Meeting Review:
Airborne Aerosol Inlet Workshop

27-28 February and 1 March 1991

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Why Atmospheric Aerosols are Important and Why it's Important to Measure Them Well.

PASIN and PAIR--Airborne Aerosol Inlet Passing Efficiency Measurements.

Aircraft Studies of Size-Dependent Aerosol Sampling Through Inlets.

Airborne Filter Intercomparisons and Comparisons With Cloud Water and Ground-Level Filter Measurements.

The Drying of Hydrated Aerosols by the De-Iced Particle Measuring Systems Aerosol Spectrometer Probes (ASASP, PCASP).

Flow Speed and Particle Trajectories Around Aircraft: Theory and Measurements.

Aerosol Sampling and Transport.

On the Aerodynamic Design of Gas and Aerosol Samplers for Aircraft.

Applications of Principles of Aerodynamics to Inlet/Diffuser Design.

Aerosol Sampling and Transport: Recent Findings at the Universities of Cincinnati (USA) and Odessa (USSR).

Design and Testing of Aerosol Inlets and Transport Systems.

An Aircraft Aerosol Inlet for Operation at Mach 0.7 at Altitudes from 8km to 20km.

Using Simultaneous Radon Gas and Radon Daughter Measurements to Evaluate Sub-Micron Aerosol Sampling Efficiencies of Airborne Sampling Systems.

Proposed Development and Testing of Insoluble Particle Collectors.

FORWARD

"We don't want to work on inlets; we just want an inlet that works"
James "Chuck" Wilson, 1991

According to Webster's New Collegiate Dictionary, a workshop is defined as a brief intensive educational program for a relatively small group of people in a given field that emphasizes participation in problem-solving effort. The Airborne Aerosol Inlet Workshop was envisioned as this type of forum. We feel that this workshop was successful in increasing the awareness of the participants to the problems of sampling aerosols with aircraft-mounted inlets. The unique aspect of this workshop was that it attracted experts from other technical and scientific disciplines, but whose expertise could possibly be applied to the inlet problem. These specialists provided invaluable insight into the difficulties of trying to use the sampling techniques commonly used at present. At the same time, the interest of these experts was piqued as they saw applications for their skills and experience in new areas about which they had not previously been aware of the need.

In order for this workshop to be of benefit to the community, we felt that we should publish the results as quickly as possible. The majority of those who made presentations at the workshop have responded admirably by providing us with written copies of their presentations. All of the presentations made important contributions to the subject of the workshop, and we felt that it was important to publish them in their entirety. There are, no doubt, numerous typographical errors that we have overlooked as well as a number of places where the discussions at the end of presentations might seem to make little sense. In this latter case, many times questions were asked while looking at a visual being displayed by the presenter and is confusing in the context of a written report like this. We apologize for these errors and decided not to indulge in too rigorous editing in order to expedite the publishing of this technical note as soon as possible.

The long-term effects of this workshop are hard to gauge at this time. However, our hope is that it will act as a document that will alert the scientific community to the possible problems in interpreting data taken with airborne inlets and will inspire others to develop new technologies that will minimize these problems.

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PART I--INTRODUCTION

Workshop Objectives

An international workshop on airborne aerosol inlet technology was convened in Boulder, Colorado and met from February 27 to March 1, 1991. This meeting was organized for the express purpose of discussing the current state of airborne measurements of aerosols and to address two major questions.

- Are the presently-used samplers adequate to provide airborne measurements of aerosols with sufficient quality and accuracy to address scientific questions?

- If not, then what are the limitations of these samplers; how can they be improved, and what steps should be taken to make these improvements?

The workshop organizers recognized that those who use inlets to make airborne measurements are not necessarily those with sufficient expertise to answer these questions. Hence, an attempt was made to identify a broad range of disciplines from which experts could be invited to contribute to this workshop. The list of participants (Appendix B) includes atmospheric chemists and physicists, aerosol physicists, and engineers, aerodynamicists, modelers, and experimentalists.

Workshop and Report Structure

The workshop was structured into three distinct components (the agenda may be found in Appendix A). The first two days were devoted to presentations followed by working group sessions. The presentations of the first day dealt with observational data from aircraft that helped define the advantages and disadvantages of current aerosol sampling systems. The second day included presentations by those individuals doing theoretical, laboratory, and wind tunnel studies of aerosol inlet systems. The working session at the end of each day served to summarize the preceding presentations, to fill in missing pieces not previously addressed, and to provide an additional forum for discussions left unfinished from earlier in the day.

The final day began with an overall summary of the previous days, after which the participants were divided into three groups: modelers, laboratory and wind tunnel experimentalists, and airborne observationalists. The objective of these groups was first to define how the expertise of their group could be applied to the inlet problem and then to identify the ideal method to apply this expertise. The groups then reconvened to present results and discuss them before assembling a final list of conclusions and recommendations.

The remainder of this report presents a perspective of the importance of the aerosol measurement problem, followed by a summary of the working group sessions and the conclusions and recommendations that resulted from these discussions. The extended abstracts of the presentations made during the workshop may be found in Appendix C, with the discussion that followed each presentation.

PART II--OVERVIEW AND CONTEXT OF PROBLEM

The Role of Aerosols in Atmospheric Processes

(This summary is taken from the keynote talk of Jeremy Hales of Battelle Northwest. The complete text may be found in Appendix C.)

Atmospheric aerosols impact atmospheric process in a number of ways. For instance, they are a prime factor in moderating the radiative energy balance of the atmosphere. Various studies have documented decreasing visibility, especially in the northern hemisphere, due to increased aerosol concentrations in the troposphere. Investigators of many nations are making measurements of aerosols and radiative impacts both *in situ* and remotely in many regions of the world. The general observation of increasing optical depth is consistent; however, these measurements also indicate large spatial and temporal variations that depend upon a multitude of factors and clearly indicate the need for more extensive measurements.

Aerosols are also intimately involved in cloud processes. The DMS hypothesis, whereby clouds are nucleated in part by dimethyl sulfide oxidation products, is generally accepted as a possible mechanism for modifying maritime clouds and significantly affecting the global radiation balance. Aerosols are also a primary determinant of precipitation chemistry by mediating wet conversion processes and altering cloud water pH. Aerosols strongly influence wet and dry deposition rates of many species.

Aerosols are often at the end of the reaction chain of photochemical and non-photochemical conversions of gaseous precursors and act as important reservoirs for species such as nitric acid. Studies in the past few years have shown the importance of aerosols as reaction sites for heterogeneous chemistry. This has been dramatically illustrated in the case of polar stratospheric clouds that are directly linked to the destruction of ozone in the polar regions of the stratosphere.

Last, but certainly not least, the effects of aerosols on society are well recognized. At the forefront are issues such as human health (respiratory impacts), climate and weather, visibility, acid rain, nuclear fallout, equipment reliability, manufacturing processes, and the formation of the polar ozone holes.

Difficulties in Characterizing Aerosols

(This summary is taken from the keynote talk of Jim Vincent of the University of Minnesota. The complete text may be found in Appendix C.)

The impact of aerosols on global climate is a result of the multidimensional characteristics of these aerosols. Aerosol particles range in size from less than 0.01 μm to greater than

3

10 μm, at concentrations from less than 1 cm^{-3} to greater than 10^5 cm^{-3}. At the same time these particles' morphology can range from simple liquid spheres to highly complex structures with rough surfaces or aggregate chains. The chemical composition can be any combination of heterogeneously or homogeneously mixed species as well as mixed solid and liquid phases (e.g., a solid nucleus covered with liquid layer).

The method of aerosol measurement is strongly dependent upon the characteristics one wishes to study. Visibility depends on a particle's optical properties, and accumulation-mode aerosols (0.1 to 1.0 μm) have the greatest impact on solar insolation. A complete understanding of a particle's optical properties requires accurate measurements of surface area, shape and chemical composition. On the other hand, when studying cloud droplet nucleation, particles in the size range 0.01 to 0.1 μm have the greatest impact. Measurements of the surface area and chemical composition of these particles are also essential for understanding nucleation rates.

The multidimensionality of aerosols greatly complicates attempts to characterize them, especially when measurements and collections are being made from airborne platforms. The most accurate way of determining the chemical, optical, and structural properties of aerosols is by impaction on filters and subsequent chemical and microscopic analysis. Removing the aerosols from the airstream and depositing them on a filter when the aircraft is moving in excess of 50 ms^{-1} is a non-trivial task because of the loss of particles on inlet walls and tubing and chemical changes due to dynamic heating. Attempts to optically measure size distributions of aerosols are confounded by the sensitivity of these techniques to the aerosols' optical properties, shape, and orientation (when non-spherical).

Although aerosols play an important role in atmospheric processes and global climate change, we currently lack adequate measurement capabilities to address these critical problems. We need to measure the spatial and temporal distribution of aerosols throughout the world with extensive characterization of the aerosol properties. This workshop has clarified our airborne aerosol measurement needs and limitations and has provided guidance for future inlet development research.

PART III--WORKING SESSION SUMMARIES

The discussions of each of the five working groups are outlined in the sections that follow. We have summarized the major points of these discussions in PART IV.

Working Group on Airborne Observations to Date

These talks and the subsequent discussion focussed on airborne experiments whose data can be used to infer inlet passing efficiencies. Two types of experiments were discussed: intercomparisons and the examination of deposits in inlets. Several investigators have intercompared airborne aerosol filter measurements with other aircraft, surface collectors, or optical particle counters, and have found "good agreement," although differences of 50 percent or more may not always be detectable in such experiments. When inlets were washed out after flight to compute passing efficiencies, losses of 50 percent or more were observed for the mass of supermicron particles, while submicron losses were 50 percent or less (50 percent on NCAR's Electra, but considerably less on their King Air).

Currently there is a dearth of data from inlets in flight which can be used to evaluate the significance of the many potentially-important factors identified below. Although wind-tunnel tests will be essential for isolating individual factors at minimum cost, some flight conditions cannot be adequately simulated in a wind tunnel, so both approaches must be used in concert. Airborne tests will also be needed to validate models which are formulated from wind-tunnel tests. This model validation will depend heavily on measurements of the particle deposition patterns within inlets after exposure in flight.

Undersampling of Coarse-Mode Particles

Although we have known for years that coarse-mode particles are undersampled, we have not had a clear idea of the flow regimes responsible for these losses. What is the best way to sample supermicron aerosols? What is the maximum cut size that can be obtained for each inlet? The role of large aerosols as CCN and as initiators of drizzle makes it important that we find ways to characterize them from aircraft. We are limited in sampling large aerosols by our lack of understanding of the physics underlying transport in inlets at small scales and high airspeeds. In view of the low number-concentration of these big particles, it may well be that grossly subisokinetic inlets will prove useful, to preconcentrate large particles by virtual impaction. It is clear that no single inlet is likely to work well for every size-range, so designing special inlets for big particle sampling may be necessary.

Questions About Accumulation-Mode Inlet Losses

Different groups have very different opinions concerning the potential for inlet losses of accumulation-mode particles, because the existing observational base is inadequate to provide a definitive answer. Consistent losses of (submicron) non-sea salt sulfate (NSS) aerosol noted in the PASIN program on an Electra were absent or equivocal in lower-airspeed measurements on a King Air during PAIR. Intercomparisons between platforms by several groups have not shown clear evidence of significant submicron aerosol losses. These aircraft/balloon/tower/surface/aircraft intercomparisons provide valuable information, but intercomparisons alone are not necessarily a sufficient means of inlet validation. The diversity of opinions on submicron losses makes further investigations essential.

Evaporative Losses

It is inevitable that bringing air into an inlet system will cause dynamic heating, potentially modifying the size of an aerosol population. On commonly used research aircraft, this dynamic heating ranges from 5 to 20°C, which is enough to cause dramatic changes in volatile aerosols. OPC (Optical Particle Counter) investigators probably need to routinely dry their aerosol completely before analysis, since it may be impossible to determine the extent of hydration on their inevitably-warmed (and thus partially-dried) samples. This warming may also cause the evaporation of ammonium nitrate aerosol, methanesulfonic acid, dissolved volatile inorganic acids such as HCl and HNO_3, and volatile organics, thereby confounding attempts to study the phase-distributions of these species. We need advances in OPC technology, so that small aerosols can be measured in undisturbed flow (in the same manner that supermicron particles are measured by an FSSP, for instance).

It is clear that understanding the thermodynamics of each inlet system will be an essential part of characterizing its value for various uses. The interpretation of OPC intercomparisons with other systems, in particular, will require good information on the thermodynamics of their flows. Wherever possible, thermodynamic measurements should be made inside inlets.

External Flow and the Location of Inlets on Airframes

Flow modelling indicates that some locations may be more or less desirable for mounting inlets. Although shadowed and enhanced zones have been predicted for droplet-size particles (tens of microns in diameter), airframe flow patterns also have important implications for sampling much smaller particles. Inlet performance is probably quite sensitive to the angle between streamlines and the inlet axis (isoaxiality), so inlet design and mounting must account for precise flow angles. This external (to the inlet) flow can be dominated by obstructions, upwash, and meter-scale vortices behind the wing/fuselage junction. Several lines of evidence suggest that inlet performance may be highly sensitive to location and orientation on the airframe.

6

Of equal concern is the potential that the instantaneous flow angles may change dramatically on a very short time scale, so that aligning inlets with the mean flow may still be inadequate to attain isoaxial sampling. The effects of vibration, aircraft motions and attitude changes, and atmospheric turbulence should be studied carefully, since they have a similar potential to distort streamlines and induce flow problems inside inlets. On smaller scales, particle trajectories could be changed at the entrance of the inlet as they respond to eddies caused by turbulence and aircraft motions, leading to impaction on inlet edges. Measurements of the instantaneous flow angle on a suitably rapid time scale are essential for addressing these questions.

Flow Inside Diffusers

Most airborne aerosol measuring systems require that airspeeds be slowed from that of the free stream (45 to 200 m/s relative to the aircraft) to that which the sampler can accommodate (at most a few m/s). The most common method of doing this has been the use of diffuser cones, which slow the air by increasing its cross-sectional area as it moves downstream. Other possibilities which warrant further study include subisokinetic sampling with cylindrical tubes, the use of sampling systems which can operate at higher speeds (such as some electrostatic collectors), and the use of slower platforms (such as airships). The latter may provide a unique way to intercompare aerosol concentration measurements at altitude.

It is now becoming clear that the large area-ratios we have commonly used in diffusers to slow air down have probably produced highly turbulent, separated flow inside the diffusers. (Exit cross-sectional area divided by the entrance area has often been near 100). Diffuser theory must be studied intensely under the conditions of airborne aerosol sampling, and a data base concerning flow inside these ubiquitous devices must be generated as soon as possible to test diffuser flow models. Of particular interest are measurements of turbulence and its distribution throughout these cones.

Although the technique is still being developed, laser doppler velocimetry (LDV) may prove useful for observing the trajectories of particles near inlets. LDV measurements of particle tracks in diffusers would be of immense value, in both wind tunnels and airborne systems. LDV studies could also help to evaluate the importance of secondary aspiration and bounce from diffuser tips, mechanisms which are probably significant in some flow regimes and some samplers.

Most of the aerodynamic studies on flow inside diffusers have been done on aircraft-engine sized intakes, which are tens to hundreds of cm in diameter. It is quite likely that scale effects may limit our ability to use this data base on the several-mm diffuser openings commonly used for aerosol inlets. For example, a 3 mm-thick shock-induced turbulent layer would have little influence on an engine intake, but would throw the entire flow of a 5 mm opening into shock. Shock waves have been shown to deposit even very small particles onto

7

nearby surfaces. The difficulty of scaling aerodynamic models down by orders of magnitude makes experimental validation of inlet designs and flow models extremely important.

Shrouded Probes and Double-Diffusers

Two variations on the simple diffuser deserve further attention. One is the use of a shroud around the diffuser tip. Shrouds have the potential to align streamlines along the diffuser axis before air enters the diffuser, thereby reducing the impact of instantaneous misalignment on aspiration efficiency. Some shrouds are also designed to serve as a preliminary diffuser, slowing the airspeed slightly and reducing the area ratio required in the second diffuser. These "double diffuser" configurations effectively exclude the disturbed high-speed boundary layer from the first diffuser by only drawing air from its (hopefully laminar) centerline into the second diffuser.

These double diffuser systems offer tremendous promise, since they should reduce boundary-layer and edge effects by increasing the size of openings while also reducing the area ratio (and thus the potential for flow separation) in each diffuser. Their behavior must be *carefully modelled and characterized in wind-tunnels*, though, since it will be size-dependent to some degree. For the largest particles, for instance, a double-diffuser will essentially act as a virtual impactor, enriching the giant aerosols in the slowed airstream that ultimately enters the detector. While OPC's may have adequate data to perform a size-dependent correction on their data for a nonunity inlet efficiency, with filter systems it will be important to design for unit efficiency over the entire particle range of interest.

Electrical Effects

It is possible that electrostatic effects are responsible for some inlet losses. Very large and nonuniform electrical fields (tens of kV/m) are sometimes measured on aircraft, and it is possible that they could interact with charged aerosols. David Pui showed experimental evidence that charging can affect inlet aspiration efficiencies. Efficiencies decrease because charged particles are attracted to the walls of the inlet. It would be useful, therefore to measure charge and electric fields on aerosols, inlets, and aircraft surfaces whenever possible on future flight programs, to see whether any of these factors correlate with losses.

Working Group To Identify Inlet Design Issues

This set of talks and the subsequent working group discussions focused on the application of principles from both aerodynamics and classical aerosol physics to the question of aircraft aerosol sampling errors. This was in contrast to the first day's reports, which came largely from the perspectives of atmospheric chemists who already do airborne aerosol sampling. It is now clear that the body of (low-airspeed) literature on which we have relied to design

airborne inlets may not adequately describe important characteristics of air-flow and particle trajectories at flight speeds.

Virtually all of the workshop participants gained a much broader perspective on airborne sampling as a result of this cross-discipline exchange. The aerosol physicists learned, for instance, about the flow separation and shock that are likely to occur with sharp-edged inlets operating at speeds an order of magnitude higher than those described in the aerosol sampling literature. Aerodynamicists were sensitized to the particle bounce and inertial problems which blunt or curved edges can create for aerosol sampling. We all gained a greater appreciation for the folly of any one discipline trying to address this question alone. It is clear that a heavily interdisciplinary approach will be needed to understand and improve on the problems of airborne aerosol sampling.

Expansion Ratios and Separated Flow

It is likely that airflow in most existing inlets separates from the walls, generating turbulence and depositing some sizes of particles inside the inlet. Even inlets with aerodynamically curved leading edges probably cause flow separation, if their expansion ratios are greater than about 5. (Many existing diffusers have expansion ratios of tens to hundreds, since they have to slow air from, say, 100 m/s to 1 m/s.) Greater expansion ratios imply longer diffusers, which gives boundary layer turbulence more time to develop. Expansion angles smaller than 7 deg might reduce the tendency for separation, but at the expense of longer inlets, and therefore more surface area, on which to lose particles.

Double or triple diffuser systems may offer the solution to this dilemma for some particle sizes, since undisturbed air from the axis of a small expansion-ratio diffuser could then be expanded in another small ratio diffuser. The disturbed boundary-layer flow from the high-airspeed first diffuser would simply be discarded, so that only the (approximately) laminar core-flow would enter the second diffuser. This scheme relies on the assumption that at the end of the first diffuser the particle concentrations represent those of the free stream. Since the streamlines must diverge even in the first diffuser, this assumption will fail for larger particles, and it will be essential to characterize the size-response of the system. OPC's may be able to correct for this size bias during data processing, but filter samplers will have to be designed with great care to ensure unbiased sampling over their size ranges of interest.

Inlet Shape

Sharp edges make inlets much more prone to flow separation due to the slight misalignment errors which result from aircraft motions and atmospheric turbulence. These sharp tips may also make inlets more prone to corona discharge and electrostatic effects on inlet efficiency. At airspeeds below 10 m/s, small isoaxiality errors on thin-walled inlets generate modest sampling errors with a roughly cosine functionality. At aircraft speeds, however,

misalignment creates flow separation and intense turbulence inside inlets. Since neither atmospheric turbulence nor off-axis aircraft motions can be eliminated, it is clear that we must design our inlets to reduce their sensitivity to nonaxial external flow.

Rounded inlets, such as those NACA (National Advisory Council on Aeronautics) designs which are used on all aircraft leading edges and engine intakes, are much more forgiving of off-axis flow. It is clear that some rounding will be needed to reduce the tendency for flow separation in aerosol inlets. Even these tips could still cause problems, however, because high Mach numbers are generated very near curved surfaces at the entrance. This is likely to generate shock waves in many systems, thereby inducing turbulence downstream. While this shock is generally not a problem in engine air intakes because it is confined to a small fraction of the opening, it might fill a large fraction of a 5 mm aerosol inlet opening.

Present-day inlets are not necessarily the optimum design for airborne measurements. Data were presented to show that flow separation is a strong function of the expansion ratio of diffuser type inlets. Many of the inlets presently in use have large expansion ratios which probably means that the flow may be continuously or intermittently separated at some point in the inlet. The number and angle of bends in an inlet also affect the amount of material impacted on the walls at various particle sizes and flow rates. The effect of bends has been modeled extensively in past studies of groundbased inlets. Some of these low airspeed results might be scalable to airborne conditions, but this must be verified.

Flow Rate Through the Inlet

Most scientific applications require inlets that sample aerosols isokinetically. To do otherwise biases the measurement through enhancement of particular sizes of aerosols, depending upon whether the flow is sub- or super-isokinetic. Some discussions during the workshop suggested that such enhancements are not always detrimental. They could even be beneficial in those applications where subisokinetic sampling might effectively preconcentrate large particles, thereby improving the S/N for OPC's, for instance. Modeling studies should be designed to investigate a variety of flow conditions, in order to apply this technique quantitatively. It is likely that the degree of isokineticity also influences the tendency toward flow separation downstream in a diffuser.

State Parameters

Relative humidity was shown to be a major determinant for sizing errors in optical counters that duct air into their sample volumes. In addition, humidity can affect the charge on particles, their tendency to bounce or adhere on inlet surfaces, and possible runback on the

surface of the sampler. This latter effect might be important if deliquesced aerosol are entrained by the vortices at the edges of the inlet and then pulled into the inlet by a reverse-flow.

Temperature and pressure are fundamental parameters that help determine the characteristics of the flow around both aircraft and inlet. In airborne operations the value of these parameters can vary widely depending upon the scientific application. The temperature may range from 30°C in marine boundary layer flights to -80°C in the middle stratosphere where the NASA ER-2 conducts polar ozone research. The ambient pressure may range from 1000 mb near sea level to 50 mb in the middle stratosphere.

Although no single inlet would need to operate over this entire range of conditions, the following conditions represent the extremes encountered by one group or another:

Airspeed	40	- 200 m/s
Pressure	1000	- 40 mb
Temperature	-80	- +30°C
Relative humidity	0	- 100 percent
Inlet Flowrate	1	- 10,000 l/min
Attitude		± 10 deg pitch
		± 5 deg yaw
		± 5 deg roll

Particle Bounce

A major cause of decreased aspiration efficiency is the loss of particles on the inlet walls through gravitational sedimentation, diffusional migration, and turbulent deposition. The first effect is probably insignificant at the flowrates normally encountered in airborne applications, but the latter two effects could be important. Particles that strike the walls of the inlet may or may not adhere depending upon the composition of the particle, composition and roughness of the wall, the presence or absence of a liquid layer on either the wall or the particle, the velocity and angle with which the particle strikes the wall, the charges on the particle and the wall, and the temperature difference between the particle and the wall. It is essential that models be designed to account for these factors.

The Need for Experimental Validation of Models

It is likely that we will encounter some significant scaling problems as we try to design small inlets using macroscale aerodynamic rules of thumb. Experimental confirmation of flow regimes is therefore critical for confirming the results of design and modelling studies. The working group concluded that in *no case* has the internal flow of a currently-used inlet been adequately modelled or measured under airborne conditions.

11

They also concluded that there is insufficient experimental data to validate present inlet models. The significant problems of this airspeed and flow regime are simply so different from any in the existing literature that model verification will have to await more experimental work. Information on the flows and pressures at various locations within an inlet would be particularly informative for understanding the flow regime. For particle deposition, however, data on the shape of aerosol deposits (by section) at various Reynolds numbers and turbulence is needed. Both Willeke and Huebert have found material deposited near the tip of a tube, for instance, but their data is inadequate to evaluate models at aircraft speeds.

Several different types of inlets were discussed, from simple diffusers to shrouded inlets to double diffusers. In each case there is inadequate data available to assess their performance. This type of evaluation is essential, though, since in each case the tendency toward size sorting must be well characterized.

Based on the wide range of conditions, instruments, size-ranges of interest, and scientific objectives, it is clear that no single inlet could ever satisfy all needs for airborne aerosol sampling. It will be important for each investigator to define his or her own needs and devise an inlet system to suit them. We will then need to be very cautious about using a successful design on a different aircraft or for different types of particles.

Working Group on Inlet Modeling Needs and Directions

The information presented and discussed during the previous two days of the workshop identified the critical issues to be addressed if we are to improve our ability to characterize atmospheric aerosol. Understanding the sampling characteristics of airborne aerosol inlets requires a multidisciplinary approach that combines modeling, laboratory, wind tunnel and airborne studies. The modeling sub-group of working session III focused on how inlet modeling studies fit into this framework.

There are two major reasons for studying aerosol inlets: to understand the performance of presently used samplers and to design new inlets with improved performance. The first objective is important because of the vast amount of airborne data that have been taken over the years. From these data have come a significant fraction of our present knowledge of atmospheric aerosols. It is likely that even more information will be gleaned from these data once the limitations of the samplers are better known. A coordinated modeling effort will play a major role in achieving both of these objectives.

Functions of Aerosol Inlet Models

Theoretical evaluations and model simulations of the air flow and particle trajectories around and through aerosol samplers serve three important functions. First, the physical

processes that govern the sampling behavior of inlets must be identified. This must be an iterative process between theoretical evaluations and experimental validations. Most of the workshop participants felt that the physics of the problem had yet to be completely defined. The factors controlling inlet efficiency (e.g. anisoaxiality, anisokineticity, etc.) can be evaluated in model sensitivity tests.

The second important function of models is to help experimentalists design quantitative tests once the important parameters of the problem are identified. As an example, simulations could show locations in an inlet where flow separation is expected, or points of maximum particle deposition. Appropriate sensors could then be fabricated and located in these areas to compare measurements with the models.

Finally, once models have been tuned by comparison with experiments, they can be used to design new samplers that minimize the limitations of existing inlets.

Components of the Modeling Problem

The modeling group identified three components of the inlet problem:

- Understanding and predicting the flow around the airborne platform on which the inlets are mounted.

- Characterizing the flow and particle trajectories at the entrance to the sampler.

- Characterizing the flow, particle trajectories, and size and mass distributions inside the sampler.

An ideal model would account for all the possible factors that could affect aspiration efficiencies. These include inlet shape, flow rate, state parameters (temperature and pressure), relative humidity, air motion (average speed and direction as well as turbulence), particle bounce, and electrical effects. The simulation of all these would be a formidable, though not impossible task. A major difficulty in modeling such a multi-dimensioned problem is not just how to handle the fundamental equations, but rather what values to use for quantities such as particle charge and surface effects. The modelers will have to rely on the experimentalists to provide more information on the physical parameters that constrain the problem.

A Modeling Exercise

The group adopted an idea for a model intercomparison, based on the modeling exercise of Kuehn *et al.* (1991). In that case, the geometry of a cleanroom, obstructions within the

13

room, and particle generation points were carefully defined. Then several modeling groups were challenged to simulate flow velocities and particle concentrations throughout the cleanroom. Six groups of modelers responded: the results were very informative, due to both their similarities and their differences.

This workshop group recommended a similar approach to the airborne inlet problem. This could attract modelers not presently active in the field of airborne aerosol measurements, who might have valuable expertise for deriving solutions. The exercise would also highlight the pro and cons of models currently used for addressing aerodynamic problems of this type.

The modeling sub-group recommends that a well-defined airborne inlet problem be presented to the modeling community: predict the behavior of particles and airflow at locations several inlet diameters in front of a sampler, directly at its entrance, and at several points within the sampler. The number of variables that constrain the problem would be reduced to those considered fundamental. The problem would be posed to a number of different modeling communities because each of the three components of the problem requires a different computational approach. There would be three problems to be solved:

- With respect to flow around the aircraft, the modelers would be given a geometrically simple shape and asked to predict the flow angle and velocity at several locations about the body and to predict the concentrations of two different particle sizes at those locations. These predictions would be made for two altitudes, two airspeeds, and two angles of the aircraft with respect to the mean flow.

- The next exercise would be to predict the velocity and particle field at the entrance to an inlet given the same conditions as in the previous case in addition to specifying a flowrate into the sampler. The inlet geometry would be one of the geometrically simpler samplers presently in use.

- Those modeling the interior of the inlet would be asked to predict the velocity vector and particle concentrations one and ten entrance diameters away from the entrance, and also at the bend and sampling plane of the inlet system (i.e. where filters or OPC's are located). The same conditions as the previous case would apply.

This exercise should be appealing to modelers who are interested in comparing their methods with those of other groups. The benefit to those searching for solutions to the inlet problem is threefold: researchers from outside the relatively narrow field of airborne aerosol science would be encouraged to contribute their expertise; evaluation of model results would allow analysis of the strengths, weaknesses, and applicability of such models; and finally, good agreement would open the way for more sophisticated applications under more realistic conditions. It is essential that the resulting models be used both to analyze the strengths and weaknesses of present samplers and to design and develop new samplers.

14

Evaluation of Previous Models and Scaling

A final recommendation is that the results of previous inlet model simulations be evaluated for their applicability to airborne samplers. It is not obvious that studies which were done for conditions substantially different from those encountered on aircraft (at lower airspeeds or for much larger openings) can be scaled to the conditions which airborne aerosol inlets encounter. These scaling issues need to be given serious attention, so that airborne aerosol inlet designers will know what parts of the existing inlet literature are applicable to flight conditions.

Working Group on Objectives for Aircraft Experiments

There are two broad classes of questions which should be addressed by aircraft measurements of inlet efficiencies. First, *is there a problem?* It is still not clear to what extent sampling problems affect accumulation-mode aerosols, for instance, and whether the problems noted on some platforms in certain locations are also concerns for other aircraft and in different regions. Although losses of super-micron aerosols have been acknowledged for years, what are the practical cutoffs in this size-range? Clearly many more field measurements are needed to define the extent of the problem.

If problems are identified, *what is causing them?* Although modeling and wind-tunnel experiments will be able to test particular loss mechanisms, they cannot replicate aircraft motions, atmospheric turbulence, and those other parameters which are unique to working on aircraft. It will be necessary to use flight tests to determine the importance of these factors.

Intercomparisons

Several methodologies were suggested for aircraft inlet studies. Intercomparisons can be useful for identifying the extent of the problem. Simultaneous measurements with the same technique on aircraft and either ships, ground stations, towers, or other aircraft in relatively well-mixed regimes may identify significant differences (or a lack thereof) due to inlets. This approach has the advantage that it can be carried out during other experiments, using existing samplers. Many of our impressions about the utility of existing inlets were derived from such intercomparisons. Of course, since (potentially small) differences between large numbers are the basis of this method, duplicate samplers on each platform will be important for characterizing the actual field precision of each technique and for evaluating the significance of observed differences.

Intercomparisons between different techniques on the same platform may also be valuable. Comparing dry-mass estimates from optical particle counters (OPC's) with those of filter systems or cascade impactors is a case in point. Another is comparisons between aspirated

15

OPC's (such as the ASASP) with external ones (FSSP) that do not depend on inlets. The potential exists to characterize the size-dependence of inlet characteristics, so that OPC data can be corrected for losses or enhancements in each size-range. Thermally-conditioned OPC data might then be used to derive corrected estimates of sulfate and ammonium concentrations for comparison with filter values. Comparisons of this type also need to be done in the lab, so that the precision of an inlet-free comparison of the methods can be established and used as a standard for significance of observed airborne differences.

Paired, carefully-intercalibrated OPC's could also be used to rapidly evaluate the impact of changes in airspeed, attack angle, flow-rates, and other variables in flight. One would serve as a reference (to note changes in the ambient particle population), while the other would sample from various points behind the inlets being tested. This technique has the advantage of deriving size-dependent information on losses or enhancements in the space of just a few minutes for each test. Thus, many more experiments could be done per flight hour than are possible with integrated sampling.

Intercomparing measurements of gas-phase Rn-222 and radon daughters (which distribute themselves according to the surface area of existing aerosol and are thus mostly on small particles) is another approach that offers promise. If the precision of the measurements can be shown to be adequate, this method would be particularly sensitive to accumulation-mode particle losses, which are less easily studied by bulk chemical (mass or volume) analysis. Of course, this method relies on an assumption of secular equilibrium among radon and its daughters, which would have to be tested in an artifact-free manner to increase confidence in the results.

It is of particular importance that intercomparison experiments benefit from the expertise of aerodynamicists and particle physicists to include new inlet designs alongside those which are already in use. This will not only move us forward by trying out new ideas, but it will also permit us to evaluate the large body of data which we have already collected and published using earlier inlet systems. Both of these are seen as important objectives, since we need to understand past programs and to design better ones for future experiments.

Direct Examination of Deposits in Intakes

In addition to intercomparisons, it is particularly important that we develop and employ methods for examining aerosol deposits in inlets. The advantage of this approach is that it relies on absolute measurements rather than differences, so it has the potential to observe small percentage losses. This approach can also identify the specific sites of deposits, and will thus be particularly useful in defining the mechanisms and causes of inlet artifacts. The disadvantage of this approach is that it is often expensive and time-consuming, so that it may fit in less readily with some existing measurement programs.

Extraction of soluble material from inlets has already been demonstrated, and might be added with a minimum of redesign to many field programs. It may be possible to position electron-microscope grids at various locations within an inlet to microscopically examine the number and morphology of deposited particles. Formvar and other surface coatings should be investigated as methods for marking the sites of aerosol impact. Examining deposits lends itself particularly well to the validation of models and to process-studies, and in some forms it may also be useful in generalized sampling programs. In geophysical studies, the fact that one inlet can be used for only one sample per flight (when deposits are to be analyzed), can sometimes be a significant drawback. Development of new methods for examining deposits should be strongly encouraged.

Whenever possible, numerous techniques should be used simultaneously, both to make the most economical use of flight hours and to provide the best context for interpreting results. Identifying the variables responsible for inlet losses will require many types of information. The analysis-of-deposits and intercomparison approaches can provide support for one another when used in concert. Side-by-side filters, OPC's, and cascade impactors, with a variety of inlet configurations, thermodynamic, and flow sensors, offer the best potential for clarifying loss mechanisms.

Flight Measurements for Model Validation

It is also important to consult with modelers and aerodynamicists to identify that information which will be of greatest value to their model evaluations. Incorporating pressure transducers or hot-wire anemometers at critical points in functioning inlets may permit useful analyses of the flow regimes responsible for aerosol deposition.

Individual and Collaborative Approaches

Our attack on these questions will necessarily include both individual experiments and some larger, collaborative ones. Many investigators already have plans for flight programs in which they will be studying atmospheric aerosols. With our increasing sensitivity to the potential for inlet artifacts, we can (and many will) add inlet tests to the geophysical objectives of our research. The immediacy of these flight programs allows us to make progress right away, without the long delays that naturally accompany proposing a new program dedicated solely to studying inlet science. This approach also encourages - and benefits from - the ingenuity of individual groups working on the diverse platforms with which they are most familiar.

Some large collaborative experiments will also be needed. An interdisciplinary approach is clearly necessary to resolve these inlet questions, and that implies the cooperation of groups in several institutions. Designing an ideal inlet for a particular application will require fluid

mechanical design work, wind-tunnel testing by aerosol physicists, and flight testing by the chemical users of the system. These larger efforts will take longer to implement, but will benefit from a broader viewpoint than may be possible in many of our individual programs.

One collaborative effort might be directed at characterizing the NCAR Electra. One reason is that this is the platform on which Huebert et al. (1990) noted losses that apparently included accumulation-mode particles. The Electra is to be used for studying aerosols in several major atmospheric chemistry experiments over the next few years. Another reason is that NASA and NOAA also have Electras or P-3's, so that results would be immediately applicable to other heavily-used research aircraft. The large payload and size of the Electra would enable numerous inlet experiments to be conducted simultaneously, while its range would allow access to most of the important tropospheric regions of interest. As the need for such an experiment becomes clearer, a working group should be established to define it and to prepare proposals for those agencies with an interest in atmospheric aerosols.

The Need for More Rapid Communication Among Investigators

We recognized a need for more rapid methods of communication for the results of individual experiments. Since it often takes a year or several to get data cleaned up and published, the aerosol measurement community does not become aware of experimental results until long after they could be used. Some mechanism, whether a newsletter, more frequent workshops, or an Omnet bulletin board, is needed to permit a more rapid dissemination of early conclusions to the rest of the airborne measurement community.

Working Group on Future Laboratory and Wind Tunnel Studies

This group discussed how the sampling characteristics of inlets could be evaluated in wind tunnels, how applicable the results from wind tunnel tests are to airborne conditions, and what facilities are available to perform such tests. There are a number of advantages in using wind tunnels to simulate flight conditions when evaluating instruments. The most obvious advantage is that a large number of tests may be conducted under a wide range of conditions in a relatively short period of time. Many hours of flight time, at a substantially higher cost per hour, would be required to accomplish the same objectives, often with less control over the experimental conditions in flight.

Visualizing Flow Fields

The flow around inlets should be studied in wind tunnels that attain aircraft velocities. Sophisticated measurement techniques are available for determining the structure of the flow around the inlet and for visualizing the trajectories of particles into and around the inlet tip. The structure of the flow inside the inlet is more difficult to measure, though. If an inlet

were fabricated with a transparent material, then flow visualization could also be used to define the internal flow structure. Miniature hot wire anemometers can be used to measure internal velocity profiles, but they probably cannot determine the angle of flow. Phased doppler velocimeters can remotely determine the velocity structure of the air directly at the inlet entrance. It was also suggested that water tunnels might be used to study diffuser flow if appropriate scaling were done to account for the different properties of water and air.

One problem with testing inlets stems from the difficulty of generating a well-characterized aerosol (in both shape and concentration) and of insuring that the particles are distributed uniformly and homogeneously throughout the air of interest. However, once reliable aerosol distributions are generated in the lab, particle losses (or enhancements) that result from particle bounce, deposition, or anisokinetic flow can be evaluated in a controlled environment. Sensitive flow visualization techniques can even record the trajectories of particles as they impact the inlet walls and either bounce away or adhere.

Transferability of Wind Tunnel Results

The primary concern when analyzing the results from wind tunnel studies is whether such results are transferable to the airborne environment. Two steps must be taken to provide a convincing argument for the applicability of wind tunnel evaluations. First of all, the most critical operating conditions (e.g. air speed, attack angle, temperature, pressure, humidity, and turbulence) expected in flight must also be producible and measurable in the wind tunnel. Second, the inlet under evaluation must be instrumented with sensors that measure critical internal flow and thermodynamic parameters under both wind tunnel and flight conditions. If the measurements made with the internal sensors are in agreement over the range of interesting wind tunnel and flight configurations, this will demonstrate the utility of wind tunnel measurements for simulating inlet behavior in flight.

Access to High-speed Wind Tunnels

There are many wind tunnels in operation internationally. These facilities are normally in great demand and their availability for aerosol inlet studies is uncertain. The capabilities of these tunnels vary widely, so the usefulness of each facility for aerosol inlet work will need to be established. Some of the better wind tunnels (which can duplicate aircraft speeds and environmental conditions at altitude) are owned and operated by government agencies whose regulations can be a major stumbling block for outside users. In general, these government facilities can only be used if someone in that facility has an interest in collaborating. University facilities can often be used at lower cost (or free, if a scientist within the university is involved in a collaborative effort), but they are generally far less capable of simulating airborne sampling conditions.

Summary and Conclusions

Wind tunnels must be an integral part of our multidisciplinary efforts to evaluate old inlets and develop new technologies. Present-day wind tunnel instrumentation is capable of measuring velocity profiles and particle trajectories to answer questions about the effects of anisokinetic flow, inlet shape, thermophoresis, particle and inlet charge, and relative humidity. A concerted effort should be made to identify facilities that are suitable for addressing the inlet performance questions raised in this workshop.

A parallel evaluation must be made to determine the most critical performance parameters that could be monitored (and with what transducers) in the wind tunnel and in flight. The recommendation of this group is that equal priority should be given to testing new designs and the inlets presently in use.

PART IV--CONCLUSIONS AND RECOMMENDATIONS

Summary of Working Group Findings

Our understanding of aerosol inlet science is changing rapidly. Although we have known for years that coarse-mode particles are undersampled, we have not had a clear idea of the flow regimes responsible for these losses. Recent evidence suggesting that some accumulation-mode particles may also be deposited in inlets has forced a reexamination of the conventional wisdom concerning inlet passing efficiencies. It is now clear that the body of (low-airspeed) literature on which we have relied to design airborne inlets may not adequately describe important characteristics of air-flow and particle trajectories at flight speeds.

Currently there is a dearth of data from inlets in flight which can be used to evaluate the significance of the many potentially-important factors identified below. Although wind-tunnel tests will be essential for isolating individual factors at minimum cost, some flight conditions cannot be adequately simulated in a wind tunnel, so both approaches must be used in concert. Airborne tests will also be needed to validate models which are formulated from wind-tunnel tests. This model validation will depend heavily on measurements of the particle deposition patterns within inlets after exposure in flight.

CONCLUSIONS: Our Present Understanding

- Although we have known for years that coarse-mode particles are undersampled, we do not have a clear idea of the flow regimes responsible for these losses.

- Recent evidence suggesting that some accumulation-mode particles may also be deposited in inlets has forced a reexamination of the conventional wisdom concerning inlet passing efficiencies.

- Different groups have very different opinions concerning the potential for inlet losses of accumulation-mode particles, because the existing observational base is inadequate to provide a definitive answer.

- Bringing air into an airborne inlet system inevitably causes dynamic heating, potentially modifying the size of aerosol populations.

- Inlet performance may be highly sensitive to both location and orientation on the airframe.

21

- Instantaneous flow angles may change dramatically on very short time scales, so that aligning inlets with the mean flow may still be inadequate to attain isoaxial sampling. Since neither atmospheric turbulence nor off-axis aircraft motions can be eliminated, inlets should be designed to reduce their sensitivity to nonaxial external flow.

- Many of the inlets presently in use have large expansion ratios which probably means that the flow is continuously or intermittently separated (and thus highly turbulent) at some points in the inlet.

- Shrouds have the potential to align streamlines along the diffuser axis before air enters a diffuser, thereby reducing the impact of instantaneous misalignment on aspiration efficiency.

- Double diffuser systems offer tremendous promise: they should reduce boundary-layer and edge effects while also reducing the area ratio in each diffuser, but their size-dependent efficiencies must be carefully modelled and characterized in wind-tunnels.

- Subisokinetic sampling could be beneficial for some situations: it might effectively preconcentrate large particles, thereby improving the S/N for OPC's, for instance.

- Very large and nonuniform electrical fields are sometimes measured on aircraft, and it is possible that they could interact with charged aerosols.

- It is likely that airflow in most existing inlets separates from the walls, generating turbulence and depositing some sizes of particles inside the inlet.

- Particles that strike the walls of an inlet may or may not adhere, depending upon the composition of the particle, composition and roughness of the wall, the presence or absence of a liquid layer on either the wall or the particle, the velocity and angle with which the particle strikes the wall, charges on the particle and the wall, and the temperature difference between the particle and the wall.

- In *no case* has the internal flow of a currently-used airborne inlet been adequately modelled or measured under airborne conditions.

- At present, there is insufficient airborne experimental data to validate any existing inlet models.

- Based on the wide range of conditions, instruments, size-ranges of interest, and scientific objectives, no single inlet could ever satisfy all needs for airborne aerosol sampling.

- The potential exists to characterize the size-dependence of inlet characteristics, so that OPC data can be corrected for losses or enhancements in each size-range.

- The primary concern when analyzing the results from wind tunnel studies is whether such results are transferable to the airborne environment, since it may be impossible to replicate the effects of aircraft motions and turbulence.

RECOMMENDATIONS: Approaches for Resolving Aerosol Inlet Questions

- Since understanding the sampling characteristics of airborne aerosol inlets requires modeling, laboratory, wind tunnel, and airborne studies, interdisciplinary cooperation will be essential for progress on inlet problems.

- Wherever possible, thermodynamic measurements should be made inside inlets to provide input for diffuser-flow models.

- The difficulty of scaling aerodynamic models down by orders of magnitude (from engine intakes to millimeter sizes) makes experimental validation of aerosol inlet designs and flow models extremely important.

- Experimental validation of inlet flow models is also essential because an inlets' inevitable tendency to sort aerosols by size must be well characterized.

- From a modeling standpoint, the inlet problem should be treated as three components: understanding the flow around the airborne platform; characterizing the flow and particle trajectories at the entrance to the inlet; and characterizing the flow, particle trajectories, and size and mass distributions inside the inlet.

- Modelers need experimentalists to provide them with extensive information on the physical parameters that constrain the problem.

- A well-defined airborne inlet problem should be posed to the modeling community to stimulate interest and to evaluate the capabilities of existing models: predict the behavior of particles and airflow at locations several inlet diameters in front of a sampler, directly at its entrance, and at several points within the sampler.

- Scaling issues need to be given serious attention, so that airborne aerosol inlet designers will know what parts of the existing inlet literature are applicable to flight conditions.

- Many more airborne field measurements are needed to define the extent of accumulation-mode aerosol losses.

