration measurement accuracy.

Measurements of NO_x will continue to be critical due to the role of NO and NO_2 in atmospheric chemistry, and their influence on atmospheric ozone. In addition, NO_x emissions must be characterized to ensure compliance with ICAO standards. Due to the importance of NO_x emissions, a variety of extractive and non-extractive techniques have been demonstrated in gas turbine combustor and engine exit measurements. However, NO_x measurements have been assigned a lower priority than the oxidizing species because it performs a minimal role in the formation of sulfuric acid aerosols. In addition, ground-based and in-flight measurements of NO_x emission indices have previously been shown to be well correlated, indicating that the plume processes influencing NO_x are well understood [Friedl, 1997].

Although NO_x emissions are of general engine emission importance, the various (non-NO_x) NO_y species are not thought to have a major role in aerosol and particulate formation. Nitrous and nitric acid may form aerosols, possibly in combination with sulfuric acid; however, concentrations of nitric acid are expected to be several orders of magnitude less than sulfuric acid in the engine exhaust. Techniques were identified that could be applied to HNO_2 and HNO_3. Further development is needed to optimize techniques for HNO_2 measurements. HNO_3 concentration measurements have already been demonstrated using CI-MS, with non-extractive techniques requiring additional work.

Time-resolved measurements of temperature, velocity, and species concentrations were included on the list of desired measurements. Thermocouples are typically adequate for engine exit measurements. Several non-intrusive techniques for temperature measurements have been used in combustor test facilities, but are generally difficult to apply. PIV and LDV are well-established for obtaining velocity profiles, but require seeding the flow with non-reactive particles. LIF and PLIF can measure species concentrations nearly instantaneously, but absolute species concentrations can be difficult to quantify. Combinations of absorption and fluorescence are the most likely to be successful at obtaining instantaneous concentration profiles of trace species, but not all species can be detected with fluorescence techniques.

Measurements of total hydrocarbons are routinely made to meet ICAO standards. However, hydrocarbon chemistry is not believed to be a major factor in aerosol formation. Speciation of organic compounds present in engine exhausts [Spicer et al, 1994] have shown that less than 0.2 ppm of PAH

were present at typical cruise conditions, so liquid or solid phase hydrocarbon aerosols are not expected to be a major contributor, compared with sulfuric acid aerosols.

Overall, there is good overlap between estimated species concentrations and instrumentation detection limits. Measurement techniques for very reactive species, such as SO_3, O, HNO_2, and H_2O_2, will require additional development. Chemical ionization mass spectrometry (CI-MS) is a promising technique for many of the trace species, but careful quenching and dilution of the extracted sample must be performed to ensure an unaltered measurement. Infrared absorption (IR-TDLAS) has sufficient sensitivity for measurements of most of the trace species at the engine exit, with the advantage of being non-extractive. For combustor exit measurements of OH, a combination of UV absorption and fluorescence is expected to be successful, since UV absorption measurements of OH have been made in elevated pressure flames, and PLIF measurements of OH have been demonstrated in optically-accessible subscale combustor test facilities.

The techniques listed in Table I are divided up into extractive and non-extractive techniques, with the assumption that extractive measurements can be made from the combustor and the engine exit. Efforts were made to include a measurement uncertainty for each technique. These uncertainties are for the detection limit as listed, and may be less for other measurement values. Order-of magnitude estimates of species concentrations at the combustor and engine exit are listed. These numbers are predominantly from equilibrium calculations (combustor exit) and Miake-Lye et al, 1992 (engine exit). An assessment of the technology readiness was included, with an "A" designating techniques that have been used in gas turbine engine tests. "B" status was assigned to techniques that have been demonstrated in the laboratory, typically in burners, shock tubes, or flow reactors. "C" technology readiness was given for techniques that should be applicable for the specie listed, but have not yet been proven. Although efforts were made to be comprehensive, techniques may have been unintentionally omitted.

Many researchers contributed to the compilation of instrumentation techniques listed in Table I. The efforts of Bruce Anderson, Pratim Biswas, Mike Coggiola, Gus Fralick, Gary Hunter, David Liscinsky, Randy Locke, Quang-Viet Nguyen, Daniel Oh, Al Viggiano, and Joda Wormhoudt are especially appreciated. Thanks are also due to Mike Coggiola, Daniel Oh, David Pui, Terry Rawlins, Jerry Seitzman, Dick Strange, Al Viggiano, and Michael Winters for their contributions to the workshop instrumentation session.

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Miake-Lye, R. C., Dodds, W. J., Fahey, D. W., Kolb, C. E., and Langhoff, S. R., Engine trace constituent measurements recommended for the assessment of the atmospheric effects of stratospheric aircraft. Aerodyne Research report ARI-RR-947, 1992.

Spicer, C. W., Holdren, M. W., Riggin, R. M., and Lyon, T. F., Chemical composition and photochemical reactivity of exhaust from aircraft turbine engines. Annales Geophysicae, 12, 944-955, 1994.

Table I. Estimated Mole Fractions for Aerosol Precursors and Particulates

Species	Combustor Exit	Engine Exit
SO2	1 E-5	1 E-6
SO3	1 E-7	1 E-6
H2SO4	1 E-11	1 E-9
NO	0.001	1 E-5
NO2	1 E-5	1 E-6

HNO2	1 E-7	1 E-9
HNO3	1 E-10	1 E-11
CO	1 E-6	1 E-7
CO2	0.05	0.05
HO	1 E-4	1 E-5
HO2	1 E-6	1 E-7
H2O2	1 E-7	1 E-8
O	1 E-6	1 E-12

Table II. Measurement Techniques for Characterizing Aerosol Precursors and Particulates

Species	Measurement technique	Detection limit or accuracy			Technology readiness1
		Extractive	Non-Extractive		
			Combustor exit	Engine exit	
SO_2	IR-TDLAS			1 ppmv	A
	CI-MS	100 ppt (+/- 20%)			A
	Commercial fluorescence analyzer	10 ppb (+/- 0.5 ppb)[b]			B
	LIF		30 ppb	0.6 ppb	B
	Point Contact Microsensors			1 ppm	C
	UV-WMS		5 ppbv[c]	2 ppbv[c]	B
	Flame Photometric Detection	1 ppbv (+/- 1 ppbv)			A
	FTIR-ES			170 ppmv[c]	C
SO_3	IR-TDLAS			5 ppmv	A
	CI-MS	100 ppt (+/- 30%)[a]			A
	Point Contact Microsensors			2 ppm	C[1]
H_2SO_4	CI-MS	100 ppt (+/-30%)[a]			A
SO_4^{2-}	Extractive Condensation, Ion Chromatography	1 ppbv (+/- 1 ppbv)			A
Particulates	Smoke number	1-100 SN			A
	Gravimetric sampling	Particulate accumulation (µg/cm^2)			A
	CNC/EAC	3-200 nm			A
	CNC/EAC	10^6/cc			A
	LII		1 ppm	1 ppm	B
	Rayleigh		(size distribution)	(size distribution)	C
	Dynamic light scattering		>10 nm	>10 nm	B
	Mie scattering		40-2000 nm	40-2000 nm	B
	Electron Microscopy	Morphology			A
	Aerosol Mass Spectrometer	Bulk composition			B
	Single Particle Mass Spectrometer	Bulk composition			A
	Coated impactor	Surface composition			B
	Soluble mass fraction	Hydration properties			B
	Quartz Crystal Microbalance	Particulate accumulation (µg/cm^2)			B

Species	Measurement technique	Detection limit or accuracy			Technology readiness1
		Extractive	Non-Extractive		
			Combustor exit	Engine exit	
NO	Chemiluminescence analyzer	10 ppm (+/- 4%)			A
	FTIR-ES			50 ppmv[c]	A
	IR-TDLAS			0.4 ppmv	A
	PLIF		5 ppm		A
	UV absorption		5 ppm	5 ppm	B, A
	Point contact microsensor			1 ppm	B
NO_2	Chemiluminescence analyzer with catalytic conversion	2 ppm (+/- 4%)			A
	IR-TDLAS			1 ppmv	A
	FTIR-ES			30 ppmv[c]	B
	Point contact microsensor			0.5 ppm	B
	LIF			50 +/- 10 ppm	C
HNO_2	CI-MS	100 ppt (+/- 30%)[a]			B
	IR-TDLAS			5 ppmv[c]	B
	UV Absorption			100 ppmv (+/-2%)[c]	B
	PD-LIF		1 ppm	100 ppb (+/- 10 ppb)	C
HNO_3	CI-MS	100 ppt (+/- 20%)			A
	IR-TDLAS			2 ppmv[c]	B
	FTIR-ES			20 ppm[c]	B
	PD-LIF			10 +/- 1 ppb	B
CO	Commerical analyzer	5 +/- 2 ppm			A
	FTIR-ES			10 ppmv[c]	A
	IR-TDLAS			0.2 ppmv	A
	Point contact microsensor			1 ppm	B
CO_2	Commercial analyzer	120 +/- 50 ppm			A
	IR-TDLAS			300 ppmv	A
	FTIR-ES			30 ppmv[c]	A

Species	Measurement technique	Detection limit or accuracy			Technology readiness1
		Extractive	Non-Extractive		
			Combustor exit	Engine exit	
HO	IR-TDLAS			1 ppmv	C
	PLIF		1 ppm	1 ppm	A
	LIF		25 ppbv	0.3 ppbv	B
	LIF	0.02 ppbv (+/- 40%)			A
	UV-WMS		3 ppbv[c]	0.2 ppbv[c]	B
HO_2	Conversion by NO to HO	0.05 ppbv (+/- 30%)[a]			A
	IR-TDLAS			5 ppmv	B
H_2O_2	CI-MS	0.1 ppbv (+/- 30%)[a]			C
	HPLC	0.01 ppbv[a]			B
	PD-LIF	5 ppbv (+/- 50%)[a]			C
	IR-TDLAS			2 ppmv	C
O	2-photon LIF		500 ppm +/- 15%		B
	LIF		10 +/- 5 ppm		B
	REMPI		500 ppm +/- 15%		B
Temperature	Thermocouple (Type R)		3200 °F +/- 5%; 2000 K +/- 5%	3200 °F +/- 5%; 2000 K +/- 5%	A
	Pyrometry		3700 +/- 100°F; 2300 +/- 60 K	3700 +/- 100°F; 2300 +/- 60 K	C
	Raman		+/- 10%	+/- 10%	B
	LIF		+/- 10%		B
	Rayleigh			+/- 5%	B
	Acoustic thermometry		4000 +/- 100°F; 2500 +/- 60 K		B
Velocity	PIV		+/- 2%	+/- 2%	A
	LDV		+/- 2%	+/- 2%	A
	Filtered Rayleigh			+/- 5%	B
Species Concentration Profiles	UV absorption/LIF (line of sight)			+/- 1%	B
	TDLAS (line of sight)			+/- 1%	A
	PLIF (planar)		5 ppm +/- 10%	5 ppm +/- 10%	A
	Raman		.05 +/- 40%	.05 +/- 40%	B

[a] function of sample line conversion
[b] with HC removal
[c]for typical engine exit compositions, temperatures, and pathlengths
1A=Demonstrated in engine tests; B=Demonstrated in laboratory; C=Not yet demonstrated

Abbreviations:

CI-MS	Chemical Ionization Mass Spectrometry
CNC/EAC	Condensation Nuclei Counter/Electrostatic Aerosol Classifier

FTIR-ES	Fourier Transform Infrared Emission Spectroscopy
IR-TDLAS	Infrared Tunable Diode Laser Absorption Spectroscopy
LIF	Laser-Induced Fluorescence
LII	Laser-Induced Incandescence
PD-LIF	Photodissociative Laser Induced Fluorescence
UV-WMS	Ultraviolet Wavelength Modulation Spectroscopy

AEROSOLS AND PARTICULATES WORKSHOP SAMPLING PROCEDURES AND VENUES WORKING GROUP SUMMARY

Peter Pachlhofer
NASA Glenn Research Center
Cleveland, Ohio

and

Robert Howard
Sverdrup Technology, Inc.
Arnold AFB, Tennessee

The Sampling Procedures and Venues Workgroup discussed the potential venues available and issues associated with obtaining measurements. Some of the issues included Incoming Air Quality, Sampling Locations, Probes and Sample Systems. The following is a summary of the discussion of the issues and venues.