- Since modeling and wind-tunnel experiments cannot replicate aircraft motions, atmospheric turbulence, and those other parameters which are unique to working on aircraft, their results must be compared to flight tests.

- Intercomparisons between aerosol samplers can be useful for identifying the extent of the inlet losses, if they are accompanied by careful tests of the precision of each system being compared.

- It is particularly important to develop and employ methods for examining aerosol deposits in inlets, since this approach has the potential to observe small percentage losses and to identify the specific sites of deposits for model validation.

- Whenever possible, several techniques for testing inlet performance in flight should be used simultaneously, both to make the most economical use of flight hours and to provide the best context for interpreting results.

- Incorporating pressure transducers or hot-wire anemometers at critical points (as defined by modelers) in functioning inlets may permit identification of the flow regimes responsible for aerosol deposition.

- Since many investigators already have plans for flight programs in which they will be studying atmospheric aerosols, inlet tests should be incorporated into these experiments relatively quickly and inexpensively.

- Some large collaborative interdisciplinary experiments are needed: one might be an effort directed at characterizing the NCAR Electra. (Accumulation-mode losses have been observed on this platform and it is similar to other heavily used sampling platforms).

- Some mechanism, whether a newsletter, more frequent workshops, or an Omnet bulletin board, is needed to permit a more rapid dissemination of early conclusions to the rest of the airborne measurement community. A common archive for results would be valuable.

- Wherever possible, wind tunnels should be used to test inlets. A large number of tests may be conducted under a wide range of conditions in a relatively short period of time, at less cost than doing the same number of tests on an aircraft.

- In wind tunnels, laser doppler velocimetry and sophisticated visualization techniques should be used to determine the structure of the flow around inlets and the trajectories of particles into and around inlet tips.

- A concerted effort should be made to identify high-speed wind tunnels that are suitable (and accessible) for addressing airborne aerosol inlet performance questions.

24

- A parallel evaluation must be made to determine the most critical performance parameters that could be monitored (and with what transducers) inside a diffuser in a wind tunnel and in flight, to establish the comparability of the two environments.

In spite of the potential for inlet artifacts, we feel it is important to continue to conduct airborne aerosol research, with an increased emphasis in each program on inlet characterization. We encourage proposers, reviewers, and program managers to include appropriate tests of inlet efficiency in all experiments for which their geophysical studies require a high degree of sampling efficiency. The alternative of stopping airborne aerosol research until "ideal" inlets are defined would eliminate nearly all of the opportunities for making improvements in these inlets. It is clear, however, that our proposals will now be expected to address the impact of inlet uncertainties on the conclusions which we can draw from our airborne geophysical studies.

PART V--APPENDICES

Appendix A--Agenda

Agenda
Airborne Aerosol Inlet Workshop
February 27, 28, and March 1
Boulderado Hotel
Boulder, Colorado

Workshop Overview

Darrel Baumgardner, Aviation Facility, ATD/NCAR

Workshop Objectives, Structure, Goals, and Documentation

Scientific Overview--The Role of Aerosols in Atmospheric Processes

Jake Hales, Battelle Northwest

Review of Airborne Aerosol Inlet Technology

James Vincent, University of Minnesota

Observational Studies from Aircraft

Moderator--Larry Radke, Research Aviation Facility, NCAR

"PASIN and PAIR--Airborne aerosol inlet passing efficiency measurements"
Barry Huebert, University of Rhode Island

"In-situ assessments of aircraft inlet performance using a laser optical particle counter"
Antony Clarke, University of Hawaii

"A summary of airborne filter intercomparisons in AES multi-aircraft air chemistry experiments"
Richard Leaitch, Atmospheric Environment Service, Canada

"Drying of hydrated aerosol by the de-iced airborne PMS ASASP/PCASP Probes"
Walter Strapp, Atmospheric Environment Service, Canada

"Aerosol sampling at 0.7 Mach aircraft speed"
R.F. Pueschel, G.V. Ferry, K.G. Snetsinger, NASA Ames Research Center

"Flow speed and particle trajectories around aircraft: Theory and measurements"
Cynthia Twohy and Diana Rogers, Research Aviation Facility, NCAR

Working Session I

Session Leader, Barry Huebert, University of Rhode Island
Suggested Topics:
   Summary of Presentations
   Discussion of similarities and differences between studies
   Lessons learned from these studies
   Missing Pieces and unanswered questions

Inlet Designs and Testing

Moderator, Richard Leaitch, Atmospheric Environment Service, Canada

"Recent research in aerosol sampling and transport at the University of Minnesota"
David Pui, University of Minnesota

"On the aerodynamic design of gas and aerosol samplers for aircraft"
Paul Soderman and W.H. Brune, NASA Ames Research Center

"Applications of principles of aerodynamics to inlet/diffuser design"
Russ Seebaugh, Denver Research Institute

"Computations of particle flows around simple inlets, wings, and fuselage"
Daniel Rader, A.S. Geller, and Steven Kempka, Sandia National Laboratories

"Overall efficiencies of inlets sampling at small angles of pitch or yaw"
Klaus Willeke, S. Hangal, and S. Kalatoor, University of Cincinnati

"Design and testing of inlets and aerosol transport systems"
Andrew McFarland, Texas A&M University

"Design and test of sampling inlets for airborne aerosol spectrometer"
Bernd Georgi, A. Kasenbrink, M. Below, B. Ilgen, University of Hannover

"Development of an isokinetic aerosol sampling aircraft inlet"
Chuck Wilson and M. Stolzenburg, University of Denver

"Using simultaneous radon gas and radon daughter measurements to evaluate submicron aerosol sampling efficiencies of airborne sampling systems"
Mark Kritz, State University of New York

"Proposed development and testing of insoluble particle collectors"
Michael Ram, University of New York at Buffalo

"Aircraft electrical charge: An aerosol inlet issue"
Lawrence Radke and James E. Dye, National Center for Atmospheric Research

Working Session II

Session Leader, Chuck Wilson, University of Denver
Summary of Presentations
How well can inlet dynamics be modeled?
How does flow distortion by the aircraft affect sampling?
Can sampling be affected by charging of the aircraft?
What other atmospheric properties may affect sampling efficiencies?
(e.g., temperature, pressure, humidity)
What are advantages and limitations of wind tunnels evaluations?

Session Summaries

Session moderators and leaders

Working Session III

Session Leader, Darrel Baumgardner, NCAR/ATD/RAF
Sub-Group I--Inlet Modeling Needs and Directions
Sub-Group II--Objectives for Aircraft Experiments
Sub-Group III--Future laboratory and wind tunnel studies

Appendix B--Attendees

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Table 2: Societal Importance of Atmospheric Aerosols

- Human Health
- Climate and Weather Effects
- Visibility
- Chemical Deposition and Ecological Response
- Atmospheric Chemistry and Pollution
- Nuclear Fallout
- Equipment and Process Reliability
- Economics

The measurement of aerosols, and the interpretation of their scientific and societal aspects, is difficult for a number of reasons. First--and in contrast to the counterpart situation involving specific trace gases--the characterization of aerosols in *multidimensional*, in the sense that aerosol properties are *distributed* over a number of variables. Most aerosols are composed of particles whose sizes vary over extended ranges in complex fashions; just as importantly, however, aerosol particles often are composed of internal mixtures of a host of chemical species, whose concentrations also are distributed. Moreover, one often is encountered by a variety of (often complex) particle morphologies, which also may be distributed in some fashion. This compound and distributed character of aerosols is a scientific encumbrance simply from a data-presentation standpoint. More importantly, however, the comprehensive measurement of aerosol features often implies a huge burden on the individuals and systems charged with the task. We have attempted to represent these features visually in Figure 1, which presents a distribution of particle size and composition for a hypothetical aerosol. Since representation of more than two chemical species is difficult on a perspective plot, we have indicated the dimensions corresponding to additional species by the multiple arrows on the primary composition axis.

[Figure 1]--Hypothetical Multidimensional Distribution of Aerosol Particle Size and Composition.

Appendix C--Extended Abstracts

Why Atmospheric Aerosols are Important
and
Why it's Important to Measure Them Well

By

Jeremy M. Hales

Jeremy M. Hales is currently Manager at the Atmospheric Sciences Department at Battelle Northwest in Richland, Washington. He is a chemical engineer, receiving his BS and MS from the University of Washington and his PhD from the University of Michigan. Currently, Dr. Hales' primary interests are centered on the measurement and modeling of pollutant removal processes.

The objectives of this overview are to summarize the scientific and societal significance of atmospheric aerosols, to demonstrate the importance of characterizing them accurately, and to indicate some of the difficulties in providing valid measurements of this type. As with practically everything else, aerosol measurements are, typically, much more difficult to perform onboard aircraft than on the ground, and so the group of people assembled at this workshop face an amplified challenge of an already difficult problem.

The attendees of this workshop are generally experts in the aerosol field, so we won't dwell at length on their scientific and societal importances here. We shall, rather, simply summarize several of aerosols' more prominent features in Tables 1 and 2 below. As can be noted from these tables, aerosols have a direct bearing on a wide spectrum of scientific and societal issues, ranging from human health impacts, to climate modification, to economics. Upon observing these lists, one reaches the inescapable conclusion that, individually and collectively, aerosols are significant determinants of our daily lives, and that their scientific understanding is correspondingly important.

Table 1: Scientific Importance of Atmospheric Aerosols

- Human Response
- Ecological Response
- Radiant Transport (Solar Attenuation, Visibility Reduction,...)
- Cloud Nucleation
- Cloud and Precipitation Chemistry
- Wet-Deposition Delivery
- Dry-Deposition Delivery
- Atmospheric Chemistry Processes
- Resuspension

A second complicating issue involves aerosol particles' generally dynamic character and their propensity to metamorphose during the sampling process. Aerosols are well known for their activity as condensation sites for ambient gases (especially water vapor). Moreover, particles such as ammonium nitrate have been demonstrated to volatilize to form gaseous constituents as dictated by thermodynamic driving forces. In addition, aerosol particles' propensity to agglomerate and fragment, especially during the sampling process, can be problematic.

Finally, aerosols display a number of physical properties (gravitational, inertial, electrical, and phoretic effects) which often bias and otherwise confound their sampling. Moreover, these physical properties are typically strongly size-dependent, often varying primarily as functions of particle number, surface area, mass, or optical characteristics. Because of this, it is easy to inadvertently ignore important features of aerosol size distributions as a result of biased sampling, or simply the manner in which the size distribution is represented. Figure 2 presents size-distribution spectra of the same aerosol in terms of number, area, and volume weighting as an illustration of this final point.

In the final analysis, it may be concluded that the issues being addressed by this workshop are important ones, which present some uncommonly difficult challenges for the atmospheric sciences. This workshop is a timely one, with the potential of significantly benefiting atmospheric research throughout the coming decade.
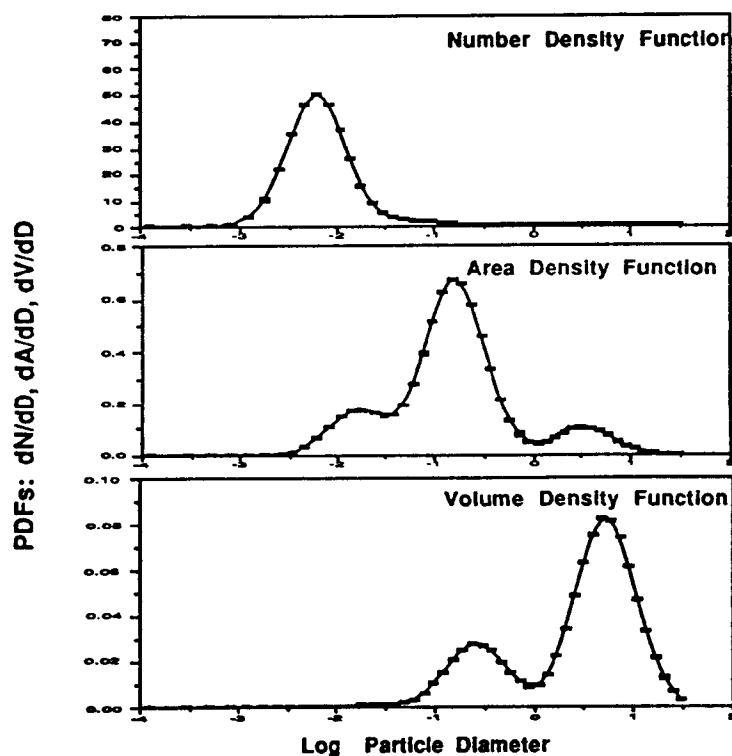
[**Figure 2**]--Representations of particle-Size Distribution for a Hypothetical Three-Mode Aerosol, in Terms of Number, Area, and Volume Characteristics.

37

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DISCUSSION:

Clarke: Regarding your plot of scavenging efficiency vs σ_g and mean diameter that you show for various spreads of distribution, have you compared that to any measurement program to see if the modeling results are in any way consistent?

Hales: Yes, if you look at historical measurements of precipitation scavenging of aerosol particles, basically what they do is release a tracer of some type of aerosol particle that is size distributed, put a bunch of buckets under it, collect the stuff that comes down in rain, and measure it chemically. Typically the size distribution of that aerosol spectrum has not been well characterized because it's tough to release things and measure them.

Secondly they only report averages, and if you look at the values of those types of experiments for doing anything practical, it's almost nil. Because you simply cannot go back and say, ok, what's the efficiency of precipitation scavenging on another distribution of particles that is different from the one you did use.

Georgi: According to the time resolution of the measurements, it would be much different if you were studying nucleation, if you were studying accumulation range, or if you were studying sedimentation. Which time resolution is required?

Hales: It depends how fast things are changing in time in your aerosol spectrum. That is really difficult because of the diversity of things. One thing I can comment on is that the world has been waiting for a real-time sulfate analyzer for a long time. Such an analyzer would be a real boom. There are a few real-time sulfate aerosol analyzers around, and the best one is at Brookhaven and Peter Daum could probably tell you more about it. They get alright results, but it is not perfect and very hard to use.

Radke: The arctic haze folks here were very interested to see a hot spot in the modeling results for Northern Greenland. Is this an artifact or are you really predicting that?

Hales: We are getting a fair amount of stuff going up there. The Europeans are contributing a fair amount as well. I think it may be a bit of an artifact of the wind fields supplied by the perpetual January CCM0. On the other hand, there is also a lot of map distortion. The longitude lines are spread too much.

Aerosol Sampling: A Review of Factors
Influencing Inlet Characteristics

By

James H. Vincent

James H. Vincent is Professor of Industrial Hygiene at the University of Minnesota, Editor-in-Chief of the Journal of Aerosol Science, and the current President of the British Occupational Hygiene Society. He is the author of "Aerosol Sampling: Science and Practice" (Wiley, 1989) and editor of "Ventilation '88" (Pergamon, 1989).

1. INTRODUCTION

Historically, the main justification for aerosol sampling--and hence, the greatest stimulus for research and development--has been the possible adverse effects of aerosol inhalation on human health. In recent years, criteria for health-related, particle size-selective sampling have been proposed and have given impetus to the development of new sampling instruments. This in turn has identified the need for more research into the scientific basis of the sampling process.

Meanwhile, other issues--including the need to "representatively" sample atmospheric aerosols for non-health-related reasons--are also important. In this paper, much of what is described was developed within the context of workplace and static sampling at ground level in ambient atmosphere. Here the aerodynamic conditions are very different from those pertaining to sampling from aircraft. The following should therefore be regarded as a broad basis and starting point for thinking about aerosol sampling under those more extreme and unusual conditions. All the points made are covered in greater detail by Vincent (1989). A small, but by no means exhaustive, selection of references is given in the test to indicate some milestones.

2. GENERAL SCIENTIFIC CONSIDERATIONS

The main scientific basis for aerosol sampling involves a combination of fluid and aerosol mechanical considerations. These overlap since aerosol mechanics is substantially concerned with the aerodynamic transport of particles. However, the distinction is drawn between the flow at relatively high Reynolds number (Re = $UD\sigma/n$, where U and D are the characteristic velocity and dimensional scale of the flow respectively and σ and n are the

respective air density and viscosity) in the vicinity of a macroscope sampling device and the flow at relatively small Reynolds number about a microscopic particle. For the former, the nature and shape of the streamline pattern (including identification of the positions of stagnation and separation) on the outside and the inside surfaces of the sampler body) are all-important. So, too, is the presence--or otherwise--of freestream turbulence. As far as the particles are concerned, their ability to respond to changes in air velocity and direction (both in the mean flow and in turbulence fluctuations), as well as the effects of external forces (e.g., gravitational, electrostatic) and diffusion, are also important. The design of sampling instruments should take proper account of such factors.

3.   INDICES OF SAMPLER PERFORMANCE

Most aerosol samplers operate on the principle of aspiration. That is, air and particles are drawn (usually by means of a pump) into the solid body of the sampling device itself through one or more orifices, and, thence, inside a sampler--to a sensing region (usually a filter where the particles may either be collected for subsequent assessment or detected directly.

Aspiration efficiency describes the basic efficiency with which airborne particles are transported aerodynamically from the aerosol outside a sampler and through the plane of the sampling orifice. This may be defined for most practical purposes by

$$A = N_s/N_o \tag{1}$$

where N_s is the number of particles per unit time passing through the plane of the sampling orifice and N_0 is the number originally contained within the sampled air volume. *Entry efficiency* is the modified (or apparent) aspiration efficiency

$$A_{app} = (N_s + N_r)/N_o \tag{2}$$

where N_r is the number of particles which enter after rebounding from the outer surface of the sampler (see below). Finally, *overall sampling efficiency* (or *effectiveness* is)

$$A_{overall} = (1 - L)(N_s + N_r)/N_o \tag{3}$$

where L is the fractional loss of particles between the sampling orifice and the filter (or sensing zone) by deposition on the internal walls.

4. BASIC STUDIES OF ASPIRATION EFFICIENCY

Most of the research which has been reported has been aimed at understanding the nature and quantitative behavior of aspiration efficiency. In many aerosol sampling applications, the air from which the aerosol is to be sampled is in motion relative to the sampler, with a finite wind ranging in velocity from as low as a few cm/s (as in many workplaces) to as high as several 10s m/s (as in the ambient atmosphere). In sampling from aircraft, effective wind speeds lie outside the top end of this range.

For moving air, the individual aerosol particles are usually considered to be "perfectly" suspended in the air, so that the effects of gravitational settling may be neglected. Now the dominant physical process governing transport is *inertia*, relating to the abilities (or otherwise) of particles to follow the streamlines of the distorted air flow near the sampler. The magnitude of the inertial forces is governed by particle aerodynamic diameter (d_{ae}, embodying particle geometrical size, shape, and density) as well as by the characteristic velocity (U) and dimensional scale (D) of the flow system as a whole. Combining these, we have the inertial parameter (Stokes's number) given by

$$St = d_{ae}^2 \; \tau^* \; U \; / \; 18 \; n \; D \qquad (4)$$

where τ^* is the density of water and n, as before, is the viscosity of the air. For very small St, particles follow the streamlines of the air flow near the sampler very closely, so that aspiration efficiency is close to unity (or 100 percent). However, for larger values of St, where particles are more likely to deviate from the air flow, aspiration efficiency can differ significantly form unity--being either larger of smaller depending on whether the particle population in the sampled air volume is enriches or depleted by the effects of inertia.

Aspiration efficiency is therefore seen to be a strong function of St. But it is also a function of the Reynolds numbers for the flow and for the particles (re and Re_p respectively), the *ratio between wind speed and the velocity* at which air enters through the plane of the sampling orifice (U/U_s), the ratio of sampler orifice size to sampler body size (δ/D), the sampler orientation (θ), and the sampler aerodynamic "bluntness" or "bluffness" (B). Thus, generally, we can state that

$$A = f \; [St, \; Re, \; Re_p, \; (U/U_s), \; (\delta/D), \; \theta, \; B] \qquad (5)$$

The history of aerosol sampling research shows that, with respect to moving air, by far the greatest effort has been devoted to *thin-walled*, tube-shaped probes. This has been driven by the need to be able to sample aerosols representatively (i.e., particles of all sizes with 100 percent efficiency) in well-defined moving air systems such as are found in stacks and ducts. This aspect is now quite well understood under "normal" terrestrial conditions, as indicated by the recent work by Vincent et al. (1986) which investigated the nature of the

41

air and particle flows near thin-walled probes at low wind speeds. The proposed a model for the performance of thin-walled probes of both small and large diameter for probe orientations from 0° (facing the wind) to 90°, and obtained good agreement with available data.

Blunt samplers cover the vast majority of devices used in practice (including the thin-walled probe as a limiting case), and this general case has been relatively neglected. Here the bluff presence of the body of the sampler complicates the flow picture to such an extent that theoretical models for the aerodynamics of particle transport, and hence for determining aspiration efficiency, are difficult to realize. Only for very simple blunt sampler configurations (e.g., two-dimensional or axisymmetric samplers with a single orifice facing into the wind) has substantial progress so far been possible (Vincent, 1987), although recent mathematical studies by Professor D. B. Inghan and his colleagues at the University of Leeds in England indicate promising signs for the future. In general, however, progress has been hampered greatly by the lack of sufficient reliable experimental data against which to test new theories.

Calm air sampling is a limiting case of considerable practical importance to some workplace situations. It refers to the case where particle motion in the vicinity of the sampler is dominated by gravitational settling (rather than the freestream as indicated above for the moving air case). However this scenario is unlikely to be of much significance in sampling from aircraft.

5. INTERFERING FACTORS

In recent years, attention has been drawn to a number of factors which may interfere with the aspiration process as described above.

In particular, freestream air turbulence might reasonably be expected to influence particle transport, since it is well-known that diffusive processes act generally to "smooth out" particle concentration gradients. Qualitatively, in relation to aerosol sampling, the effect of this would be a tendency to restore aspiration efficiency towards unity. The magnitude of the effect should depend on the effective coefficient of turbulent diffusion for the particles. This in turn may be shown to be related to the *intensity* of the turbulent air motions near the sampler (in effect the mean-square value of the velocity fluctuations) and their characteristic *length scale*, coupled with considerations of the particles' ability to respond to the velocity and directional changes associated with those motions. In experimental studies in wind tunnels, a clear effect of turbulence on aspiration efficiency has been demonstrated, appearing as a bias whose magnitude increases with particle size, turbulence intensity and turbulence length scale (Vincent et al. 1985).

6. WALL EFFECTS

It has been implicit in much of the research referred to above that aspiration efficiency is the dominating index of sampler performance. It would be convenient if that were true. But, as indicated earlier, there are other indices of performance involving contributions from interactions between particles and the sampler walls which, under certain practical conditions, might be more appropriate. Unfortunately, this renders matters even more complicated.

Wall interactions fall into two categories; those *outside* the sampler and those *inside*. For the former, the ideal case is that where particles arriving at the external surface of the sampler by impaction stick there and so are permanently removed from the flow. Here, $N_r=0$ in Equation (2), so that $A_{app} \equiv A$. In reality, however, this assumption might not hold, depending on the nature of the flow field near the sampling orifice and on the nature and size of the particles. Arriving particles might fail to adhere or be removed if either a) their velocity on impact and coefficient of restitution are such that "bounce" can occur, or b) the local air velocity in the boundary layer close to the sampler surface is great enough to cause the particle to be dragged free from adhesion forces and so be "blown-off." If particles thus freed find themselves in a part of the flow which is converging towards the sampling orifice, they will enter through the plane of the orifice and so appear to have been aspirated. Thus, N_r is not zero, and so we have $A_{app} > A$. Such oversampling is greatest for large, dry, gritty particles and for high sampling flow rates. A similar effect has also been observed for liquid droplets sampled using a thin-walled probe at high sampling flow rates, where the effect in question now involves the shattering of droplets as they collide at high velocity with the sampler wall. Evidence and physical explanation for these effects have been given by Vincent and Gibson (1981), Mark et al. (1982) and Lipatov et al. (1988).

Wall effects inside the sampler between the plane of the sampling orifice and the "sensing region" may be similarly large. Here, due to combinations of impaction, gravitational settling, electrostatic deposition, and molecular and turbulent diffusion, particles may be deposited on the internal walls and so be removed from the air before they are *actually* sampled. The properties of the development of the boundary layer on the inside surfaces and possible effects of the penetration of turbulence from the flow outside the sampler can play a significant role, as described by Okazaki et al. (1987a and b) and Wiener et al. (1988). Now L in Equation (3) is not zero, and the effect is for $A_{overall} > A_{app}$.

From the above remarks, it is seen that overall sampler performance is governed not only by the pure aspiration process but also by interactions which particles make with the walls of the sampler. Those associated with the external walls tend to increase the amount which is sampled, those associated with the internal walls to decrease it. The net effect on the overall sampling efficiency depends on the balance between the two. The complicated processes involved are not yet fully understood as far as practical samplers are concerned. But we do know enough to conclude that such wall effects should never be ignored.

7. CONCLUDING REMARKS

A summary has been presented of the factors which influence the performances of aerosol samplers in general, involving those concerned with "ideal" behavior (i.e., inertial-dominated pure aspiration from a smooth flow) as well as those factors which might be considered as interferences (e.g., freestream turbulence, electrostatic effects, external and internal wall effects). Some of these are more predominant than others for sampling under the "usual" terrestrial conditions such as found in workplaces or in the atmospheric boundary layer close to ground level. For more extreme conditions, such as those found during sampling from aircraft, the balance between such processes--both outside and inside the sampler, and particularly how these regimes are coupled--is likely to change in very interesting ways. This is an area which has so far received very little attention from workers in the field of aerosol sampling, and so knowledge is scant. Understanding such processes is therefore a most promising area for further research.

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DISCUSSION

Daum: Is the fraction of rebound particles a function of particle size?

Vincent: Yes, it is a function of particle size; however, it depends on the nature of the rebound. We are not sure if it is actually rebounding because it's bouncing, and if it is bouncing, then is it a function of particle size and of the coefficient of restitution for the particular material. In some cases, they may well be bouncing when high velocities at impact are involved.

      Another situation at lower velocities may well be a kind of blow-off impact. After a particle has come into contact with the surface, the adhesion force is not high enough to retain it there against the drag force if you try to remove it. If that's the case, the coefficient of restitution doesn't come into force. What does come into it is the size of the particle because that defines the amount of drag.

      Also, the shape of the particle or dimension of the particle which is actually in contact with the surface is important. If the particle is very granular or gritty then the radius of surface contact may be very small. In that case the forces holding the particle are not associated with the particle radius as such.

Daum: What about submicron particles? ($.3\mu$m)

Vincent: It depends on how fast it's arriving. When the submicron particle is so low in the boundary layer that the drag force might be in the laminar sub-layer, the drag forces might not be that significant. But if the submicron particle is arriving with enough velocity (100 m/s), you have to look at the conditions of the bounce. It's quite possible that it will have significant bounce.

Ram: Does your model equally take into account liquid and solid particles or is it for solid particles?

Vincent: The model for aspiration efficiency is general.

Radke: Please describe the experiments that you did with the effects of charging of the aerosol and the inlets.

Vincent: The experiments were within the context of an industrial hygiene project, so they don't readily provide data of a sort that can be theorized. Essentially what we did is we developed an experimental situation where we applied a potential to a sampler, mounted on the torso of a mannequin simulating someone wearing a personal sampler. We knew that the aerosol was charged. In every workplace we have ever been to, we have measured aerosol charge distributions and have found them to be significantly above Boltzmann equilibrium. The other factor is that they are equally distributed between positive and negative. We found for this type of aerosol, where there is no net charge but a high magnitude of charge, regardless of the polarity of the sampler, the effect was always to reduce the amount of aerosol aspiration.

Radke: What sort of charges were you putting on your mannequin? Aircraft charges can be quite large.

Vincent: Equivalent of up to 10 Kv.

Willeke: You commented that you're curious to see to what extent the work that you have done at lower velocity can be applied to higher velocity. I wonder to what extent do you feel impaction is important inside the inlet, in view of the fact that when you fly at high speeds you cannot maintain total isometric position? You will always have particles that get pushed to the inside against the wall. What is your feeling as to the importance of that effect compared to other things that you have mentioned.

46

Vincent: A higher velocity at impaction is always going to be increased in relative importance, because the many other factors that can add to the confusion--electrostatic, freestream turbulence, or gravitational factors. The magnitude and effect depend on how long the particle has to undergo this. At higher velocity, the time scale is much reduced. On the other hand, the inertial factor is much increased. You would expect impaction to go up with higher velocity and the other factors to go down.

Sheridan: Have you modeled the flow stream lines for particles entering an inlet of a user cone geometry? That is the type of inlet that is common on aircraft.

Vincent: No.

Kritz: When you start sampling on faster moving planes, the ram heating becomes important so that the temperature at the filter plane (e.g., on the ER-2) can be about 20°C higher than in freestream. When you're dealing with something like sulfates (sulfuric acid droplets), there is always a possibility that evaporation can occur to some degree. Perhaps the filter recaptures some of that vapor. Have you ever gotten into that question in a quantitative way?

Vincent: I don't know how to model it. We do have people who study aerosol dynamics--that is their specialty. Perhaps there are people who are here with that specialty. If not, perhaps they should be. Does David Pui know any thing about this? You've looked at condensation/evaporation during sampling at high velocity and subsequent temperature effects.

Pui: Recently we have done work dealing with process equipment in the micro electronic industry. Over there they evacuate the chamber and pressurize the chamber, and we get the particles during this vacuum pump compressing. There are models to describe this, but I don't know how valid that would be to aircraft sampling.

Deshler: You showed some experimental evidence for the difference between actual and the rebound of particles with the blunt inlet. Do you have anything for thin-walled sampling tubes?

Vincent: There are two or three very good papers in the *Journal of Aerosol Science* which describe expandable data, but it is very limiting. Thin-walled probes illustrate the effect very well.

Ram: What techniques do you use to measure the charge distribution of aerosol?

Vincent: My colleagues and I have developed a spectrometer where you vary the voltage between the potential difference between the plates, measure the penetration of particles of defined size (in this case it was an optical dimension), and then you have a falling curve--voltage versus penetration. From tangents to that curve, you can derive the electrical mobilities of the particles of that particular size.   That select curve defines the charge distribution of a particle that size.

PASIN and PAIR--Airborne Aerosol Inlet
Passing Efficiency Measurements

By

Barry Huebert

Barry J. Huebert is currently a Professor of Oceanography at the Center for Atmospheric Chemistry Studies in the Graduate School of Oceanography, University of Rhode Island. He received his BA in chemistry from Occidental College and his PhD in physical chemistry from Northwestern University. He is the Convenor of the Marine Aerosol and Gas Exchange: Atmospheric Chemistry and Climate (MAGE) committee of the International Global Atmospheric Chemistry Program and a member of the Commission on Atmospheric Chemistry and Global Pollution. His primary research interests include nitric acid vapor and its removal from the atmosphere; colorful ties; airborne sampling of aerosols, gases, and cloud water; and the development of experimental strategies for measuring fluxes and reaction rates in the marine boundary layer.

Although numerous investigators have studied the aspiration and passing efficiencies of aerosol inlet probes, few have done so under the high airspeed conditions typical of airborne sampling. We have evaluated the aerosol passing efficiency of a variety of inlet systems during for experiments on NCAR aircraft.

DYCOMS

During the Dycoms program, we found discrepancies between concentrations in cloudwater and the air below cloud, which we attribute to curved-inlet aerosol losses.

Dycoms (Lenschow et al. 1988) took place in the summer of 1985, in the stratocumulus-capped marine boundary layer west of San Diego. We collected liquid cloudwater at several levels with modified Mohnen slotted rods (Huebert et al. 1988). Aerosols were measured below the cloud using a 1.75" i.d. curved inlet tube. In the absence of precipitation in the stratocumulus-capped marine boundary layer, there is no reason to expect that soluble species such as nitrate, sulfate, and sodium should change concentrations with altitude, even though they might change phase by dissolving in cloudwater as an air parcel rises, cools, and condenses water to form a cloud.

We divided out observed in-cloud concentrations by the below-cloud concentrations to calculate apparent enrichments for total nitrate, sulfate, and sodium. These in/below cloud ratios should be close to one, if soluble material is conserved in the stratocumulus-capped marine boundary later (as total water and ozone usually were). However, the apparent

49

enrichments were all much greater than one. Sulfate and nitrate appeared to be enriched by factors of 3 to 4, while sodium was enriched by a factor of ten or more! The enrichments were so large that our estimated uncertainties could not begin to explain them.

One of the few possible explanations for this apparent enrichment is that we had severely underestimated the below-cloud aerosol concentrations, due to losses in our sampling system. The fact that (large particle) sodium had the greatest apparent enrichment points to inertial inlet losses as a strong possibility. Since our inlet Reynolds numbers were large enough (4,000 to 5,000) that turbulence in the intake tube was likely, it is conceivable that the vast majority of the ambient aerosols were being deposited in the intake tube, causing the filters to severely underestimate ambient concentrations.

FIRE

In the Fire program, flown west of San Diego on NCAR's Electra in 1987, a curved inlet passed significantly less material than a straight one.

We used the same curved intake filter sampler as on Dycoms but added an external sampler (just a diffuser cone with the filter pack immediately behind it, all outside the fuselage) with no curved tubes ahead of the filters. Both filter samplers were mounted side by side on the left forwardmost window plate of the Electra. We built a nozzle-tip capping system to serve as a forward valve on the external sampler, to shield the cleaned sampler from contamination.

We defined the passing efficiency of the curved intake relative to the external sampler to be the ratio of analyte found on the curved-intake's filter to that found on the external sampler's filter. All of these relative aerosol passing efficiencies were less than one. They ranged from 0.43 for sodium to 0.62 for total sulfate and 0.88 for ammonium, as compared to 1.08 for nitric acid vapor. It is instructive to note that the relative passing efficiencies increase as the particle size decreases. This pointed to inertial processes as a probable cause of the observed losses in the curved tube.

PASIN

In the Particulate Matter Airborne Sampling Inlet Experiment (Pasin) (Huebert et al. 1990), we analyzed the material deposited within one inlet tube after each flight, and added it to that collected on its filter to establish an efficiency reference. Six different inlets were used simultaneously with six filter samplers, to evaluate the effects of tube diameter, radius of curvature, and surface coating. Details can be found in Huebert et al. 1990. The Pasin filters collected different amounts of material when they should have been sampling the same aerosol. Extraction of the 1″ metal reference tube routinely showed that 50 to 90 percent of the aerosol material had been deposited in the tube.

Pairs of samplers were located on the forwardmost right windowplate, the forwardmost right windowplate, the forwardmost plate atop the fuselage (between two pylons), and the third

window back on the left side. All of the nozzles were identical in size and shape, with a 5.3 mm diameter opening and a relatively sharp edge. Each intake started with a diffuser, or expansion cone, which graduated the internal diameter from the 5.3 mm at the tip to the internal diameter of the tube.

The included angles of the diffusers were all 7°. All nozzle tips were mounted 30 cm from the fuselage, with the central axis of the nozzle parallel to the axis of the airframe. The following abbreviations identified the six inlets: EXT was the straight-in external sampler, 4"MET was a 4" metal intake, 2"MET was a 2" metal intake, 1"MET was the extractable 1" metal reference intake, 2"SMR referred to a 2" small-radius intake, and 2"TEF was a teflon-coated 2" intake.

The average continental and marine passing efficiencies for each analyte in each inlet are shown in Figure 1. In the MBL samples, we used sodium concentrations to estimate non-sea-salt (NSS) sulfate efficiencies. Since much of the NSS sulfate will reside in submicron aerosols, it offers a size-contrast to the supermicron marine sodium results. The most striking aspect of Figure 1 is that no aerosol passing efficiency ever averaged as high as 60 percent, even for the small NSS sulfate particles. Most efficiencies are 50 percent or less, suggesting large losses in inlet lines. It is also apparent that the passing efficiency for (submicron) NSS sulfate is greater than that for (supermicron) sodium in very inlet tested, which again implicates inertial loss mechanisms.
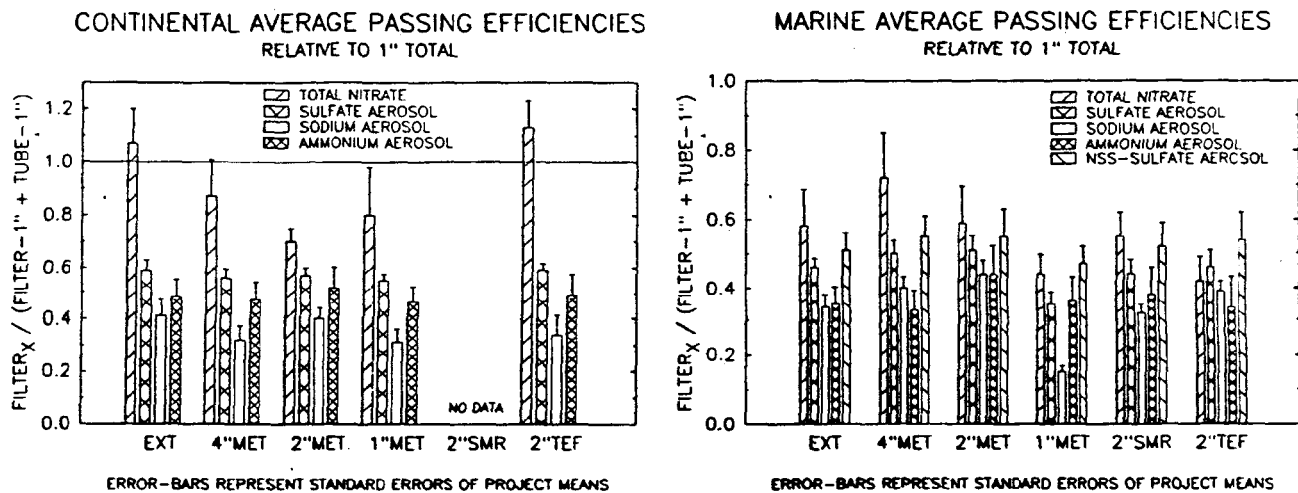
[Figure 1]--Pasin average passing efficiencies for continental and marine samples.

We compared two adjacent, symmetrically-mounted 2" aluminum intakes, which differed only in that one was teflon coated. For nitrate, ammonium, and NSS sulfate, the teflon coating

51

had no effect, suggesting that electrostatic effects on teflon lines are not a major concern. The sodium results, however, were significantly different form unity, implying that losses in the 15 percent range might be caused by charging on the teflon tube walls.

The Pasin results may be able to explain the discrepancies noted on the Dycoms program. If the Dycoms intake had passed only about 10 percent of the sodium aerosol, it would have caused an apparent factor of 10 enrichment for sodium. Likewise, a passing efficiency of 25 percent to 30 percent for sulfate and nitrate would cause those apparent enrichments. The 2"TEF intake on Pasin had measured efficiencies two or three times higher than these, but it also had a slightly different construction. They Dycoms intake had a solid teflon tube inserted as a liner, and some rippling of that surface was evident. With a Reynolds number near 4,000 in both cases, the rippling could have made the Dycoms flow much more turbulent. We certainly saw in Pasin that efficiencies of 10 to 30 percent are possible in relatively common intake configurations.

The Fire results had clearly demonstrated that curved tubes lead to deposition in the intake, but they had given us no indication that the external intake was also causing large losses. This points out a potential weakness of simple intercomparison experiments. Before Pasin, we had no reference against which to evaluate the absolute efficiencies.

PAIR

In the PAIR program, flown on NCAR's King Air in October of 1990, we compared two nearly-identical side-by-side inlets to evaluate the effects of nozzle lip-shape and isoaxiality. Both inlets were extracted after each sample to compute their efficiencies directly. Pitostatic ports around each tip allowed us to align one inlet along the mean streamlines in flight, to test for alignment-related losses.

We found that alignment errors of less than 5° had little or no impact on the efficiencies, even for the sharp-edged tip. We noted no difference between efficiencies of curved-leading-edge (blunt) and sharp-leading-edge diffuser tips. In all flights at 75 m/s, the sodium passing efficiency was within a few percent of 29 percent, while that for NSS averaged 94 percent. At 90 m/s airspeed, though, the NSS efficiency ranged from 66 to 95 percent. Thus, the higher airspeeds on the Electra (100 m/s) may be partly responsible for the still-lower NSS efficiencies observed on Pasin.

For most of the Pair flights, both inlets were mounted side-by-side midway back on the top of the fuselage. However, when one of the intakes was placed in the forwardmost location atop the King Air, its efficiency dropped to 10 percent for sodium and 79 percent for NSS at 90 m/s. It is likely that flow off the windshield at this point is far from parallel with the aircraft axis, and that this large misalignment caused the efficiency drop. This emphasizes the importance of selecting the optimum location for mounting aerosol intakes.

CONCLUSIONS

It appears that deposition just inside the tip of an inlet may be responsible for the removal of as much as half of the ambient aerosols that enter it. Very high turbulence is expected there, both because of the necessity to match high airspeeds (which makes for very large initial Reynolds numbers) and because of the potential for flow separation when using long diffuser cones.

It is clear that future intakes should be oriented parallel to the average streamlines at their mounting position, rather than parallel to the aircraft axis, as has been common practice in the past. Either modelling or measurements will be needed to establish the position of those streamlines before the sampler drawings ever leave the designers' office. Of course, this still cannot ensure isoaxial flow, since atmospheric convection and turbulence will continually change the airflow vector by several degrees, and the changing fuel load causes most aircraft to alter their pitch during flight. A forgiving inlet lip shape seems to be essential

Turbulent particle deposition in bends must be responsible for the especially low passing efficiency of the 1" intake for sodium-containing aerosols. The bend clearly increases the loss of large particles.

We are still at a loss to explain why the passing efficiencies are also low for accumulation-mode aerosols under some conditions. The literature on inertial and turbulent deposition mechanisms suggest that particles with small Stokes's numbers should not be impacted in our intakes at a measurable rate, yet none of our intakes on Pasin had an efficiency above 50 percent, even for non-sea-salt sulfate. On Pair we did get unit efficiency for NSS at low airspeeds, but it dropped in many cases at airspeeds that approach those of the Electra.

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DISCUSSION

Radke: (Comment on variability) The coarse mode sea salt aerosol is strongly dependant on the wind speed over the water. The largest sea salt particle that you get can certainly vary from day to day and the mass distribution is, of course, dependant on the largest particle that you can loft. That may not explain the whole thing, because you may have data that shows the same thing for non sea salt particles.

Daum: During PASIN, did you run a blank on that tube?

Huebert: Yes, repeatedly.

Daum: By a blank I mean, did you prepare the tube, fly it, never open it, then come back and wash it out, or did you just wash it out on the ground?

Huebert: We washed it out on the ground. We mounted it on the aircraft. We left it for a day and then took it off. We did not fly it. It is simply too expensive to fly it without taking a sample, so we didn't take that kind of a field blank.

Georgi: Did you get any ASASP size distribution measurements during this flight? What size were the particles?

Huebert: I have a lot of concern about optical size distribution measurements based on this sort of thing. We did look at ASASP and FSSP data and concluded that there were not dramatic differences from day to day. All of this marine data was collected in the vicinity of Hawaii.

Radke: Air speed? Angle of attack? Gross weight?

Huebert: Those are all things that we tried to elevate as controlling factors.

Ram: Temperature?

Huebert: We have looked to some extent at all of those factors and have not found that any one of those can explain the flight-to-flight differences that occurred.

Hales: How do you distinguish between sea salt sulfate and non-sea salt sulfate?

Huebert: In this case, I used sodium concentrations and the ratio of sodium to sulfate in sea water to make that correction. If your point is that the ratio of sodium to sea salt sulfate is not always well-known, I agree with that.

54

Wilson: On PAIR the total misalignment was 4° from the streamline?

Huebert: Yes, 4 or 5°.

Ram: You had a very limited range to work with and within that range were your sensors isoaxial? Did they tell you that it was aligned or could you have still made some changes in the isoaxiality?

Huebert: No, we were able to align it so that we got an average Δp across those that was quite small. We might have had 20 to 40 mm of mercury pressure difference for the fixed one which was off by 3°. We would get that down so that it was bouncing around within a mm or so on either side of 0 of the one optimumly aligned. It made me feel that we were able to do a good job of getting it aligned with the *average* streamline.

Willeke: Do you know what size the particles are that you collected?

Huebert: That's the second thing about this program. Due to a software error, we have no data from the Knollenberg ASASP probe. We are intending to re-fly it. The interpretation of all of the data is going to be greatly impaired because we lost all of that optical size distribution data and thus cannot confidently compare different flights; their aerosol populations may have differed.

Daum: How do you reconcile the differences between your Electra data sets and your later data sets? What's the bottom line?

Huebert: The way I see the bottom line is that regardless of which aircraft you're on, regardless of which air speed, you've got a real problem with coarse mode particles.

             For the accumulation mode particles, I think that at least at Electra air speeds, there is some significant problem with sampling at those air speeds. Regardless of which intake we used on the PASIN program at 200 kts air speed, we were unable to get more non-sea salt sulfate on the filters than there was in the intake.

Daum: There is a substantial difference in the sulfate concentration mixing ratio that you observed in the program--The Electra program versus the later program.

             What were the absolute concentrations in the Electra program for sulfate and other species?

Huebert: I don't remember those numbers. We have that data, and I can get that. They weren't terribly small concentrations. We didn't have a problem with sensitivity.

Daum: The assumption that a lot of people make in this business is that the sea salt sulfate and the non-sea salt sulfate are really in two separate size ranges. If you've got air that has been processed in a cloud for a while, you really feel that that is true. You may have some of your non-sea salt sulfate associated with sea salt, and it could be variable on day-to-day basis depending on how much processing is going on. Maybe that's the source of your difficulty of being able to reconcile that data. Maybe there are other factors that you're not taking into account by your analysis.