Incoming Air Quality

The influence of inlet air to the measurement of exhaust species, especially trace chemical species, must be considered. Analysis procedures for current engine exhaust emissions regulatory measurements require adjustments for air inlet humidity (SAE Procedures). As a matter of course in scientific investigations, it is recommended that "background" measurements for any species, particulate or chemical, be performed during inlet air flow before initiation of combustion, if possible, and during the engine test period as feasible and practical. For current regulatory measurements, this would be equivalent to setting the "zero" level for conventional gas analyzers.

As a minimum, it is recommended that measurements of the humidity and particulates in the incoming air be taken at the start and end of each test run. Additional measurement points taken during the run are desirable if they can be practically obtained. It was felt that the presence of trace gases in the incoming air is not a significant problem. However, investigators should consider the ambient levels and influences of local air pollution for species of interest.

Measurement Locations

Desired measurement locations depend upon the investigation requirements. A complete investigation of phenomenology of particulate formation and growth requires measurements at a number of locations both within the engine and in the exhaust field downstream of the nozzle exit plane. Desirable locations for both extractive and in situ measurements include:

- Combustion Zone (Multiple axial locations)

- Combustor Exit (Multiple radial locations for annular combustors)
- Turbine Stage (Inlet and exit of the stage)
- Exit Nozzle (Multiple axial locations downstream of the nozzle)

Actual locations with potential for extractive or non-intrusive measurements depend upon the test article and test configuration. Committee members expressed the importance of making investigators aware of various ports that could allow access to various stages of the existing engines. Port locations are engine specific and might allow extractive sampling or innovative hybrid optical-probe access. The turbine stage region was one the most desirable locations for obtaining samples and might be accessed through boroscope ports available in some engine designs.

Probes and Sampling Systems

Discussions of probes and sampling systems quickly identified issues dependent on particular measurement quantities. With general consensus, the group recommends SAE procedures for measurements and data analyses of currently regulated exhaust species (CO_2, CO, THC, NO_x) using conventional gas sampling techniques. Special procedures following sound scientific practices must be developed as required for species and/or measurement conditions not covered by SAE standards. Several issues arose concerning short lived radicals and highly reactive species. For conventional sampling, there are concerns of perturbing the sample during extraction, line losses, line-wall reactions, and chemical reactions during the sample transport to the analyzers. Sample lines coated with quartz or other materials should be investigated for minimization of such effects.

The group advocates the development of innovative probe techniques and non-intrusive optical techniques for measurement of short lived radicals and highly reactive species that cannot be sampled accurately otherwise. Two innovative probe concepts were discussed. One concept uses specially designed probes to transfer optical beams to and from a region of flow inaccessible by traditional ports or windows. The probe can perturb the flow field but must have a negligible impact on the region to be optically sampled. Such probes are referred to as hybrid probes and are under development at AEDC for measurement in the high pressure, high temperature of a combustor under development for power generation.

The other concept consists of coupling an instrument directly to the probe. The probe would isolate a representative sample stream, freeze chemical reactions and direct the sample into the analyzer portion of the probe. Thus, the measurement would be performed in situ without sample line losses due either to reactions or binding at the wall surfaces. This concept was used to develop a fast, in situ, time-of-flight mass spectrometer measurement system for temporal quantification of NO in the IMPULSE facility at AEDC.

Additional work is required in this area to determine the best probe and sampling technique for each species measurement requirement identified by the Trace Chemistry Working Group.

Venues

A partial list of Venues was used as a baseline for discussion. Additional venues were added to the list and the list was broken out into the following categories:

- Engines
    - Sea Level Test Stands
    - Altitude Chambers
- Annular Combustor Test Stands
- Sector/Flametube Test Stands
- Fundamentals Rigs/Experiments

A list of the information desired for each venue was created along with the a list of contact persons for each venue. The original partial list of venues has been updated with the new information and is attached to this summary.

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ATTACHMENT I

COMBUSTOR FACILITIES AND CAPABILITIES FOR PARTICULATES AND AEROSOLS MEASUREMENTS

Jean Bianco
NASA Glenn Research Center
Cleveland, Ohio

ENGINE TEST FACILITIES AND CAPABILITIES SEA LEVEL

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: PSL
TEST HARDWARE: Full Engines

CONDITIONS:
PRESSURE 140 psia
TEMP -50-900°F non-vitiated, 3000°F vitiated
FLOW 480 pps
VITIATED OR NON-VITIATED both
EXIT TEMP 3500°F
ATM OR ALT EXHAUST atm and alt to 70,000 ft.
OTHER:
NITROGEN 131,500 SCF storage at 2400 psig
NATURAL GAS 10" header supply at 45 psia
OXYGEN 210,000 SCF at 2400 psig, flows to 11.5 pps
HYDROGEN 560,000 SCF at 2400 psi, (1 pps at 350 psig, 2.75 pps at 1000 psig)

HEATER TYPE Non-vitiated: (2) J57 engines & afterburners via shell and tube; Vitiated: (3) GH2 heaters.
HEATER PRESSURE/TEMP 60 pps, 450 psia, 500°F(1999 goal)
FUEL STORAGE (2) 25,000 gal tanks; Jet A and any other jet fuel
FUEL FLOW pump 1: 200 gpm; pump 2: 10 gpm
FUEL PRESSURE pump 1: 60 psig; pump 2: 720 psig
H2O COOLING PRESSURE/FLOW 500 gpm/40 psig

AVAILABILITY: Variable
TEST FREQUENCY: Daily, 3-5 days per week
COST($/DAY): ~$5,000 per run hour, ~$1,000 per day per non-run day
SETUP/COORDINATION COST: Preparation and installation costs for engineering and technicians is about $15K per week, excluding design and fabrication costs.
INSTRUMENTATION
Standard gas analyzers - Rosemount; CO, CO2, NO, NOx, O2, UHC;
Smoke meter; particle measurement system
SAMPLING
PROBES: X-Y traverse mechanism available, no facility probes.
LINES: Smooth-bore stainless steel, approx. 50 feet long, electrically heated.
OTHER REMARKS:

CONTACT: Technical - Rick Sorge (216) 433-8304
(Acting) Facility Manager - Mahmood Abdelwahab (216) 433-5701

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Pratt & Whitney Middletown Facility
FACILITY: X960 High Pressure Combustion Laboratory Test Facility
TEST HARDWARE: Moderate pressure testing at representative inlet temperatures

CONDITIONS:

PRESSURE 650 psia
TEMP 1200°F
FLOW 100 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER
HYDROGEN 2400 psi
OXYGEN 2400 psi
NITROGEN 2400 psi

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE (3) 1000 gal, (3) 4000 gal; (1) 10,000 gal tank
FUEL FLOW 44 GPM
FUEL PRESSURE 1500 psig
H2O COOLING PRESSURE/FLOW 700 psi

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC; Smoke meter
SAMPLING
PROBES: Capable of sampling at 30 locations.
LINES: Heated transfer lines
OTHER REMARKS:

CONTACT: Charlie Graves (407) 796-5289

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: AEDC
FACILITY: SL1, SL2, SL3
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED non-vitiated
- EXIT TEMP
- ATM OR ALT EXHAUST atm
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC; Smoke meter
SAMPLING
PROBES: gas sampling, temperature, pressure, Mach/flow angularity
LINES: steam or electrical heated stainless steel
OTHER REMARKS:

CONTACT: Robert Howard (931) 454-4783

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Pratt & Whitney
FACILITY: West Palm Beach
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
- PROBES:
- LINES:

OTHER REMARKS:

CONTACT: Robert Lohmann (516) 796-4964

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Missouri Air National Guard
FACILITY:
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
- PROBES:
- LINES:

OTHER REMARKS:

CONTACT:

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric
FACILITY: Peebles
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
- PROBES:
- LINES:

OTHER REMARKS:

CONTACT: Paul Sabla (513) 552-2024

ENGINE TEST FACILITIES AND CAPABILITIES
ALTITUDE

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: PSL
TEST HARDWARE: Full Engines

CONDITIONS:

PRESSURE 140 psia
TEMP -50-900°F non-vitiated, 3000°F vitiated
FLOW 480 pps
VITIATED OR NON-VITIATED both
EXIT TEMP 3500°F
ATM OR ALT EXHAUST atm and alt to 70,000 ft.
OTHER:
NITROGEN 131,500 SCF storage at 2400 psig
NATURAL GAS 10" header supply at 45 psia
OXYGEN 210,000 SCF at 2400 psig, flows to 11.5 pps
HYDROGEN 560,000 SCF at 2400 psi, (1 pps at 350 psig, 2.75 pps at 1000 psig)

HEATER TYPE Non-vitiated: (2) J57 engines & afterburners via shell and tube; Vitiated: (3) GH2 heaters.
HEATER PRESSURE/TEMP 60 pps, 450 psia, 500°F(1999 goal)
FUEL STORAGE (2) 25,000 gal tanks; Jet A and any other jet fuel
FUEL FLOW pump 1: 200 gpm; pump 2: 10 gpm
FUEL PRESSURE pump 1: 60 psig; pump 2: 720 psig
H2O COOLING PRESSURE/FLOW 500 gpm/40 psig

AVAILABILITY: Variable
TEST FREQUENCY: Daily, 3-5 days per week
COST($/DAY): ~$5,000 per run hour, ~$1,000 per day per non-run day
SETUP/COORDINATION COST: Preparation and installation costs for engineering and technicians is about $15K per week, excluding design and fabrication costs.
INSTRUMENTATION
Standard gas analyzers - Rosemount; CO, CO2, NO, NOx, O2, UHC;
Smoke meter; particle measurement system
SAMPLING
PROBES: X-Y traverse mechanism available, no facility probes.
LINES: Smooth-bore stainless steel, approx. 50 feet long, electrically heated.
OTHER REMARKS:

CONTACT: Technical - Rick Sorge (216) 433-8304
(Acting) Facility Manager - Mahmood Abdelwahab (216) 433-5701

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: AEDC
FACILITY: Cell T-1 thru T-7
TEST HARDWARE: Full Engines

CONDITIONS:
PRESSURE 40 -260 psia
TEMP - 80 - 1200 °F
FLOW 20 - 800 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST: Atm and Altitude to 100,000 ft
OTHER
HYDROGEN
OXYGEN
NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC; Smoke meter
SAMPLING
PROBES: gas sampling, temperature, pressure, Mach/flow angularity
LINES: steam or electrical heated stainless steel
OTHER REMARKS: Test Section Size 3 - 28 ft diameter, 9-85 ft length
Speed Range 0-Mach 4.0
CONTACT: Robert Howard (931) 454-4783

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: AEDC
FACILITY: Cell J-1 and J-2
TEST HARDWARE: Full Engines

CONDITIONS:
PRESSURE
TEMP 1480 °R
FLOW
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST: Atm and Altitude to 80,000 ft
OTHER
HYDROGEN
OXYGEN
NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC; Smoke meter
SAMPLING
PROBES: gas sampling, temperature, pressure, Mach/flow angularity
LINES: steam or electrical heated stainless steel
OTHER REMARKS: Test Section Size: J-1 20 ft diameter x 67.3 ft length
J-2 28 ft diameter x 50-85 ft length
Speed Range 0-Mach 3.0
CONTACT: Robert Howard (931) 454-4783

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: AEDC
FACILITY: Cell C-1 and C-2

TEST HARDWARE: Full Engines

CONDITIONS:
PRESSURE 130 psia
TEMP -110 - 1020 °F
FLOW 1500 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST: Atm and Altitude to 100,000 ft
OTHER
HYDROGEN
OXYGEN
NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC; Smoke meter
SAMPLING
PROBES: gas sampling, temperature, pressure, Mach/flow angularity
LINES: steam or electrical heated stainless steel
OTHER REMARKS: Test Section Size: C-2 28 ft diameter x 50-85 ft length

Speed Range 0-Mach 3.8
CONTACT: Robert Howard (931) 454-4783

ANNULAR TEST FACILITIES AND CAPABILITIES

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ECRL 1B
TEST HARDWARE: Sector and Full Annular

CONDITIONS:

PRESSURE 165 psia
TEMP ambient-620°F non-vitiated; 2000°F vitiated
FLOW 250 pps
VITIATED OR NON-VITIATED both
EXIT TEMP 4000°F
ATM OR ALT EXHAUST both
OTHER