Huebert: It is certainly the case that cloud processing can deposit non-sea salt sulfate on relatively large particles. However, in precisely the region where we flew the PASIN program, we went out last February on a Soviet ship, the Akademik Korolev, and did very careful size distribution measurements with a micro-orifice uniform deposit impactor. We found the non-sea salt sulfate is in the accumulation mode aerosols. Virtually none, 5 or 10 percent maximum on ship board measurements in the equatorial Pacific was in the coarse mode. If you were going to find it on large particles, you would expect to find more of that at ship level than you would at 50 meters where the Electra was flying.

             For the PAIR program, we have done similar measurements in Rhode Island, and we simply don't find much non-sea salt sulfate on large particles. There is a conventional wisdom that it is in the accumulation mode, and in these marine areas that seems largely to be correct.

Georgi: I think you have to be very careful that you are mixing ground things and high altitude. What you are doing is measuring factors. The factors are varying between 50 percent and 30 percent. I think it is difficult to measure if you have not all complete data which are really compared. Otherwise it is difficult for the mathematics (statistics).

Huebert: You are making a very important point which, if I can extend to another point off of what you have mentioned, that these effects may be dramatically different at different altitudes with different aerosol populations.

             I specifically did both of these programs in the marine boundary layer. Both because that's where I found the problem initially and where I want to be able

to sample to study DMS and sulfate production from DMS, and because I expected the concentrations to be higher there. In order to do something like this and get a reasonable signal to noise ratio in the free troposphere, you are going to have to fly for hours and hours and still get huge error bars.

One of the reasons I did it in the marine boundary layer was to minimize problems with sensitivity. One of the results of that is that most of these aerosols are wetted. Mineral aerosol which may not be wetted may not tend to stick nearly as much. The morphology of a particle may have a lot to do whether it chooses to stick on a surface. Wetted sea salt aerosol and non-sea salt sulfate may have the greatest possible chance of sticking to the inside of inlets, so there could be a lot of things like mineral aerosols for which you don't have nearly as serious a problem because if they hit the inside of the inlet, they may very well bounce off and continue downstream to the filter.

Radke: Of course in the boundary layer all the sulfate aerosols are going to be wetted.

Georgi: I think it is difficult to compare if you have similar aircraft at different speeds--a large one and a little one.

Huebert: One thing I might mention with regard to the King Air measurements at 180 kts. We still don't have the finished data set to look all of the factors that might be important. There are a lot of factors besides the ASASP data. There is much that we can do with this.

Simply on the basis on how lousy the observers felt when they got back, it seemed like the more turbulent flights, the ones where we were really being beat around (and in a King Air at 180 kts you can get beat around a lot), were the ones where the efficiency was lowest. The ones where there was very little turbulence were the ones where the efficiency was highest at 180 kts. It made me wonder if something related to changes in the attitude of the aircraft or some factor like that might be the factor that its really important to get our hands on.

Kritz: That's turbulence and air speed. It's the bouncing around that makes the difference, not just simply that it is a general rule you bounce more.

Huebert: You understand that this is a very subjective measure.

Radke: While the erp factor is a tough one to quantify. During the FIRE project and your previous marine stratocumulus experiment, the Electra, of course, gives

a pretty smooth ride. You can't reach too far with that conclusion. The question is--is the change in the attitude of the airplane which is large on the King Air important or is it the turbulence itself which affects streamlines important?

Georgi: I think it is consistent of how fast planes fly. We discovered on Greenland because the problem there was a frozen auto pilot, and we had to do everything manually. You could see it directly on the optical particle counter which variations we get.

Soderman: Do you know your diffuser expansion angle?

Huebert: The included angle was 7°. The trade off you have here is the larger the angle on the diffuser the greater the tendency for flow separation. The smaller the angle, the greater the problem you have with aeronautical engineers at RAF such as Norm Zrubek who doesn't want to have to worry about the wobble of something that is sticking way the heck out in front. If you have a smaller angle, that means the whole diffuser has to be much longer. We used a 7° included angle, but it would be worth checking the smaller ones.

Seebaugh: When you analyzed the filters, were you able to see if there was a different concentration of particles in areas separated from the centerline?

Huebert: We didn't. We extracted them whole, but that's a very good point.

Seebaugh: I would suspect you have fully separated flow.

Huebert: It could very well be.

Daum: We have used quite a large filter. Actually 5" in diameter. We have done tests where we analyze for sulfate in all four quadrants.

Hales: My expectation is that a continual loss would occur if the angle were as large as 20°. I'd be real surprised if those misaligned inlets weren't acting pretty much like a whistle and that would really mess your sample. If that were the case, and you were experiencing a great deal of turbulence, I can see a situation whether you're on the Electra or the King Air it wouldn't make much difference. You would be momentarily experiencing some pretty weird angles on your probe.

Huebert: It's possible. The amount of noise on the aircraft prevents us from detecting that.

58

Rader: I had two ideas. Would it be possible to put a particle counter inside the aircraft, take the filters out, work up the size distribution inside, and compare that with your external probe. Also, is there any probe that you can put near the inlet that would give you some high-speed response time to give you an idea of how the local velocity and angle of attack is varying. The Rosemount 858 probe may capture it. You can only vary your inlet by 4 or 5°. I've been on aircraft I know where it seemed like you were going mostly straight down, so I'm wondering could you somehow try to evaluate rapid changes in altitude?

Huebert: Those are two very excellent points. On the PASIN program, we have tried to have an ASASP inside the aircraft collecting air from just ahead of the filter. I think you still need to have the filter there so that the dynamic environment inside the diffuser is the same as it would be when sampling with a filter. We tried to sample with an ASASP directly ahead of the filter. The idea was that at that point the airspeed is down to 1 m/s and so presumably you ought to pull material into the ASASP without sampling artifacts, which could be important outside the aircraft. We couldn't get the flow to go the right direction. I'm not exactly sure why that was, but we had some difficulty with the pump inside the ASASP, and we wound up abandoning that project.

That's one that I would like to do. I think there's a way to get around the potential for sampling artifacts with an ASASP and that is to have two samplers side by side as we did on this program and sample immediately ahead of the filters on both of them. With both of them, you are sampling at a pretty low air speed, so artifacts relative to getting material into the ASASP ought to be minimized. Then you can look at the effective angle.

Wilson: (Directed to Rader) We run that experiment repeatedly at Mach 0.7, 50 mb. We have some very interesting results from an FSSP and a PCAS on an ER-2, and we compared them extensively. The reason that this is not an easy thing to do is as follows:

The thermodynamics of the sampling heating which are severe at Mach 0.7 with 20°K heating will not be absent from the boundary layer because of the humidity in the boundary layer. Mark Stolzenburg has calculated, inventing by the way in the process--transition regime/heat transfer in order to do it, a couple heat and mass transfer so that we can evaluate what happens to

sulfuric acid and water particles in the .2 sec that we have between the inlets and the instrument and in the .01 sec of extreme heating we have we take that into account and yet we were unable to reconstruct size distribution which work except in some cases. So the inside versus outside aerosol optical instruments have the comparison will involve more than just a sampler machine.

The second thing I would point out and that's the questions I would like to ask you, In these $7°$ allegedly safe diffusers, can we anticipate that the particles are going to, in fact, follow the streamline? We pick off our samples from the center streamline of the diffuser, and we allege that the concentration that we haven't had any inertial separation in the diffuser when we do that. From our experience, the comparison of the inside and outside instruments, while very interesting, will raise more questions than it will answer unless we first attack some of these; such as, what in fact is the flow trajectory in our diffuser and what in fact are the particle trajectories, and the thermodynamics, we calculate sulfuric acid in water supercooled in the stratosphere because we felt we had the thermodynamics. To get that in a real aerosol and ask people what the vapor pressures are, these calculations are out of the question because the thermodynamics are not known. I don't know if one would attempt to try to compute evaporation of the multi component aerosol. Because each component brings you a degree of freedom and complexity. Evaporation of these multi-component hydrated aerosol will be very difficult to model.

Huebert: There is another point you've raised which is that of trying to get a more instantaneous measurement of the attack angle. I think that is very important for us to try to do.

Radke: Let's next time put some transducers on the nozzle.

Huebert: It's not a trivial matter to do this, because transducers are that kind of size and you want to get them as close as possible to where you're measuring the pressures so that you get a fast response, but at the same time, maintain the same flow regime that you would have, which you can't do with these clunky things right out there. I think that's a very important thing for us to address. Incidentally, structurally from the standpoint of this workshop, a lot of the discussion we are having now and what could we do in the future to improve this is what we want to continue in the working groups.

Clarke: I'd just like to say one more thing, the next talk which I'll be giving in reference to this particular air comparison of internal particle size instrument and the external probe both of Darrel's and Rudy Pueschel's on the Electra and the DC-8 and the issues of relative humidity will be discussed in context with that comparison, so stay tuned.

Aircraft Studies of Size-Dependent Aerosol Sampling Through Inlets

By

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INTRODUCTION

Aerosol are known to play a important role in a variety of atmospheric processes including biogeochemical cycles (Galloway et al. 1985, Huebert et al. 1990a), cloud physical processes (Takahashi, 1981) (Charlson, 1987) (Albrecht, 1989), and atmospheric radiative transfer (Coakley and Cess, 1985). Aircraft measurements are often essential for obtaining vertical and horizontal aerosol information. Despite their importance, the quality of aerosol measurements from aircraft remains a point of concern (Huebert et al. 1990b).

In this paper we will examine aircraft aerosol measurements made by an optical particle counter (OPC) using an aspirated sampling system. Characterization of the aspirated inlet system and comparison of resulting data with a wing mounted forward scattering spectrometer probe (FSSP) will be described. The aerosol measurements discussed here occurred during the 1989-1990 Global Backscatter Experiment (GLOBE) (November 1989 and March 1990) aboard the NASA DC-8 and the 1989 Central Pacific Atmospheric Chemistry Experiment (CPACE) (March 1989) aboard the NCAR ELECTRA. GLOBE typically occurred at 8-12 km altitude over the Pacific Ocean and included flights between California, Hawaii, Samoa, Tahiti, New Zealand, Australia, Japan and Alaska. CPACE took place in the vicinity of the Hawaiian islands and included more than 50 hours flown in the marine boundary layer.

SAMPLING SYSTEM

The main goal of our participation in these aircraft experiments was to examine the spatial variability of aerosol physicochemical properties. Our OPC (PMS LAS-X) was modified to size aerosol into 256 diameters ranging from 0.16 to 7.7 microns and was calibrated using

latex spheres and a differential mobility analyzer for various aerosol compositions (e.g., sodium chloride, sulfuric acid, ammonium sulfate) (Clarke, 1990). By heating the aerosol to various temperatures, we were able to obtain near real-time information on aerosol size and inferred composition (i.e., sulfuric acid, ammonium sulfate, dust and salt) (Clarke et al. 1987). The fast response of this method is particularly valuable for regions of low aerosol concentrations such as the remote troposphere (Clarke and Porter, 1990).

During both experiments, the sampled air entered a thick wall diffuser (after Andreae et al. 1988) with a diffusing half angle of 6.5 degrees (Figure 1a). The diffuser tip had a parabolic curve on the outside with an inner edge radiused at 0.025 cm. This rounded edge effectively increased the opening of the diffuser from 0.513 to 0.572 cm. Blunt diffusers with parabolic leading edges originated from aircraft studies (Kuchemann and Weber, 1953) which showed that this shape induced less turbulence in aircraft engine intakes.
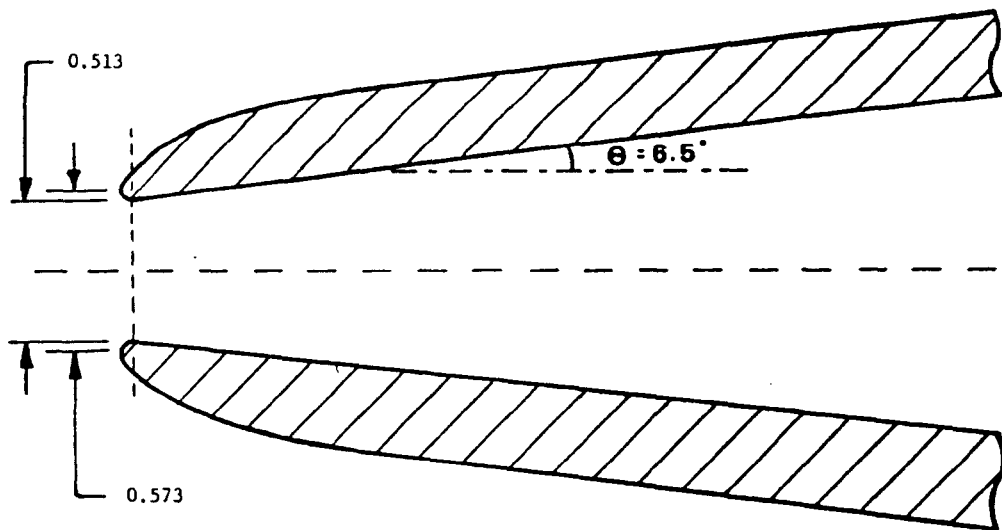
[**Figure 1a**]--The use of blunt diffusers, such as this one used during GLOBE and CPACE, have been shown to reduce flow separation in jet intakes.

Following the inlet diffuser, the air stream entered the aircraft fuselage through a bend in the sample line. During CPACE, the air sample inlet was located on top of the aircraft fuselage (approximately 10 meters behind the cockpit). The sample tube for this experiment had a 45 degree turn with a bend radius of approximately 50 cm and a tube ID of 2.54 cm. For GLOBE, the sample line had a 45 degree turn with a bend radius of approximately

64

102 cm and a tube ID of 5.2 cm. (Figure 1b) During GLOBE, the sampling line and diffuser were mounted on the side of the fuselage (approximately 16 meters behind the cockpit) and pointed slightly downward (5 degrees). This angle was designed to account for the aircraft average angle of attack at 200 m/s and 8 km altitude, as specified by modeling studies by the manufacturer (McDonnell Douglas) at our measurement location.
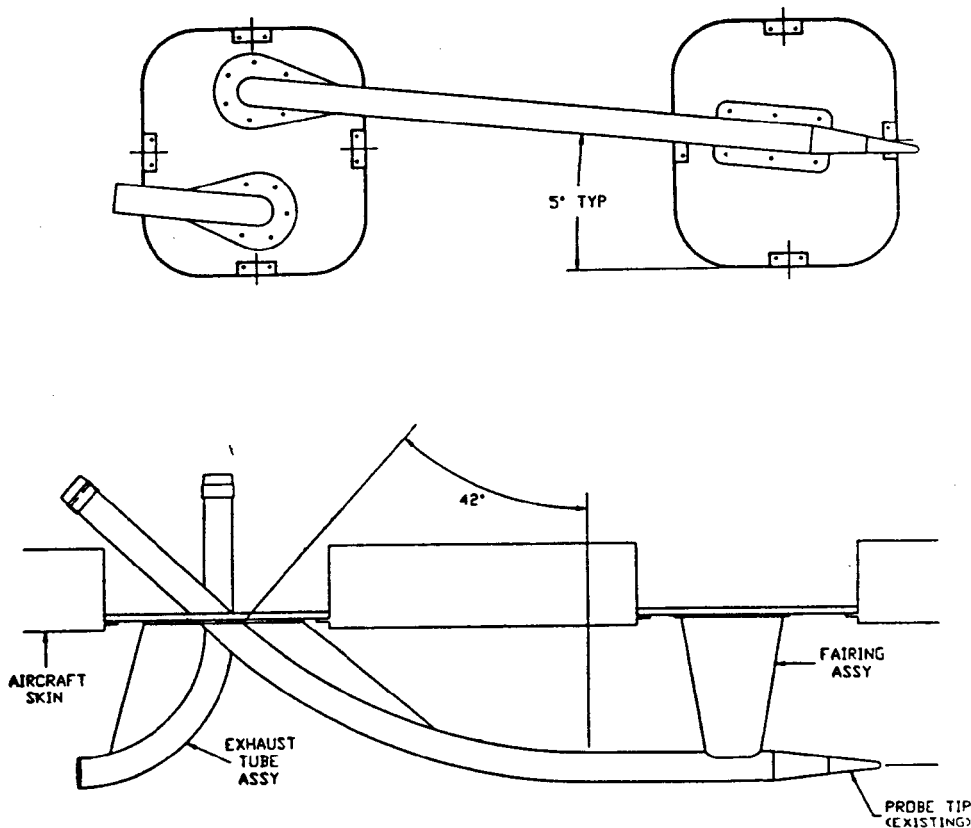
[Figure 1b]

Once inside the aircraft, a smaller thin wall tube was located in the center of the larger sample tube in order to transfer air (with isokinetic flow) to the OPC heating system. After passing through the heating system, the air entered the OPC and finally returned to the large sample line to be removed by the exhaust vent. Sample line flows were maintained by the suction provided by a exhaust vent.

During both experiments, isokinetic conditions were maintained at the diffuser (Figure 1a) by adjusting a sample line valve (located prior to the exhaust vent) until the aircraft and tip velocities at the diffuser (constantly displayed and stored on computer) were in agreement. Diffuser velocities were calculated from sample line velocities which were obtained from a Kurz velocity probe (model 1440). Equation 1 was used to convert the Kurz sample line

65

velocities (STP equivalent) to actual sample line velocities. Tip velocities were determined by converting tube volumetric flows to flows at ambient conditions in a similar fashion.

$$VF2 = VF1(P1/P2)(T2/T1) \tag{1}$$

Equation 1 describes the change in volumetric flows at different conditions where T is the temperature, P is the pressure, and VF is the volumetric flow rate. This equation is valid as long as mass is conserved in the system (i.e., no leaks) and does not require an adiabatic system.

VIRTUAL IMPACTOR THEORY AND PERFORMANCE

An important addition to the system was a virtual impactor (VI) which was designed to increase the relative concentration of coarse particles delivered to the OPC (Clarke, 1990). A VI operates by directing a high velocity jet onto a low velocity orifice such that larger particles with higher inertia penetrate the orifice and become concentrated in the low sample flow. The use of the VI reduced the problem of statistical uncertainty in counting larger particles, a common problem when measuring low aerosol concentrations on aircraft. Figure 2 shows the design of the VI which incorporates recent design improvements (Chen et al. 1986; Loo and Cork, 1988).

An empirical calibration for our VI was performed by comparing size distributions collected concurrently with and without the VI (over 40 hours) during an experiment at Mauna Loa Observatory (MLO) in Hawaii (3500 m altitude and 660 mb pressure) (Clarke and Porter, 1990). An empirical calibration eliminates concern over the loss of particles expected at the collection nozzle for particle Stokes's numbers near 50 percent separation efficiency (Chen et al. 1985). Figure 3a shows the size distributions obtained with and without the VI. The resulting size dependent coarse particle enhancement (gain) in the flow to the OPC is shown in Figure 3b. Unfortunately, during aircraft flight, the VI flow rates varied with height. Therefore, a method was required to determine the aerosol gain caused by the VI at different nozzle Reynolds numbers (i.e., different flows, pressures and temperatures).

Chen et al. (1985) have described the performance of their VI by plotting the separation efficiency, η, (the size dependant fraction of the aerosol mass collected in the sample line divided by the total aerosol mass) as a function of the square root of the particle Stokes's Number ($St^{1/2}$) (their Figure 7). Using this method, they show that, for a particular VI, the separation efficiency (η) at each $St^{1/2}$ will fall on the same curve regardless of the nozzle Reynolds number. In order to evaluate our VI performance under different nozzle Reynolds numbers, we have converted each aerosol diameter of our VI calibration at MLO to its $St^{1/2}$ using the conditions at MLO. Then we have used the VI flows, pressures and temperatures under aircraft conditions in order to convert each $St^{1/2}$ back to a new aerosol diameter. In order to do this, a iterative process was needed since the Stokes's Number depends on both the aerosol diameter and the Cunningham correction factor which is also a function of aerosol diameter (Reist, 1984).

AMBIENT AIR IN
(15 lpm)

FILTERED AIR IN ➡

BODY ➡

SEPARATION NOZZLES ⎯

EXCESS AIR ⬅

ENHANCED COARSE OUT
TO TOAD
(1.2 lpm)
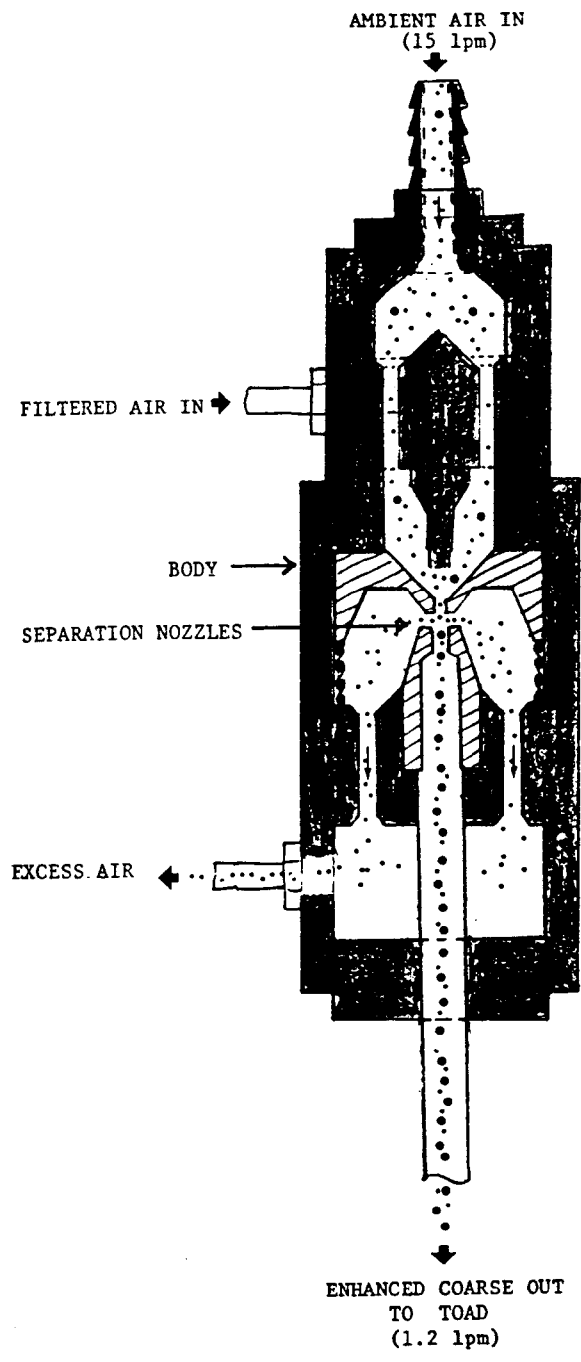
[Figure 2]--The design of the virtual impactor used during the
GLOBE and CPACE. During GLOBE and CPACE, no central
core of filtered air was used so that the VI functioned in a more
conventional manner.

67
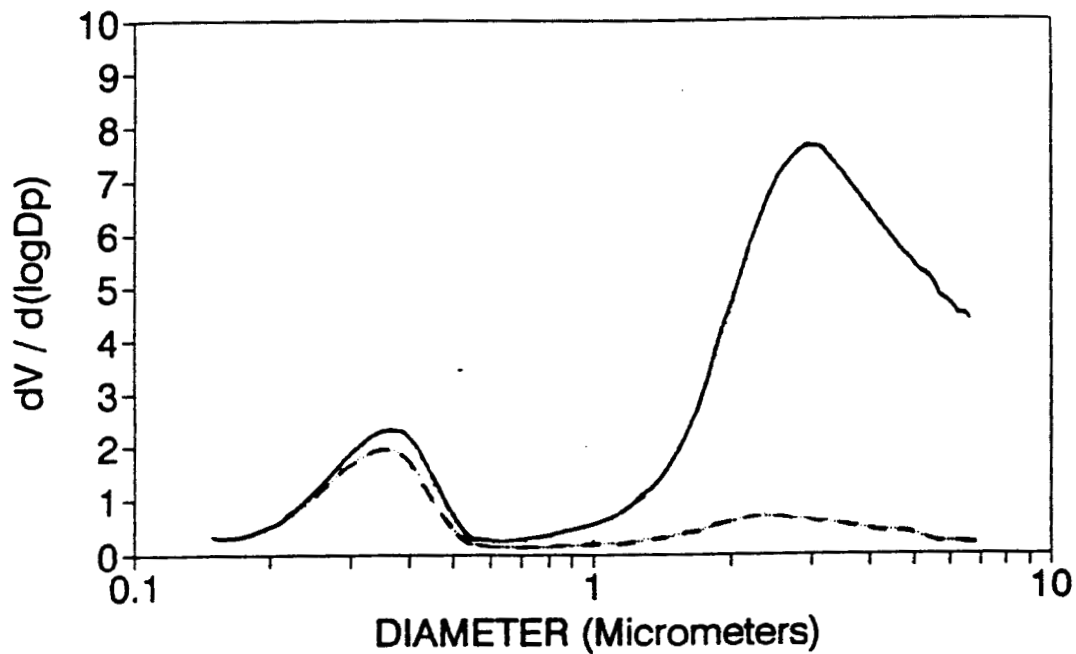
[**Figure 3a**]--An empirical comparison of OPC aerosol size distributions collected concurrently with and without the VI for over 40 hours at Mauna Loa station, Hawaii.
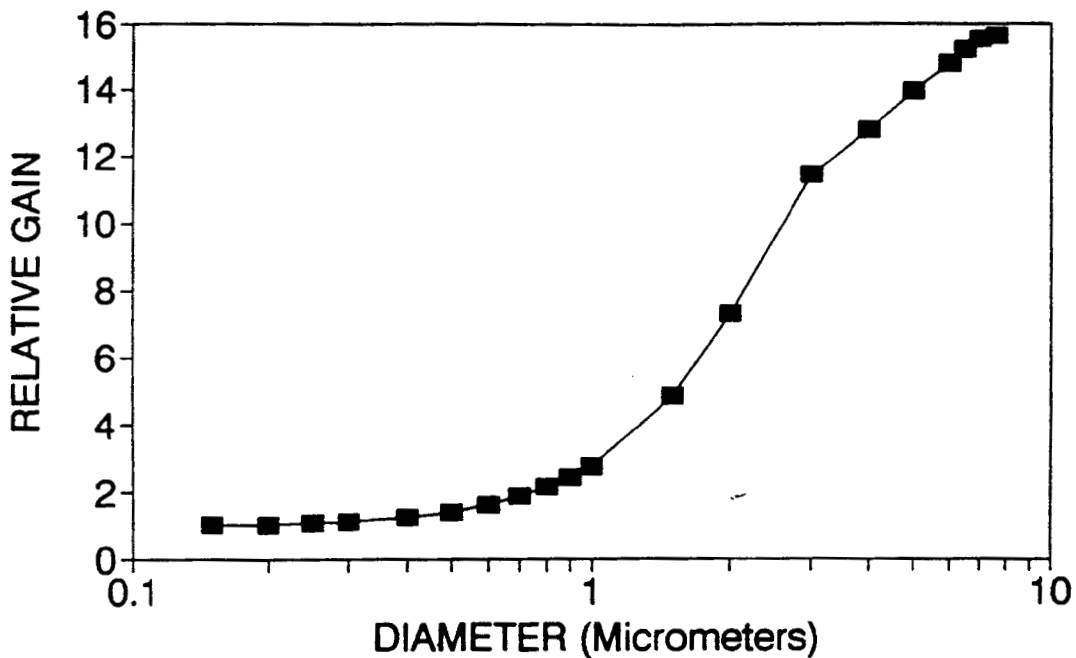
[**Figure 3b**]--The relative gain for the VI based on 3a. This was used as a basis for deriving VI performances under aircraft conditions (see text) such as 3c.

68

Unlike the VI results described by Chen et al. (their Figure 7), in our case the sample flow ratio, FR (sample flow divided by total flow), was not constant due to our varying total flows. Therefore, a way was needed to estimate effective aerosol gains for each $St^{1/2}$ under each of the conditions experienced. In order to estimate the new separation efficiency, we re-expressed the separation efficiency based upon the MLO data as a percentage of the maximum efficiency, Equation 2. In this form, the normalized percentage, η_{norm}, for each $St^{1/2}$ varied from zero to 100 percent.

$$\eta_{norm} = (\eta_{MLO} - FR_{MLO}) / (1 - FR_{MLO}). \qquad (2)$$

These percentages were then converted back to a separation efficiency η_{new} with the new flow rates by,

$$\eta_{new} = \eta_{norm}(1-FR_{new}) + FR_{new}. \qquad (3)$$

Finally the η_{new} values are converted back to our effective gain by multiplying by $1/FR_{new}$. Figure 3c shows the expected aerosol gain using the above method for two different conditions during GLOBE2. For the first case, the ambient pressure was 210 mb, the sample flow was 1.05 lpm and total flow was 13.9 lpm. The second case had an ambient pressure of 360 mb, a sample flow rate of again 1.05 lpm and a total flow rate of 20.2 lpm. The sudden change in slope between 3 and 5 microns in both the VI gains appears to reflect real losses at this size in our particular VI. Similar VI losses were observed in the study by Chen et al. (1985) although newer VI designs have effectively removed these losses (personal communication). However, since all gains are referenced to the empirical MLO calibration, any losses in the VI do not affect the final corrected distribution.

EXPECTED VIRTUAL IMPACTOR GAIN
FOR SAMPLE FLOW = 1.05 LPM
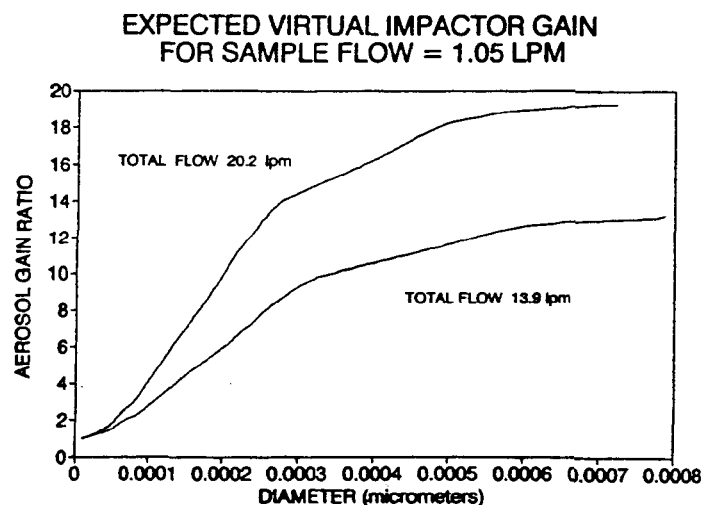
[Figure 3c]--The modeled enhancement cause by the VI for total flow rates of 13.9 and 20.2 with a constant sample flow of 1.05 lpm. These VI gain factors were applied in Figures 4a and 4b to obtain normal concentrations from the VI distributions.

Figures 4a and 4b show two size distributions measured concurrently by the OPC both with and without the VI. The distributions derived from the VI have been obtained by converting the measured VI distribution to equivalent ambient concentrations using the gain shown in Figure 3c. From these figures we see the marked improvement in the counting statistics for the coarse particles made possible by use of the VI.

COMPARISON OF OPC AND VI OPC
GLOBE2 FLIGHT8 (1:29-2:08)UTC
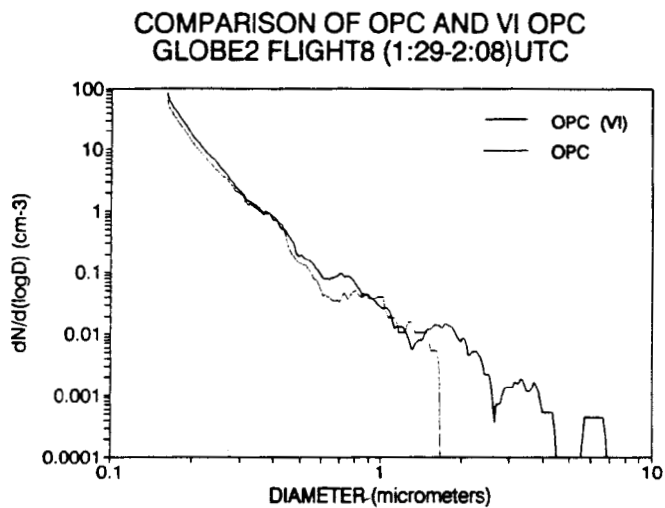
[**Figure 4a**]--The aerosol number distribution measured during GLOBE2 flight 8 (1:29-2:08 UTC) using the OPC with and without the virtual impactor. The corrections for the VI used in this figure are shown in Figure 3c (13.9 lpm).

COMPARISON OF OPC AND VI OPC
GLOBE2 FLIGHT12 (4:52-5:43)UTC
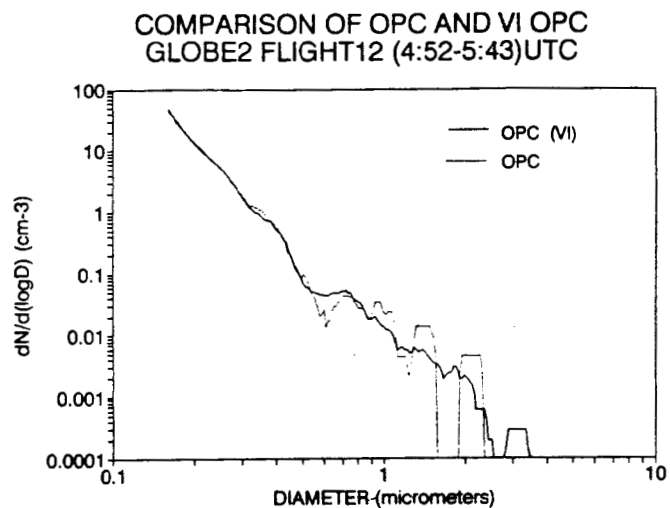
[**Figure 4b**]--The number distribution measured on GLOBE2 flight 12 (4:52-5:43 UTC) with and without the VI. The correction applied for the VI distribution are shown in Figure 3c (20.2 lpm).

70

AEROSOL LOSSES

In our aspirated system, the aerosol must pass through various tubes prior to measurement by the OPC. Whenever possible we have used current theory to asses the size dependent losses in each portion of the system. Upon entering the diffuser, aerosol pass the diffusing cone where aerosol loss can occur, particularly if flow separation occurs. In order to minimize aerosol loss, the diffuser was designed without a sharp edge and with a diffusing half angle of 6.5 degrees, Figure 1a, after Andreae et al. (1988). However, at the DC-8 velocities the likelihood of flow separation at isokinetic conditions remains likely (Kücheman and Weber, 1953).

Due to the lack of relevant literature we were not able to estimate the magnitude of aerosol losses in the diffuser. Okasaki and Willeke (1987) have shown that when an air stream enters a horizontal constant radius inlet, aerosol loss occur primarily from aerosol penetration into the developing boundary layer near the entrance. They also point out that the thickness of this boundary layer decreases with larger flow rates. In our system, when air passes through the diverging diffuser, the flow will be gradually decreasing until it reaches the sample tube. Therefore in our diffuser inlet it seems reasonable that the boundary layer would be increasing gradually in the diverging part of the diffuser and then grow further in the initial part of the main tube. In light of this reasoning we apply the aerosol inlet losses proposed by Okasaki and Willeke to the initial portion of the sample tube (following the diverging part of the diffuser) in the absence of a better method. Some implications of not knowing the proper correction to apply for diffuser losses will appear later in this paper when we discuss several subisokinetic tests performed during CPACE. Indeed, as mentioned by Huebert et al. (1990), a study of diffuser aspiration efficiency as well as transmissions inside the tip would be very useful.

Once the aerosol enters our system the aerosol losses which occurred can be grouped into gravitational losses in horizontal lines and impaction losses in tube bends. For losses occurring in bends, the empirical studies of Pui et al. (1987) were employed. Some amount of extrapolation was needed since Pui et al. only measured losses for Reynolds numbers of 100, 1000, and 6000 while our largest Reynolds number was 8000. Horizontal gravitational losses were modeled according to the formulation of Schwendiman as reported in Okasaki and Willeke (1987). Losses in our heating system were determined during lab experiments using dried NaCl aerosol. The various transmission losses were then combined to determine the total transmission for our system. For dry cases an aerosol density of 2.6 g/cc was used to represent dust. For wet cases, a density of 1.2 g/cc was used to represent a mixture of water and salt solution. Several tests cases were calculated to determine how our transmission losses would vary with height (i.e., 200 versus 1000 mb). These showed that the variability was approximately 6 percent at the largest sizes and therefore a single transmission was used at all heights (see Figure 5 for GLOBE transmission losses).

71

MODELED TRANSMISSION LOSSES
GLOBE (Dry Conditions)
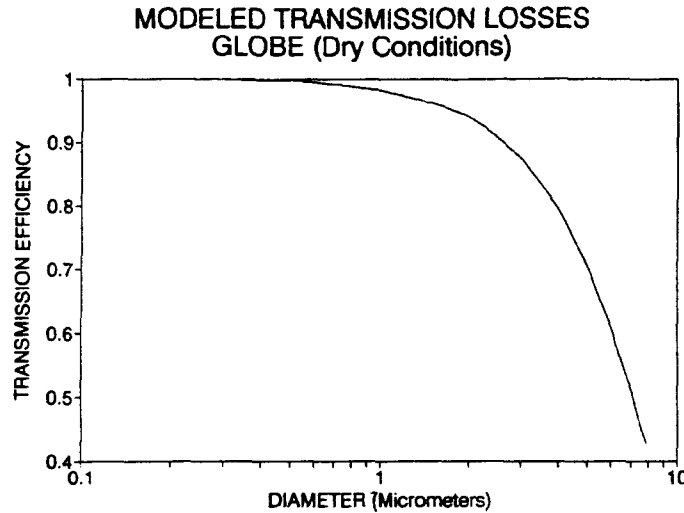
[Figure 5]--The modeled size dependent transmission for our
GLOBE system. Losses modeled include gravitational settling,
impaction in bends, and losses for inlet ducts.

SAMPLE LINE RELATIVE HUMIDITY

When ambient air enters the diffuser probe, it is decelerated. This causes the sample line
pressure and temperature to be higher than the ambient values. This also reduces the
relative humidity (RH) in the sample line compared to the ambient value. Under isokinetic
conditions and assuming isentropic compression of the flow to rest, the resulting stagnation
pressures and temperatures are given by (Emmons, 1958):

$$P2 = P1[1+(\alpha-1)M^2/2]^{(\alpha/(\alpha-1))} \tag{4}$$

$$T2 = T1[1+(\alpha-1)M^2/2)] \tag{5}$$

where α is the ratio of the specific heat at constant pressure to that at constant volume
(Cp/Cv) and M is the Mach number. The assumption of the flow being brought to rest is
reasonable because the tube velocities were always less than 2 percent of aircraft velocities.
The consequent change in relative humidity from ambient for an adiabatic system can be
calculated using a ratio of the Clausius Claperon Equation to get:

$$(RH2/RH1) = (P2/P1)EXP((L/Rv)(1/T2 - 1/T1)) \tag{6}$$

where L is the latent heat of evaporation and Rv is the gas constant of water vapor.

72

Many aerosol are hygroscopic and pick up water at relative humidities less than 100 percent (Tang, 1980). Therefore, it is useful to know how relative humidity will deviate from ambient values as the air traverses the sample line. In Figure 6, we show the ratio of the sample line RH to ambient RH for calculated adiabatic compression in the diffuser (assuming isokinetic sampling at 110 m/s), Equation 6, and some periodically measured values during CPACE. The obvious disagreement is a result of non-adiabatic conditions occurring in the sample tube downstream of the diffuser (i.e., heat entering or leaving the sample line). While flying at low altitudes, the sample line temperatures were warmer than the cabin temperatures and heat was lost from the sample line into the cabin. This caused the sample line temperatures to be lower than those predicted from adiabatic theory and RH values to be higher. On the other hand, at higher altitudes (lower temperatures) heat enters the sample line from the cabin causing the sample line temperature to be larger than predicted by adiabatic theory and RH values to be lower. These sample line RH changes will have little effect on the interpretation of our dried aerosol OPC size distributions (the aerosol have been heated and surrounded by dried sheath air before sizing by the OPC). However, these concerns should be kept in mind when losses are being evaluated or other aerosol sizing devices are employed that are sensitive to RH values (e.g., impactors etc.).

TUBE AND AMBIENT RH COMPARISON
AS A FUNCTION OF PRESSURE
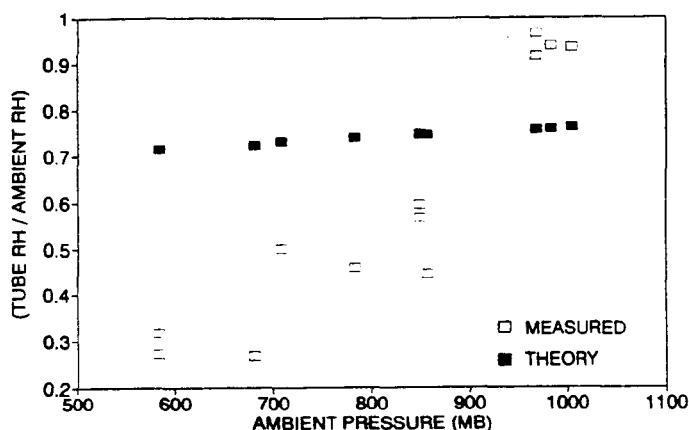
[Figure 6]--The ratio of the tube RH to the ambient RH at different ambient pressures (i.e., heights). The obvious disagreement between the measured and modeled ratios is a result of non-adiabatic conditions in the sample line (i.e., heat entering or leaving the sample tube). For low/high altitudes the adiabatic sample line temperatures are higher/lower than cabin temperatures therefore heat will leave/enter and sample line and increase/lower the sample RH.

SUBISOKINETIC TESTS

Several subisokinetic tests were performed during CPACE in order to evaluate our diffuser transmission under subisokinetic conditions. These were carried out in the moist boundary layer since they required a steady concentration of coarse particles at reasonably high concentrations. Figure 7a shows the OPC number distribution measured for marine aerosol at subisokinetic diffuser flows of 10, 20, 50, 140 m/s and the isokinetic flow of 106 m/s.

CPACE FLIGHT 11 (11:32-11:57)LOCAL
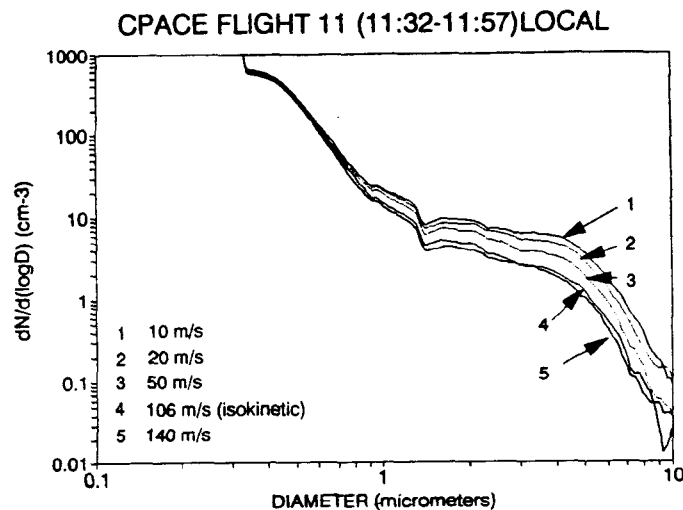
[Figure 7a]--A test (for marine sea salt) in which we have varied the velocity of our thick walled diffuser from the isokinetic value (100 m/s) to subisokinetic values of 10, 20 and 50 m/s as well as one superisokinetic value of 140 m/s. As expected, the more subisokinetic flows display the largest coarse particle increases.

The superisokinetic setting displays little deviation from the isokinetic size distribution. At the largest sizes (8-10 microns) the variability reflects poor sampling statistics. Separate system losses were calculated for flows present during each case. The irregular fluctuations at larger sizes reflect low counts and poor statistical sampling. In this figure a diameter shift of 1.9 has been applied to convert our measured dry aerosol into an ambient aerosol at 70 percent RH. This was necessary because the largest aerosol in the clean marine boundary layer are typically hygroscopic sea salt which would have picked up water under ambient marine conditions (Tang, 1980). The same data is shown in a different way in Figure 7b where each distribution is divided by the isokinetic distribution resulting in a size dependent aerosol gain caused by subisokinetic sampling. From these figures we can see very little enhancement occurred below 1 micron (for the aircraft speed of 106 m/s) even under the most subisokinetic conditions. The size distribution at larger sizes measured during the superisokinetic setting (140 m/s) approaches about 75 percent of isokinetic values and is consistent with modeled behavior for a straight isokinetic inlet (Rader and Marple, 1988). Also shown (boxes) are the modeled aerosol gains from Rader and Marple (1988) for a thick wall diffuser with a outer to inner wall diameter ratio of 1.3 and a subisokinetic flow

74

rate equivalent to 50 percent of the aircraft speed. Since we were not able to determine how they have defined their diffuser thickness ratio we will define the diameter ratio for our diffuser at the point where the inner diameter becomes smallest (see Figure 1a). The ratio of outer to inner diameter at this location results in a thickness ratio of 1.45. The slight difference evident in the aerosol enhancements for our measured and their theoretical aerosol gains is consistent with differences in thickness ratios. While these results appear to show good agreement, we must emphasize that the uncertainty in the definition of diffuser shape and thickness ratios make direct comparison difficult. Nevertheless, this behavior suggests that aerosol behavior in the diffuser responds similarly to that of a straight inlet for small variations from isokinetic settings.

NONISOKINETIC NOZZLE AEROSOL GAIN
COMPARED TO ISOKINETIC (106M/S)
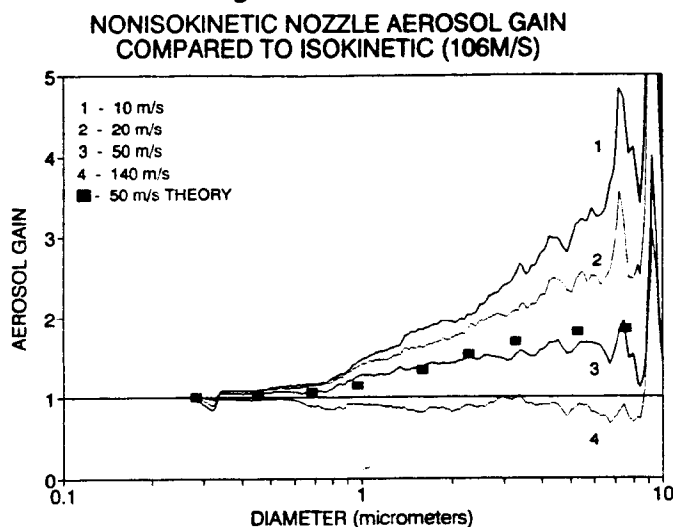
[**Figure 7b**]--A plot of the same number distributions shown in 7a divided by the isokinetic number distribution (i.e., an aerosol enhancement). Also shown are the modeled aerosol gains from Rader and Marple (1988) for a thick walled diffuser operating at 50 percent subisokinetic flows.

In order to assess the performance of our inlet diffuser under different subisokinetic conditions we will apply the method described earlier (i.e., the model of VI performance under different conditions) to the probe tip. The physical conditions for aerosol entering a subisokinetic diffuser is fundamentally equivalent to that for the collection nozzle of a VI, Figure 2. As described above, the method involves several steps. The first step is to obtain a reference aerosol gain at some subisokinetic setting for our diffuser. For this test we have used the aerosol gain which occurred at the 50 percent subisokinetic settings as our reference standard. Next we have calculated the $St^{1/2}$ for each aerosol diameter using the conditions of our reference run and then converted each $St^{1/2}$ back to a aerosol diameter using the conditions of each case of interest. The final step is to convert the aerosol separation efficiency (η) of each $St^{1/2}$ from the reference to a new separation efficiency and then aerosol gain (discussed previously in the VI calibration section). The results of this operation are shown in Figure 8 for two subisokinetic cases (10 and 20 m/s with an aircraft

75

speed of 106 m/s). Also shown are the observed aerosol gains at 10 and 20 m/s (same as Figure 7). We can see the modeled gains are much larger than the observed gains and that this difference is largest for the most subisokinetic conditions. Separate overall system losses were made for each subisokinetic conditions in making these comparisons and we do not believe that uncertainties in these modeled losses can account for these differences. Some of these differences may be caused by deposition of particles near the tip inlet, in the same manner as that observed for a VI collection nozzle (Chen et al. 1985). Another possible explanation is that under the more subisokinetic conditions, the thickness of the boundary layer increases resulting in more turbulent deposition as aerosol penetrate this layer. Indeed Emmons (1958) has shown boundary layer flow is particularly sensitive in the case of diffusers.

MEASURED & MODELED SUBISOKINETIC GAIN
COMPARED TO ISOKINETIC AT (106m/s)
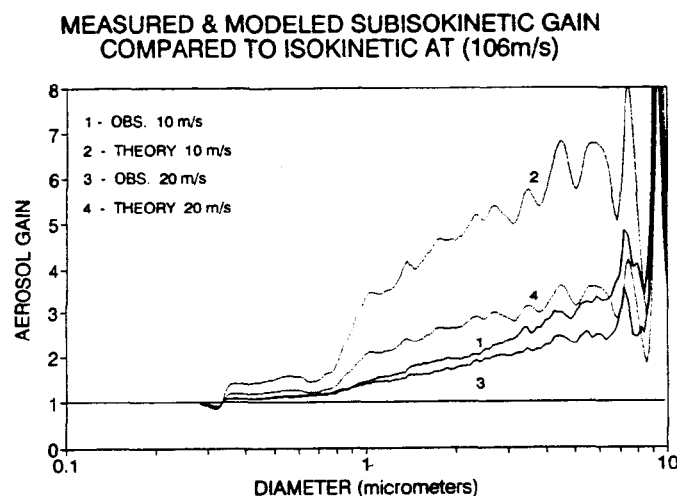
[**Figure 8**]--We have shown the observed aerosol enhancement caused by subisokinetic sampling for diffuser velocities of 10 and 20 m/s (solid lines) with aircraft speeds of 100 m/s (similar to Figure 7b). Here we have also shown modeled aerosol enhancements (dotted line) which are based on measured enhancements at 50 m/s. The fact that modeled aerosol enhancements are much larger than the observed enhancements suggests additional nozzle losses are occurring for the more subisokinetic conditions which were not occurring under less subisokinetic settings (i.e., 50 m/s).

COMPARISON WITH THE FSSP

Here we present the initial results of comparison of aerosol distributions measured during GLOBE by the OPC and the wing mounted FSSP 300 operated by NASA Ames. A more detailed comparison of aerosol measurements during GLOBE is planned for the near future after each research group had time to process their data. In this comparison we have

76

restricted ourselves to study dry periods when the relative humidity was below 30 percent (i.e., the most frequent condition during GLOBE).

During GLOBE both the OPC and the FSSP had experienced occasional problems. On one flight during GLOBE the OPC was partially obstructed which eliminated the larger aerosol from the measurements for the entire flight. During GLOBE, the FSSP300 operated by NASA Ames was operational for most of the experiment with the exception of intermittent noise that appeared at 0.6 micrometers. Due to its aspirated configuration, analysis of OPC data requires consideration of the various issues discussed above (e.g., losses, RH etc.). Although the FSSP offers the benefit of aerosol measurements in the free air they also suffer from certain difficulties such as response times and beam intensity inhomogeneities (Baumgardner and Spowart, 1989).

During GLOBE most aerosol measurements were made above the boundary layer where coarse mode aerosol concentrations were often very low. In an effort to compare the FSSP and OPC during GLOBE we have averaged together 7 hours of measurements for periods of enhanced coarse mode aerosol. Adding in many more hours of size distributions with low coarse mode aerosol concentrations would be of little benefit in reducing the problem of statistical uncertainty at the larger sizes. Figures 9a and 9b are examples of OPC and FSSP distributions during GLOBE under dry conditions (RH < 20 percent). In Figure 9a the measured OPC size distribution are an average of 8 different periods (a total of 7 hours from different flights) using the VI. Intermittent noise in the FSSP size distribution (at 0.6 micrometers) occurred in several of the size distributions of this average and were removed by averaging over adjacent channels. The second case (measured without the VI) was measured while descending into Hawaii (~ 670 mb) and is most likely "dust" of Asian origin.
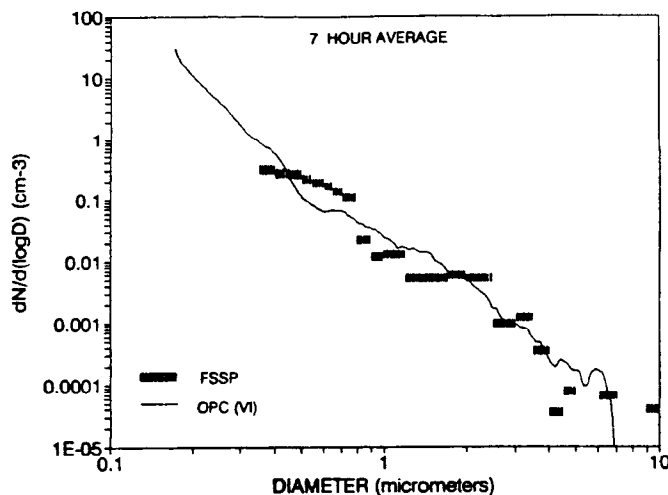
[Figure 9a]--An example of the aerosol number distribution measured concurrently by the FSSP and OPC (with the VI) during GLOBE2 during flight 14 at 2:21-3:51 UTC.

Such high concentrations of large dry aerosol minimize sampling uncertainty and are the best periods for comparisons. The size dependent ratio of the two instruments are shown in Figure 10 for this situation (see Figure 9b). In general, there is good agreement except for apparent undercounting by the FSSP 300 at smaller sizes. The disagreement at larger sizes is primarily due to poor count statistics due to low concentrations.

COMPARISON OF THE FSSP AND OPC
GLOBE2 FLIGHT4 (23:57-0:05)UTC
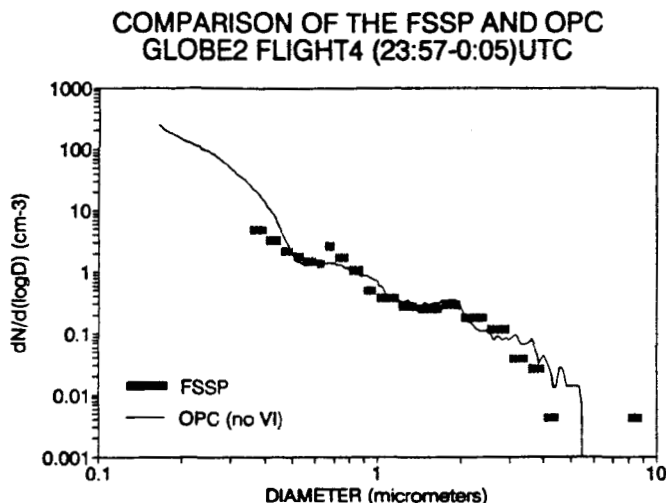
[**Figure 9b**]--An aerosol number distribution measured by the FSSP and OPC (no VI) during flight 4 at 23:57-0:05 UTC with increased coarse particle concentrations.

RATIO (OPC/FSSP)
GLOBE2 FLIGHT4 (23:57-0:05)UTC
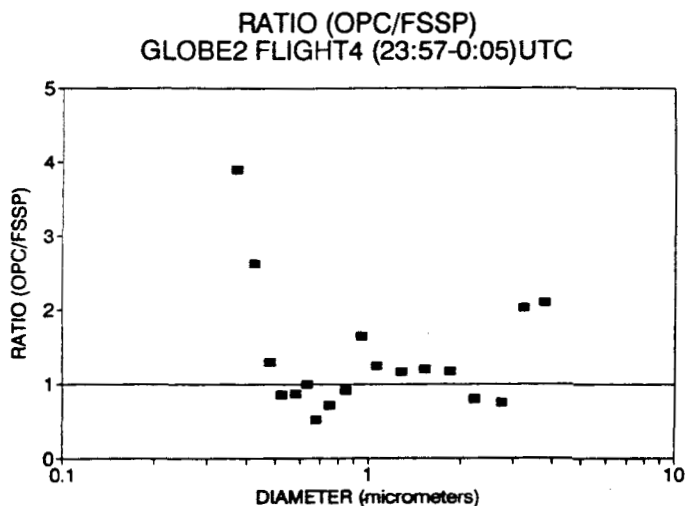
[**Figure 10**]--Comparison of the OPC (no VI) and FSSP for the case shown in 9b.

78

CONCLUSION

Optical particle counters (with suitable RH control) can be used effectively to examine the size dependent mechanisms that affect aerosol sampling through aspirated systems. The results of two aircraft experiments in the remote troposphere have enabled us to examine the requirements and performance of an aspirated inlet for aerosol sampling from aircraft. This evaluation is based on size resolved data accumulated by a laser optical particle counter probe. Additional intercomparisons were made with a wing mounted forward scattering spectrometer probe in conjunction with other instrumentation.

Specific observations suggested by our measurements follow:

1. A major problem encountered in aerosol comparisons in clean regions such as the remote troposphere is the difficulty of obtaining a statistically representative sample for the larger aerosol (where most aerosol mass resides). The corrections made for aerosol losses in our system were often small when compared with the variability caused by poor sampling statistics, particularly at the larger sizes. The use of a properly calibrated VI was shown to markedly reduce this uncertainty. In this paper we have shown that if a VI calibration already exists for some VI flow combination, pressure and temperature, then it is possible to provide an adequate assessment of VI enhancement at other combinations of flow, pressure and temperature.

2. The general problem confronting aerosol sampling by aircraft is the determination of aerosol aspiration and inlet losses for various diffuser configurations and subisokinetic conditions. In our study we found encouraging agreement between the theoretical work of Rader and Marple (1988) and inlet tests for a 50 percent subisokinetic condition and a thick wall ratio of 1.3-1.4 although we were not certain of the characteristics of their modeled diffuser. This apparent agreement of measured and modeled size dependent gains at 50 percent subisokinetic flows suggest inlet performance is predictable at least in a relative sense. However, increasing deviations of modeled and measured performance for larger particles under increasingly subisokinetic conditions indicates that unmodeled diffuser losses must be occurring for larger particles. The subisokinetic tests also indicate small particle (<0.5 μm) losses are relatively insensitive to extreme deviations from isokinetic sampling. This insensitivity suggests that small particle losses are independent of changes in shear and boundary layer development at the probe tip. Hence, we expect small particle losses for our diffuser to be only a few percent at isokinetic conditions.

3. When measuring aerosol in moist atmospheres from aspirated inlets care must be taken to determine or control the degree to which the sampling process has dried out the ambient aerosol before measurement. This drying out will affect the sizing of the aerosol distribution and transmission losses as well. Our tests show that actual

sample line RH measurements are necessary because nonadiabatic conditions can significantly alter the sample line RH from RH values computed from adiabatic theory.

4. Our preliminary comparisons with the aspirated OPC system and the wing mounted FSSP have shown good agreement. Some of the biggest disagreements reflect uncertainties caused by poor sampling statistics at the larger sizes. The future comparisons planned for GLOBE aerosol measurements after revised assessment of instrument performance by the various instrument groups should provide a more detailed comparisons.

In view of the importance of accurate aerosol sampling from aircraft, we hope to see additional theoretical and experimental work done on the problems of aspirated aerosol measurements. At the moment, our greatest concern are the unmodeled losses which may be occurring in our diffuser. The present study (super and subisokinetic tests) suggest these diffuser losses are not sensitive to small deviation from isokinetic conditions in our particular diffuser. The fact that a wide variety of diffusers exist in the literature, each of which has a different aspiration efficiency and internal losses makes comparisons difficult. Effort should be put forth to determine which type of diffusers are best suited for aircraft aerosol sampling. It is also important to determine their performance under varying wind shears and ambient turbulence which may vary depending on the placement of the diffuser on the aircraft.

An alternative to diffuser inlets might also be considered in future studies. The potential for large particle losses in diffusers also suggests that a straight non-diffusing tip, operated under controlled and well characterized subisokinetic conditions, may be desirable for size resolved measurements such as those reported here. The potential for reduced inlet losses and enhanced coarse particle counts could be a distinct advantage for these measurements.

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DISCUSSION

Huebert: Almost anything looks like it agrees well on a log plot with five or six orders of magnitude on it. It looked to me like the internal and external plots frequently differed by a factor of two or numbers like that. Is that the state of the art? Is that the best we're going to be able to do with optical particle counters?

Clarke: I don't think so. I think you have to keep in mind that this was a first comparison. It was not even a comparison in the sense that yours was a deliberate comparison. This was an after-the-fact, flight-of-opportunity comparison where we were doing other things than just taking the data and looking at it. It is the first cut of the data, so we haven't made all the corrections possible, and these were never sat down and calibrated side-by-side before or after the measurement program. There are a lot of things that could be done better if you made it a point to intercompare these instruments.

What I think does show up here is that this a reasonable approach in trying to model behavior. Crossing two inlets with two optical particle counters, one that you play with and one that you keep the same, is a good approach so that you have a reference for the changes that you are making, because you do have a variable air mass out there. That's one of your problems--it shows up in sampling. If you have two of them so you can compare them side-by-side, one with a perturbed condition and one not, this would be a big help.

In the illustration I showed for the good statistics, we had for the DC-8 with Rudy Pueschel's data. The variability over the size range from .4 to 4 microns was really not bad. It was only on the order of 20 percent or so, not a factor of two. In general it would appear that the DC-8 agreement doesn't seem to have the discrepancy that shows up between 1 and 4 microns that showed up with Darrel's data on the FSSP on the Electra. Remember, we had a different inlet system (much larger) and the velocities were higher. The boundary layer would have been smaller on the DC-8 than it was on the Electra. That may be a factor in the diffuser.

Radke: Are you seeing any differences between 100 and 200 m/s as far as the inlet performance?

Clarke: This is what I was saying just now. The behavior with the last comparison I showed with Rudy Pueschel was on the GLOBE data which was the 200 m/s and didn't seem to show the discrepancy that we found at 100 m/s. It appears to be even a little better in that case suggesting again that the boundary layer thickness in the diffuser is less because you have higher velocities.

Baumgardner: I should point out that the FSSPs that were flown on the PASIN and CPACE and that which was flown on the GLOBE experiment were two different types of FSSPs. The one that was flown on the Electra experiment was an FSSP-100, which is different than the FSSP-300 which was flown during the GLOBE experiment. The big difference is that the sample volume on the 300 is about a factor of ten smaller than the sample volume on the 100. The second thing is that they define the sample volume two totally different ways. There could be a possibility that that is part of the difference, too. Actually, I think the 300 probe is a very interesting probe, because it also goes down to a smaller size than a 100. The 100 only gets down to about .5 - .6 microns, and the 300 gets down to .3 - .35, which makes intercomparisons much nicer in that overlapping range.

Seebaugh: Is everyone satisfied with the assumption that the particles follow the streamlines around the aircraft which are being offset by 5 feet or more from the centerline by the effect of the fuselage?

Clarke: Our hope was that we were far enough back that even with the distortion due to the aircraft it would still be more or less parallel with the skin at that point, and the correction...

Seebaugh: I'm not talking about being parallel. Are the particles following these same streamlines around the airplane? Does that really matter?

Clarke: I think here that they were.

Rader: When comparing with the theory, a warning on the theory. It's calculated just at the entrance point on the nozzle outward. Subisokinetic condition particles may well have some radial motion from the sampling process, because it's deflected on the inlet near the opening. Liu, in the last year or two, published a paper with the same sort of finite difference technique. They actually looked at particle impaction near the entrance and found that it was pretty significant. Especially if these ratio might be independent. See how that agrees with your data. Problems of getting in close for getting input, particles hitting walls, who knows what's happened.

Clarke: I suspect that it really is going on. Also, I forgot to mention, because you are operating in subisokinetic conditions, all of your flows and loss mechanisms change. We did model all of the loss mechanisms after reduced flow to account for the differences as well. You're right, I just let them be. That's what's going on in subisokinetic conditions.

Georgi: I have one question about the counting efficiency between the different instruments, especially in the small size range. Are they similar or are they different. One might have 50 percent when the other one 30 percent.

Clarke: I think with our probe we have 256 size bins. Counting efficiency will fall off at the very smallest size bins. Then we have noise. We put a filter in front of the instrument so we can get an exact noise figure with or without particles present. I think we do expect some fallout of the smaller sizes, but not very much. Rudy may know more about counting efficiency of the FSSP in the smaller size range. I don't know what percentage that is.

Pueschel: All I can say, Tony, is we have effects of mounting location.

Georgi: I was wondering; you mentioned all the time gaining something. What about cutoff of this virtual impactor?

Clarke: It is the size cut in the sense that a typical impactor is. You're not impacting it onto anything except air. Basically, the size cut is, if you want to use that term, is described by (smooth line dimension) ... This is the empirical one determined from 40 hours at Mauna Loa observatory. This is a ratio of two real measurements. These are what normally would be reported as size distributions over 40 hours of accumulated data. This is what we obtained using the virtual impactor, and this is the ratio of those. You get an increase relative to your tube velocities--you have an impinging velocity and a collecting velocity. If they're 20:1, then you will get roughly a 20:1 increase in the coarse particles. The idea is that you're impinging lower moving airspeed. This one is designed to feed our optical particle counter, so you design it for the flow parameters to be 1.

Airborne Filter Intercomparisons and Comparisons
With Cloud Water and Ground-Level Filter Measurements

By

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1. INTRODUCTION

Since 1981, the Atmospheric Environment Service (AES) in cooperation with the Canadian Institute for Aerospace Research (IAR) has conducted a number of airborne experiments to study processes fundamental to "Acid Rain". These experiments have included the sampling of aerosol and cloud water from aircraft for chemical analysis. In addition, a number of supporting airborne instrument measurements have been made, and filter and instrument measurements have been conducted at supporting ground sites. These measurements are used here to assess the possibility of losses of sulphate and nitrate during sampling from the aircraft.

Five intercomparisons of airborne filter measurements of particulate sulphate ($p\text{-}SO_4^=$), particulate nitrate ($p\text{-}NO_3^-$) and nitric acid are described here. As well, airborne concentrations of $p\text{-}SO_4^=$, $p\text{-}NO_3^-$ and HNO_3 are compared with optical particle counter estimates of aerosol mass, ground-level filter (GLF) concentrations of $p\text{-}SO_4^=$, $p\text{-}NO_3^-$ and HNO_3 and concentrations of sulphate and nitrate measured in the cloud water* (hereafter $cwSO_4^=$ and $cwNO_3^-$).

The measurements are from three studies conducted over central Ontario during the summer of 1982, the winter of early 1984 and the summer of 1988. These studies were chosen because two aircraft were used in each study and intercomparisons were performed. During 1982, the two aircraft were the IAR deHavilland Twin Otter (T.O.) and the IAR Beechcraft 18. During 1984 and 1988, the IAR T.O. and the Canada Centre for Remote Sensing DC-3 were used.

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* The concentrations of sulphate and nitrate are multiplied by the measured liquid water content (LWC) to convert to units directly comparable to the filter measurements.

2. INSTRUMENTATION

Filters samples were collected using a triple-filter system consisting of a front filter to collect aerosol, a middle filter to trap HNO_3 and an impregnated back filter to trap either SO_2 or NH_3. Some specifics of the filters used during each study are given in Table 1. The inlets used on each aircraft are described in Table 2. During the two summer studies (i.e., 1982 & 1988), the sampling at the intake of the inlet was nearly isokinetic. For the winter study, the inlets were left open because the aircraft were often flying in supercooled cloud and the small isokinetic diffusers could easily ice over. With the exception of the 1982 T.O. inlet, all inlet surfaces were teflon to facilitate the sampling of HNO_3. With the exception of the 1988 T.O. inlet, all were diffuser type inlets: the 1988 T.O. inlet was a short straight inlet opening from 0.3 cm ID to about 0.6 cm ID at the filter housing inlet. Laminar flow is expected in all inlets except the 1988 T.O. inlet, for which the Reynolds number is estimated at 10^4.

Measurements of total aerosol mass in the 0.17-1 μm size range were estimated with a wing-mounted Particle Measuring Systems ASASP-100X (i.e., optical particle detector; hereafter ASASP). Calibrations of this probe have been described by Leaitch and Isaac (1991) and Liu et al. (1991).

Cloud water was sampled during 1982 with standard slotted-rod collectors (Winters et al. 1979). Cloud droplets cross the streamlines around the 1 cm diameter cylindrical collector rods and impact into 0.3 cm wide slots cut along the length of the rods. The rods are deployed vertically into the airstream and the impacted water runs down the interior of the slot into a collection bottle. During 1984, rods without slots were used as the cloud water was supercooled and the rods collected rime. The rimed rods were extracted and placed in clean bags for the ice to melt. During 1988, two different slotted-rod collectors were used: the standard type described above; and a modified type in which the outside diameter of the rods is half that of the standard one, but the slot width is the same. These two collectors were flown side-by-side to examine whether or not the efficiency of collection is improved by changing the size of the rods. It is not the intention to discuss the results of the cloud water collector intercomparison here, except to say that the outcome does not have a significant bearing on the present discussion.

GLF measurements were made with similar filter systems in an open-faced configuration. The filters were held inverted about 5 metres above the ground and sheltered by an aluminum hemispherical cap. In high winds, it is possible that some coarse particles may not be captured by this system, however, for most conditions it is expected that particles up to at least 10 μm are efficiently captured.

3. COMPARISONS DURING INTERCOMPARISON FLIGHTS

The results of airborne filter intercomparisons are shown in Table 3. Two separate intercomparisons were performed in 1982, two in 1984 and one in 1988. Concentrations of $p\text{-}SO_4^=$, $p\text{-}NO_3$, $p\text{-}NH_4^+$ and HNO_3 are given for each filter. Below each absolute comparison is a normalized comparison, where the concentrations have been normalized relative to $p\text{-}SO_4^=$ on the particular filter. The purpose of this is to underscore internal consistencies between the filters. For example, it is suspected that a leak in the flow system led to an overestimation of the flow rate on the T.O. during the Febrary 23, 1984, intercomparison. In this case, the relative agreement between species concentrations is quite strong although the absolute concentrations measured on the T.O. are much lower, except in the case of HNO_3 which is at detection limit on both filters. The covariance of the species concentrations suggests that for this case there was agreement between the filters in terms of collection efficiency.

The $p\text{-}SO_4^=$ intercomparisons show differences of 2-29 percent, relative to the highest concentration in each case. In absolute terms the discrepancies range from 0.08 μg m^{-3} to 1.9 μg m^{-3}. Given that the uncertainty in the filter measurements, due to filter blank variability and analytical uncertainty, is about ± 1 μg m^{-3} for the 1982 data and ± 0.4 μg m^{-3} for the 1988 data*, all of the discrepancies in $p\text{-}SO_4^=$ are within the uncertainty of the filters.

The $p\text{-}NO_3$ intercomparisons are more variable. The $p\text{-}NO_3^-$ concentration measured on July 5, 1982, compare very well (the difference of 11 percent is well within filter $p\text{-}NO_3^-$ uncertainty, which is the same as quoted above for $p\text{-}SO_4^=$). The concentrations measured during the July 17, 1982, and August 27, 1988, intercomparisons are within, but at the limits of the uncertainties, and the discrepancies between the filters are in excess of 80 percent in each case. Assuming that in the summertime substantial $p\text{-}NO_3^-$ may be found in the coarse aerosol, due to neutralization of HNO_3 on alkaline dust particles, then these larger discrepancies may indicate sampling problems with the coarse aerosol. The $p\text{-}NO_3^-$ concentration for the February 23, 1984, case is very high relative to all other cases and $p\text{-}SO_4^=$ in this case, and the normalized results suggest little discrepancy in $p\text{-}NO_3^-$. In this case, it is expected that the $p\text{-}NO_3^-$ was present in the fine particles in this case, because colder air temperatures favoured the formation of NH_4NO_3. Note that NH_4^+, in equivalent units, is well in excess of either $p\text{-}NO_3^-$ or $p\text{-}SO_4^=$.

The multi-aircraft intercomparison results for $p\text{-}SO_4^=$ and $p\text{-}NO_3^-$ are consistent with relatively good inlet transmission efficiencies for the fine aerosol (i.e., particles <1 μm) and uncertain efficiencies for the coarse particles (i.e., >1 μm).

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* The uncertainties quoted assume the sampled air volume to be 1.5 m^3. This is considered a typical value, although the actual volumes may range between 1 m^3 and 2 m^3.

4. FILTER-ASASP COMPARISON

The total mass of aerosol in the size range 0.17-1 μm was estimated from the T.O. ASASP data and compared with the T.O. p-SO$_4^=$ for 1988. This particular comparison, shown in Figure 1, was made because it is recognized that most of the p-SO$_4^=$ in continental regions exists in this size range (e.g., Milford and Davidson, 1987). The total mass was estimated assuming a dry particle density of 2 g m^{-3*}. Figure 1 indicates a strong relationship between the p-SO$_4^=$ and the estimated total mass, suggesting there are no large random errors in p-SO$_4^=$ measurement. For higher concentrations, the fraction of p-SO$_4^=$ in the fine aerosol is about 30-50 percent. This fraction is about 20 percent for intermediate concentrations, and falls to <10 percent for the lowest concentrations. Heintzenberg (1989) in reviewing the relative composition of the fine aerosol finds SO$_4^=$ to comprise 20-40 percent of the total fine particle mass. Taking into account uncertainties associated with the total mass density assumption and due to filter blanks, which are greater in relative terms at the lower concentrations, there appear to be no p-SO$_4^=$ losses in the T.O. inlet system detectable outside of other uncertainties.

5. MULTI-LEVEL INTERCOMPARISONS

During 1988, there were three instances when filters were sampled on the T.O. and DC-3 at different altitudes, cloud water was sampled on the T.O. and filters were sampled near ground level at Egbert, Ontario all within a two-hour period. These cases provide additional detailed data to examine the sampling inlet issue.

Figure 2 shows the location and times of the sampling relative to the Egbert ground station. All the filters were collected while flying between Egbert and Dorset, Ontario, about 125 km NE of Egbert. In Figure 3, vertical profiles of aerosol number concentration measured with the T.O. ASASP over Egbert and over Dorset for flights 7, 13 and 48 are shown to indicate how aerosol varied at either end of the filters. Note, on flight 48, the extreme variability in the aerosol between about 750 mb and 950 mb is due to penetration in and out of cloud. The concentrations of major ions in the filter and cloud water samples are given in Table 4.

5.1 SULPHATE

The aerosol during flight 7 was relatively well mixed up to about 2 km (Figure 3), but about 30 percent higher over Egbert compared to Dorset. P-SO$_4^=$ is higher the T.O. compared with the DC-3, but reasonably close to the DC-3 sample at the same time as the T.O. filter (also within the filter uncertainty). All three aircraft p-SO$_4^=$ concentrations are lower than

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* This particular ASASP has been determined to effectively dry the aerosol before detection (Leaitch and Isaac, 1991).

the GLF by much more than the horizontal variability; however, in this case the GLF was collected over a 6-hour period in this case and a decreasing trend in concentrations was apparent in succeeding GLF. The $cwSO_4^=$, which temporally is most comparable to the DC-3 filter at 1.1 km, is lower than the DC-3 1.1 km filter value, however, the cloud water sample was collected nearer Dorset, where aerosol concentrations were lower.

During flight 13, higher aerosol number concentrations are observed near the ground over Dorset. Almost 2 hours later much lower concentrations are seen near the ground over Egbert. Given the temporal and spatial variability of the aerosol on this occasion, the airborne and GLF p-$SO_4^=$ intercompare well. The $cwSO_4^=$ agrees very well with the p-$SO_4^=$ at 1.3 km and 1.8 km, particularly after taking into account how the numbers of droplets compare with the number of particles.

The airborne p-$SO_4^=$ concentrations during flight 48 are somewhat lower than the GLF results, although the difference between the GLF and the T.O. filter is close to the filter p-$SO_4^=$ uncertainty. The higher T.O. p-$SO_4^=$ compared to DC-3 p-$SO_4^=$ is partially explained by lower aerosol concentrations measured on the DC-3. The $cwSO_4^=$ at 1.8 km is about one-half of the p-$SO_4^=$ at 1.6 km, however the number of cloud droplets measured during the cloud water collection is only about one half of the average number of aerosol particles observed during the filter collection.

General correspondence between $SO_4^=$ measured at the ground, in the air and in the cloud water is indicated by these three cases. Most of the differences among the three types of $SO_4^=$ collections used here can be explained by uncertainties other than inlet transmission losses (e.g., temporal and spatial variability, filter uncertainty).

5.2   NITRATE

The p-NO_3^- concentrations during flight 7 at 0.6 km, 1.1 km and 1.8 km are within filter uncertainty. There is good correspondence of the T.O. p-NO_3^-+HNO_3 with the $cwNO_3^-$ at 2.1 km, supporting the indication of the filter samples that p-NO_3^- was less prominent than HNO_3.

P-NO_3^- on all filter samples, including the GLF, during flight 13 is very low relative to HNO_3. The differences among these p-NO_3^- values are again within filter uncertainty. The $cwNO_3^-$, which compares closest in both time and space with the DC-3 filter at 1.3 km, agrees within 20 percent of this filter's p-NO_3^-+HNO_3 concentration.

P-NO_3^- concentrations measured on the filters during flight 48 are once again very low relative to HNO_3 and within filter blank variability. The $cwNO_3^-$ is about 57 percent of the T.O. HNO_3 (p-NO_3^- is negligible), and the $cwSO_4^=$ is about 46 percent of the T.O. p-$SO_4^=$.

This suggests that the lower number concentration of cloud droplets relative to the average aerosol number concentration during the filter was due to a lower number of particles available for scavenging by the cloud, rather than incomplete nucleation scavenging.

For these few cases, p-NO_3^- was a relatively low concentration constituent and, as a result, it is difficult to make a general assessment of errors in sampling for this reason. It appears that for these cases such errors are again probably not any more significant than the filter uncertainty.

6. INTERCOMPARISONS OF CLOUD WATER, GROUND-LEVEL AND AIRBORNE FILTER DATA

6.1 SULPHATE

The previous analysis is extended in a more general sense to all three field studies. Figures 4-6 show comparisons of $SO_4^=$ concentrations measured on the GLF samples, in the airborne filter samples and in cloud water samples for various flights during the 1982, 1984 and 1988 studies respectively.

During 1982 (Figure 4), the relative correspondence of the airborne filters with the GLF is reasonably good, however, the absolute correspondence between GLF and cloud water is much better. Of the four cases with the highest GLF p-$SO_4^=$ (i.e., July 7, 14, 15 & 22), for which filter uncertainties are less significant, two cases (July 14 & 15) have airborne p-$SO_4^=$ much lower than either the ground-level p-$SO_4^=$ or the cw$SO_4^=$. Lower airborne p-$SO_4^=$ compared with GLF p-$SO_4^=$ will generally be expected because of vertical gradients in aerosol concentrations, however, it is not clear exactly how the airborne filters should generally compare with the cloud water samples. This is because aqueous-phase production of $SO_4^=$ will contribute towards relatively higher $SO_4^=$ in the cloud water, but incomplete nucleation scavenging will contribute towards relatively lower cw$SO_4^=$. Of the eight cases shown, the airborne p-$SO_4^=$ is significantly lower than either the GLF or cw$SO_4^=$ on July 14 and 15.

The result is somewhat different for the 1984 winter $SO_4^=$ data shown in Figure 5. Here it is seen that of 11 cases, the airborne p-SO_4= is higher than the GLF p-SO_4= in 5 instances and similar in another 2. Relative to the cloud water, the airborne filters indicate similar or higher $SO_4^=$ concentrations in 9 of the 11 cases. It is important to observe here that the sampling inlets used on both aircraft during this study were not equipped with isokinetic diffusers, but rather were simply large diameter open-ended tubes.

Rounding off $SO_4^=$ is a general comparison of the GLF, airborne filter and cloud water data for 1988 summer study. In 10 of the 13 cases presented, the airborne p-$SO_4^=$ is similar to or higher than the GLF p-$SO_4^=$. The same is true in 12 of the 13 cases for the comparison of the airborne p-$SO_4^=$ with the cw$SO_4^=$. In Figure 7, the number concentration of aerosol particles measured with the ASASP and the cloud droplet number concentrations measured

with the FSSP during the filter and cloud water samples respectively are shown. With the exception of flight 37, there is good correspondence between the relative relationships of the ASASP and FSSP with the airborne $p\text{-}SO_4^=$ and $cwSO_4^=$, indicating consistency among the measurements.

These general comparisons involving $SO_4^=$ measurements show good consistency among the various measurements, particularly for the 1984 and 1988 data. Discrepancies are apparently greater for the 1982 data, although this is not supported by the airborne intercomparison data given in Table 3.

6.2 NITRATE

The general comparison of nitrate measurements for each study is shown in Figure 8-10. For the GLF, $p\text{-}NO_3^- + HNO_3$ (i.e., $t\text{-}NO_3^-$) is shown, and for the airborne filters, $p\text{-}NO_3^-$ and $t\text{-}NO_3^-$ are shown.

In all but the last 2 cases for 1982 the airborne $p\text{-}NO_3^-$ is below detection limit (i.e. absent from plot). Also, with the exception of the July 7 & 15 cases, the airborne $t\text{-}NO_{3_-}$ agrees with the GLF $t\text{-}NO_{3_-}$ to within the filter uncertainty. Interestingly, $cwNO_3^-$ is higher than the GLF $t\text{-}NO_3^-$ as well as the airborne $t\text{-}NO_3^-$, in all but the first case. This has been suggested by Leaitch et al. (1986) as being possibly due to HNO_3 deposition near the ground or poor sampling of coarse aerosols at the ground as well as in the aircraft. One factor suggesting that the NO_3^- was tied up with the coarse aerosol is that $cwNO_3^-$ concentrations correlated very highly with the calcium ion concentrations in the cloud water.

The 1984 winter results (Figure 9) for nitrate, as for sulphate, are much different than the 1982 results. Note that for many of the samples, particularly in the latter half of the study, $p\text{-}NO_3^-$ was a very significant component of the $t\text{-}NO_3^-$. In at least 10 of the 11 cases, the airborne $t\text{-}NO_3^-$ is the same as or higher than the GLF $t\text{-}NO_3^-$ to within the filter blank variability. Both the GLF and airborne $t\text{-}NO_3^-$ are lower than the $cwNO_3^-$ in the first 6 cases, which has been previously attributed to the scavenging of N_2O_5 by the cloud water (Leaitch et al. 1988). In 4 of the last 5 cases, the $cwNO_3^-$ is much lower than that measured with the filters. $P\text{-}NO_3^-$ does not appear to have been under-sampled during this study, however, as mentioned above, it is likely that much of the $p\text{-}NO_3^-$ was in the fine aerosol.

Finally, varying amounts of $p\text{-}NO_3^-$ were found in the aerosol in 1988. Still, its concentrations relative to HNO_3 were generally quite low. This has been noted for the GLF data in Tables 3 and 4 also. In at least 8 of the 13 cases, the airborne $t\text{-}NO_3^-$ concentrations are similar or higher than the GLF $t\text{-}NO_3^-$ concentrations to within the filter uncertainty. $CwNO_3^-$ is similar or lower than the airborne $t\text{-}NO_3^-$ also in at least 9 of 13 instances. The large discrepancy between cloud water and airborne filter data observed for the 1982 summer study is not evident for this summer study.

91

7. SUMMARY

These various intercomparisons and comparisons of different measurements lead to the following impressions. With respect to the sampling of sulphate on filters installed in these relatively slow-moving aircraft, it appears that any error or loss occurred in the sampling system is within the analytical and filter blank uncertainties. The comparisons done using the open-ended large diameter tube used during the winter 1984 are not particularly different from the other cases for which diffusers were used. It is clear that to accurately test inlet efficiency for sulphate retention that either further improvements in filter measurements are necessary, situations with very high concentrations must be examined or very long sampling times are required.

The situation with respect to the sampling of p-NO_3^- from these aircraft is more complicated. The winter 1984 data suggest that p-NO_3^- is being sampled as well as p-$SO_4^=$, however, it is also believed that under these conditions the p-NO_3^- is mostly located in the fine aerosol. The data from the 2 summer studies are different: the 1982 study suggests the possibility that significant p-NO_3^- was tied up in the coarse aerosol and that the sampling of it was poor; the 1988 study suggests that p-NO_3^- was a minor component relative to HNO_3 and that sampling errors were within the analytical and filter blank uncertainties.

Although inlet losses of sulphate and nitrate are not clearly indicated here, it is clear that there is room for further testing of these inlet systems.

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Table 1:   **FILTER TYPES**

1982 Triple Filter Pack   1984   Triple Filter Pack
- 47 mm filters   - 94 mm filters
- teflon   - quartz-fibre
- nylon   - NaCl-impregnated cellulose
- K_2CO_3-impregnated W41   - K_2CO_3-impregnated cellulose

1988 Triple Filter Pack
- 47 mm filters
- teflon
- nylon
- K_2CO_3-impregnated W41 or
citric acid-impregnated W41

Table 2:   **INLET TYPES**

Year	Aircraft	Type (dimensions approximate)
1982	Twin Otter (50-60 m/s)	Isokinetic teflon diffuser on 1.6 cm. I.D. curved aluminum tube; F.R. 30-50 l/m.; length 1 m.; 15 cm. above skin; mounted ahead of engines.
	Beech 18 (50-60 m/s)	Isokinetic teflon diffuser on 1.9 cm. curved aluminum tube with 0.64 cm. alum./teflon isokinetic inset; F.R. 30-50 l/m.; length 1 m.; 15 cm. above skin; mounted ahead of engines.
1984	Twin Otter	4.5 cm. I.D. teflon-coated curved aluminum tube followed by plexiglass cyclone; F.R. 300-500 l/m.; length 1 m.; 22 cm. above skin; mounted ahead of engines.
	DC-3 (50-60 m/s)	Open-ended 4.45 cm. curved aluminum tube with 2.5 cm. teflon tube insert, and brass cyclone separator at 2 m.; F.R. 300-500 l/m.; length 3 m.; 30 cm. off skin; mounted ahead of engines.
1988	Twin Otter	Blunt-ended isokinetic aluminum diffuser mounted in small pylon with teflon tube insert; O.D. of tip 1.3 cm; teflon tube I.D. 0.3 cm opening to 0.6 cm; F.R. 30-50 l/m.; length 19 cm.; 30 cm off skin; mounted near mid-point of aircraft behind engines.
	DC-3	Rectangular teflon block with two 1.9 cm. I.D. curved air passages approx. 0.7 m.long milled; isokinetic teflon diffuser; 30 cm. off skin; mounted ahead of engines.

94

Table 3:   **DIRECT FILTER INTERCOMPARISONS**

1982	Aircraft	p-$SO_4^=$	p-NO_3^-	p-NH_4^+	HNO_3
		(————————— µg m^{-3} —————————)			
July 5	Twin Otter	2.16	0.84	1.02	0.39
	Beech 18	2.99	0.94	0.93	0.62
Norm.*	Twin Otter	1.0	0.39	0.47	0.18
	Beech 18	1.0	0.31	0.31	0.21
July 17	Twin Otter	21.0	0.32	5.50	1.80
	Beech 18	22.9	1.84	5.48	4.92
Norm.	Twin Otter	1.0	0.02	0.26	0.09
	Beech 18	1.0	0.08	0.24 0.21	

1984	Aircraft	p-$SO_4^=$	p-NO_3^-	p-NH_4^+	HNO_3
		(————————— µg m^{-3} —————————)			
Feb. 21	Twin Otter	1.76	0.07**	0.37	0.08**
	DC-3	1.36	0.07	0.41	0.08
Norm.	Twin Otter	1.0	-	0.21	-
	DC-3	1.0	-	0.30	-
Feb. 23	Twin Otter	2.40	5.54	2.01	0.08
	DC-3	3.39	8.15	2.83	0.08
Norm.	Twin Otter	1.0	2.31	0.84	-
	DC-3	1.0	2.40	0.83	-

1988	Aircraft	p-$SO_4^=$	p-NO_3^-	p-NH_4^+	HNO_3
		(————————— µg m^{-3} —————————)			
Aug. 27	Twin Otter	3.82	0.55	1.40	2.78
(0.6 km)	DC-3	3.74	<0.1	1.50	2.03
Norm.	Twin Otter	1.0	0.14	0.37	0.73
	DC-3	1.0	<0.03	0.40	0.54

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* Normalized to sulphate concentration

** Detection Limit

Table 4: COMPARISONS OF 1988 FILTERS AT DIFFERENT ALTITUDES

Flight 7:

Aircraft	Alt. (km)	Pres. (mb)	p-SO$_4$$^=$	p-NO$_3$$^{-*}$	p-NH$_4$$^+$	HNO$_3$	AS	FS
			(------------------------- μg m^{-3} -------------------------)				(cm^{-3})	
Egbert	0.2		6.67	0.86	2.06	2.64		
DC-3	0.6	943	2.73	0.37	0.92	1.72		
DC-3	1.1	877	2.40	0.86	0.35	1.32		
T.O.	1.8	811	3.14	bdl	0.91	1.39	732	
Cloud W.	2.1	778	1.39	1.51	0.47			695

Flight 13:

Aircraft	Alt. (km)	Pres. (mb)	p-SO$_4$$^=$	p-NO$_3$$^{-*}$	p-NH$_4$$^+$	HNO$_3$	AS	FS
			(------------------------- μg m^{-3} -------------------------)				(cm^{-3})	
Egbert	0.2		4.86	0.35	1.95	2.10		
DC-3	0.6	941	6.34	0.05	2.00	1.56	>500	
DC-3	1.3	835	4.97	bdl	1.51	1.82	>500	
T.O.	1.8	810	3.42	bdl	0.81	1.23	338	
Cloud W.	1.6	825	3.75	2.28	1.36			410

Flight 48:

Aircraft	Alt. (km)	Pres. (mb)	p-SO$_4$$^=$	p-NO$_3$$^{-*}$	p-NH$_4$$^+$	HNO$_3$	AS	FS
			(------------------------- μg m^{-3} -------------------------)				(cm^{-3})	
Egbert	0.2		5.46	0.66	2.18	4.28		
DC-3	0.6	947	2.16	0.34	0.99	2.38	489	
T.O.	1.6	825	4.03	0.01	1.49	3.32	609	
Cloud W.	1.9	804	1.85	1.89	0.95			303
Cloud W.	2.4	753	0.69	0.82	0.15			384

- AS refers to the number concentrations of aerosol particles measured with the ASASP-100X.
- FS refers to the number concentrations of cloud droplets measured with the FSSP-100.