HEATER TYPE Non-vitiated: natural gas; Vitiated: J-58
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE (2) 20,000 gal tanks, (2) 10,000 gal tanks
FUEL TYPE
FUEL FLOW 70 gpm
FUEL PRESSURE 75 psig
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW 1200 gpm/160 psig

AVAILABILITY: Ready for occupancy in June 1998
TEST FREQUENCY: daily
COST($/DAY): $1000/day + $55/Megawatt Hr
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard Gas Analyzers: CO, CO2, NO, NOx, O2, UHC;
Smoke meter, particle measurement system
SAMPLING
PROBES: 8 pitots, gas sampling on one probe; Probe actuated +/- 30° from vertical can give exhaust gas profile
LINES: Heated
OTHER REMARKS:

CONTACT: Technical - Gary Huber (216) 433-5688
(Acting) Facility Manager - Bob Freedman (216) 433-2038

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ECRL 2A
TEST HARDWARE: Sector and Full Annular

CONDITIONS:
PRESSURE 150 psia
TEMP 600°F or 700-2500°F
FLOW 31.0 pps
VITIATED OR NON-VITIATED vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE J-47 vitiated
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE (2) 20,000 gal tanks and (2) 10,000 gal tanks
FUEL TYPE Jet A or JP-5 for J-47 and J-58 or natural gas for J-47
FUEL FLOW 10 GPM
FUEL PRESSURE 500-600 psig
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW 600 GPM/150 psig

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Technical - Queito Thomas (216) 433-3700
(Acting) Facility Manager - Bob Freedman (216) 433-2038

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ASCR
TEST HARDWARE: Flametube, Sector, and Regional Engine Full Annular

CONDITIONS:
PRESSURE 900 psia
TEMP 1300°F
FLOW 3-12 pps Flametube; 3-38 pps Sector/Full Annular
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP 3200°F
ATM OR ALT EXHAUST atm
OTHER
NITROGEN: 2000 psig

HEATER TYPE shell and tube
OTHER HEATER PRESSURE/TEMP *50 pps, 150 psig, 1700°F*

FUEL STORAGE (1) 20,000 gal tank
FUEL TYPE Jet A
FUEL FLOW 20 gpm
FUEL PRESSURE 2000 psig
H2O COOLING PRESSURE/FLOW *3000 gpm/60 psig; 670 gpm/250 psig; 300 gpm/1500 psig*

AVAILABILITY:
TEST FREQUENCY: 2 days/week
COST($/DAY): 450 psia air only - $2K; 1250 psia air, flow less than 25 pps - $6-10K; 1250 psia air, flow more than 25 pps - $10-16K; cost/occupancy hour: $2,092
SETUP/COORDINATION COST: Flametube - assy $600, installation $240, + instrumentation; Sector - unknown at this time
INSTRUMENTATION

Standard Gas Analyzers: CO, CO2, NO, NOx, O2, UHC; (2) Smokemeters - 1 filter type and 1 optical; particle measurement system
Non-intrusive laser diagnostics: YAG pumped dye laser systems with wave length extension systems for obtaining UV light, Measurements include: planar mi scattering, phase doppler particle analysis(PDPA), LDV/PDPA, laser induced flourescence(LIF), planar laser induced flourescence(PLIF), RAMAN, SCHLIEREN, C2 FLUORESCENCE; Acoustics

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

OTHER REMARKS:
ORGANIZATION: NASA LeRC
FACILITY: ASCR(CONTINUED)

SAMPLING

PROBES: SS, Water cooled, multi port; 2 probes can be used simultaneously in Flametube at axial locations 2.4", 4.5", 6.0", 7.5", 9.0", 11.0", 16", and 22" downstream of the combustion section inlet flange; 21 sampling lines are available for the Sector rig

LINES: Steam traced and Electrically heated; Inner Liner Material: First 12 ft are carbon black teflon, remainder is SS; Line Length: 100-120 ft

CONTACT: Technical - Pete Pachlhofer (216) 433-5705
Facility Manager - Jeff Swan (216) 433-5434

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Allison Engine Company
FACILITY: Test Department Combustor Facility
TEST HARDWARE: Flametube, Sector and Full Annular

CONDITIONS:
PRESSURE
TEMP
FLOW
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER:

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Ron Mutzl (317) 230-4702
John Spratt (317) 230-2106

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: AlliedSignal
FACILITY: C100 Combustor Facility
TEST HARDWARE: Full Annular

CONDITIONS:
PRESSURE 120 psia
TEMP -72 - 800°F
FLOW 20 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL TYPE
FUEL FLOW
FUEL PRESSURE
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
RR Optical Smokemeter
SAMPLING
PROBES: Traversing, rotating rake at the back end of the rig, donut shaped, 5-6 ports, 8-10" downstream of injector, H2O cooled
LINES: Electrically heated
OTHER REMARKS:

CONTACT: Joe Zelina (602) 231-4576

ORGANIZATION: AlliedSignal
FACILITY: SanTan Facility
TEST HARDWARE: Full Annular

CONDITIONS:

PRESSURE 80 psia
TEMP
FLOW 2pps
VITIATED OR NON-VITIATED vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL TYPE
FUEL FLOW
FUEL PRESSURE
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Joe Zelina (602) 231-4576

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A18
TEST HARDWARE: HP Sector, HP Annular Combustors
Emissions and Altitude Relight Testing

CONDITIONS:

PRESSURE	440 psia(30 ATM)
TEMP	1140°F(1600°R)
FLOW	200 pps

VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A19
TEST HARDWARE: HP Flametube, HP Single Module, LP Sector, LPAnnular Combustors
Emissions and Altitude Relight and Exit Temperature Profile Testing

CONDITIONS:

PRESSURE	440 psia(30 ATM)
TEMP	1040°F(1500°R)
FLOW	45 pps

VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A5
TEST HARDWARE: MP Flametube, LP Single Module, LP Sector, LP Annular Combustors
Emissions, Exit Temperature Profile, LBO Testing