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* In cloud water samples, refers to t-NO$_3$$^-$

* In cloud water samples, refers to t-NO$_3$$^-$

* In cloud water samples, refers to t-NO$_3$$^-$

Muskoka, Summer 1988
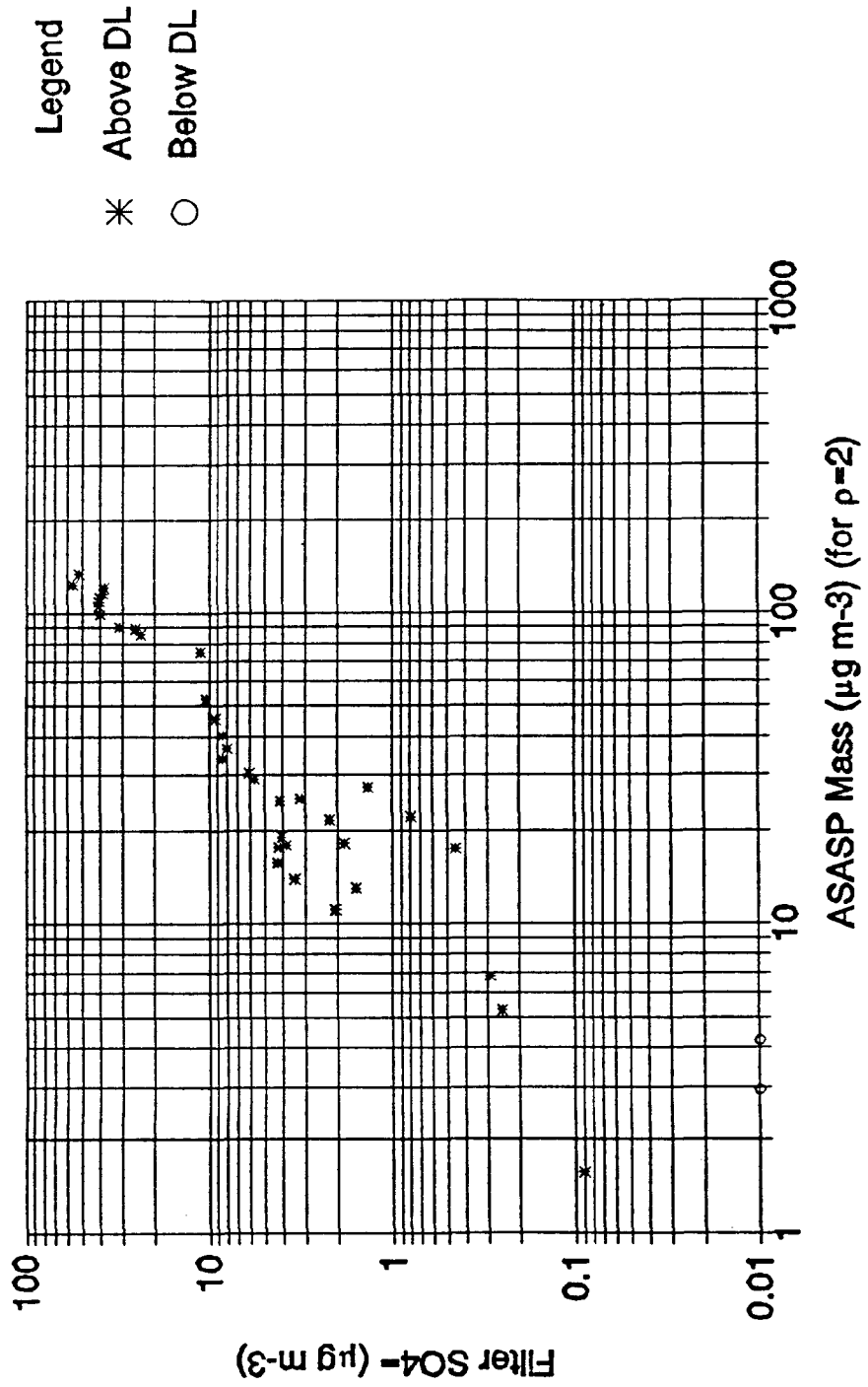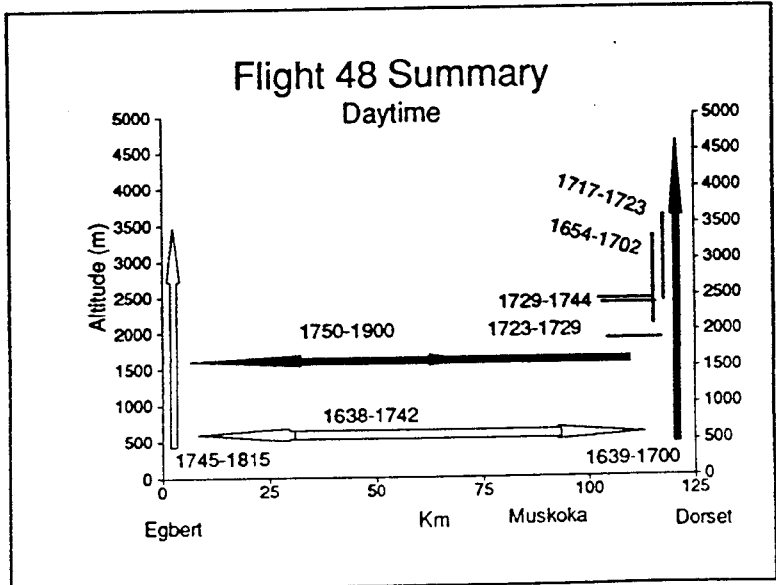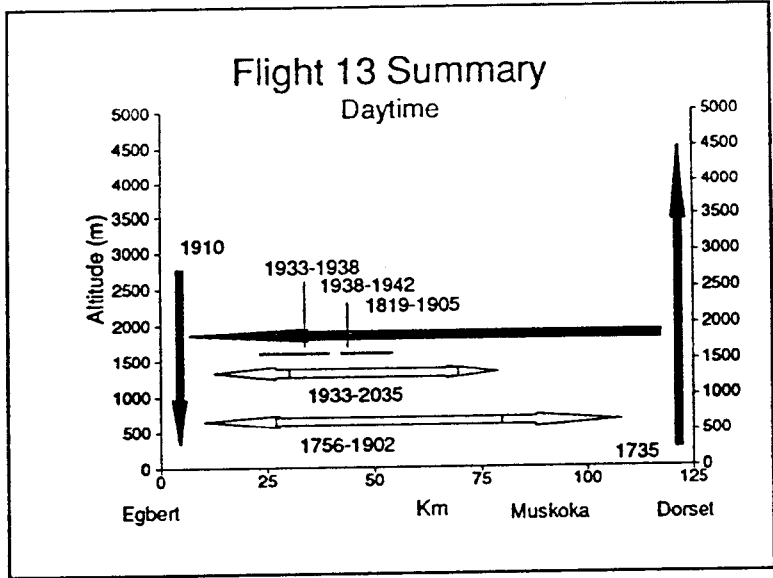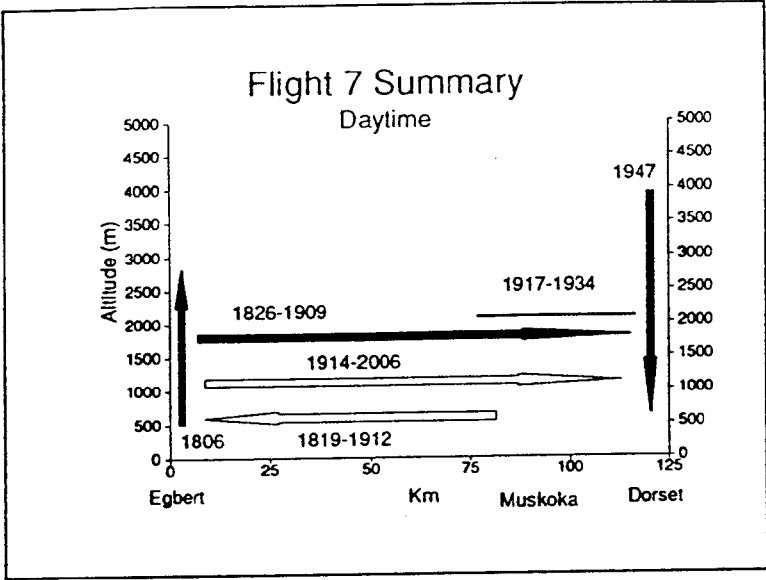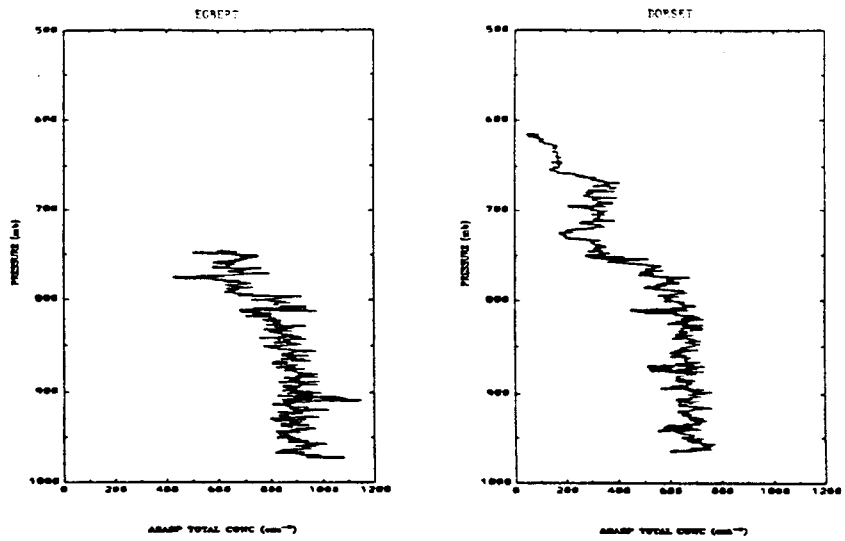
Legend
Above DL   ✳
Below DL   ○

[Figure 1]

[Figure 2]

[Figure 3]

[Figure 4]

100

[Figure 5]

101

Sulphate in Air and Cloud (Summer 1988)

[Figure 6]

102
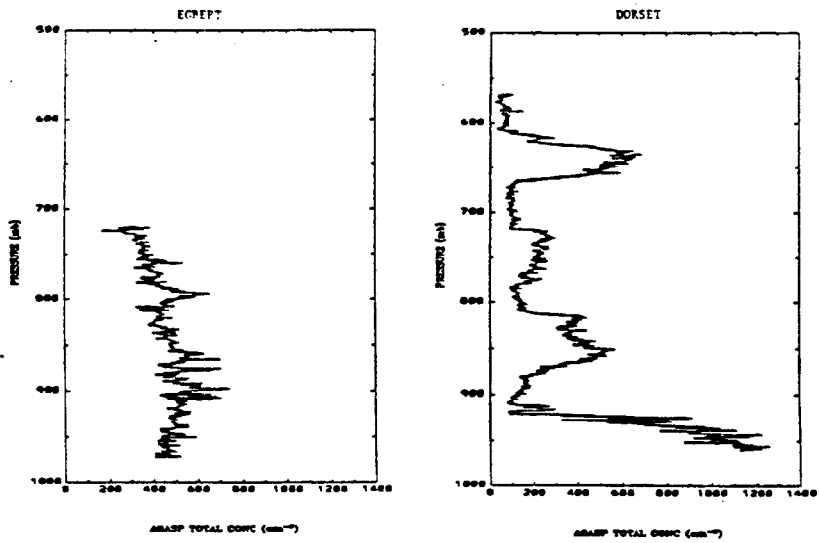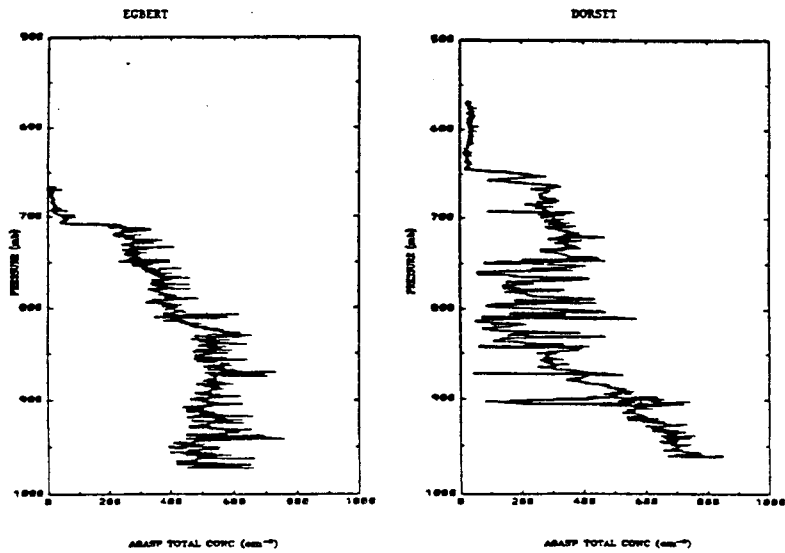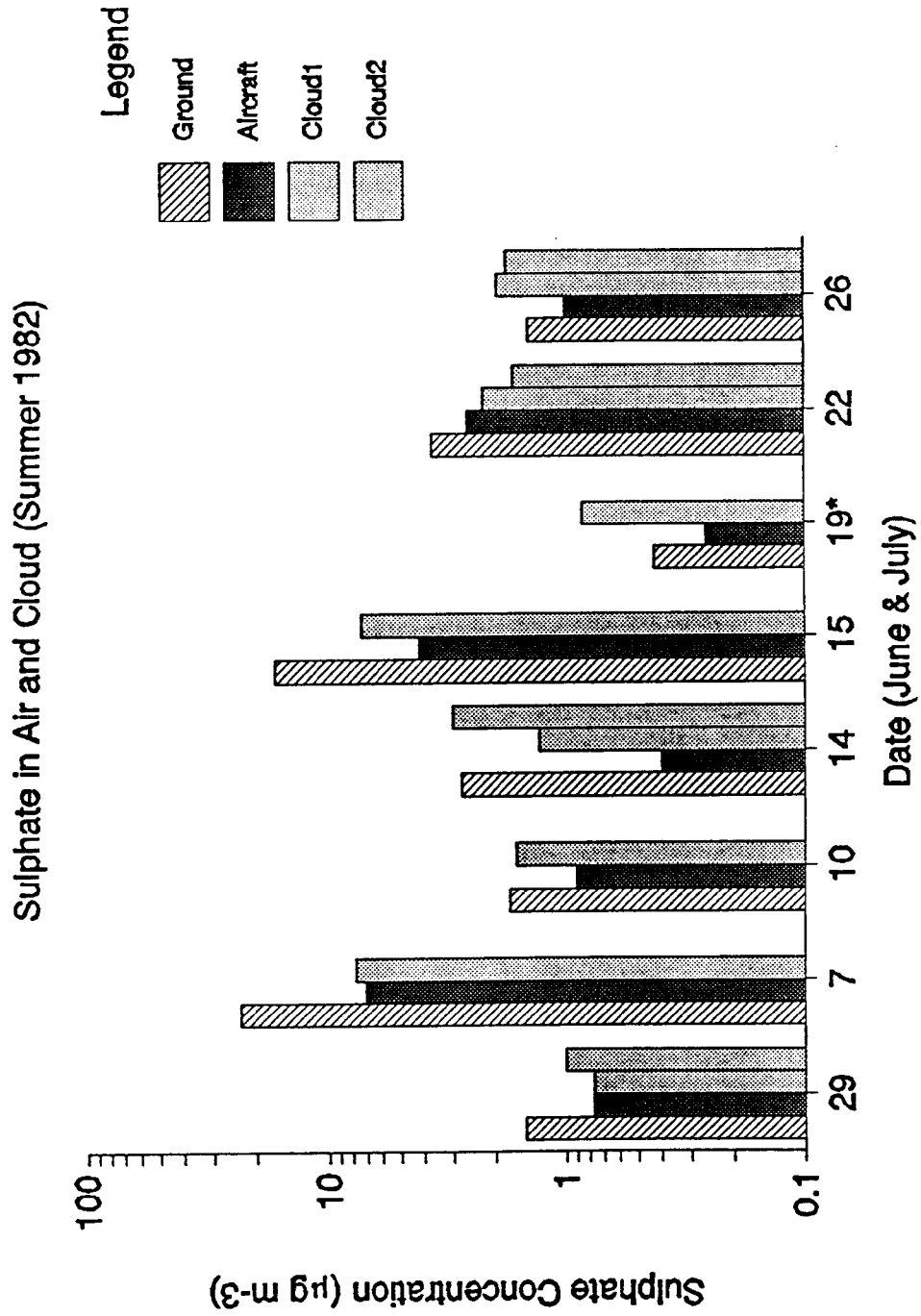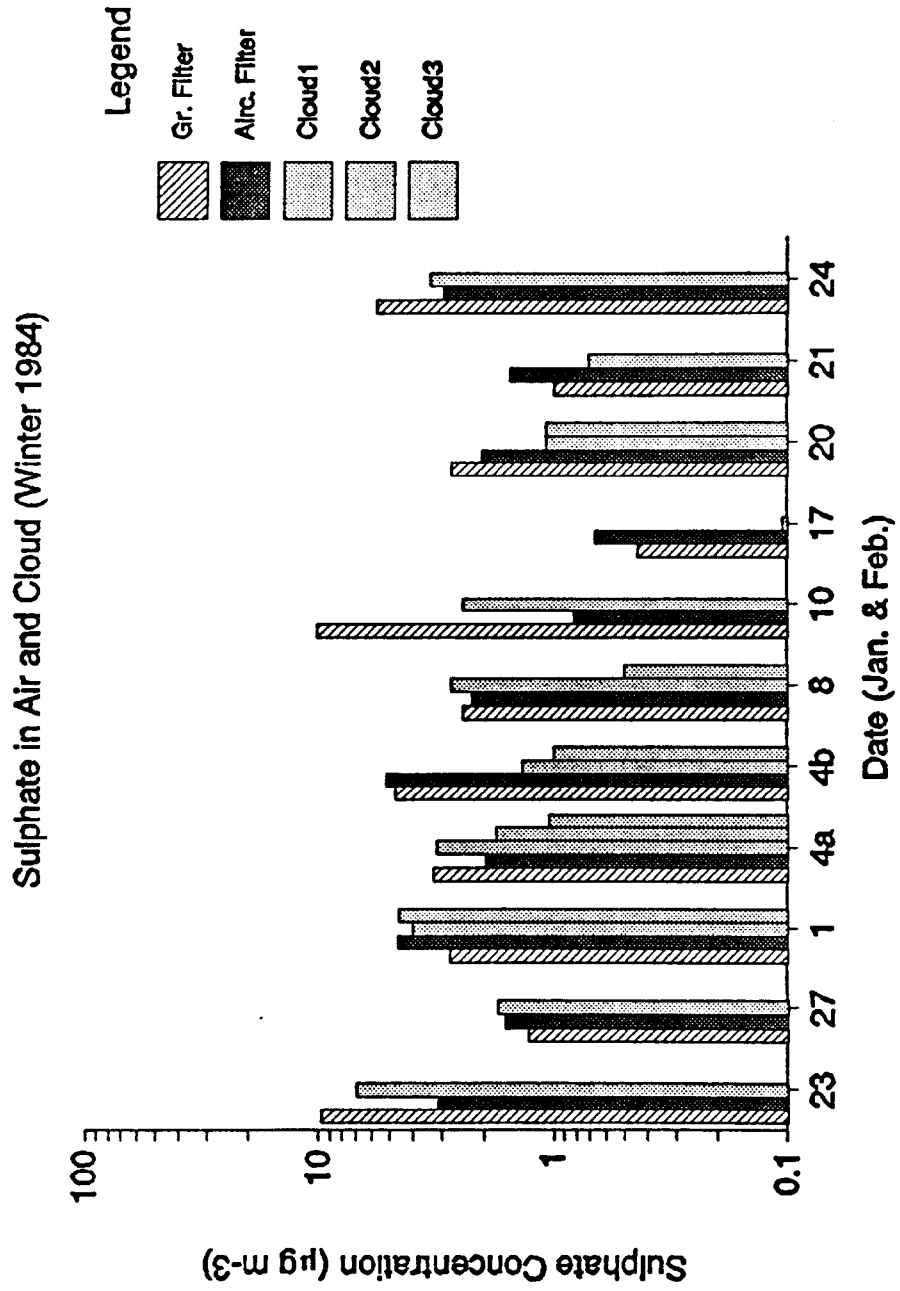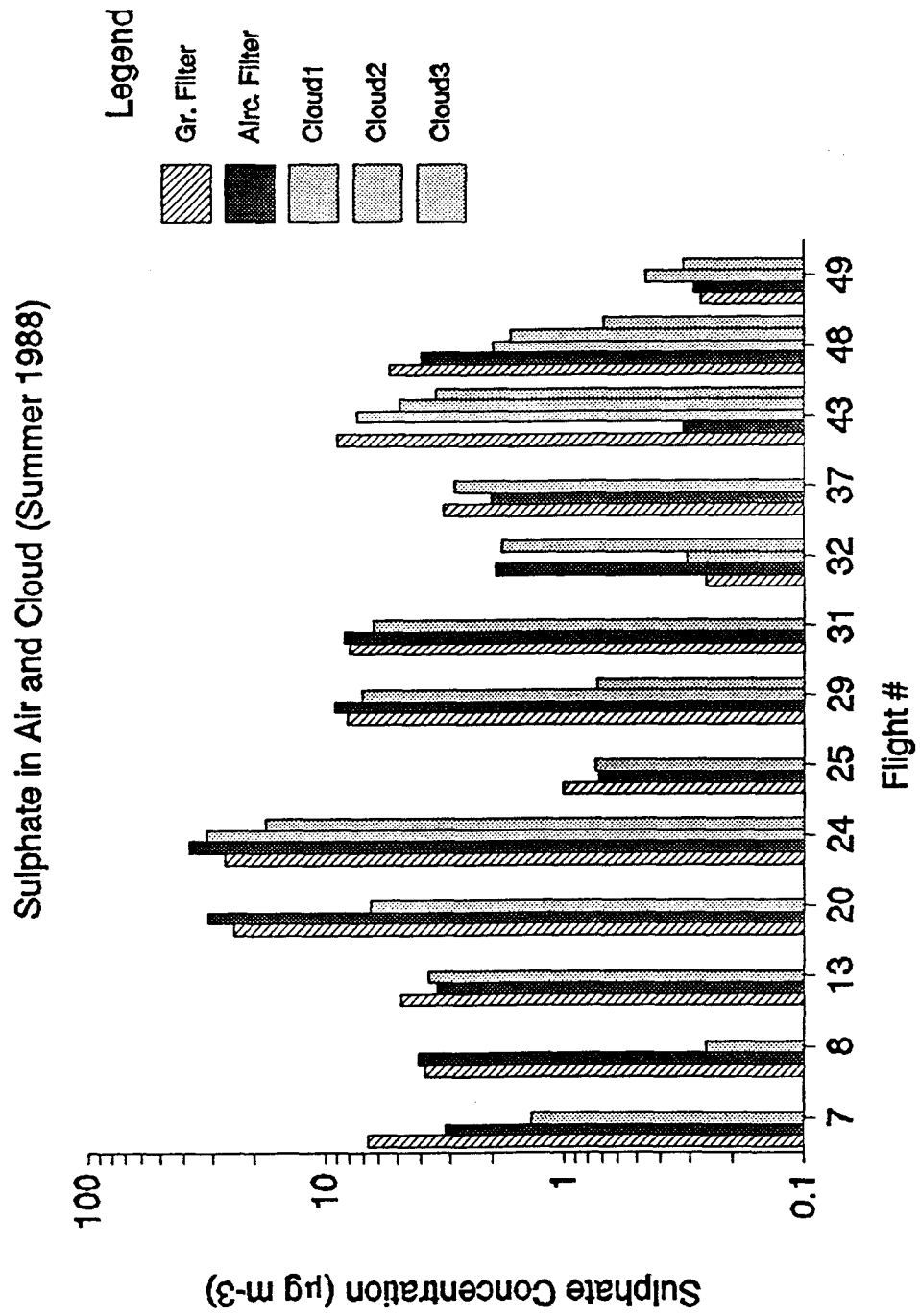
CDNC and APNC (Summer 1988)

Legend

ASASP
FSSP1
FSSP2
FSSP3

Number Concentration (cm-3)

Flight #

[Figure 7]

103
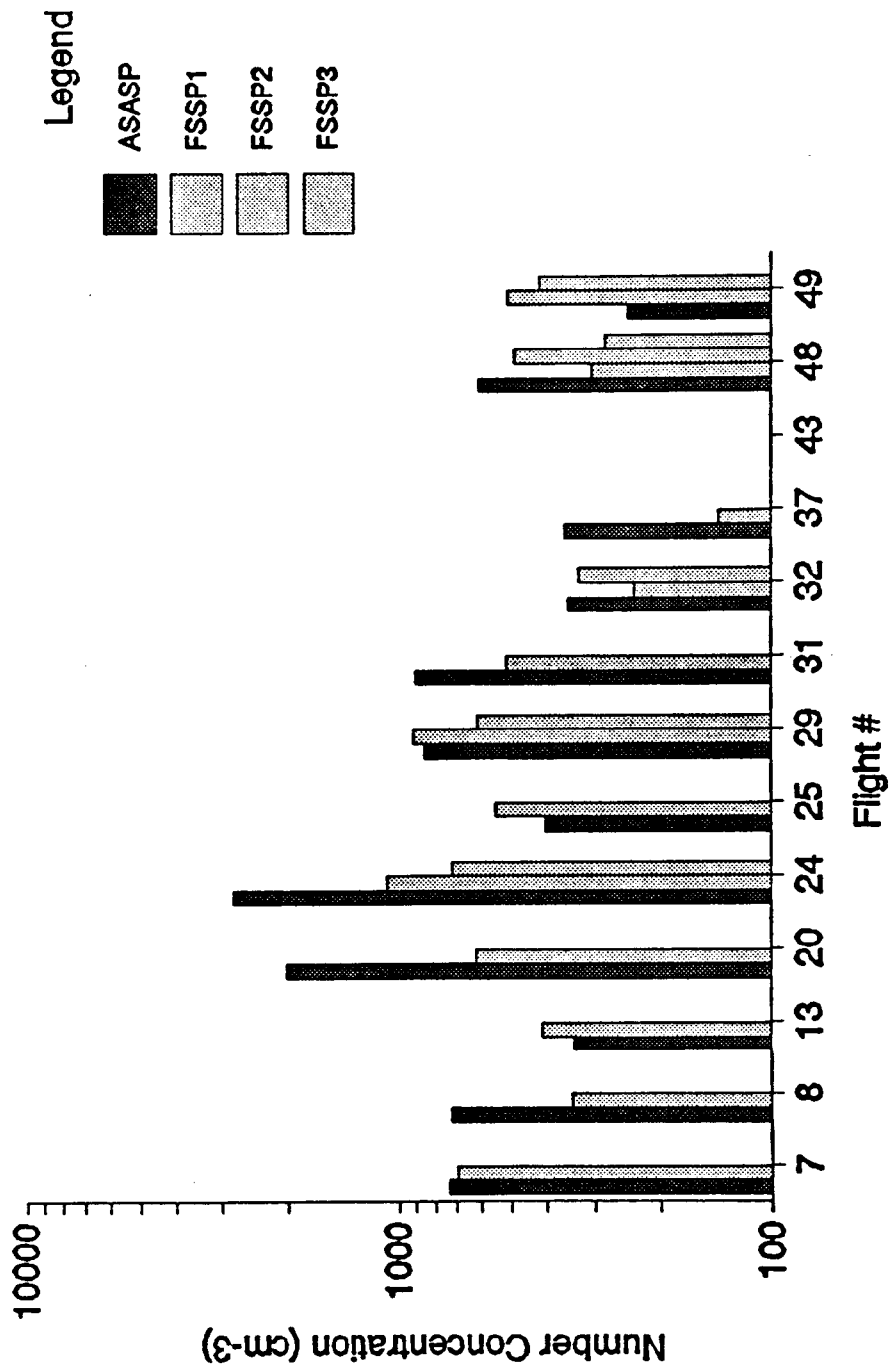
Nitrate in Air and Cloud Water (Summer 1982)

Legend

- G. Flt. t-NO3-
- A. Flt. p-NO3-
- A. Flt. t-NO3-
- Cloud1
- Cloud2

[Figure 8]

104
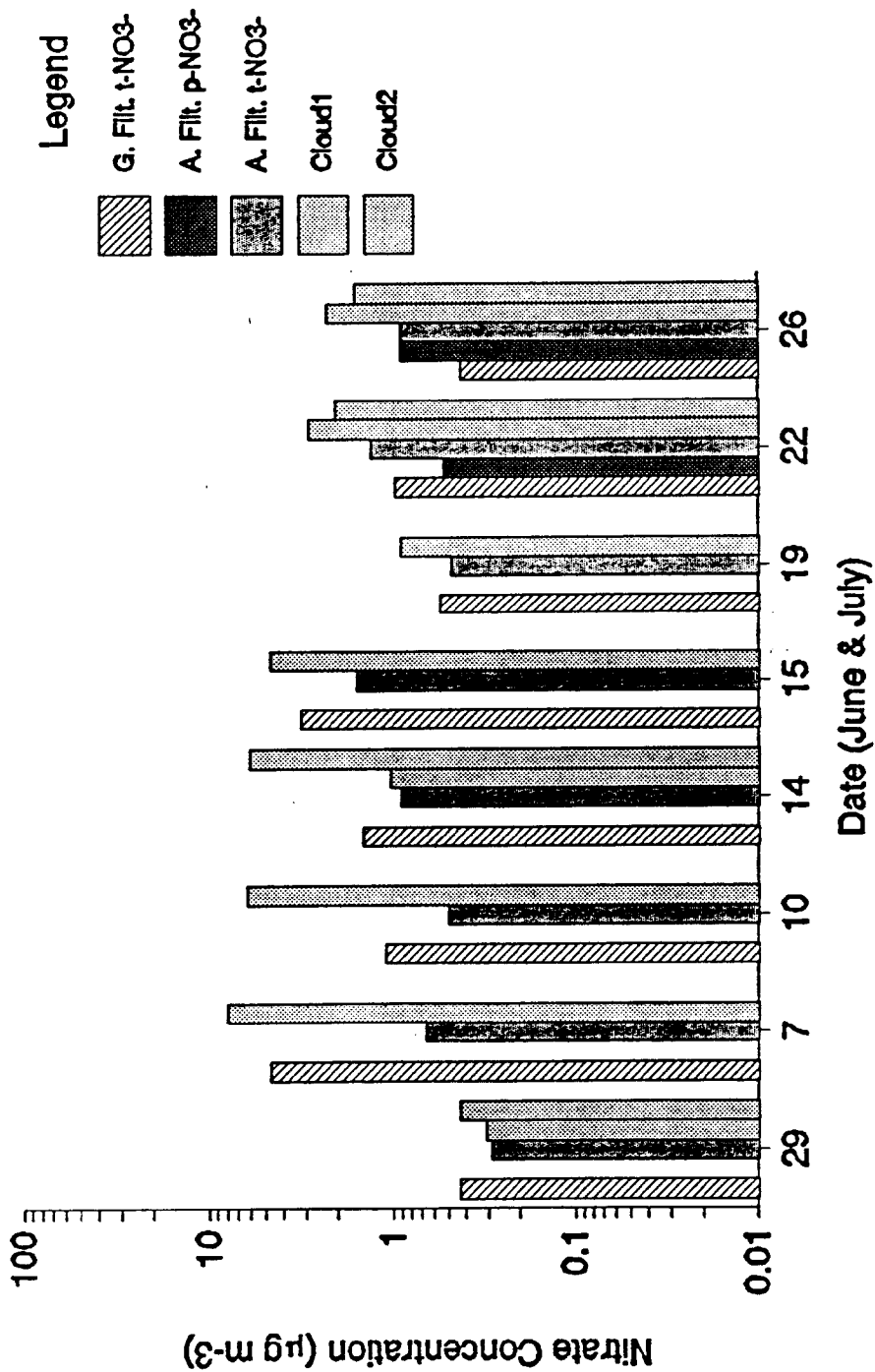
Nitrate in Air and Cloud (Winter 1984)

[Figure 9]

[Figure 10]

106

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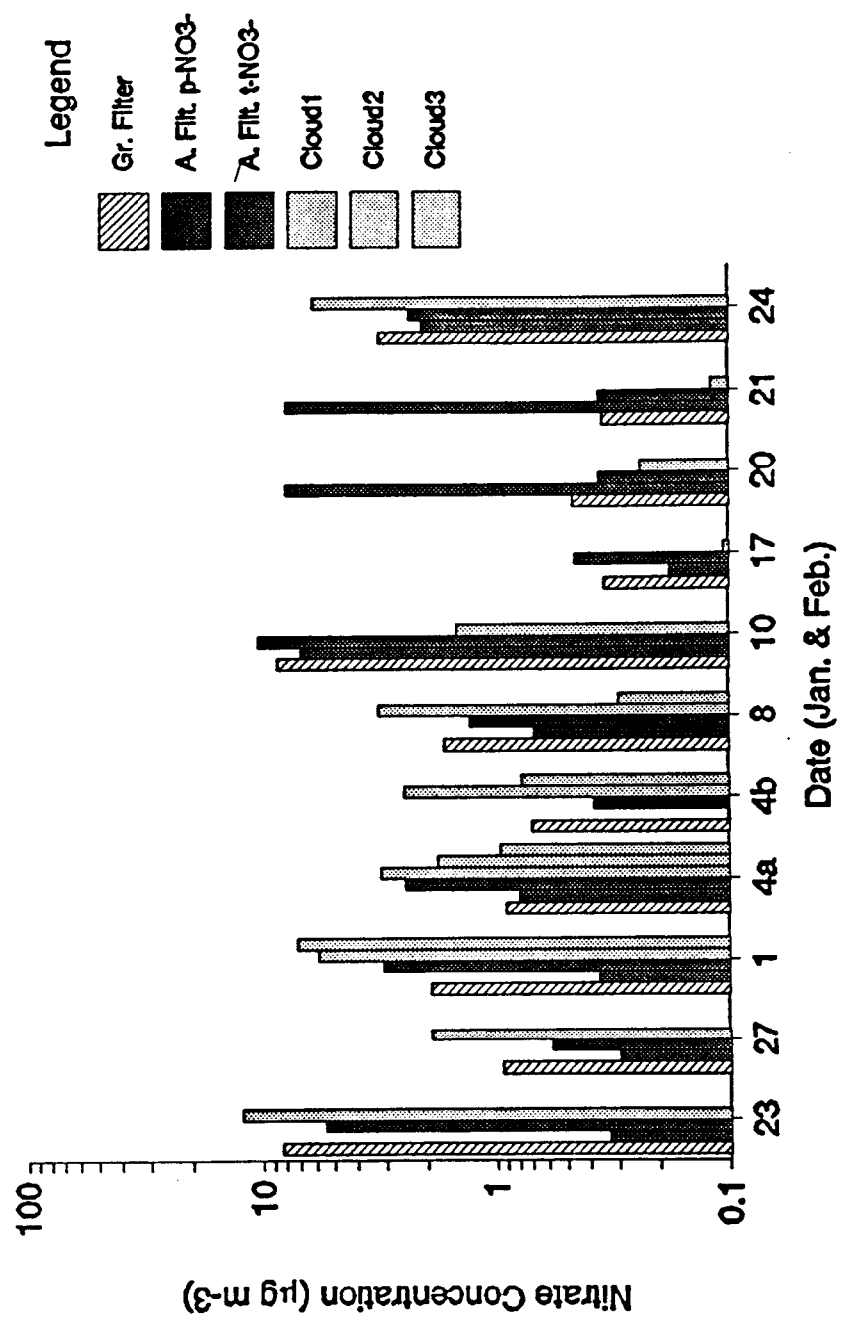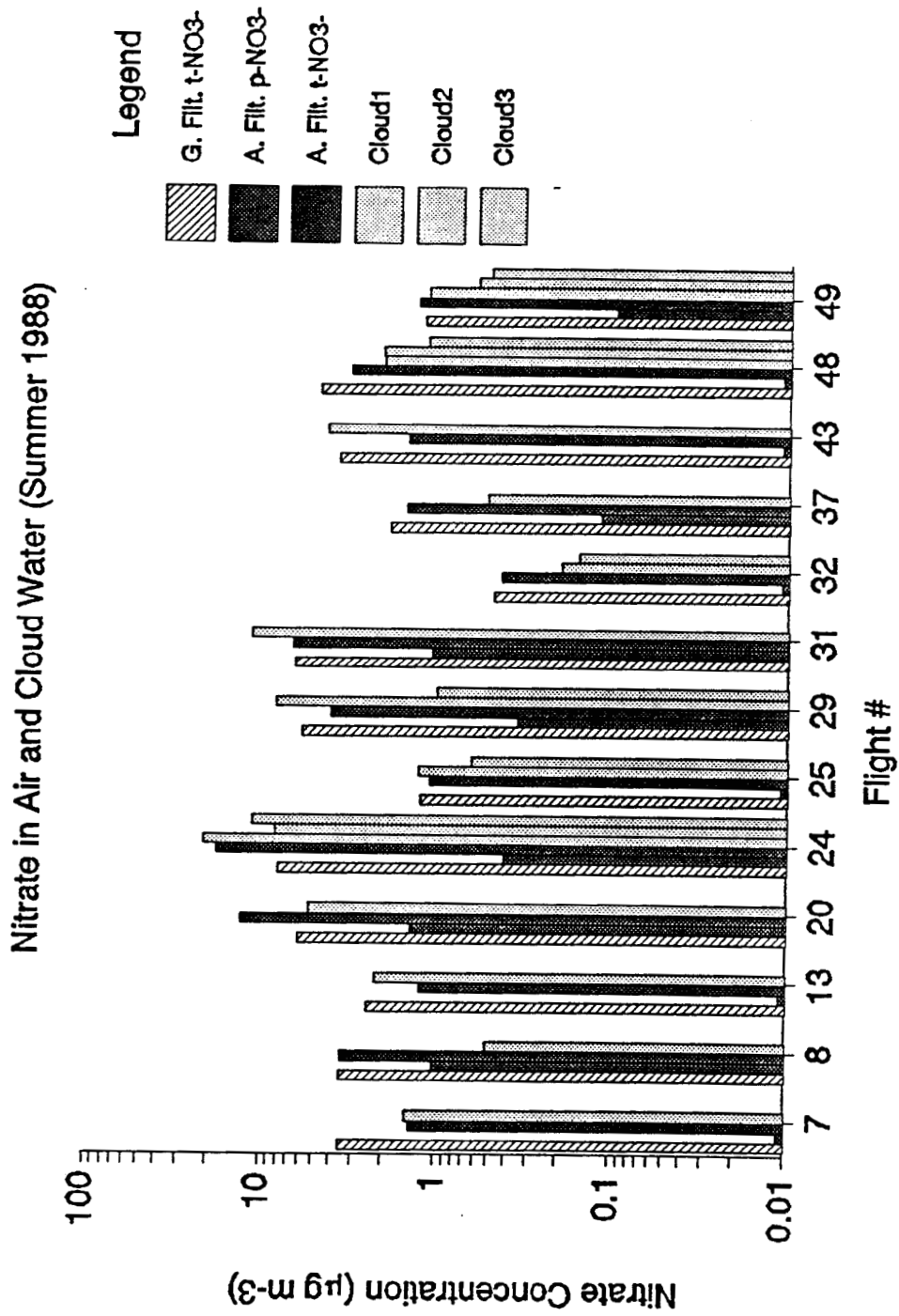
DISCUSSION

Radke: In your intercomparison of the four aircraft, did each aircraft operator do his own chemistry, or was the chemistry all done the same?

Leaitch: No, it was done independently. There was an audit done among the various places that were doing the various analyses.

Radke: So you think they were, in fact, fully intercomparible in the analysis.

Leaitch: As far as I understand, they are.

Deshler: Were there large differences in the inlet designs?

Leaitch: The Twin Otter and the DC-3, I showed you the pictures of the two. They were radically different. In fact, I didn't expect that the DC-3 inlet would give us clearly good results, but through all the comparisons of one form or another, they do suggest that they are reasonable.

Twohy: Did you make comparisons of your overall sampling efficiency of water collected by the rods versus total liquid water content to make sure you weren't undersampling the water drops?

Leaitch: I believe that we probably are undersampling. I know from wind tunnel tests that have been done in the past that the standard Mohnen collector that we use is only about 50 percent efficient. That's operating even at fairly large droplet sizes. I'm not sure why that happens. The modified collector we built seemed to have a better comparable flux efficiency. It wasn't appreciably better or appreciably worse. I'm reluctant to attribute that to fall off of droplet size at the moment.

Twohy: But if your rods weren't collecting all the water, wouldn't your comparison to the filter samples be biased?

Leaitch: No that would only be the case if there was a variation of the collection efficiency. It's not the case, because we applied correction for liquid water content, well not correction, but we applied the liquid water content to the cloud water data.

Huebert: I was trying to eyeball the differences between the ground measured concentrations and the aircraft one. My biased eye thought that they aircraft ones were lower. Did you do the statistics on that?

Leaitch: No I haven't as of yet. We have the same thing for some other studies that I will be putting into the extended abstract. I haven't done any statistics on that sort of thing. They generally are lower which is not unexpected because there measurements usually suggest that aerosol concentrations are lower off the ground.

Sheridan: The airspeeds were very different for these planes. Did you adjust the volumetric flowrate?

Leaitch: For the Twin Otter and DC-3, the airspeeds were identical. Those two aircraft did side by side formations for the sampling period. The Beach-18 and the G-I flew at their own speed. They covered the same area during the same time, they just went over it longer.

The Drying of Hydrated Aerosols by the De-Iced Particle Measuring Systems Aerosol Spectrometer Probes (ASASP, PCASP)

By

J. Walter Strapp, W.R. Leaitch, and P.S.K. Liu

Walter Strapp is a Research Meteorologist with the Atmospheric Environment Service of Environment Canada. He received a Masters Degree in Meteorology from McGill University in 1977. He has since been actively involved in airborne research in cloud physics and cloud chemistry, including development and evaluation of airborne instrumentation.

INTRODUCTION

The measurement of atmospheric aerosol size distributions has advanced significantly in the past decade with new technological advances in electronics and laser detection systems. A family of probes designed and manufactured by Particle Measuring Systems Inc. (PMS) has been used extensively by the scientific community, two of which have been actively used for airborne measurements. There have been a number of studies of the response of these instruments which have appeared in the scientific literature. Most of these studies have focussed on size calibration of the instruments, including absolute accuracy and resolution limits, the effect of Mie resonances, and the response to differing refractive indexes and adsorbing particles (Pinnick and Auverman, 1979; Garvey and Pinnick, 1983; Soderholm and Salzman, 1984; Yamada et al. 1986; Szymanski and Liu, 1986; Knollenberg, 1989; Pueschel et al. 1990). There has been little discussion of the potential modification of the aerosol by the probes' sampling technique. This study examines one characteristic of the delivery systems of the deiced airborne PMS Active Scattering Aerosol Spectrometer Probe (ASASP) and the PMS Passive Cavity Aerosol Spectrometer Probe (PCASP).

Leaitch and Isaac (1990) have reported on tropospheric aerosol size distributions over eastern North America using a deiced ASASP-100X. They contend that the probe dries the aerosol before sampling, largely based on the observation that clear air aerosol distributions show no variation attributable to relative humidity. This study provides the first direct evidence of this behavior, by comparing size distributions of a deiced PMS PCASP probe to those of a non-obtrusive PMS FSSP-300 probe.

EXPERIMENTAL

The PMS ASASP-100X is an airborne version of the wide angle open cavity laser spectrometer, housed in an aerodynamic canister and normally mounted on the exterior of the aircraft. Of particular interest here is the sampling inlet system. Air is forced through a nose cone by the forward motion of the aircraft and decelerated into a collection chamber. A constant volume pump then pulls nominally 1 cm^3s^{-1} of air through a needle inlet 150um in diameter into the interior of the probe canister. A new version of the probe, the Passive Cavity Aerosol Spectrometer Probe (PCASP-100X), moved the sensing area external to the laser in order to improve stability and sensitivity but no changes were made to the sampling technique. There are several factors which may change the relative humidity of the sampled air in both probes: the deceleration of the air before ingestion, the heated inlet needle, the heating of the interior of the canister by probe electronics, and the interaction with the dry focussing sheath flow. All of these factors could be active in drying or partially drying hydrated aerosol before sizing by the probe.

The PMS Forward Scattering Spectrometer Probe (FSSP) 300 was developed specifically to make better measurements of Polar Stratospheric Cloud (PSC) particles (Dye et al. 1990). The probe is similar to the PMS FSSP-100, measuring individual particles by detecting the light they scatter while passing through a focussed laser beam. The probe is configured to measure from nominally 0.3 to 20 μm (for a refractive index of 1.58) in 31 size channels. Of particular importance here is the fact that the FSSP-300 measures aerosol in a size region overlapping the PCASP-100X, but is much less obtrusive. Particles pass through the laser detection area by the forward motion of the aircraft, and are subject to only minor flow perturbations by the probe geometry (Norment, 1988).

During the period of February - April 1990, the Atmospheric Environment Service conducted a field program designed to collect air and cloud chemistry data. The Institute for Aerospace Research (IAR) Twin Otter research aircraft was instrumented for chemical and microphysical measurements, including a PCASP-100X (0.1-3 μm) and on several occasions a FSSP-300 (0.3-20 μm). During these occasions the aircraft was flown in a well mixed boundary layer through a range of relative humidities. One of these cases will be examined below in order to discern indications of drying by the de-iced PCASP.

RESULTS AND DISCUSSION

The data presented herein are from a Twin Otter flight on the afternoon of 24 April 1990 out of North Bay, Ontario. Conditions were partly cloudy with small cumuli based at approximately 1800 m MSL. A vertical profile was performed which indicated a very well mixed layer (constant potential temperature and H_2O mixing ratio) up to cloud base, and relative humidity increasing from approximately 40% at low altitude to nearly 100% at the top of the layer. The PCASP also displayed total number concentrations and size distributions which varied insignificantly with height (relative humidity), consistent with

110

measurement of a well mixed and dried aerosol population. In contrast the FSSP-300 number concentrations increased rapidly with height once relative humidities of approximately 70% were exceeded, consistent with hygroscopic growth of particles and thus detection of new particles in the FSSP-300 size range. Tang (1977) has described the hygroscopic growth of NH_4HSO_4 and $(NH4)_2SO_4$, which deliquesce at 39% and 79% relative humidities respectively. The rapid growth of particles seen by the FSSP-300 at relative humidities > 70% seems to be thus consistent with an aerosol composed of $(NH4)_2SO_4$. A filter exposed by the aircraft in the mixed layer less than one half hour before this vertical profile strongly indicates the presence of mostly $(NH4)_2SO_4$ and a small amount of NH_4NO_3 (Table 1), and thus the indications of hygroscopic aerosol growth from FSSP-300 particle measurements are consistent with the aerosol composition.

The actual 30 second average variations of the PCASP and FSSP-300 size distributions with height (relative humidity) are shown in Figure 1. The PCASP spectra use bins recommended by the manufacturer for non-absorbing aerosol of refractive index 1.585. The FSSP-300 channel diameters are similar to those recommended by the manufacturer (r=1.585 + 0i), but we have grouped some channels together in the highly resonant region of the Mie scattering curve to avoid multivalued response. These groupings it turns out have very little effect on interpretation of the distributions reported here. The first observation from Figure 1 is that the FSSP-300 distributions shift to larger diameters with increasing relative humidity, consistent with hygroscopic growth of the aerosol. The proximity of the FSSP-300 distributions at lower relative humidities suggest that the aerosol at 40% relative humidity is close to dry. The PMS PCASP distributions in contrast are nearly identical throughout the range of relative humidities. The most likely explanation of this behavior is that the PCASP has dried the aerosol before measurement. It is also evident that there is a shift between the PCASP spectra and the driest FSSP-300 spectrum; this observation will be discussed later.

The shift of the FSSP-300 spectrum with increasing relative humidity also implies a shift in the particles refractive index from the nominal 1.585 used by the manufacturer to a value approaching 1.33 for greatly hydrated particles. Since the manufacturer's calibration assumes a constant refractive index of 1.585, there is likely a calibration change with change in relative humidity due to the refractive index change. In order to evaluate the magnitude of this effect, Mie scattering calculated were performed for the probe for a refractive index of 1.33 + 0i, and new diameters for the bin thresholds were evaluated. The calculations reveal that as the relative humidity increases in Figure 1, at least part of the change in the spectrum could be due to the change in the particles' optical properties. Figure 2 displays the spectra for the 90% relative humidity case of Figure 1, but with the predicted size spectrum for the particle assuming a refractive index of 1.33. It is evident that the effect of changing refractive index on probe response is small compared to the observed spread in the FSSP-300 spectra with relative humidity, indicating that this is an observation of hygroscopic growth of the aerosol and not a change in optical response. Kim and Boatman (1990) have reported on response changes of a non-deiced ASASP-100X aerosol probe to changes in relative humidity (refractive index). Although their general conclusions of

111

calibration shifts seem to be relevant to the PMS FSSP-300 probe, we contend that they are not relevant to our deiced PCASP probe, since the particles are evidently dried before sampling.

Some of the difference evident between the PCASP spectra and the PCASP 40% relative humidity spectrum in Figure 1 could be due to a calibration error on the PCASP. Calibrations were performed on the probe several months after the flights with electrostatically classified NaCl and latex particles. The probe was found to consistently undersize throughout its range, probably due to a bias in the calibration gain. Application of new bin intervals based on this calibration bring the PCASP size spectrum much closer to that indicated by the FSSP-300 at low relative humidities, as shown in the comparison of the corrected PCASP size spectrum and the evidently near dry FSSP-300 size distribution at 40% relative humidity in Figure 3. It is however important to note that the sample area used for the FSSP-300 is a theoretical value, and there are presently no techniques for experimental determination. In this light, the agreement noted above may be somewhat fortuitous. However, this study does indicate that comparisons of PCASP and FSSP-300 size distributions for determining better estimates of FSSP-300 sample volumes are suspect without careful size calibration and consideration of relative humidity effects and calibration offsets.

GROWTH CALCULATIONS

The theoretical and experimental results of Tang (1977) provide sufficient information to estimate the growth of our $(NH4)_2SO_4$ aerosol size distributions with relative humidity. Calculations of the growth of an ammonium sulfate aerosol particle spectrum have been performed to provide some indication of the expected growth of the spectra observed in Figure 1. The corrected PCASP spectrum of Figure 3 has been used as a dry aerosol starting point, and estimates have been made of the spectra for the relative humidities of the observed spectra in Figure 2. The original spectra were assumed to be 75% ammonium bisulfate by mass with an insoluble core of 25% mass, and a total density of 2.0 gcm^{-3}. The expected equilibrium sizes of pure ammonium bisulfate were taken from Tang (1977) as input into simple calculations of the growth of the composite particle. The results shown in Figure 4 display several similarities to the observed spectra. The observed spectra are close together at the lower relative humidities and diverge rapidly at relative humidities in excess of 70%. The calculated growth show no growth until 79%, and then grow to roughly the same sizes as observed by the FSSP-300. The shift in the observed spectrum at the lower relative humidities may be due to the presence of the small fraction of NH_4NO_3 (Table 1) , which in the experiments of Tang (1980) had already deliquesced at 30% relative humidity, or may be due to the hysterisis indicated by Tang (1980) for evaporating hydrated $(NH_4)_2SO_4$. The spectrum observed at 90% relative humidity appears to be more advanced in growth, but as figure 6 reveals the agreement is quite good with the 95% predicted spectrum, which may be within the accuracy of our measured relative humidity. In general the observed spread between the 40% and 90% observed spectra are quite consistent with

112

the calculated spectra. Although there are some assumptions in these calculations, this simple model depicts the observed behavior of the FSSP-300 spectra reasonably well, and support the contention that the shift in the FSSP-300 size spectrum with relative humidity is indeed due to hygroscopic growth.

LABORATORY TESTS

Laboratory tests of the PCASP were performed to provide further evidence of drying by the deicing heaters of the PCASP. Although the actual conditions encountered by a wing mounted PCASP could not be exactly duplicated, attempts were made to simulate its airborne configuration. The probe was operated in a cold room near 0 C, and air was sucked through the sampling nose at a flow rate similar to that estimated for the actual operation on the aircraft. A NaCl aerosol was aspirated into the room , and the relative humidity was kept near 100%. The effect of the heaters was clear and reproducible, in this case shifting the spectrum mode from channel 5 to channel 3, and steepening the tail of the distribution. After heaters were turned off, it took approximately 4 minutes for the distribution to obtain its unheated values.

CONCLUSIONS

The above observations indicate a modification of tropospheric aerosol size distributions measured by the deiced PMS PCASP and ASASP probes by their delivery systems; they dry aerosol in the submicron size range before sampling. The probe deicing heaters, the combined heating of the canister and its contents by the electronics, and the focussing of the sample flow by a dried sheath flow are all possible drying factors, although only the drying effect of the deicing heaters was identified in this study. The appropriate method to determine whether non deiced ASASP and PCASP probes have similar drying effects would be to repeat the flight tests with the deicing heaters turned off, which we hope to achieve in flights in the near future. In view of the possible beneficial effects of a dried aerosol measurement , the deiced PCASP may provide a superior alternative for tropospheric aerosol measurements in many studies. The effects of the probe drying on the evaporation of cloud droplets, and the interpretation of interstitial aerosol measurements requires further investigation.

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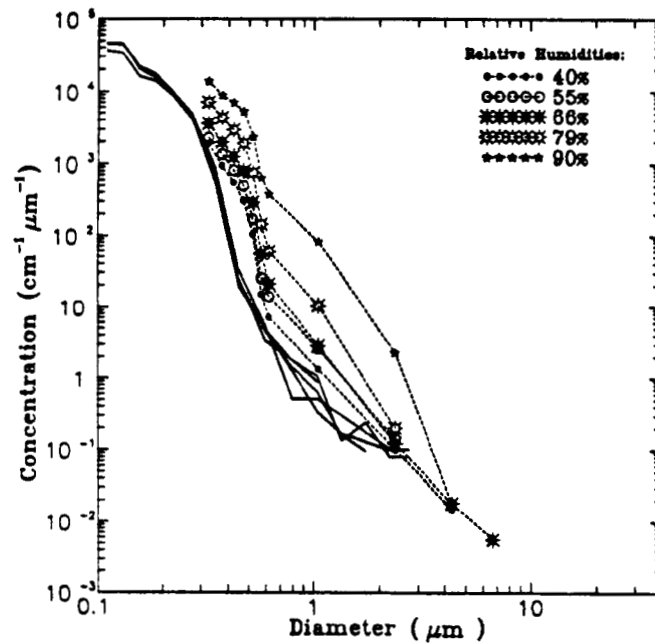
[**Figure 1**]--Comparisons of aerosol spectra observed by a PMS PCASP probe (solid) and a PMS FSSP-300 probe (dotted) in a well mixed boundary layer at relative humidities of 40, 55, 66, 79 and 90%. PCASP spectra are uncorrected for size calibrations. FSSP-300 spectra use the manufacturer's calibration for aerosol refractive index of 1.585 + 0i. All spectra are normalized to standard temperature and pressure.
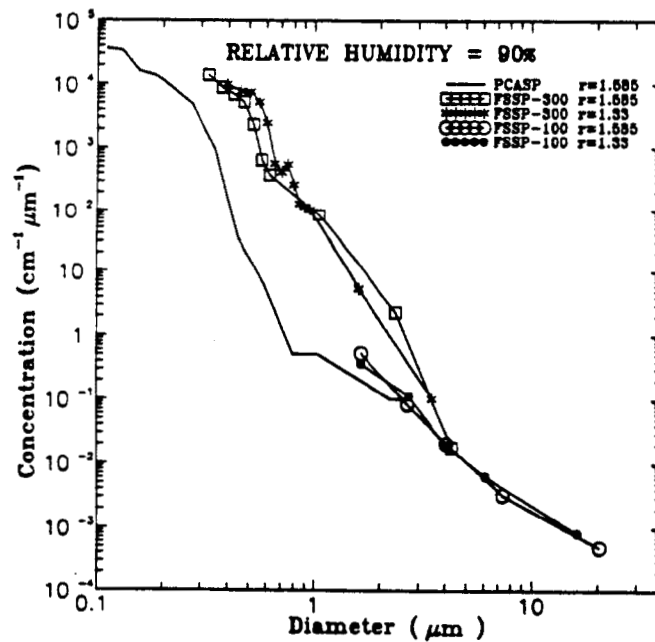
[**Figure 2**]--Comparison of the PMS FSSP-300 spectrum for the 90% relative humidity case of Figure 1 for refractive indexes of 1.585 and 1.33. The PCASP spectrum is also shown for reference.
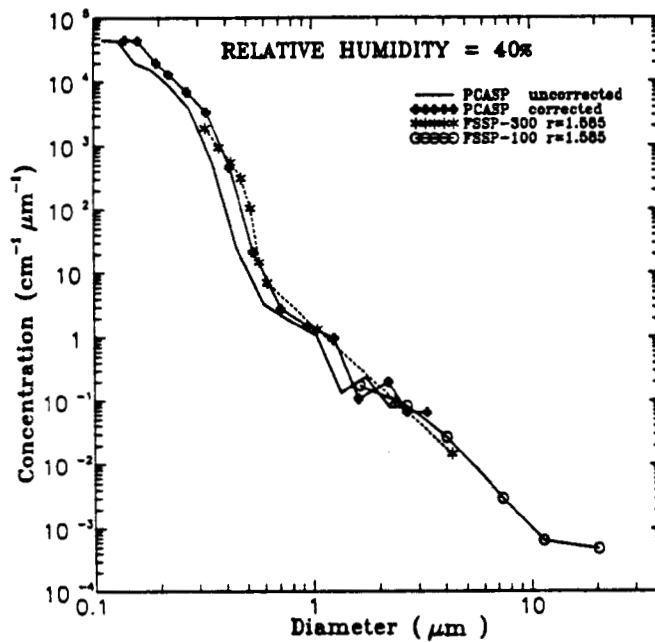
[Figure 3]--Comparison of the PMS PCASP spectra (uncorrected and corrected for laboratory calibrations) and FSSP-300 spectra for the lowest observed relative humidity. Both probes are suspected to be measuring dry aerosol at this relative humidity.
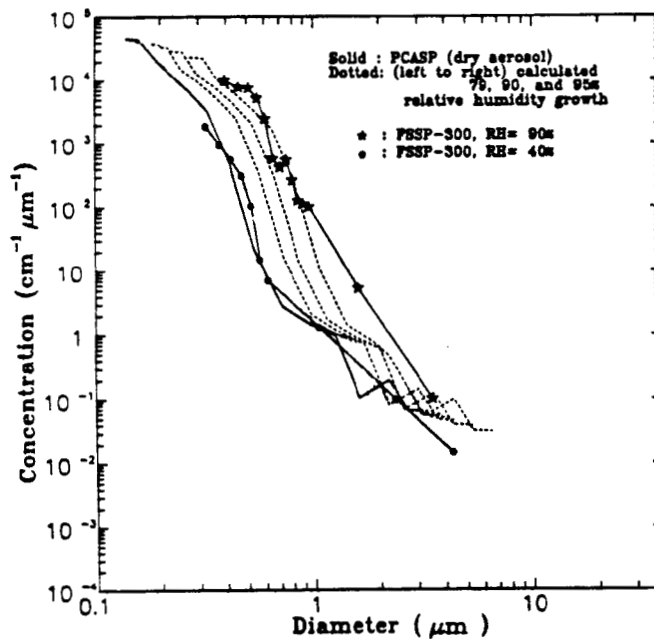
[Figure 4]--Calculations (dotted) of the growth of $(NH_4)_2SO_4$ aerosol (with a 25% by mass insoluble core) at relative humidities of 79, 90 and 95% (dotted right to left respectively). No growth is predicted for the lower relative humidities of Figure 1. The dry aerosol used as a starting point are those shown in the solid line. The range of observed FSSP-300 spectra from 40-90% are also shown.

116

[Table 1]--Concentrations of some water soluble species from filter samples taken in the clear-air mixed layer on April 24, 1990. The filter was exposed for 54 minutes at 760 m MSL simple comparison.

	μgm^{-3}	ηeqm^{-3}
NH_4^+	3.59	199.4
$SO_4^=$	8.88	185.0
NO_3^-	1.72	27.7
CI	0.15	4.23
Na^+	0.16	7.0
HNO_3	9.77	155.0
K^+	0.10	2.5

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DISCUSSION

Clarke: When you recalibrated your system, was it originally calibrated with latex spheres or was it uncalibrated?

Strapp: I think what you do is set the gain in the system. It probably shifted or wasn't set up properly. You set the gain to the mean scattering curve at one point. We just recalibrated the system.

Dye: Did you do some independent comparisons or checks on the sample volume of the FSSP-300.

Strapp: No.

Aerosol Sampling at 0.7 Mach Aircraft Speed

By

R.F. Pueschel, G.V. Ferry, and K.G. Snetsinger

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The Ames Aerosol Group is engaged in aircraft sampling in both the stratosphere and the free troposphere in support of satellite programs (SAGE, SAM, LAWS) and ozone depletion research. The aircraft used are ER-2's and a DC-8, both flying at ≈ 0.7 Mach speed. The instruments used are inertial wire impactors and PMS optical particle counters. We will present and discuss our experiences of many years in this business. Examples are: A reduction of speed of particles passing through the active volume of a conventional optical particle counter; The need for a calibration correction of the response curve of an optical particle accounting for the refractive index of the sample aerosol; Physical deformation of liquid particles collected by inertial impaction; losses of solid particles due to bouncing on solid impactor surfaces; Losses due to evaporation of volatile substances on adiabatically ram-heated impactor surfaces; Chemical/elemental identification of particles collected by inertial impaction; Increased information content from a combination of optical particle counting/sizing, inertial impaction, and satellite remote sensing.

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DISCUSSION

Clarke: You mentioned about the collection on the wire impactors. You looked at the spot made and you looked at the dried crystal. How do you establish a contact angle for that spot and would it normally vary with evaporation, and also I would guess impaction--the larger particles spreading out more than the smaller ones. Is that accounted for?

Pueschel: If spreading is the case, there is a given relation of the kinetical surface energy. That's the case for, however, only large particles. They have to be several microns in size or larger. Depending on the coating you fly you can make the surface hydrophobic to avoid splashing to a large degree. As for the drift question, how we take care of the angles, they are cylindrical essentially. You look at the center core of the cylinder where the airflow goes to normal. You avoid anything which is outside of a small strip in the center of the cylinder.

Sheridan: What is the diameter of the wire?

Pueschel: It varies. It depends on the collection efficiency we apply for different size particles. If you are interested in the submicron particles, we use 75 micron diameter wire, but then we can expose only for a short minute or you loose the resolution for large particles. If you go to a 1/2 mm diameter, we have a better collection efficiency for large particles. This is essentially our optimum.

120

Flow Speed and Particle Trajectories Around Aircraft:
Theory and Measurements

By

Cynthia Twohy and Diana Rogers

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INTRODUCTION

A moving aircraft causes distortion of upstream airflow streamlines and, consequently, departure of some particles from the streamlines. Therefore, flow speed and particle concentrations measured near an aircraft may differ from their freestream values. In general, very small particles follow flow streamlines, while very large, high inertia particles are not influenced by the streamlines and maintain their freestream speeds and concentrations. Intermediate-sized particles may experience enhancement regions, where particles are concentrated, and shadow zones, where particle trajectories do not enter.

Even the sampling of small aerosol particles, which follow flow streamlines, may be adversely affected by flow distortion around an aircraft. For example, flow and particle speed at the tip of an aerosol sampler may differ considerably from the aircraft speed; this may change isokinetic sampling requirements and sample volume calculations. Flow direction may vary substantially from the direction of aircraft motion, degrading the collection efficiency of inlets not properly aligned. In some cases, the housing of a measuring instrument itself may add to flow perturbations caused by the aircraft. Therefore, some knowledge of flow patterns and particle trajectories is necessary for judicious placement and use of airborne sensors and inlets.

PREVIOUS RESEARCH

Using both model calculations and measurements, several researchers have investigated the flow patterns around aircraft, which include the Fokker F-27, Cessna Citation, Lockheed C130E, and de Havilland Twin Otter. Conclusions from these studies which are applicable to particle sampling are discussed below.

Norment (1976) used a potential flow model to calculate particle trajectories around a Cessna Citation and AFGL Lockheed C130E. A three-dimensional model of the aircraft

was used in the calculations, for which the fuselage was approximated by a series of contiguous, plane quadrilaterals (panels). Due to potential flow assumptions, the results of this model are not valid at airspeeds above 200 m s^{-1}, within the frictional boundary layer of the aircraft, or under turbulent conditions.

Using this technique, two droplet sampling instruments (Particle Measuring Systems, PMS) on the Citation were shown to be mounted in an enhancement region for 100 to 200 μm diameter droplets. Both PMS instruments were located on the side of the fuselage, 23 cm out from the skin, but the cloud probe was mounted higher on the fuselage than the precipitation probe. While enhancement occurred at both probe sites, particle trajectories reaching the cloud probe had to pass very near the aircraft windshield. Concentration was therefore more extreme for droplets traversing this region of strong curvature. For 100 μm droplets, the concentration factor, defined as the ratio of particle flux at the sampling or target point to particle flux in the freestream, ranged from about 1.7 for the precipitation probe to over 5.0 for the cloud particle probe. This example demonstrates that a small change in probe placement can have a considerable effect.

On the side of the C130E fuselage, the intake slit for a formvar particle replicator was shown to be located in a shadow zone for 100 to 300 μm droplets (Figure 1). Just above the shadow zone, droplets are concentrated, although the concentration effect decreases with increasing distance from the fuselage. The behavior shown in Figure 1 is typical for fuselage locations on most aircraft.
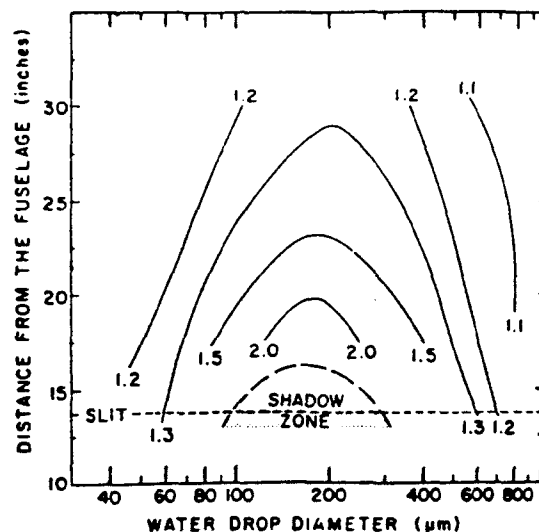
[Figure 1]--Concentration factor contours as a function of water drop diameter and distance from the fuselage along the formvar replicator arm on the AFGL Lockheed C130E [from Norment (1976); Figure 9].

122

A simpler axisymmetric model was used by King (1984a) to calculate flow potential and particle trajectories around the fuselage of a Fokker F-27 (Figure 2a and 2b; note the shadow zone and region of enhancement above it in Figure 2b). These results were compared to those of Norment and Zalosh (1974) for the C130E, and a generalized description of the flow field (away from the body and regions of high curvature) in terms of the distance behind the nose and the fuselage radius was developed. It was also shown that at locations just behind the cockpit, flow velocities could be enhanced as much as 5 to 10% over freestream values.
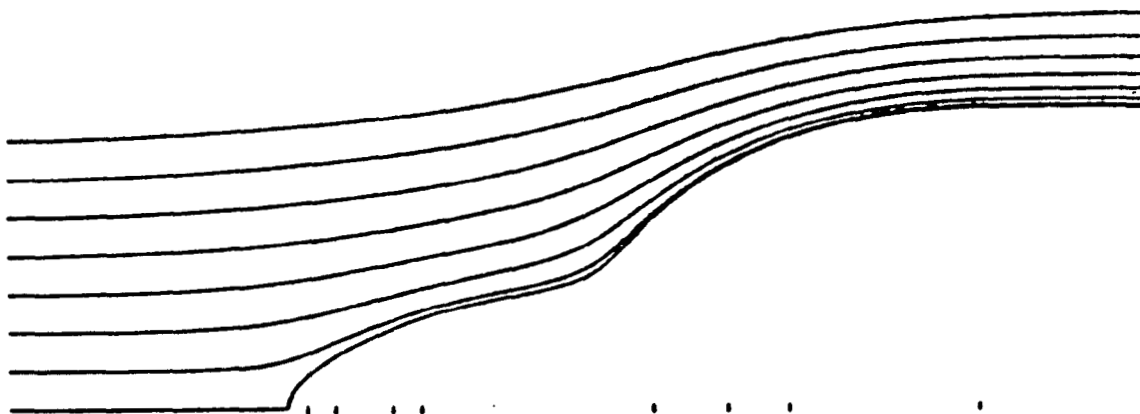
[Figure 2a]--Streamlines around the simulated shape of an F-27 fuselage [from King (1984a); Figure 4].
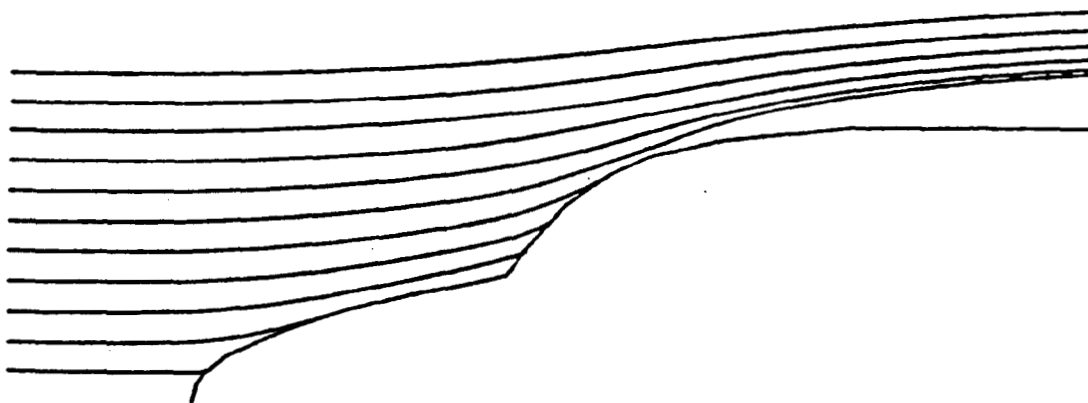
[Figure 2b]--Trajectories around the F-27 for water drops of diameter 100 μm travelling at 90 m s^{-1} [from King (1984a); Figure 6].

Particle behavior was also generalized in terms of a nondimensional number, S, similar to the Stokes number:

$$S = \frac{2a^2V\rho}{9\eta b}$$

Here, V is the freestream velocity, a is the particle radius, ρ is particle density, η is air viscosity, and b is the fuselage radius. The shadow zone width and concentration factors were shown to be at a maximum when S was equal to approximately six (in the specific case studied, for a = 100 μm, V = 90 m s^{-1}, and b = 1.8 m). In a later paper, King (1985) developed a simple algorithm for the width of the shadow zone as a function of S and distance behind the cockpit, and extended his earlier model to calculate the behavior of irregularly-shaped particles.

Predictions of airflow and particle trajectories around the F-27 were compared to in-flight measurements by King et al. (1984b). Two strut-mounted CSIRO hot-wire probes were located at the same distance back from the nose, but at different locations around the fuselage of the F-27. (The CSIRO probe operates by measuring the amount of power necessary to maintain its heated sensing element at a constant temperature while being cooled by convective heat losses and evaporation of droplets.) One probe, used as a standard, was fixed at 58 cm from the aircraft skin, and the other was retracted in flight to different distances out from the fuselage. The retractable probe was also equipped with a pitot-static tube. Velocity measurements from the pitot tube agreed well with model-calculated velocities, but only when the base of the probe strut (7 cm high and 12.5 cm wide) was also included in the aircraft model.

As expected from the calculated trajectories, the CSIRO probes detected a wide variation in liquid water content with distance from the fuselage; both shadow and enhancement zones were apparent. Using PMS-measured size distributions and model-calculated concentration factors for different droplet sizes, corrections were applied to the retractable probe data that brought measurements from the two probes into much better agreement. The wings and propellers were also investigated as possible sources of some remaining discrepancy between the two probes, but the maximum influence of either of these was calculated to be relatively small.

Large changes in flow velocity ahead of PMS probes were shown to have an effect on the orientation of particles entering the sampling plane of the instruments. For example, Beard (1983) calculated that rapid deceleration ahead of a PMS canister mounted on the wing could cause an intrinsic canting angle of 15 degrees for large drops. This contributed to

distortion of raindrop images recorded by the 2-D probe. King (1986) showed that due to the influence of the wingtip vortex, ice crystals could be oriented at a 60 degree angle relative to the sampling plane of a wingtip-mounted PMS probe.

Flow about PMS probes mounted underneath the wing of a Twin Otter aircraft was modeled by Drummond and MacPherson (1985), who calculated that the flow velocity at the sampling point was only about 90% of freestream, and decreased with increasing lift coefficient. Therefore, use of the assumption that flow and particle speed equal the aircraft speed could produce considerable errors, for example, in 2-D images produced by a scanning laser and in the sample volume used to calculate particle concentrations. MacPherson and Baumgardner (1988) measured the flow speed and angle ahead of wingtip-mounted PMS probes on a King Air with a Rosemount 858 five-hole pressure sensor, and found significant flow distortion due to the wing, pylon, and PMS canisters themselves. A full three-dimensional analysis of airflow and trajectories about PMS probes on the Twin Otter wing was performed by Norment (1988). He concluded that for the FSSP-100, net velocities at the sampling point could be as low as 77% of freestream for high attack angles, with more than half of the flow distortion caused by the probe itself.

AIRFLOW AROUND THE NCAR KING AIR AND ELECTRA

At NCAR, potential flow models of the Lockheed Electra and Beechcraft King Air-200 have been developed in order to study the flow speed, angle, and particle concentrations at various instrument mounting locations and distances from the fuselage. The modeling code used at NCAR is that of Norment (1985). Panels representing the fuselages were constructed from drawings supplied by the aircraft manufacturer. On the King Air, only the fuselage has been modeled at this time, not the wings or propellers, so results are most applicable to regions not strongly affected by these features. The forward mounting locations should be well represented by the model, while the rear locations have a thicker boundary layer, and may be influenced by the wings and propellers. They therefore may be less accurate than the forward locations.

The hot-wire probes which were mounted on the fuselage for the measurements described below are not included in the model, as they are much smaller than the aircraft fuselage and are assumed to have an relatively small effect on the flow.

Once the potential flow pattern for a given model configuration is known, one can also calculate the trajectory of a specified size particle to any target point near the aircraft. The concentration ratio, or ratio of particle concentration at the target to particle concentration in the freestream, may then be obtained. (Concentration ratio is similar to the concentration factor described above, except particle velocity is included in the calculation.) The King Air was assumed to be flying at an attack angle of two degrees, with atmospheric conditions similar to typical flight conditions.

125

Measurements of liquid water content were also made for model verification. Using a similar approach to that of King (1984b), two CSIRO hot-wire probes were mounted on top of the NCAR King Air at the same fuselage station (FS, position behind the nose) and the same distance either side of the centerline. One probe was fixed at 43 cm above the fuselage while the other was attached to a strut which could be retracted in flight. Data were taken on a series of flights in small cumulus and stratocumulus clouds in northeastern Colorado during May 1989. Speed runs in clear air provided information on convective heat losses and flow speeds at different distances from the fuselage. The fixed probe measurement was used as a standard for comparison with the retractable probe at various positions, and for simplicity, temperature was assumed to be constant with distance from the fuselage. Twohy and Rogers (1991) describe more details of the CSIRO probe data analysis. Although this study is ongoing, some results are described below.

The change in liquid water content, relative to that measured by the fixed probe, vs. distance from the skin at FS 155 (394 cm behind the zero datum plane of the aircraft) is shown in Figure 3. Error bars reflect maximum uncertainty due to differences in the clear air baseline between the two probes, bias differences between the probe values at 43 cm (not necessarily independent of the baseline error), and the constant temperature assumption. Measurements in this location, just behind the cockpit, suggest an enhancement in liquid water content at distances between 6.5 and 19 cm from the fuselage. Depletion of droplets is suggested only at 4 cm. This mounting location, just behind the cockpit, is influenced by the shape of the aircraft windshield, with possible deviation of cloud-sized droplets from flow streamlines. Mass-mean droplet diameters calculated from the FSSP data were always less than 20 μm diameter, a size which would not be expected to deviate substantially from streamlines. However, a measurable portion of the liquid water content may have been contained in droplets larger than 20 μm, and as discussed below, model results show that droplets as small as 20 μm may exhibit noticeable inertial effects.

At FS 155 for points 43 cm from the fuselage, model-calculated concentration ratios were 1.095 for 100 μm diameter droplets and 1.013 for 20 μm droplets. At 18 cm, 100 μm droplets were in a shadow zone, but concentration ratio for 20 μm droplets was 1.116; therefore, at 18 cm, about a 10% increase in 20 μm droplets would be expected. At 13 cm, the concentration ratio for 20 μm droplets increased to 1.219. These results are consistent with our liquid water measurements at this location, which indicate some enhancement near the fuselage. However, size distributions from the wing-mounted FSSP probe and concentration ratios for a variety of droplet sizes will be needed to in order to determine how precisely the measured enhancements in liquid water can be predicted by the model.

The liquid water profile measured at FS 263 (274 cm behind FS 155) shows a clear decrease in measured water content nearer the fuselage, with almost 70% depletion at 4 cm (Figure 4). Due to the increasing thickness of both the frictional boundary layer and shadow zones further aft, one would predict that fewer droplets would be present near the fuselage at this location. Some scatter in the percent of liquid water content detected at each position is also expected, since concentration ratios and shadow zones vary with droplet size.

For measurements at FS 263 taken at the same distance from the fuselage, those showing relatively less liquid water always coincided with a larger mass-mean droplet diameter (measured by the FSSP) than measurements exhibiting less depletion. As implied by King (1984a), this suggests that shadow zones are wider for larger droplets, at least for S values less than six.

For the rear location at 43 cm out, concentration ratios of 1.523 and 1.033 were calculated for 100 and 20 μm droplets, respectively. At a point 20 cm from the skin, a shadow zone for 100 μm droplets was predicted, but for 20 μm droplets, a concentration ratio of 1.148 was calculated. In this case, the model does not seem to agree with the measurements, which suggest depletion of droplets 20 μm and smaller. As mentioned before, however, the model does not include the effects of the frictional boundary layer or the aircraft wings, both of which will affect the flow at the rear location. As another potential influence, a counterflow virtual impactor (CVI) was mounted about 1.25 m ahead of the CSIRO probe in the rear position. The CVI presented a cylindrical obstruction 6.5 cm in diameter and 46 cm in height, and may have further changed the flow field from that predicted by the model. At this time, the effect of the CVI on droplet trajectories is unknown, but the existence of flow disturbance is suggested by a periodic oscillation in the retractable probe signal observed in clear air.

Although not detailed here, airflow calculations around the Electra have shown non-trivial concentration ratios for 100 to 200 μm droplets at nearly all available mounting positions. Differences between top, side, and bottom mounting locations, and the effects of moving probes away from the fuselage have also been determined. Flow angles have been predicted, with potentially important implications for the alignment of aerosol inlets.

CONCLUSIONS

Potential flow models are useful tools in understanding the airflow and particle trajectories around an aircraft. Flow velocities and particle concentrations measured near the aircraft can vary substantially from freestream values, especially for locations close to the fuselage and near regions of strong curvature like the windshield. Particle behavior is a strong function of size, with small particles tending to follow streamlines, very large particles maintaining their initial direction and speed, and intermediate-sized particles exhibiting the greatest deviation from freestream conditions. Maximum concentration and shadow zone effects occur for particles with a modified Stokes parameter, S, of about six.

These flow distortion effects are especially important for measurement of intermediate-sized particles, but affect the sampling of aerosol particles as well. For example, assumptions that flow speed at the sampler tip should equal the aircraft airspeed (isokineticity) may not be

valid, since actual flow speed may be enhanced by almost 10% at certain locations. Probe or inlet alignment should also be considered, since mean flow direction is not necessarily parallel to the fuselage as is commonly assumed. Finally, the probe itself may influence the flow field, for example, when mounted on the wing where the size of the probe is comparatively large.
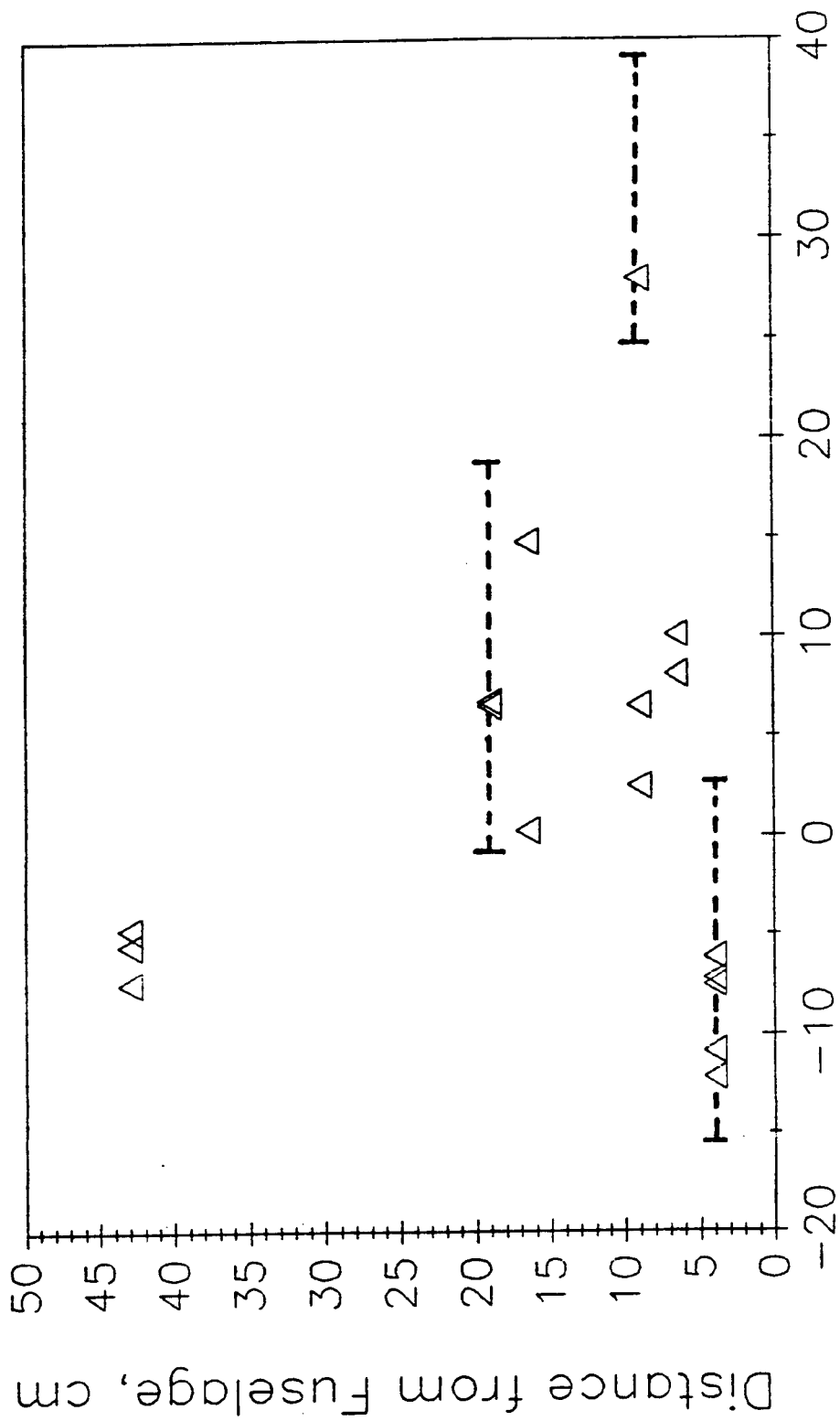
[Figure 3]--Percent difference between liquid water content measured in forward position (FS 155) at different distances from fuselage and that measured at 43 cm from fuselage.
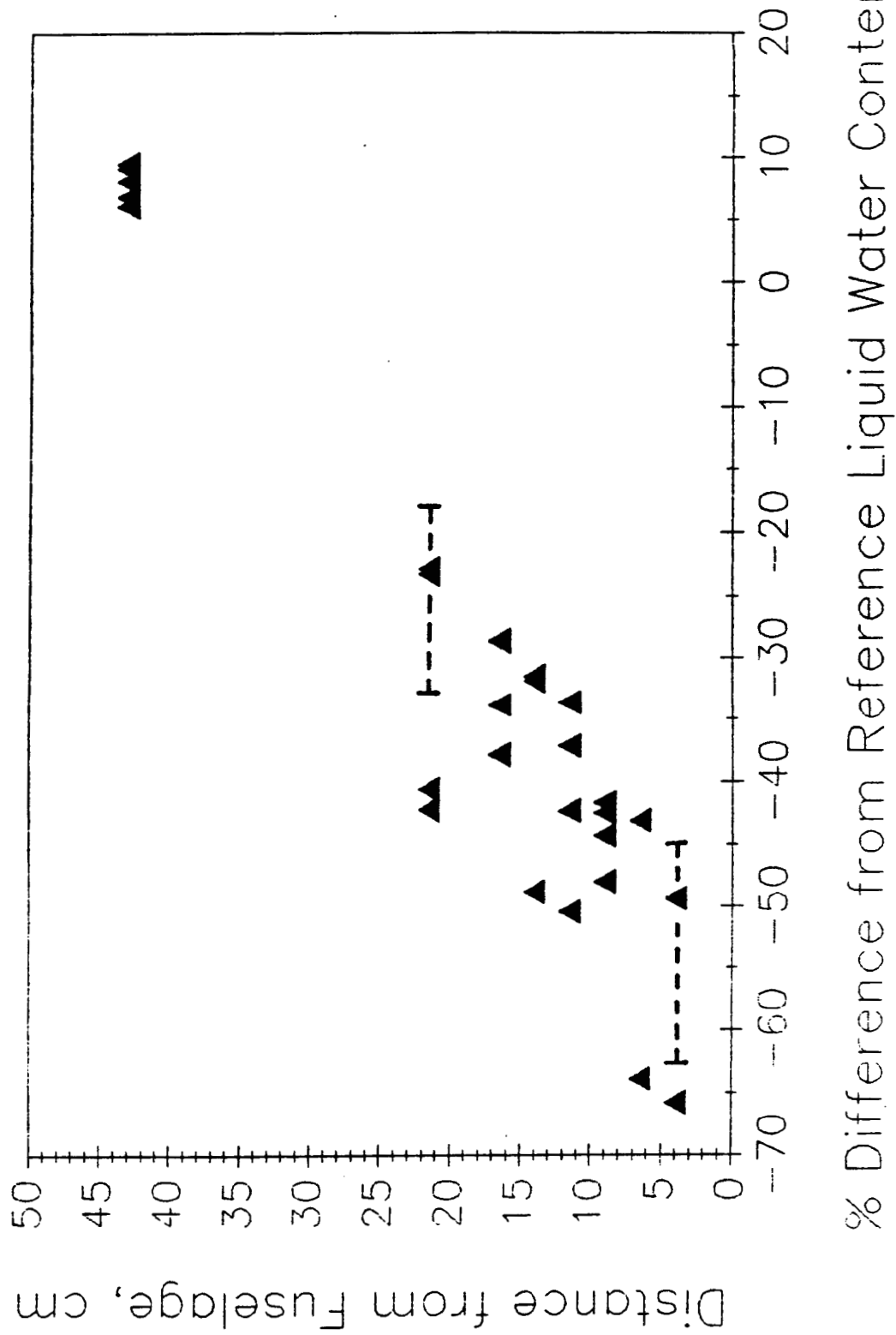
[Figure 4]--Percent difference between liquid water content measured in rear position (FS 263) at different distances from fuselage and that measured at 43 cm from fuselage.

ACKNOWLEDGEMENTS

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DISCUSSION

Baumgardner: I have a comment. Where this does apply is that it points out that the flow around the aircraft can be quite complex and change very rapidly depending upon where you are sampling from the aircraft. I noticed Richard Leaitch's sampler where it has a big body and a fairly short distance between the tip of the sampler and the body where the filter was and also, Barry, in yours that there is not that much distance between the probe tip and a fairly large blunt object. Those haven't been modeled I would imagine. I would be very surprised if the flow speed at those points was really close to the free stream. We don't know what that does to the sampling. I think what this all points out is that the airflow effects around the aircraft really need to be taken into account when you're talking about the actual sampling. Right now, you have only talked about the steady state type of problem, and we haven't even talked about what happens when you imbed onto that steady state flow fairly common turbulent fields that are in the general atmosphere and what that's going to do with your sampling.

Vincent: This is a potential flow model, and I should think the boundary layer could have quite significant effect.

Twohy: Yes, I think that the model may not be entirely accurate, especially in the rear location, for that reason. That may be why the model and measurements seem to agree better in the forward location than in the rear. Some of our data show that the boundary layer on the King Air may be as big as 6" in the rear sampling locations. Also the model doesn't yet include the wing which should have a larger effect in the rear, or turbulence.

Wilson: Would you say that we should stop getting obsessed with who gets to be nearest the front?

Twohy: I think you want to be ahead of the propellers, which no one has modeled very successfully yet.

Seebaugh: Do you have any results on flow angle on the side mounted positions on the Electra?

132

Twohy: For the overhead fuselage mount, they are pretty close to freestream or parallel to the fuselage. We did calculate some angles on the side, close to the nose. Diana, what were those locations used for?

Rogers: (Comment) We contemplated moving our PMS probe to another location other than the current one, which is on top of the cock pit. Those are just locations that have structural reinforcements that we thought could facilitate the relocation.

Seebaugh: I was thinking of Barry's location further back.

Twohy: The angles here (near the nose) were basically 10° for both attack and side slip. I think the flow may straighten out some by the time you're back here (where Barry sampled), but it probably would still be significantly off axis.

Rogers: There's some very bad flow off the wind screen; the angles may be just as bad there as in the front.

Twohy: We can calculate that now, we haven't measured it, but we can calculate it.

Clarke: Regarding the shadow zone you hint at on your earlier slides, it appeared as though your flow is isoaxial to the aircraft in your model. Do you account for angle of attack when you model that flow?

Twohy: Yes. The picture I showed you doesn't, however. This is from one of King's papers where I believe he assumes 0° angle of attack, but in the panel method, you can look at any angle of attack. We did run a couple of different angles of attack, but it didn't seem to make a whole lot of difference. That may be the neglect of the boundary layer that's causing some errors there.

Ram: Have you looked at the bottom of the King Air?

Twohy: We talked about it and did some measurements a couple of months ago, but that hasn't been looked at yet in any great detail. Theory says it could be cleaner than on top.

Ram: You have a feeling that it might be cleaner there on the bottom?

Twohy: I think the streamlines may be straighter.

Ram: Except for some obstructions that are there.

Twohy: Yes, there are some radiometer pods and antennas ahead of where we might want the sampler, which may cause other problems.

Ram: Would these things influence the flow?

Twohy: They could if they were large enough. I'm not sure that they are far enough out to really influence the flow where the sampler would be located. Anything in front of the sampler is bad, but you obviously have to make compromises, because you cannot always have an unobstructed inlet.

Pueschel: How many aircraft models are there for which we know the flow pattern?

Twohy: The ones I talked about--Citation, King Air, the Electra, F-27, Twin Otter, C-130, and somebody mentioned the DC-8 being modeled.