CONDITIONS:
PRESSURE 220 psia(15 ATM)
TEMP 1140°F(1600°R)
FLOW 10 pps
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell 306
TEST HARDWARE: LP Flametube, LP Single Module, LP Sector Emissions, Altitude Relight, Exit Temperature Profile and LBO Testing

CONDITIONS:

PRESSURE	118 psia(8 ATM)
TEMP	740°F(1200°R)
FLOW	10 pps

VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Wright Patterson Air Force Base
FACILITY:
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
- PROBES:
- LINES:

OTHER REMARKS:

CONTACT: Roquemore

SECTOR/FLAMETUBE TEST FACILITIES AND CAPABILITIES

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ECRL 1B
TEST HARDWARE: Sector and Full Annular

CONDITIONS:
PRESSURE 165 psia
TEMP ambient-620°F non-vitiated; 2000°F vitiated
FLOW 250 pps
VITIATED OR NON-VITIATED both
EXIT TEMP 4000°F
ATM OR ALT EXHAUST both
OTHER

HEATER TYPE Non-vitiated: natural gas; Vitiated: J-58
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE (2) 20,000 gal tanks, (2) 10,000 gal tanks
FUEL TYPE
FUEL FLOW 70 gpm
FUEL PRESSURE 75 psig
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW 1200 gpm/160 psig

AVAILABILITY: Ready for occupancy in June 1998
TEST FREQUENCY: daily
COST($/DAY): $1000/day + $55/Megawatt Hr
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard Gas Analyzers: CO, CO2, NO, NOx, O2, UHC;
Smoke meter, particle measurement system
SAMPLING
PROBES: 8 pitots, gas sampling on one probe; Probe actuated +/- 30° from vertical can give exhaust gas profile
LINES: Heated
OTHER REMARKS:

CONTACT: Technical - Gary Huber (216) 433-5688
(Acting) Facility Manager - Bob Freedman (216) 433-2038

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ECRL 2A
TEST HARDWARE: Sector and Full Annular

CONDITIONS:
PRESSURE 150 psia
TEMP 600°F or 700-2500°F
FLOW 31.0 pps
VITIATED OR NON-VITIATED vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE J-47 vitiated
OTHER HEATER PRESSURE/TEMP
FUEL STORAGE (2) 20,000 gal tanks and (2) 10,000 gal tanks
FUEL TYPE Jet A or JP-5 for J-47 and J-58 or natural gas for J-47
FUEL FLOW 10 GPM
FUEL PRESSURE 500-600 psig
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW 600 GPM/150 psig

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Technical - Queito Thomas (216) 433-3700
(Acting) Facility Manager - Bob Freedman (216) 433-2038

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: RL-23
TEST HARDWARE: Flametube

CONDITIONS:

PRESSURE 90 psia
TEMP 1400°F
FLOW 0.5-1.0 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP 3000°F
ATM OR ALT EXHAUST atm
OTHER 2000 psig N2

HEATER TYPE shell and tube
OTHER HEATER PRESSURE/TEMP 1.2 pps, 90 psig, 1500°F
FUEL STORAGE (1) 300 gal tank; (1) 600 gal tank; (1) 1000 gal tank
FUEL FLOW 1.5 gpm
FUEL TYPE JP-8
FUEL PRESSURE 480 psig
FUEL DISTRIBUTION
H2O COOLING PRESSURE/FLOW 25 gpm/100 psig

AVAILABILITY:
TEST FREQUENCY: 2 days/week
COST($/DAY): $55/Megawatt Hr; 3 person crew($500/day); or cost/occupancy hour of $571
SETUP/COORDINATION COST: $3K-$300K
INSTRUMENTATION
Standard gas analyzers: CO, CO_2, NO, NO_x, O_2, UHC
Particle measurement system
SAMPLING
PROBES: SS, water cooled probes, multi port; 1 stationary and 1 actuated; located at axial distances of 4", 6", and 8" downstream of the combustion section inlet flange
LINES: Electrically heated
OTHER REMARKS:

CONTACT: Technical - Dave Hulligan (216) 433-6629
Facility Manager - Jeff Swan (216) 433- 5434

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: CE-5
TEST HARDWARE: Flametube and Sector

CONDITIONS:

PRESSURE 450 psig(Rig pressure without windows up to 1100°F - Stand 1: 275 psig, Stand 2: 400 psig; rig pressure with windows up to 3200°F flame temp - Stand 1: 250 psig, Stand 2: 400 psig)
TEMP 350-1100°F
FLOW: Stand 1: 1-20 pps; Stand 2: 0-3 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP 3200°F
ATM OR ALT EXHAUST atm; 20"Hg or 26" Hg alt
OTHER
NITROGEN: 0.5 pps/335 psig; 4 legs

HEATER TYPE shell and tube
OTHER HEATER PRESSURE/TEMP 20 pps, 40 psig, 1400°F
FUEL STORAGE (2) 600 gal tanks
FUEL TYPE JP8
FUEL FLOW 6.0 gpm
FUEL PRESSURE 900 psig
FUEL DISTRIBUTION 3 separate legs
H2O COOLING PRESSURE/FLOW 15 gpm/55 psig; 150 gpm/460 psig; 50 gpm/350 psig; 250 gpm/395 psig

AVAILABILITY:
TEST FREQUENCY: 2-3 days/week
COST($/DAY): cost/occupancy hour - stand 1: $714, stand 2 - $713
SETUP/COORDINATION COST:
INSTRUMENTATION

Standard Gas Analyzers; particle measurement system;
Non-intrusive laser diagnostics: YAG pumped dye laser systems with wave length extension systems for obtaining UV light, Measurements include: planar mi scattering, phase doppler particle analysis(PDPA), LDV/PDPA, laser induced flourescence(LIF), planar laser induced flourescence(PLIF), RAMAN, SCHLIEREN, C2 FLUORESCENCE; Acoustics, Smokemeter(filter paper), Gas Chromatograph/Mass Spectrometer(GCMS); Acoustics

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: CE-5(CONTINUED)

SAMPLING

PROBES: stand 1: 1 movable probe with 1 port, 5 stationary probes with 5-7 ports, located at 5 5/8" downstream of injector flange; SS, water cooled probe; stand 2: 1 traversing probe with single port; stationary probes with 3 or 5 ports; SS, water cooled probes, axial locations downstream of injector flange - without windows: 4", 12" and 20", with windows: 5 5/8"