Reller: It was modeled by Douglas, and they gave us the boundary layer development over the airplane and pressure ratios over the airplane and flow direction, but these are on the surface and did not get out in flow field.

Seebaugh: As a comment, if you have surface flow directions, that's a real good indication of flow direction in the field away from the surface.

Twohy: Hillyer, do you want to add anything?

Norment: Well, probably the best place to put the instrument is under the wing.

Ram: On the King Air, that's where the propellers are.

Norment: There are problems with that. (Radke: Don't put it behind the propeller!) There are wing-tip vortices. The best location is well isolated from the propellers, forward of the leading edge of the wing, and down a foot or so. Then you are essentially in the freestream. Obviously you can't do this with some of these small particle probes unless they feed into some sort of pod under the wing. Then you can't get to that during the flight, so you can't do it in a lot of cases, but you can with the optical spectrometers--the PMS probes and that's the best place to put them.

Ram: Wouldn't that entail a lot of modifications? It would have to be on either the fuselage or close by, now you're talking about really significant modifications.

Norment: Yes, and you could run into trouble with the FAA, so there are practical problems.

Twohy: I thought about putting my sampler under the wing, but I would have to bring the sample through about 10 meters of tubing, and then you've lost everything you have gained, perhaps.

Baumgardner: Rudy, I was curious about the DC-8. The PMS probes seem to be incredibly close to the wings. It seems that you would have a fair amount of upwash there. Any idea about what the upwash problem there is at the leading edge?

Reller: The flow was calculated and the probes were placed outside the upwash region. (Pueschel: Three feet down and forward of the leading edge)

Baumgardner: In the photograph, the perception makes it look an awful lot closer than three feet.

Aerosol Sampling and Transport[*]

By

David Y. H. Pui

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I. Deposition in Bends and Contractions

Represented in Figure 1 is the case of a 90° bend where I means the inner bend, O means outer bend. In a developed flow, when it goes around the bend, the center stream due to higher velocity will experience a higher centrifugal force so that they tend to push away towards the outer bend. This needs to be filled in by attracting fluid from the slower moving fluid on the outside of the wall to supply this motion; therefore, in a 90° bend a pair of counter rotating vortices develop. This is for two different Dean numbers which is Reynold's numbers in the bend.

De= 17   De= 107

————— CONTOURS OF CONST. AXIAL VELOCITY
—————— SECONDARY STREAMLINES
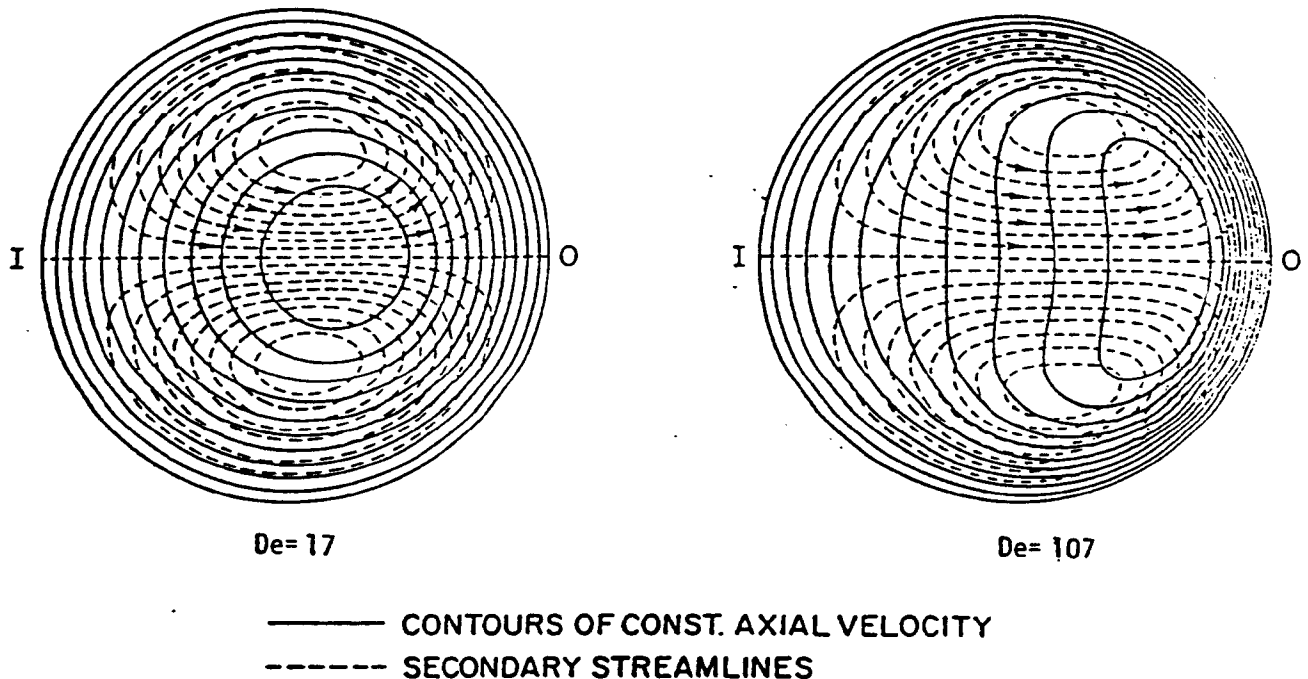
[Figure 1]--Secondary streamlines and axial velocity contours at low and intermediate Dean numbers. (McConalogue & Srivastava, 1968).

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[*] This paper is a transcription of Dr. Pui's oral presentation at the workshop.

As a result of that, particles can be deposited on the bend both on the outside and on the inside bend. When we first did this study, we looked at the state of the art, and we found that the theoretical model is well developed, but everybody is still using experimental data 20 years old in trying to compare their model with those data.

We feel we can do a good experiment and establish a good experimental base to help people with selecting the appropriate theory. Our experiment finds that, indeed, for the case of laminar flow, the theory by Cheng and Wang seems to agree very well with our experimental data (Figure 2). I should point out that for the laminar flow you will note that the deposition begins at a finite Stokes number. Again, for laminar flow, there is a finite Stokes number below which no deposition takes place.

Defining "Deposition Efficiency:" The percent of particles deposited on the tube with respect to the freestream before it makes a turn.

[Figure 2]

138
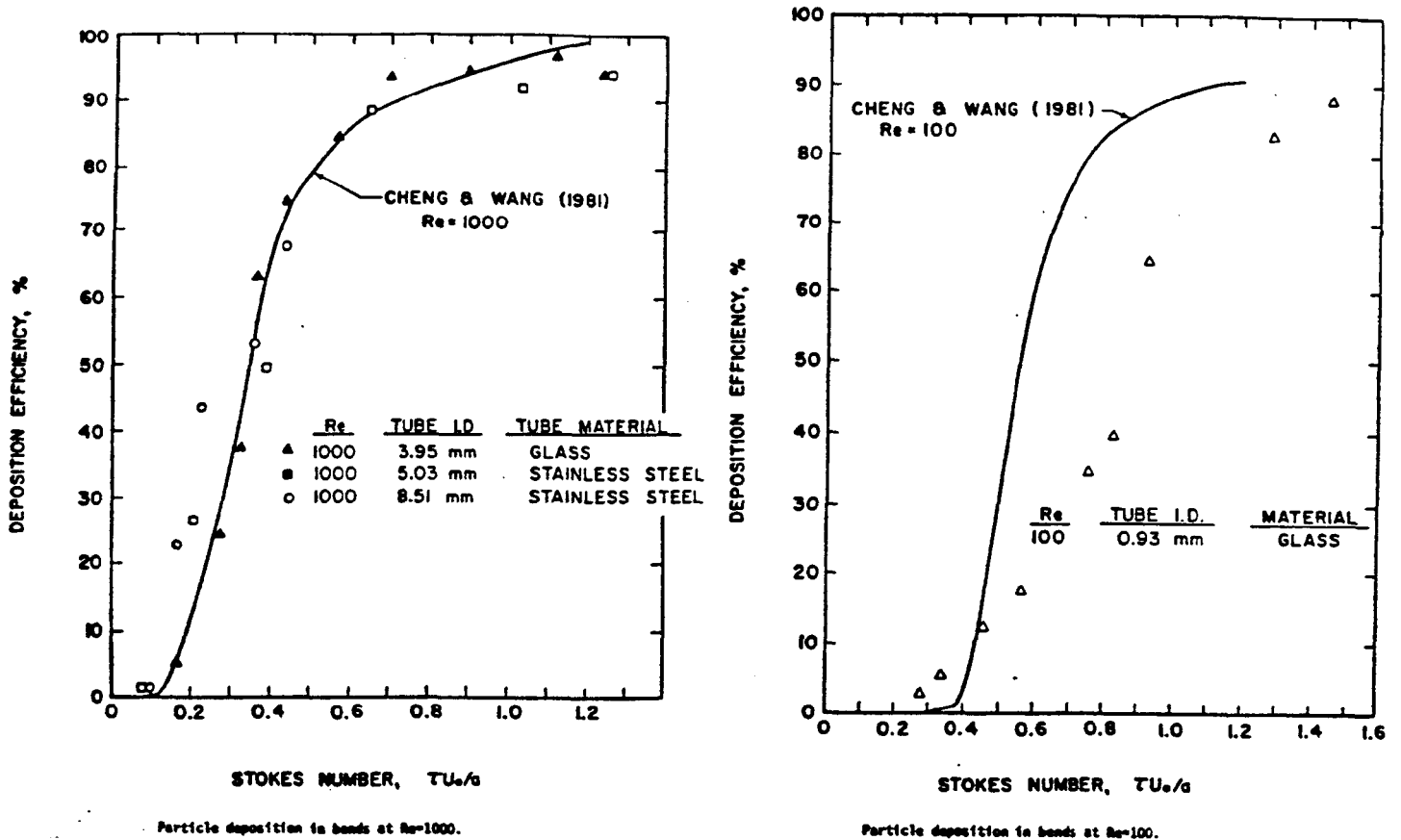
For the case of turbulent flow, (Figure 3) there will be particle loss, no matter how small the Stokes' number is. So particle loss will always happen for the turbulent flow. We find that our experimental data does not agree with any of the available theory. Consequently, we have developed a very simple model. We basically assume that since it is turbulent flow, it will have a uniform concentration across the cross section. We also make use of the migration velocity is equal to the centrifugal force of the particle. The simple equation is deposition efficiency is equal to $1\text{-}10^{-0.963\,St}$. The equation of this form also implies that if you were to plot all the experimental data in the form of penetration efficiency on a semi log axis, they should all should go in a straight line, which is the case. I should also mention that we do apply an area factor to make this curve agree with the experimental data, because in this simple model, if particle loss is only by centrifugal force, then you would expect that all the loss will be on the curvature bend surface. So half of the tube will be coated with particles. Experimental results indicate that it is coating all over the tube, because of the secondary flow. We apply an area factor, and it turns out that the area factor is .71 indicating that 71 percent of the tube is coated.

(Soderman: It is interesting that this is totally independent of the Reynolds number. Does that strike you as strange? Pui: We have not covered too wide of the Reynolds number range. I think it is up to maybe 30,000 or 50,000. Maybe above that it might be different. Certainly within the range that we looked at, all the data points were very closely together.

[Figure 3]

139
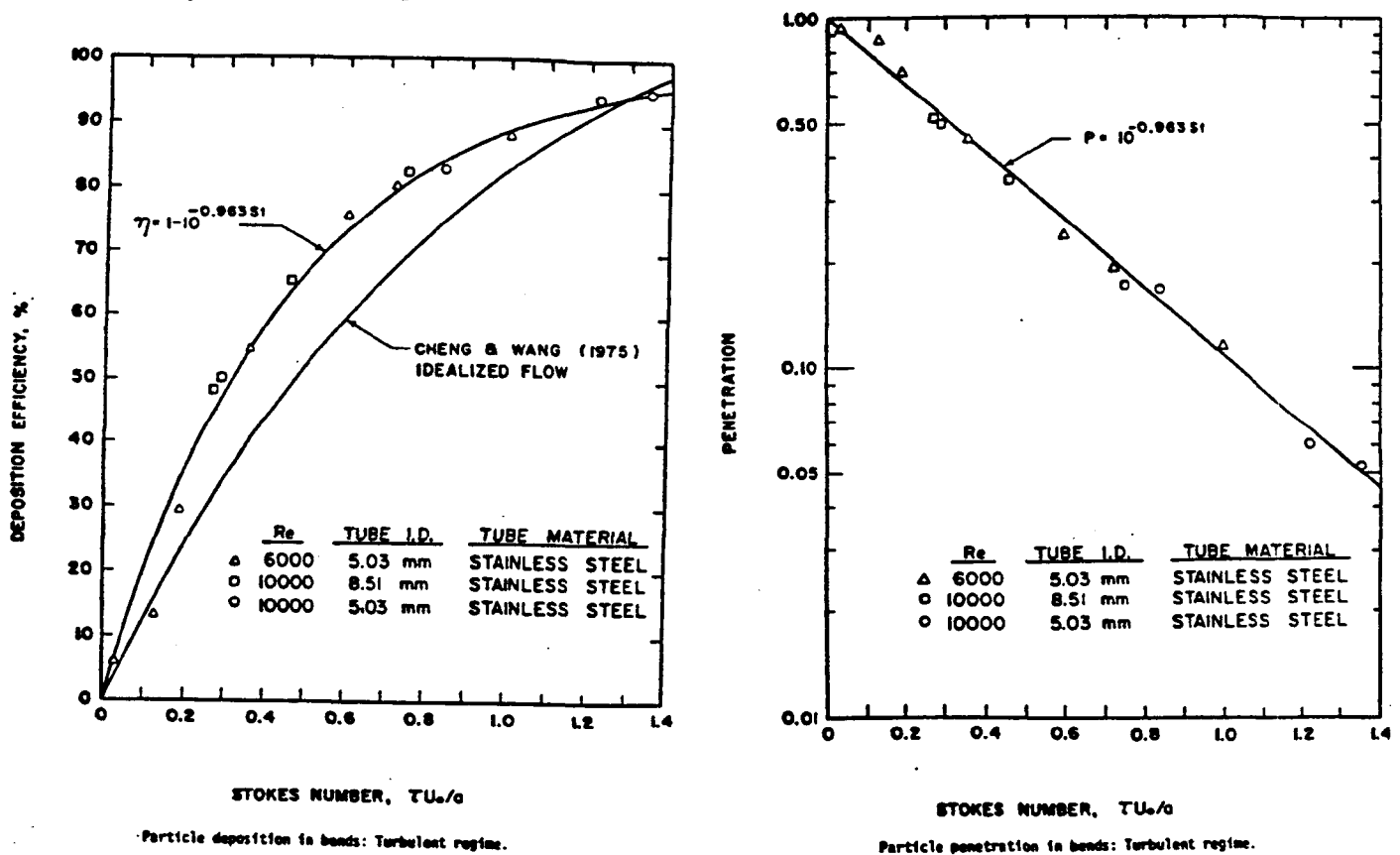
For the case of the very low Reynolds number of 100, even the earlier Cheng and Wang theory failed. So we feel that there is still room for improvement in terms of theoretical modeling. What we have done is do a 3D flow field and particle trajectory model. After about 20 hours of super computer time, we have obtained the results.

Figure 5 shows the velocity vector that shows the recirculation in this band. Our velocity profile agrees pretty well with the available experimental data. With the flow field, we can then solve the equation of motion on the flow field and obtain the deposition efficiency.

This 3D work clearly shows that the inlet velocity profile is important. Which is entirely reasonable if you have a developed flow profile at the inlet, because you have already a very thick radial velocity difference so that the secondary motions will be stronger for the parabolic inlet profile so you would expect to have more losses. For the uniform profile, it will develop and then start to have this recirculation, so you will expect that deposition will not be as pronounced, which is what we have shown here.

In the earlier work (Figure 4), we were lucky in terms of our experimental condition of 5 times the ID for the developing length that follows very closely to our theoretical calculations.
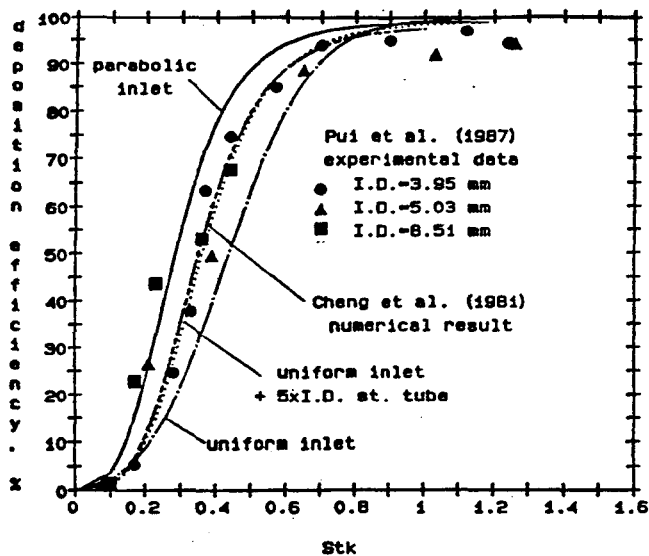
Comparison between the Present Numerical Results and the
Experimental Data of Pui's et al. (1987), and the Numerical Results
of Cheng et al. (1981), R_y=1000 (present simulation and the experimental
data of Pui's et al. R_y=5.7; Cheng's et al. R_y=8.0).

[Figure 4]

140

[Figure 5]

141

(a)

inside   outside

(b)

(c)

(d)
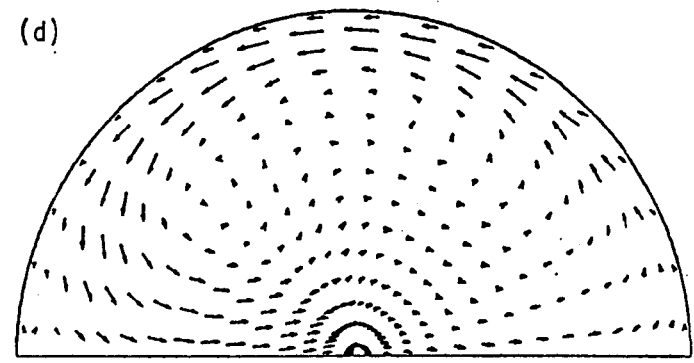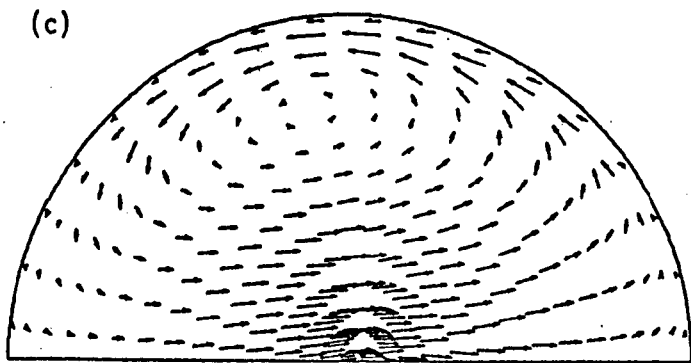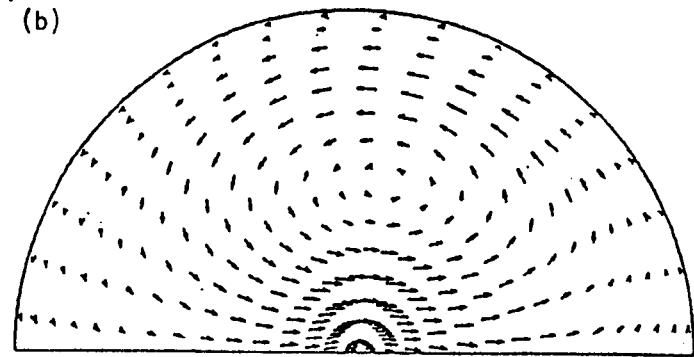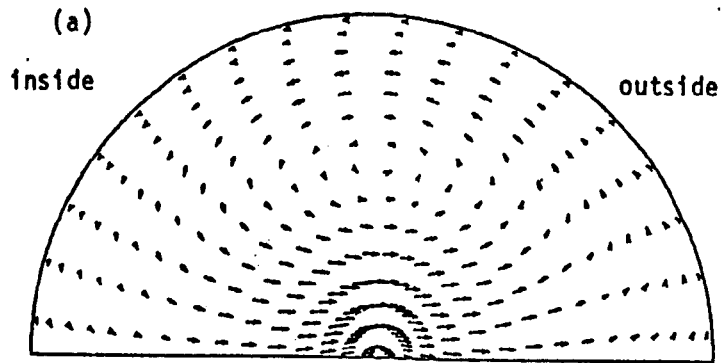
Recirculation Pattern, parabolic inlet velocity profile

(a)ϕ=12.5°, strength=2.85% (b)ϕ=56.5°, strength=4.00%.

(c)ϕ=12.5°, strength=5.60% (d)ϕ=56.5°, strength=4.24%.

D_e=38, R_o=7.0 In (a) and (b)

D_e=869, R_o=7.0 In (c) and (d)

"strength" refers to the recirculation strength In the positive θ direction. Note that the arrow head length represents the magnitude of the recirculating velocity.

This is some of the summary results showing that the deposition is obviously a function of the Stokes number (Figure 6). In addition to that it is also a function of the velocity profile before the bend, as well as this curvature ratio, which is the ratio of the bend radius to the tube radius. For a sharper bend, there will be more losses. For a more gradual bend, there will be fewer losses. And for the case of parabolic profile, there will more losses and for uniform profile, there will be fewer losses.

Figure 7 is another way of showing that it is a function of the curvature ratio and of course the Deans number, which is the Reynolds number divided by the square root of the curvature ratio. The Deans number is basically the Reynolds number for a curved tube.
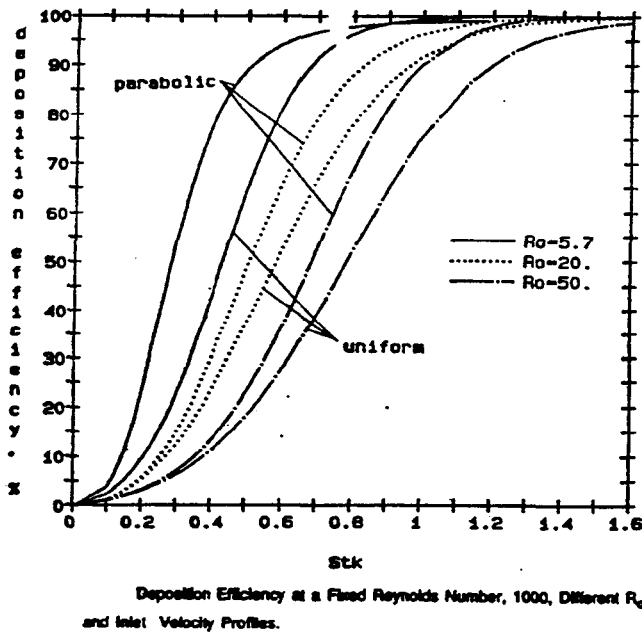
[Figure 6]
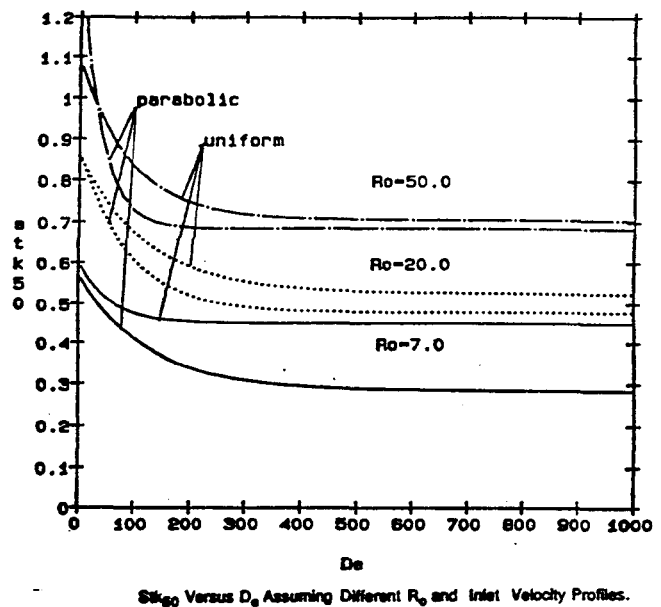
[Figure 7]

II. Sampling and Deposition in Inlets

The next topic I would like to talk about is denuders. As it turns out, what we learned about particle loss in bends helped us with a new design for denuders (Figure 8). I'm pretty sure that most of you know that the simplest denuder is the filter holder with a tube coated with a material which absorbs gas. In this case, a better design for the denuder is in the form of a two concentric glass tubes where the aerosol flow is in the annular space between the two glass tubes. This way then there is more surface for absorption and also the diffusional distance for the gas. There is a filter holder collecting the aerosol particles. This is used quite a bit for sampling acid rain precursors where you can simultaneously sample SO_2, Nitric Acid, and aerosol particles.

142

In this design there is a cyclone to remove particles larger than 2.5 microns, because they are not interested in looking at the coarse particle mode.

I was talking to a colleague at the EPA, and he was explaining to me that it was kind of awkward to use this type of denuder because the total length (three stages) would be like three feet, and you have to run it vertically to prevent particle settling in this tube. So it is difficult to use. What I discussed with him is why don't you use a coil, because there is the secondary flow which enhance mass absorption efficiency. He said what about particle loss in the coil. I pointed out to him that for laminar flow (Figure 9) the loss begins at a finite Stokes number. So you design your coil so that is has four 90° bends. If you design your coil properly you should be able to design something that will not have particle loss.
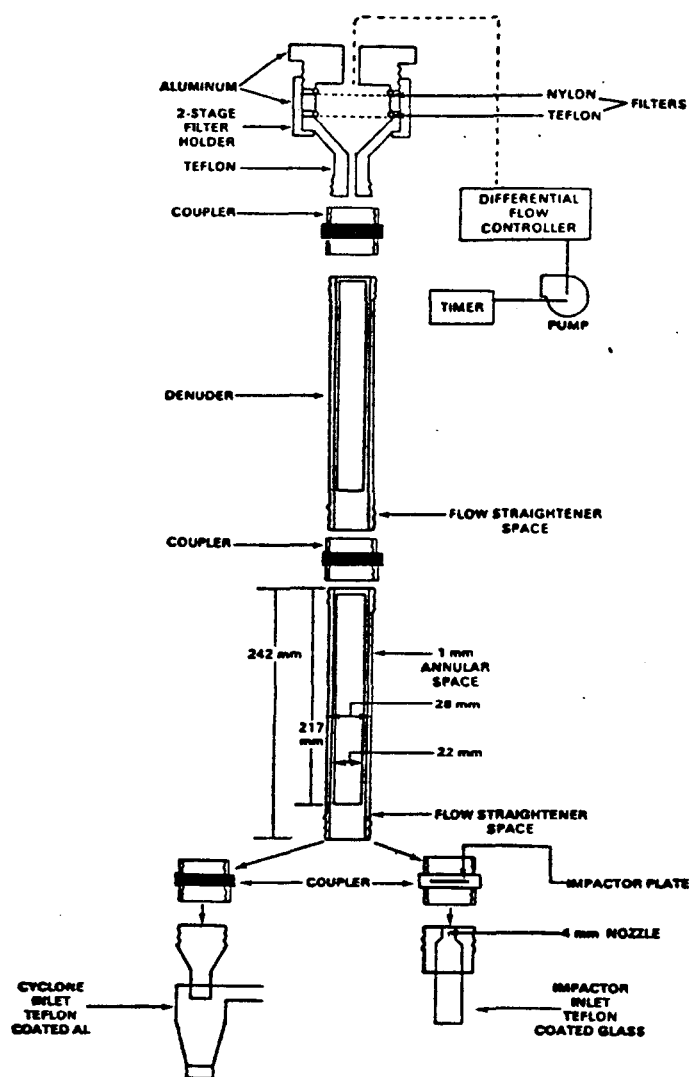
Two Stage Annular Denuder Field Sampling System.

[Figure 8]
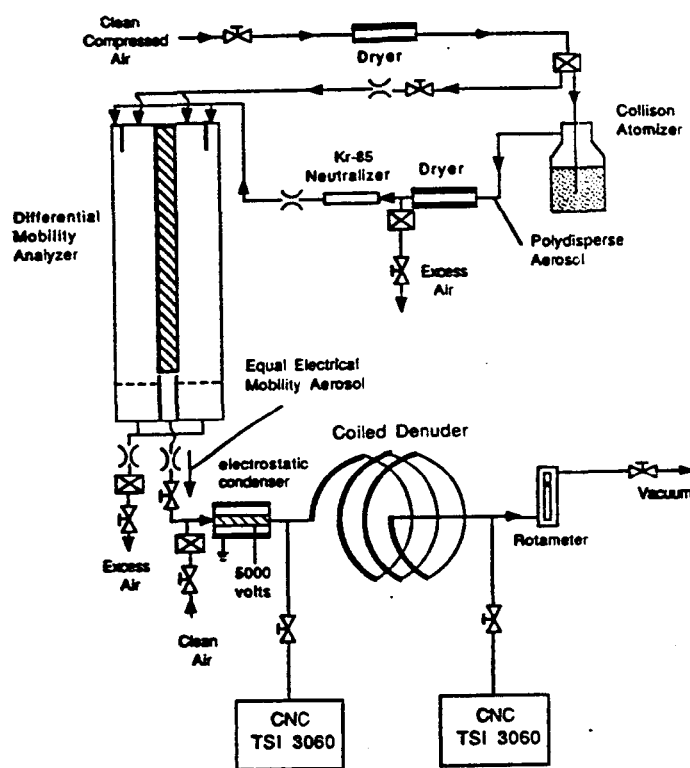
Schematic Diagram of Particle Loss Test System (Dp < 1.0 μm)
(neutral particles)

[Figure 9]

143

We then went to the glass shop and made two glass coils. I sent one to him to do the gas chemistry and the other one I used in the lab to look at particle deposition on the coil. For the case of the denuder, you would like to have the denuder being very efficient in absorbing all the gas. Yet all the particles go through to the filter. Chuck Lewis told me that gas absorption efficiency is good.

So in terms of particle collection, it is also good. The loss begins to happen at about 3 microns. Since there is a cyclone that takes out everything larger than 2.5 microns, so we are not too concerned with that. In the range of .05 microns to 2 microns there is just a couple percent of particle loss (Figure 10).

This is an example of how we apply what we know about losses in bends to make improvement on the denuders. We have also evaluated and looked at the loss at any orientation. For instance, if you are going to put it in an aircraft, it would not have any problem with orientation. Indeed, due to the secondary flow, it kind of keeps the particle in suspension and there is very little settling loss.

(Ram: What are the dimensions? How Big? Pui: It turns into a coil about 4 inch by 4 inch, maybe a foot with a 4 inch radius. It can be alternated in any orientation.)

The other reason I wanted to talk about denuders is to address the loss by electrostatic effect. For this denuder is made of glass, and glass is not a very good conductor and also it is coated with various chemicals of unknown dielectric properties. One of the things we did was to also evaluate charged particle loss in glass denuders. This what we find for neutral particles (Figure 11). This is for diffusional loss. Diffusional loss becomes important below .03 microns. We also took a look at losses due to the electrostatic effect. Figure 12 is for the singly charged particle. Here we have already corrected for the diffusional loss so we subtract our diffusional loss and this is particle loss just due to electrostatic effect. You can see that it can be important. Even for .03 microns, you can have up to 60 percent particle loss in denuders.

We have developed a simple theory using a equivalent electric field to scale our curve and find that this theory agrees reasonably well with experimental data. To make this agree, we put in a surface electric field of 210 v/cm. I understand that this is roughly what people have found in the past.

Going back earlier, we have done more work on particle deposition in tubing due to electrostatic effect. We have passed charged particles through many different type of tubing, teflon, polyethylene, tygon, etc. For this type of dielectric constant, we hypothesize that due to handling or contact, there will be charged islands produced on the inside of the dielectric tubing. There will be both positive charged islands and negative charged islands where the electric field can go between those charged islands. The charged particle coming through here will be attracted by the electric field and be deposited (Figure 13).

144
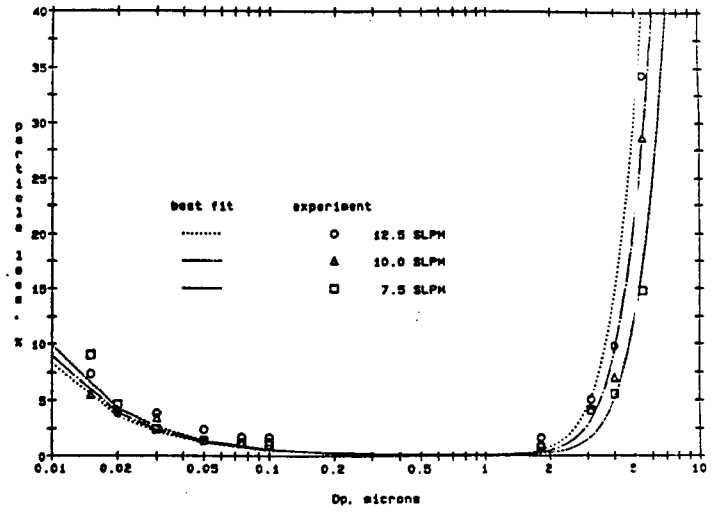
Total Particle Loss in Coiled Denuder at Three Different Flow
Rates (neutral particles).

[Figure 10]
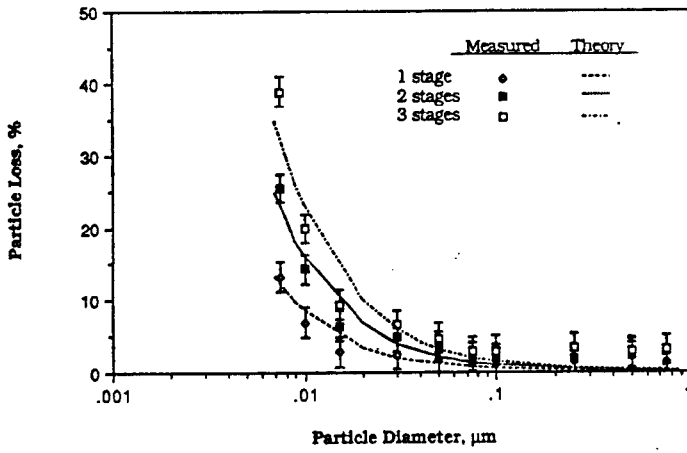
Neutral Particle loss in Uncoated Annular Denuders

[Figure 11]
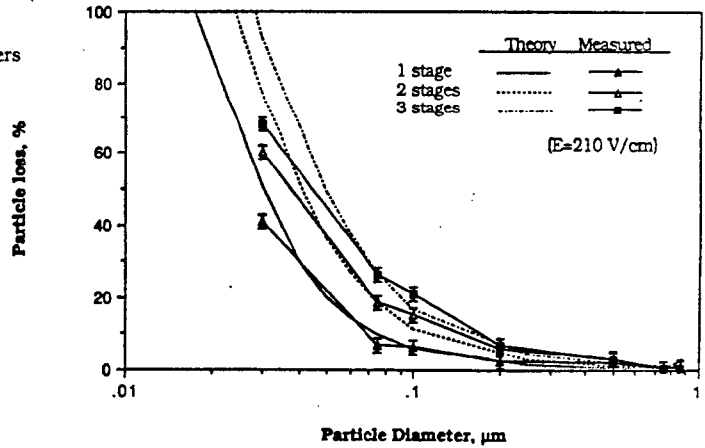
Typical Particle Loss in Uncoated Annular Denuder(s)
for Singly Charged Particles

[Figure 12]

DEPOSITION DUE TO SURFACE ELECTRIC FIELD

Charged particle preciptation inside plastic tube.
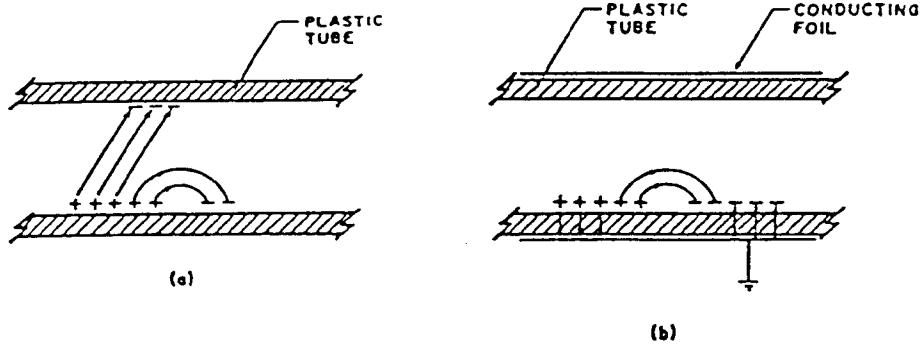
CHARGED PARTICLE PRECIPITATION DUE TO SURFACE ELECTRIC FIELD IN TUBE
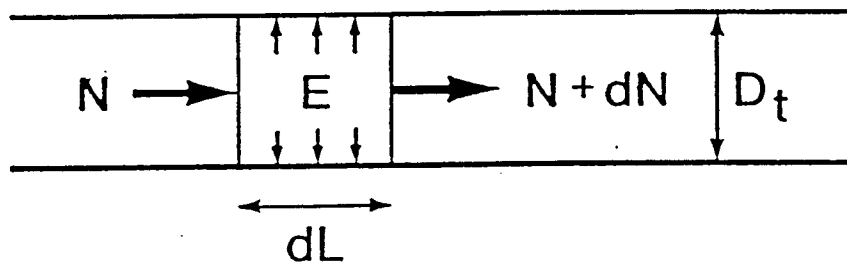
TURBULENT FLOW:

$$P = \exp\left(- A\, Z_p\, E\, /\, Q\right)$$

LAMINAR FLOW:

$$P = 1 - A\, Z_p\, E\, /\, Q$$

[Figure 13]

146

This led us to develop this simple model assuming that there is a surface electric field and uniform velocity type of concentration profile and come up with turbulent and laminar flow models (Figures 14a-14c).

For teflon tubing, we find that this is a very low flow and a relatively small diameter, and a longer length. We want to magnify the effect. The top curve is for loss due to diffusion only. These other three curves are for particles carrying charges. One is for Boltzmann charge level on the particles. This is for singly charged particles, one with a conducting foil wrapped around the tygon tubing on the outside. This is for diffusionally charged aerosol particles. You can see that penetration can be reduced to nearly zero in some cases.

(Q: What are the dimensions? A: This is .5 cm ID, length of 300 cm, flow rate of 1 lpm.)

We have also looked at polyflow, which is a trade name for polyethylene. Many manufacturers like to use this to plumb the internal plumbing of particle counters. It is opaque rigid so you switch the plumbing together very well. It turns out that it is not much better than teflon. You can have significant loss. The best tubing we have found is the tygon tubing which has loss very close to the diffusional loss.

We have evaluated the effect of having some of the filter holders have a teflon insert, depending on what type of holder you use, you could set up an electric tube between the filter and the holder so that particles can be collected on the holder rather than the filter. We find that situations like that can occur. Again, we are trying to magnify the effects. In some instances you can have 50 percent of the particles deposited on the teflon insert rather than on the filter. This is just for singly charged particles. On one hand, this is for a low flow situation, on the other hand here we are using very moderately singly charged particles. We haven't attempted to charge the teflon surface. Maybe in aircraft situations, you will have very highly charged particles, and teflon coating maybe charged when it goes through a cloud, so I don't know if it would be as pronounced or not.

III. Transport and Deposition in Tubings and Chambers

In the electronic industry, they transport high purity gases at high velocity and high pressure. The pressure here is about six atmospheres. In order to measure this contaminant level using an atmospheric instrument, one needs to reduce the pressure to ambient pressure so that the expansion chamber is often used.

This is an expansion chamber that we have evaluated (Figure 15). Pressure is reduced by going through a small orifice and gas expands and somewhere downstream an isokinetic probe is located where this particle will be drawn to the detector. Some of the parameters that can be important will obviously be the orifice diameter, the chamber diameter, the diameter of the tube upstream of the orifice, the length from the orifice to the isokinetic probe.
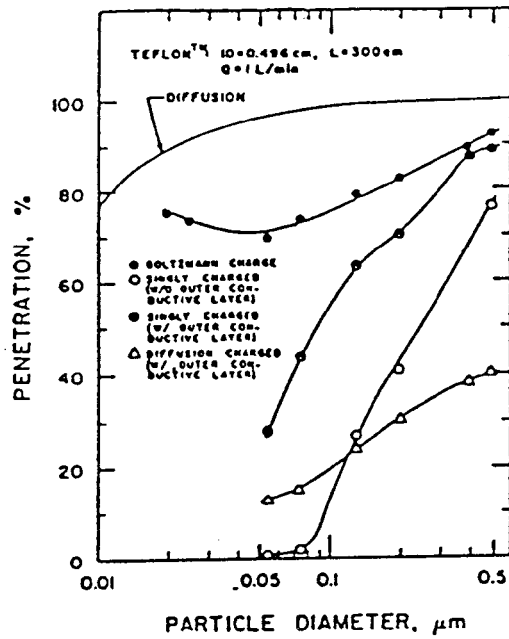
Penetration of charged particles through Teflon tube.

Fractional Particle Deposition on Filter Holder Housing
For Various Types of Filters Used

$D_p, \mu m$	Charge	Gelman Type A/E	Nuclepore Type N060	Ghia Zefluor Type P5PL
0.43	Boltzmann	< 0.001	0.002	0.006
	Diffusion	< 0.01	0.13	0.32
0.093	Boltzmann	< 0.01	<0.01	<0.01
	Diffusion	< 0.01	0.23	0.57

[Figure 14a]

148

Penetration of charged particles through Polyflo tube.

[Figure 14b]

Penetration of charged particles through Tygon tube.