LINES: Inner liner material: stand 2-teflon; stand 1-SS; Line length: stand 2-100 ft; Electrically heated lines with steam tracing at analyzers

OTHER REMARKS:

CONTACT: Technical - STD 1: Joe Morgan (216) 433-5647
STD 2: Hamilton Fernandez (216) 433-5745
Facility Manager - Jeff Swan (216) 433-5434

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: CE-9
TEST HARDWARE: Flametube and Sector

CONDITIONS:

PRESSURE 450 psig
TEMP 1050°F
FLOW 15 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP 3500°F
ATM OR ALT EXHAUST atm or alt
OTHER -

HEATER TYPE shell and tube
OTHER HEATER PRESSURE/TEMP 15 pps, 40 psig, 1400°F
FUEL STORAGE (1) 5000 gal tank
FUEL TYPE
FUEL FLOW 11 gpm
FUEL PRESSURE 900 psig
H2O COOLING PRESSURE/FLOW 175 gpm/550 psig; 135 gpm/835 psig; 42 gpm/60 psig

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY): cost/occupancy hour: rig A: $862, rig B: $707
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard Gas Analyzers: CO, CO_2, NO, NO_x, O_2, UHC
SAMPLING
PROBES: Water cooled
LINES: Electrically heated; Inner Liner Material - Smooth SS
OTHER REMARKS:

CONTACT: Technical - Bob Ehlers (216) 433-5707
Facility Manager - Jeff Swan (216) 433-5434

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ASCR
TEST HARDWARE: Flametube, Sector, and Regional Engine Full Annular

CONDITIONS:
PRESSURE 900 psia
TEMP 1300°F
FLOW 3-12 pps Flametube; 3-38 pps Sector/Full Annular
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP 3200°F
ATM OR ALT EXHAUST atm
OTHER
NITROGEN: 2000 psig

HEATER TYPE shell and tube
OTHER HEATER PRESSURE/TEMP *50 pps, 150 psig, 1700°F*

FUEL STORAGE (1) 20,000 gal tank
FUEL TYPE Jet A
FUEL FLOW 20 gpm
FUEL PRESSURE 2000 psig
H2O COOLING PRESSURE/FLOW *3000 gpm/60 psig; 670 gpm/250 psig; 300 gpm/1500 psig*

AVAILABILITY:
TEST FREQUENCY: 2 days/week
COST($/DAY): 450 psia air only - $2K; 1250 psia air, flow less than 25 pps - $6-10K; 1250 psia air, flow more than 25 pps - $10-16K; cost/occupancy hour: $2,092
SETUP/COORDINATION COST: Flametube - assy $600, installation $240, + instrumentation; Sector - unknown at this time
INSTRUMENTATION
Standard Gas Analyzers: CO, CO2, NO, NOx, O2, UHC;
Smoke meters - 1 filter type and 1 optical; particle measurement system
Non-intrusive laser diagnostics: YAG pumped dye laser systems with wave length extension systems for obtaining UV light, Measurements include: planar mi scattering, phase doppler particle analysis(PDPA), LDV/PDPA, laser induced flourescence(LIF), planar laser induced flourescence(PLIF), RAMAN, SCHLIEREN, C2 FLUORESCENCE; Acoustics

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: ASCR(CONTINUED)

SAMPLING

PROBES: SS, Water cooled, multi port; 2 probes can be used simultaneously in Flametube at axial locations 2.4", 4.5", 6.0", 7.5", 9.0", 11.0", 16", and 22" downstream of the combustion section inlet flange; 21 sampling lines are available for the Sector rig

LINES: Steam traced and Electrically heated; Inner Liner Material: First 12 ft are carbon black teflon, remainder is SS; Line Length: 100-120 ft

OTHER REMARKS:

CONTACT: Technical - Pete Pachlhofer (216) 433-5705
Facility Manager - Jeff Swan (216) 433-5434

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Allison Engine Company
FACILITY: Combustor Research Lab
TEST HARDWARE: Flametube concepts

CONDITIONS: PRESSURE 2 lines - low pressure 100 psia, high pressure 300 psia
TEMP 800-900°F, or 1300°F with electric heater
FLOW 10 pps at 100 psia, 5 pps at 300 psia
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER:
NATURAL GAS 300 psig

HEATER TYPE air to air heat exchanger, electric emersion
HEATER PRESSURE/TEMP
FUEL STORAGE 1500 gal tank
FUEL FLOW 1000 pph
FUEL PRESSURE 1000 psig
H2O COOLING PRESSURE/FLOW 3000 pph/400, 500 psig

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers(Fisher and Rosemount), Malvern Particle Size Analyzer
SAMPLING
PARTICULATES/AEROSOLS measurements were made 6-7 yrs ago on cold fuels(solid fuel), focus on combustion efficiency - solid residue was captured and analyzed for ash and carbon content(ash analyzer and particle counter + photo micrographs); special probes - 1 foot long with larger ports were used to collect particulate, SS H2O cooled probes that sampled at the same velocity as the gas stream, H2O was injected into the sample; collected the particulates through filter paper in a tank a few feet away, the tank had a water separator and flow meter
PROBES: H2O cooled, SS probes, axial location varies with each rig, .020" port size, single cup rig has sampling port 8" downstream of fuel injector with a flow path of 4"x4", two types of probes - fixed multi-port and an actuated single port; 3 probes located in one plane at different radial locations

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Allison Engine Company
FACILITY: Combustor Research Lab(continued)
TEST HARDWARE: Flametube concepts
LINES: Electrically heated
OTHER REMARKS:

CONTACT: John Rothrock (317) 230-3057

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Allison Engine Company
FACILITY: Test Department Combustor Facility
TEST HARDWARE: Flametube, Sector and Full Annular

CONDITIONS:
PRESSURE
TEMP
FLOW
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER:

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Ron Mutzl (317) 230-4702
John Spratt (317) 230-2106

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A18
TEST HARDWARE: HP Sector, HP Annular Combustors
Emissions and Altitude Relight Testing

CONDITIONS:

PRESSURE	440 psia(30 ATM)
TEMP	1140°F(1600°R)
FLOW	200 pps

VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A19
TEST HARDWARE: HP Flametube, HP Single Module, LP Sector, LPAnnular Combustors
Emissions and Altitude Relight and Exit Temperature Profile Testing

CONDITIONS:
PRESSURE 440 psia(30 ATM)
TEMP 1040°F(1500°R)
FLOW 45 pps
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell A5
TEST HARDWARE: MP Flametube, LP Single Module, LP Sector, LP Annular Combustors
Emissions, Exit Temperature Profile, LBO Testing

CONDITIONS:

PRESSURE	220 psia(15 ATM)
TEMP	1140°F(1600°R)
FLOW	10 pps

VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: General Electric - Evandale
FACILITY: Cell 306
TEST HARDWARE: LP Flametube, LP Single Module, LP Sector Emissions, Altitude Relight, Exit Temperature Profile and LBO Testing

CONDITIONS:
PRESSURE 118 psia(8 ATM)
TEMP 740°F(1200°R)
FLOW 10 pps
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Claude Chauvette (513) 243-2626

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: United Technologies Research Center(UTRC)
FACILITY: Jet Burner Test Stand(JBTS) - Ambient pressure single-injector flametube
TEST HARDWARE: Ambient pressure single-injector flametube

CONDITIONS:

PRESSURE	44 psia/	400 psia/	600 psia
TEMP	400°F /	850°F /	850°F
FLOW	17 pps/	20 pps /	4 pps

VITIATED OR NON-VITIATED vitiated and non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER
HYDROGEN 2400 psi
OXYGEN 2400 psi
NITROGEN 2400 psi

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE (3) 1000 gal, (3) 4000 gal; (1) 10,000 gal tank
FUEL FLOW 35 GPM
FUEL PRESSURE 1500 psi
H2O COOLING PRESSURE/FLOW 700 psi

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO2, NO, NOx, O2, UHC
SAMPLING
PROBES: 3 H2O cooled sampling probe rakes are located at the exit of the combustor; (4) 0.64 mm orifices span each sampling rake. Emissions can be acquired individually or for all three rakes simultaneously
LINES: Heated pump, electrically heated sample transfer lines
OTHER REMARKS:

CONTACT: Charlie Graves (407) 796-5289

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: United Technologies Research Center(UTRC)
FACILITY: Jet Burner Test Stand(JBTS) - Moderate pressure single-injector flametube
TEST HARDWARE: Moderate pressure single-injector flametube

CONDITIONS:
PRESSURE 200 psia
TEMP 900°F
FLOW 20 pps
VITIATED OR NON-VITIATED non-vitiated
EXIT TEMP
ATM OR ALT EXHAUST
OTHER
HYDROGEN 2400 psi
OXYGEN 2400 psi
NITROGEN 2400 psi

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE (3) 1000 gal, (3) 4000 gal; (1) 10,000 gal tank
FUEL FLOW 35 GPM
FUEL PRESSURE 1500 psi
H2O COOLING PRESSURE/FLOW 700 psi

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
Standard gas analyzers: CO, CO2, NO, NOx, O2, UHC; Smokemeter
SAMPLING
PROBES: Piccolo probe system at the combustor exit; a series of seven probes spanning the exit plane. Each piccolo probe has seven gas sampling ports with 0.30 in. orifices. The assembly can be sampled as a gang system or from each piccolo probe.
LINES:
OTHER REMARKS:

CONTACT: Charlie Graves (407) 796-5289

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Southwest
FACILITY:
TEST HARDWARE:

CONDITIONS:

PRESSURE 150 PSIA (10 ATM)
TEMP 1200°F
FLOW 3 PPS
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER
HYDROGEN
OXYGEN
NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT:

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: University of California at Irvine
FACILITY:
TEST HARDWARE:

CONDITIONS:
PRESSURE 225 PSIA (15 ATM)
TEMP 1200°F
FLOW 1-4 PPS
VITIATED OR NON-VITIATED
EXIT TEMP
ATM OR ALT EXHAUST
OTHER
HYDROGEN
OXYGEN
NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
PROBES:
LINES:
OTHER REMARKS:

CONTACT: Vince McDonell (714) 824-7423

FUNDAMENTAL/EXPERIMENTAL TEST FACILITIES AND CAPABILITIES (SHOCK TUBE/SHOCK TUNNEL/STIRRED REACTOR)

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: Wright Patterson Air Force Base
FACILITY:
TEST HARDWARE:

CONDITIONS:
- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
- PROBES:
- LINES:

OTHER REMARKS:

CONTACT: Roquemore

VENUES FOR PARTICULATES/AEROSOLS MEASUREMENTS

ORGANIZATION: NASA LeRC
FACILITY: Basic Combustion Lab
TEST HARDWARE:

CONDITIONS:

- PRESSURE
- TEMP
- FLOW
- VITIATED OR NON-VITIATED
- EXIT TEMP
- ATM OR ALT EXHAUST
- OTHER
  - HYDROGEN
  - OXYGEN
  - NITROGEN

HEATER TYPE
HEATER PRESSURE/TEMP
FUEL STORAGE
FUEL FLOW
FUEL PRESSURE
H2O COOLING PRESSURE/FLOW

AVAILABILITY:
TEST FREQUENCY:
COST($/DAY):
SETUP/COORDINATION COST:
INSTRUMENTATION
SAMPLING
  PROBES:
  LINES:
OTHER REMARKS:

CONTACT:

APPENDIX

INFORMATION FROM ARI-RR-947

"Engine Trace Constituent Measurements Recommeded for the Assessment of the Atmospheric Effects of Stratoshpheric Aircraft"

by

R.C. Miake-Lye, W.J. Dodds, D.W. Fahey, C.E. Kolb and S.R. Langhoff

August 1992

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In response to the National Research Council (NRC) recommendations, the Workshop on Aerosols and Particulates from Aircraft Gas Turbine Engines was organized by the NASA Lewis Research Center and held on July 29–30, 1997 at the Ohio Aerospace Institute in Cleveland, Ohio. The objective is to develop consensus among experts in the field of aerosols from gas turbine combustors and engines as to important issues and venues to be considered. Workshop participants' expertise included engine and aircraft design, combustion processes and kinetics, atmospheric science, fuels, and flight operations and instrumentation.

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