[Figure 14c]

149
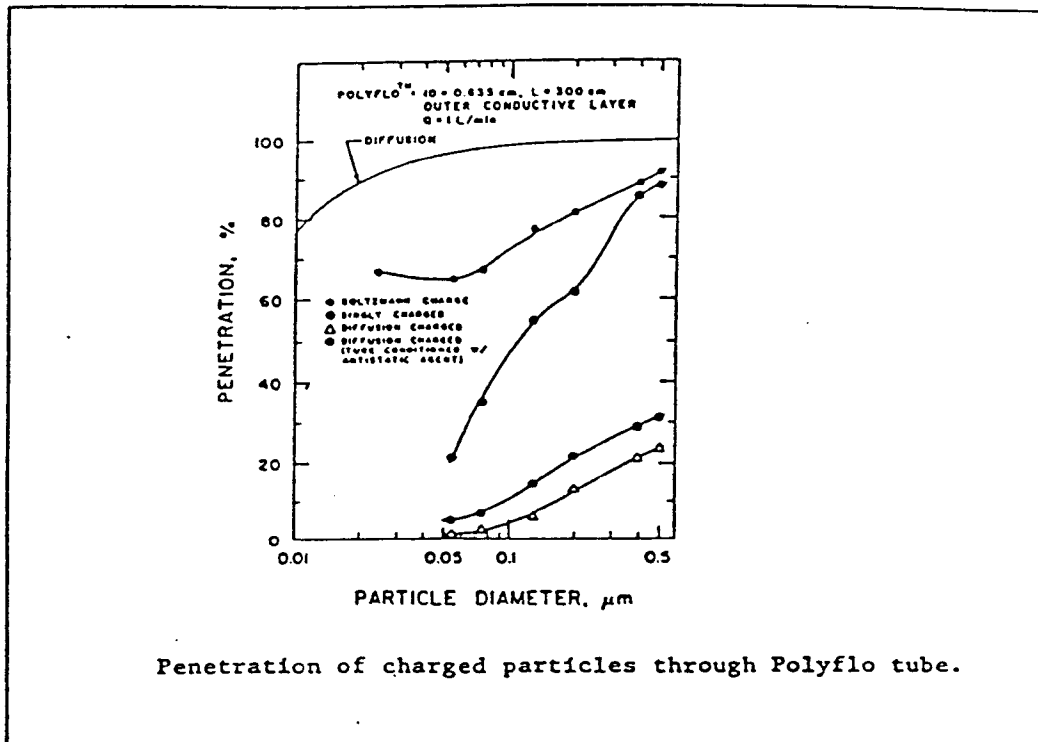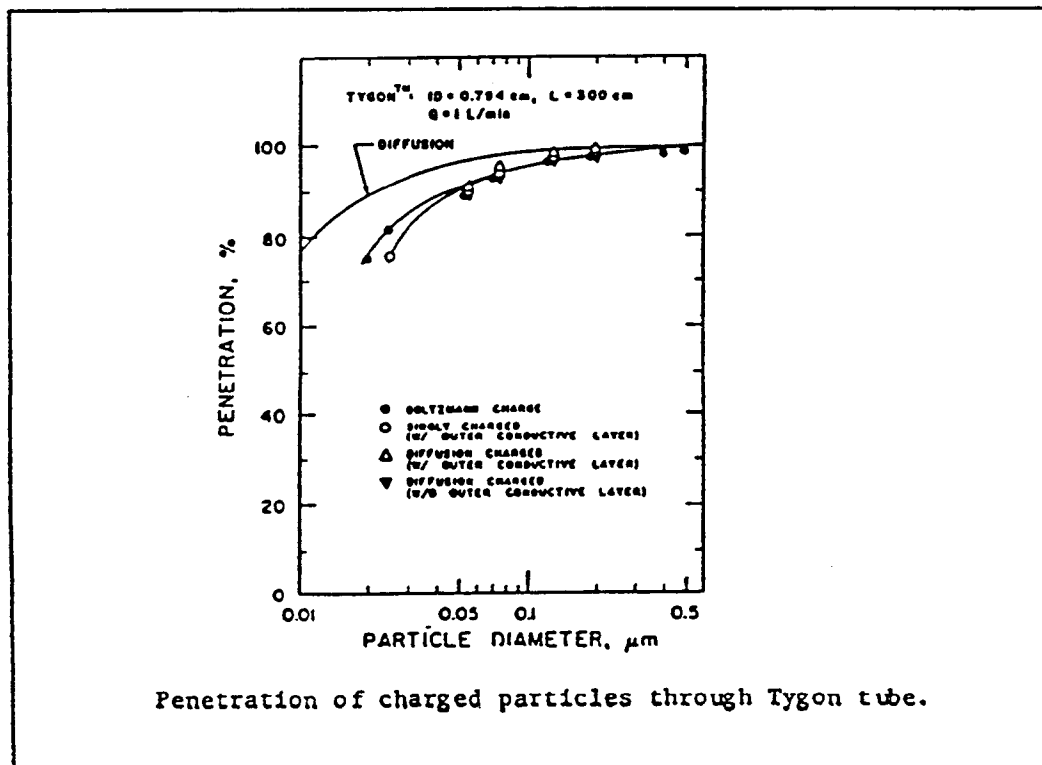
IMPACTION IN EXPANSION CHAMBER
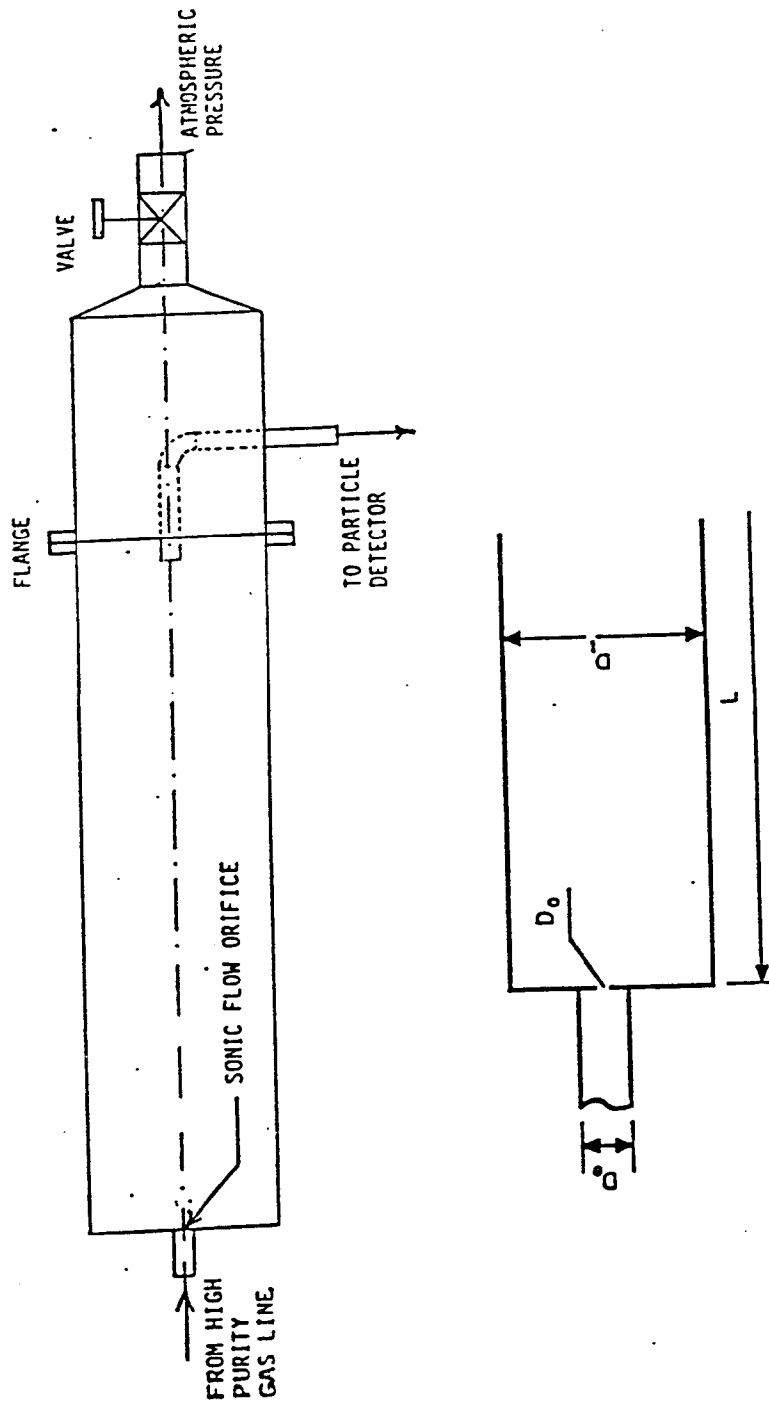
[Figure 15]

First, we did a very rough numerical calculation just to generate some information for us to try to find out what to look for. This is the orifice. This is the axis of the rotation. As you can see, the flow converges through the orifice so that the streamline has a sharp curvature, so you would expect that there will be some particle impaction onto the upstream face of the orifice (Figure 16).

Computed Streamlines

	Upstream	Orifice
U (cm/s)	80	13275
Re	1095	13852
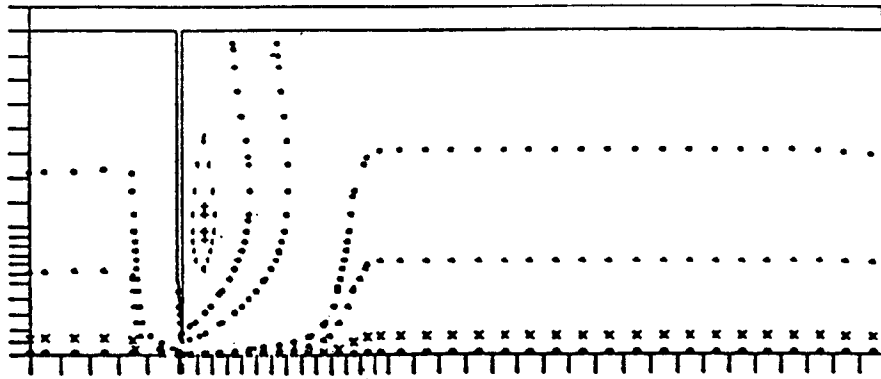
[Figure 16]

On the downstream side, you get a bend so that it will come out expanding with recirculation here, so that we would expect that there would be inertial particle loss also on the downstream face of the orifice. Additionally, there will be particles collected on the walls due to the expansion jets which carry the particles. Here are some of the dimensional numbers we have defined trying to evaluate the device (Figure 17). What we did was to generate aerosol and after running it for awhile, we would recover the material. We can recover the material on the upstream face, downstream face, and also the side wall here to find out about the particle deposition. Indeed, we find that there is particle loss in front of the orifice, on the back side of the orifice, and also on the chamber wall (Figures 18 and 19). We have made use of dimensionless quantities in trying to characterize this deposition. This is done for many different conditions over wide Reynolds numbers, expansion ratios, and different chamber diameters as well. By using this modified Stokes number, we are able to put more of the data points in one universal curve for each of the deposition loss mechanism. From this type of curve, we are able to redesign a more compact expansion chamber.

151

IMPACTION IN FRONT OF ORIFICE

$$Re = D_e U_e / \nu$$

$$Stk = \rho_p D_p^2 C U_e / 18 \mu D_o$$

IMPACTION IN EXPANSION CHAMBER

$$Re = D_o U_o / \nu$$

$$Ex = D_f / D_o$$

$$Ma = 1$$

$$Stk = \rho_p D_p^2 C U_o / 18 \mu D_o$$

[Figure 17]

We also evaluate the uniformity of particle concentration at the sampling point. We put a filter in here and after the collection, we stem out the filter in the various locations to find out whether it is uniform or not. What we find is that most of the particle loss on the chamber wall occurs at the intercept at this 7.5 degree expansion boundary with the wall. Beyond this intercept, the particle concentration is uniform. Obviously you would expect a concentration of aerosol on the orifice. There is some particle loss on the side walls since we are only drawing aerosol from the centers so that the loss is not going to affect the measurement (Figure 20). This is a unit that we have designed based on those dimensional curves. We also evaluate the unit once more and find that it agrees well with our depiction.

152

DEPOSITION EFFICIENCY OF EXPANSION CHAMBER

O   FRONT OF ORIFICE
△   BACKSIDE OF ORIFICE
▽   CHAMBER
▲   TOTAL

[Figure 18]

[Figure 19]

154
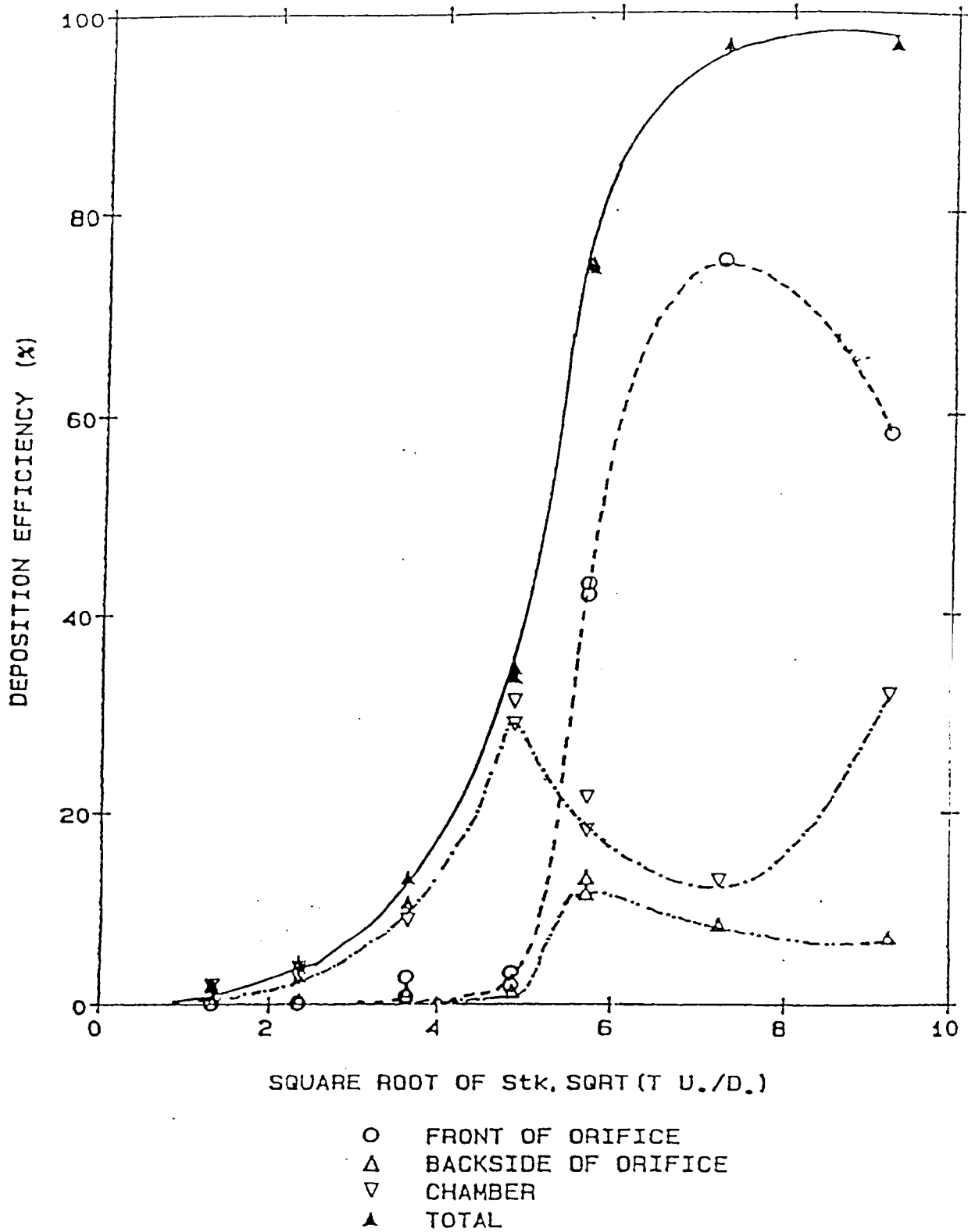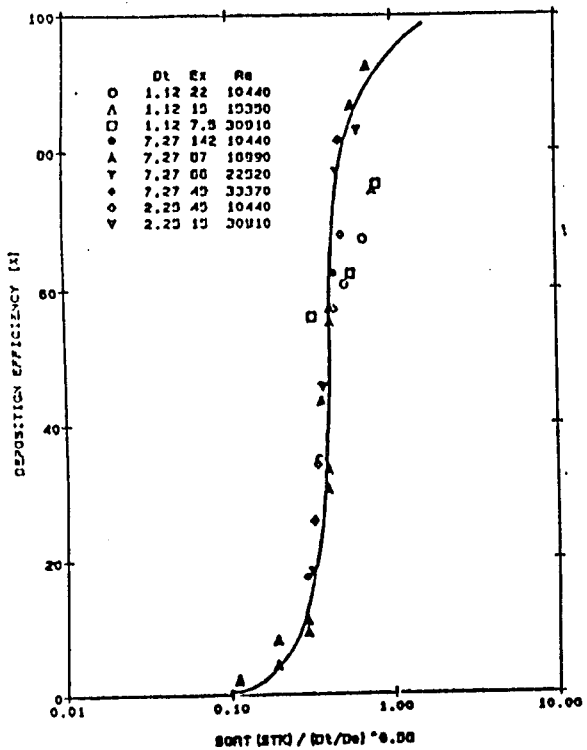
Dimensionless deposition curve for deposition on the expansion chamber wall.
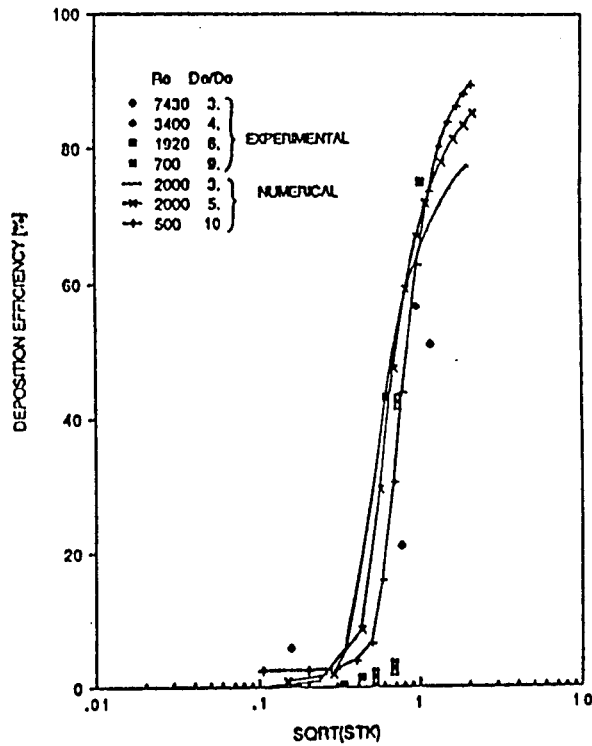
Dimensionless deposition curve for deposition on the front side of the orifice.
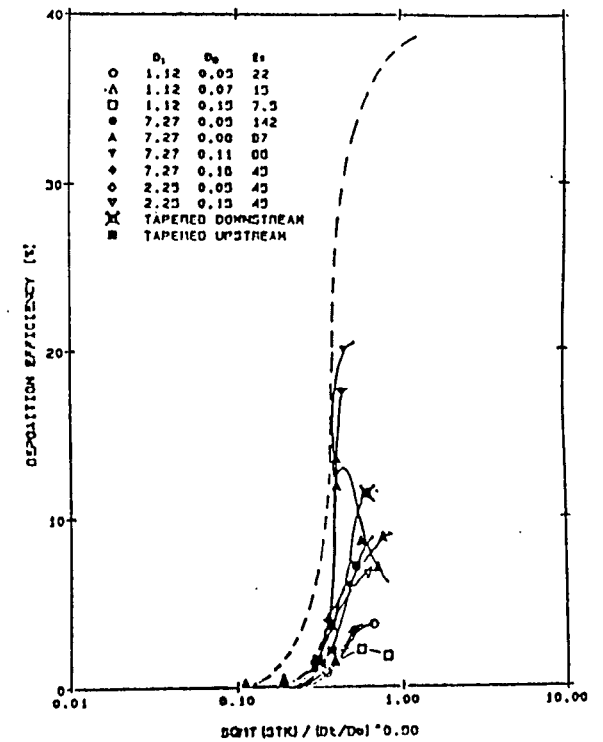
Dimensionless deposition curve for deposition on the backside of the orifice.

Current Prototype Design for Pressure Reducer

Orifice Plate
Do = 0.49 in
(1.25 mm)

3/8 in
(0.95 cm)

Fixed Orfice
with
Expansion Cone

Optional Orifice Design

13.38 in
(40.00 cm)

6.63 in
(16.8 cm)

Dt
2.0 in O.D
(5.08 cm)

1/2 in
(1.27 cm)

Exit

3/8 in
(0.95 cm)

Sampling (C N C & L P C)

[Figure 20]

155
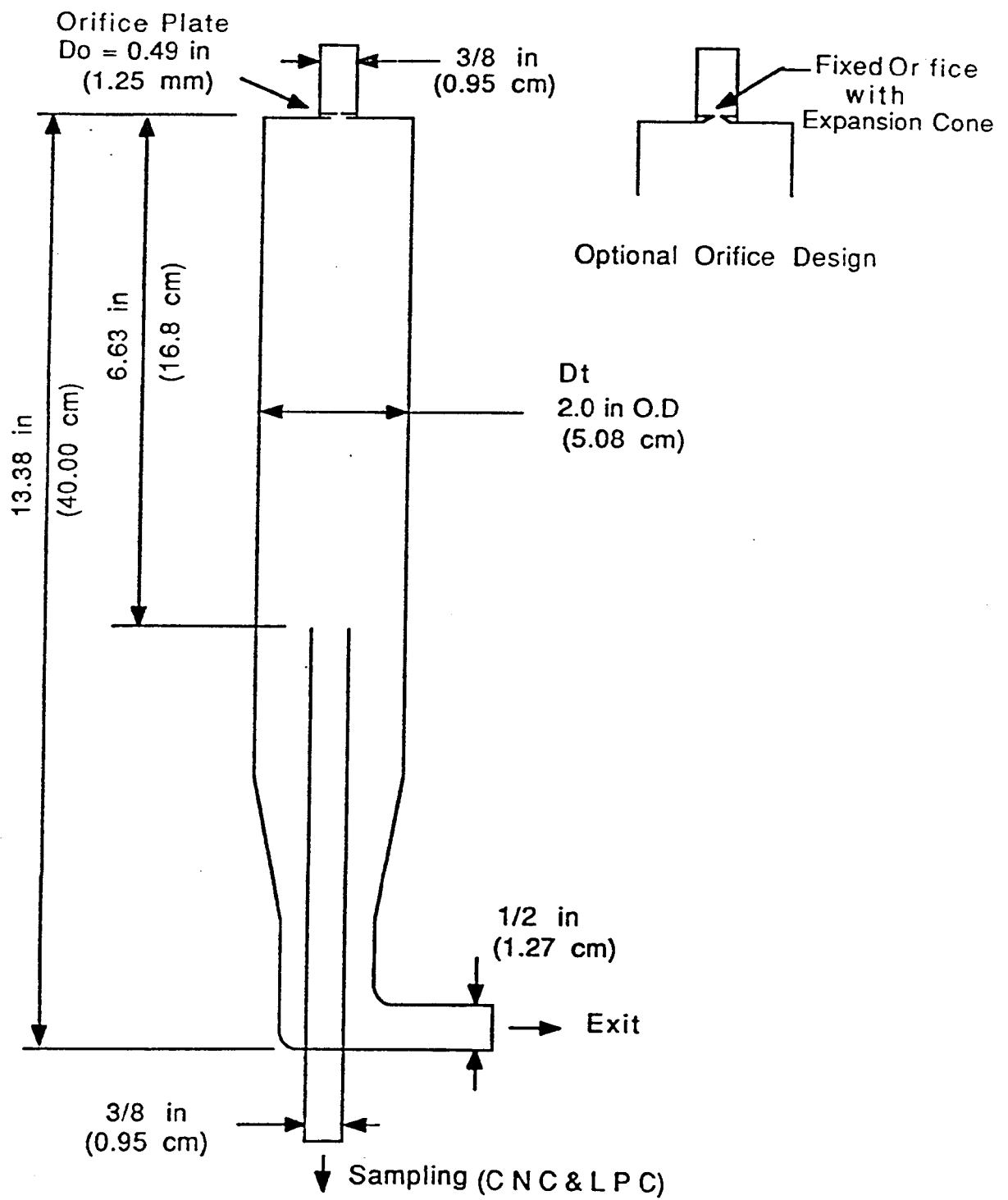
IV. Deposition in Pressure Reducing Devices

This is motivated by our desire to try model what happens upstream of the orifice (Figures 21a-21c). Downstream we think is hopeless to model theoretically because of compressible flow. We take an experimental approach and set a dimensionless curve to the data. We modeled the upstream loss in an erupt contraction. We were able to find a dimensionless curve which allows all the different curves to collapse into one (Figures 22a-22b). This is the modified Stokes number that we used inserting the middle curve that I showed you earlier. The middle curve is actually a theoretical curve resulting from this numerical work.
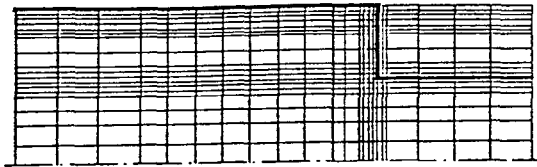
Main grid used to calculate the flow field

[Figure 21a]
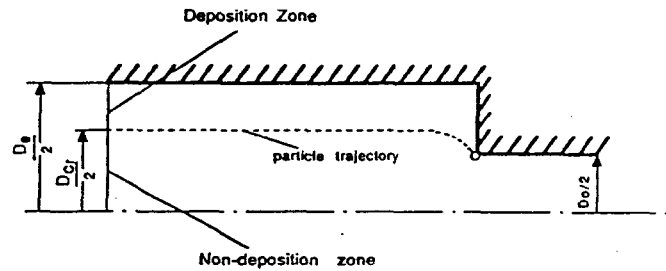
Critical diameter for particle deposition

[Figure 21b]
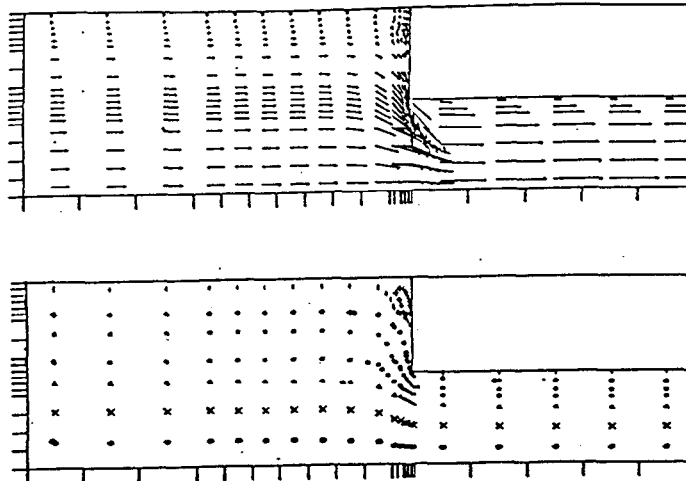
Velocity vectors and streamlines in the abruptly contracted tube at Re = 1000 and De/Do = 2.

[Figure 21c]

156

General correlation curve giving the normalized deposition
efficiency as a function of modified Stokes number.

[Figure 22a]

Theoretical and experimental deposition efficiencies on
the upstream face of a critical orifice.

[Figure 22b]

157
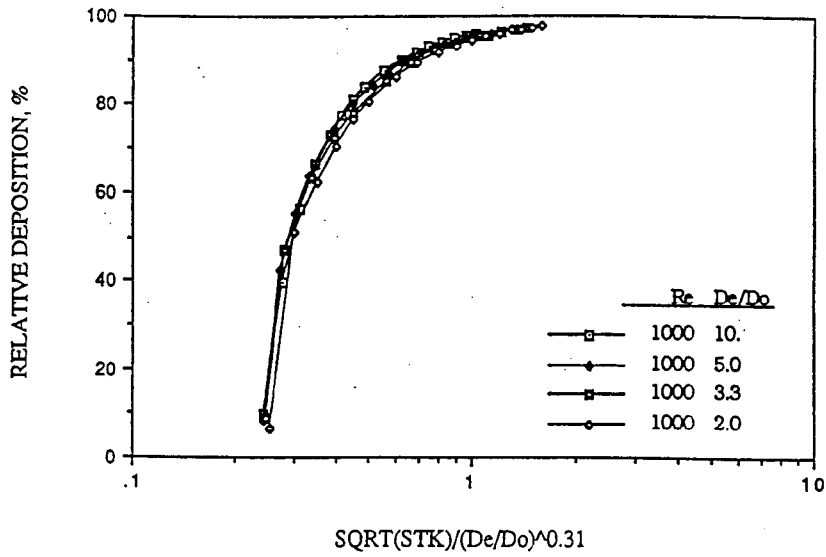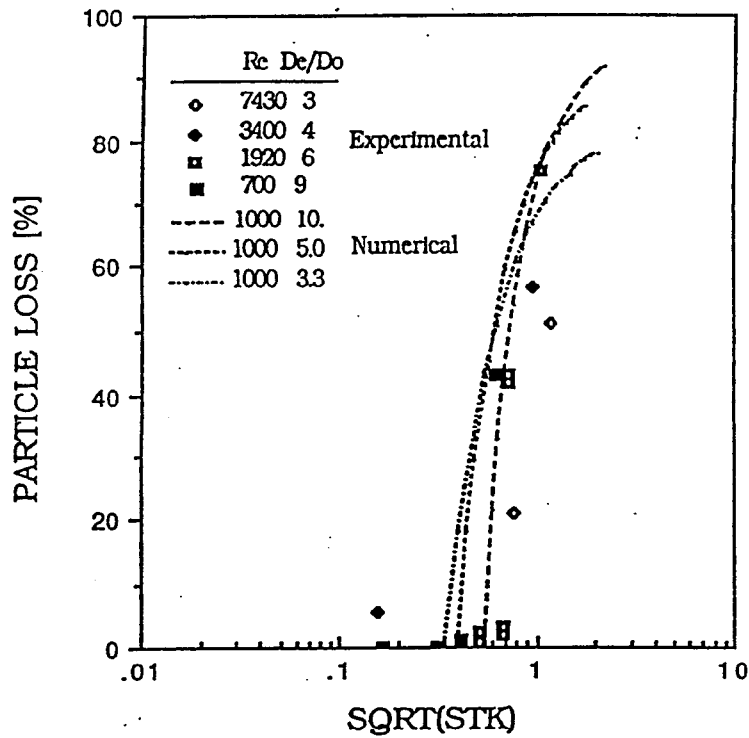
This is comparing it with particle loss in front of this orifice. Another application we find is interesting. We asked what about trying to model particle loss in nuclepore filter. Nuclepore filter has a lot strict holes in the flat surface. The model works well for 3 micron pore size (figure 23). Obviously for the 3 micron this part is effected by the diffusional deposition on nuclepore filter.

(a)

(b)

(c)
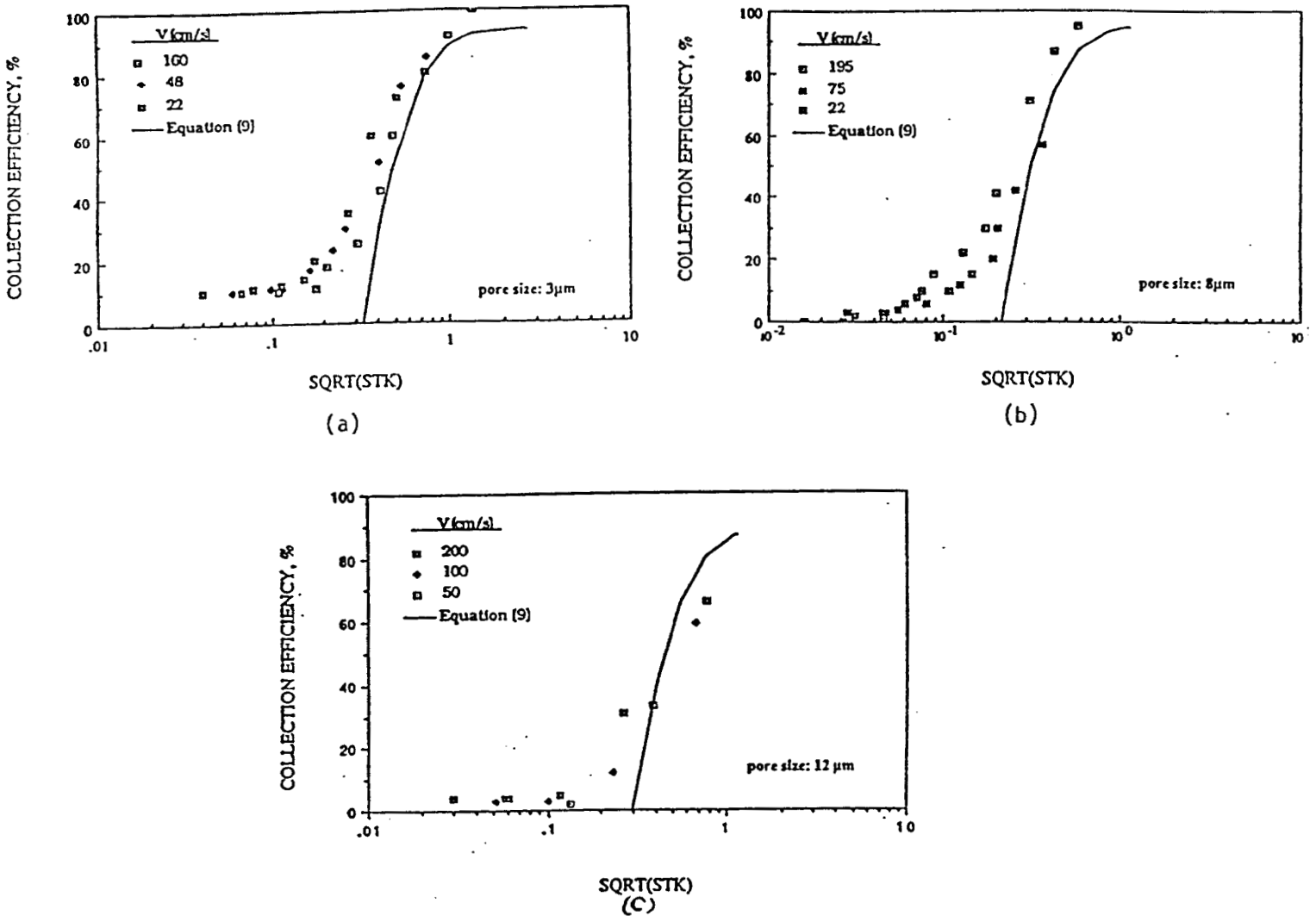
Experimental collection efficiency of three Nuclepore™ filters and their comparison with the present model.

[Figure 23]

158

V. Deposition on Semiconductor Wafers

In the cleanroom, we have wafers sitting on a work bench (figure 24) or holding on with a fiver so it would be like in freestream. If you have particles generated up here due to a filter leak, there might be a chance that the particle may be deposited on the wafer. Here are some of the theoretical calculation showing particle loss on a free standing wafer (Figure 25). The deposition velocity is a function of particle diameter. The left hand side of this curve is due to diffusional deposition, right hand side due to sedimentation. Increased deposition with flow velocity here is due to the thinning of the boundary layer with velocity so that diffusional deposition is more important.

[Figure 24]

159
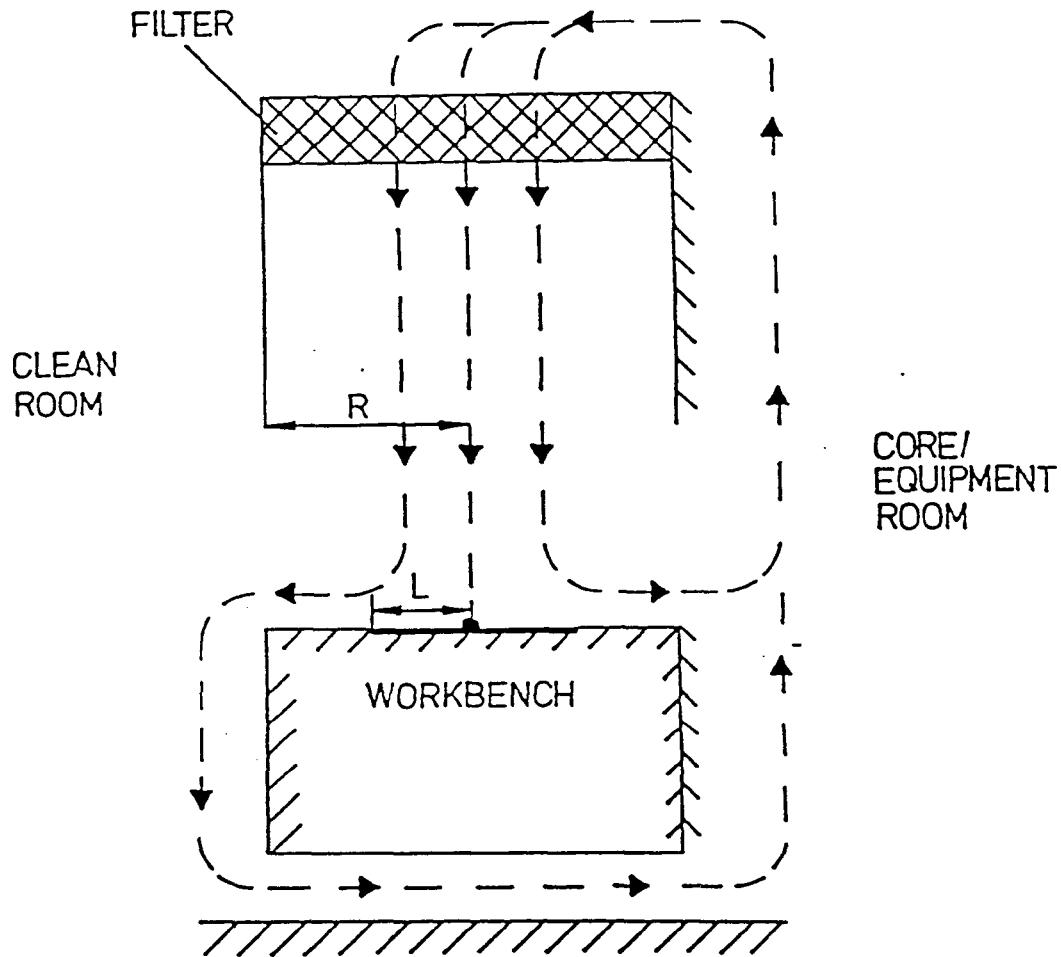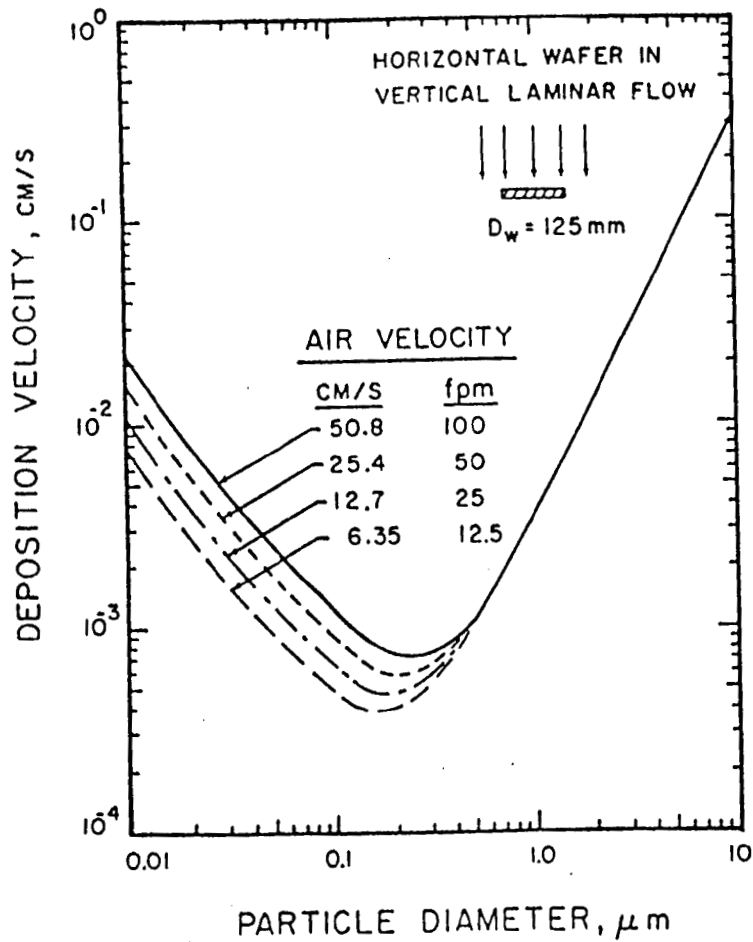
Mean deposition velocity for a 125-mm-diameter, freestanding, horizontal wafer in a VLF clean room.
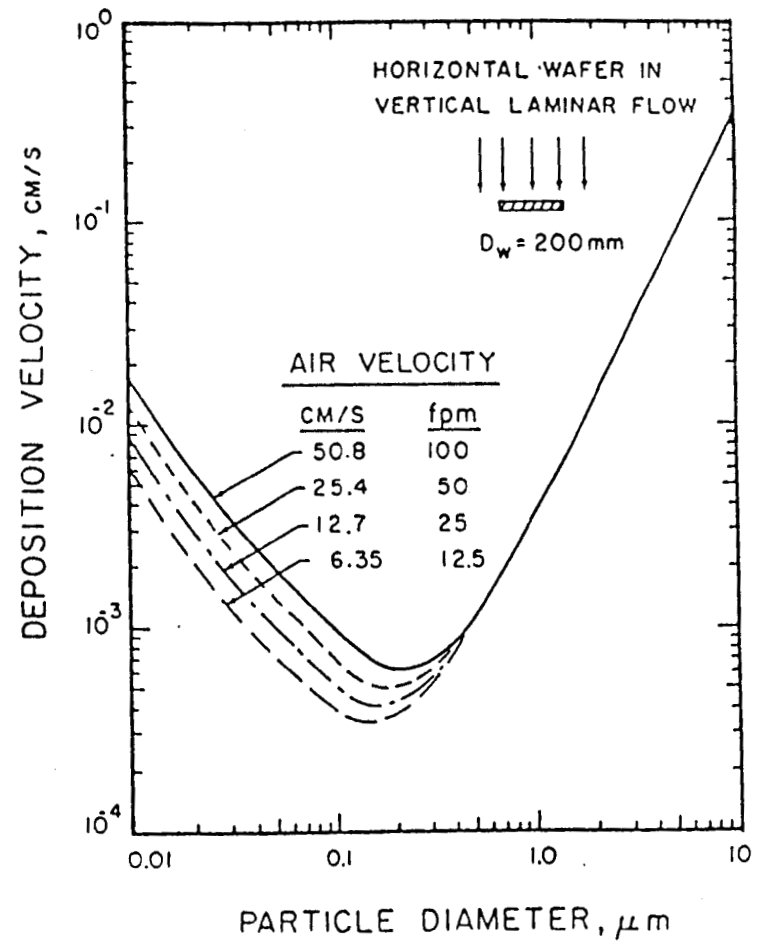
Mean deposition velocity for a 200-mm-diameter, freestanding, horizontal wafer in a VLF clean room.

[Figure 25]

160

This is the numerical calculation showing what happens if you keep the wafer a few degrees above the ambient temperature (Figure 26). All of the sudden, we are showing a big hole where no particle deposition occurs. Heating the wafer effectively prevents particle deposition to occur from a particle size of .05 micron to 1 micron. We have also done calculations showing if you do it the other way around, (have a cold wafer with hot air) you will have deposition. This thermophoretic effect is due to the fact that when you have a particle in a temperature gradient, the hot side will experience gas molecules with higher momentum then the cold side so that there is a drift of the particle from the hot side to the cold side. If you heat the wafer, it will help to prevent deposition on the wafer. On the other hand, if the surface is cold, you might have the reverse effect.
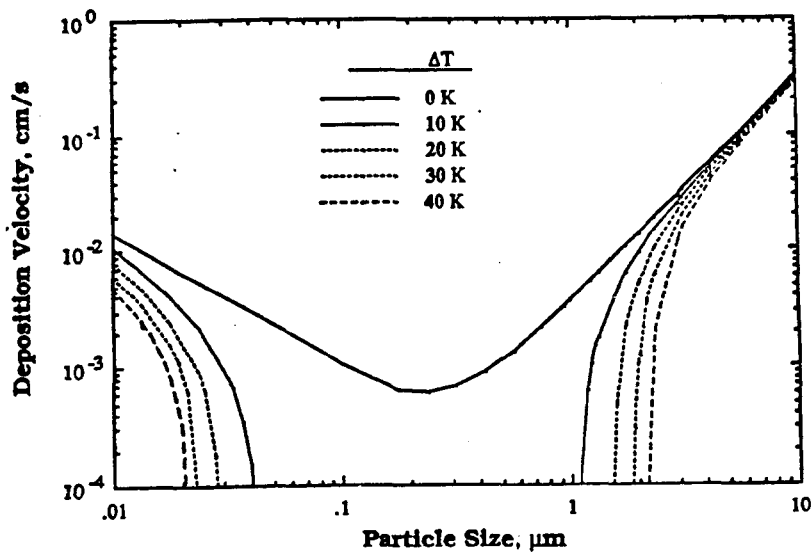
[Figure 26]

In spite of the very steep slope of this curve, our experimental data (this is using a more sensitive technique) agrees very well with the theoretical curve (Figure 27). After carefully examining the experimental procedure, we feel that the experiment is correct. Then we went back to look at the numerical calculation. Finally, we discovered that for the thermophoretic work it is such a short range fall you have to use a lot of grids. This demonstrated to us that both the numerical calculation and experimental measurements are important, one helps the other. Experimental results often times can help define boundary conditions.

I would like to emphasize what Professor Vincent indicated yesterday that he found that a lot of the numerical techniques are actually well-developed and maybe a bit ahead of experimental studies, especially for high-flow sampling.

161
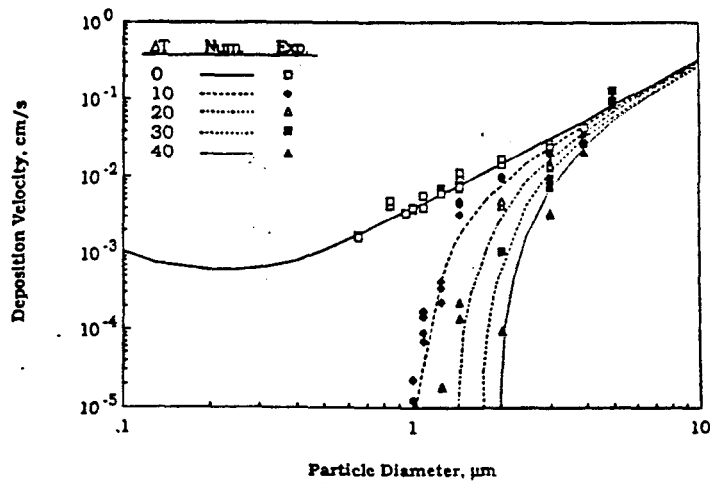
Comparison of Experimental results with numerical calculation results for thermophoretic effect of particle deposition.

[Figure 27]

VI. Particle Sampling in Stacks

This last topic is something we have done a few years back. This is what we initially tried to use in a stacked sampling situation. It would be nice if one can develop a probe without requiring isokinetic conditions. We have come up with a design with a two-step approach. The first is an isokinetic shroud on the outside (Figure 28). This is similar to the one that Professor Grinshpun indicated that Benstein has developed. In Benstein's case, he put electrostatic indicator here so this other shroud has a funnel here which creates a suction. By properly designing the other shroud, you can actually have the other shroud drawing in aerosol here at isokinetic conditions even at varying airspeeds. This is basically an isokinetic shroud which is driven by the freestream itself. What we have done here is to make a sudden expansion as soon as the aerosol is sampled isokinetically in this shroud. This may not show a very large area expansion, but once you make it with a larger area expansion, the idea is that we would like to sample the aerosol isokinetically into the shroud and immediately decelerate the flow. Once the flow is decelerated, this Belyaev and Levin equation shows that anisokinetic sampling error increases with the Stokes number and the mismatched velocity ratio (Figure 29). So that when you have the flow getting smaller, you can expand the flow (slow it down), resulting in a much lower velocity in the shroud and also for a lot of airborne work the stopping distance will probably be small. What this expansion will do is to move the sampling condition to a smaller Stokes number. When there is a big mismatch in the velocity, the isokinetic, anisokinetic sampling error in not that bad. What we have done is once it is decelerated in here than you can just draw the aerosol in a second sensing probe at constant flow into the impactor, filter sampler, etc. Even when the outside velocity varies, so long as it is isokinetically sampled into here and decelerated, this mismatch will not be so severe in terms of introducing anisokinetic sampling error.

162

UM-UNIVERSAL AEROSOL SAMPLING INLET [Ref.: Liu and Pui (1985) "A Universal Aerosol Sampling Probe for High Efficiency Particle Sampling from Flowing Gas Streams," Particle Characterization 2(4)]

UAS PROBE USED FOR SIZE SELECTIVE PARTICLE SAMPLING IN STACKS

[Figure 28]

163

[Figure 29]

164
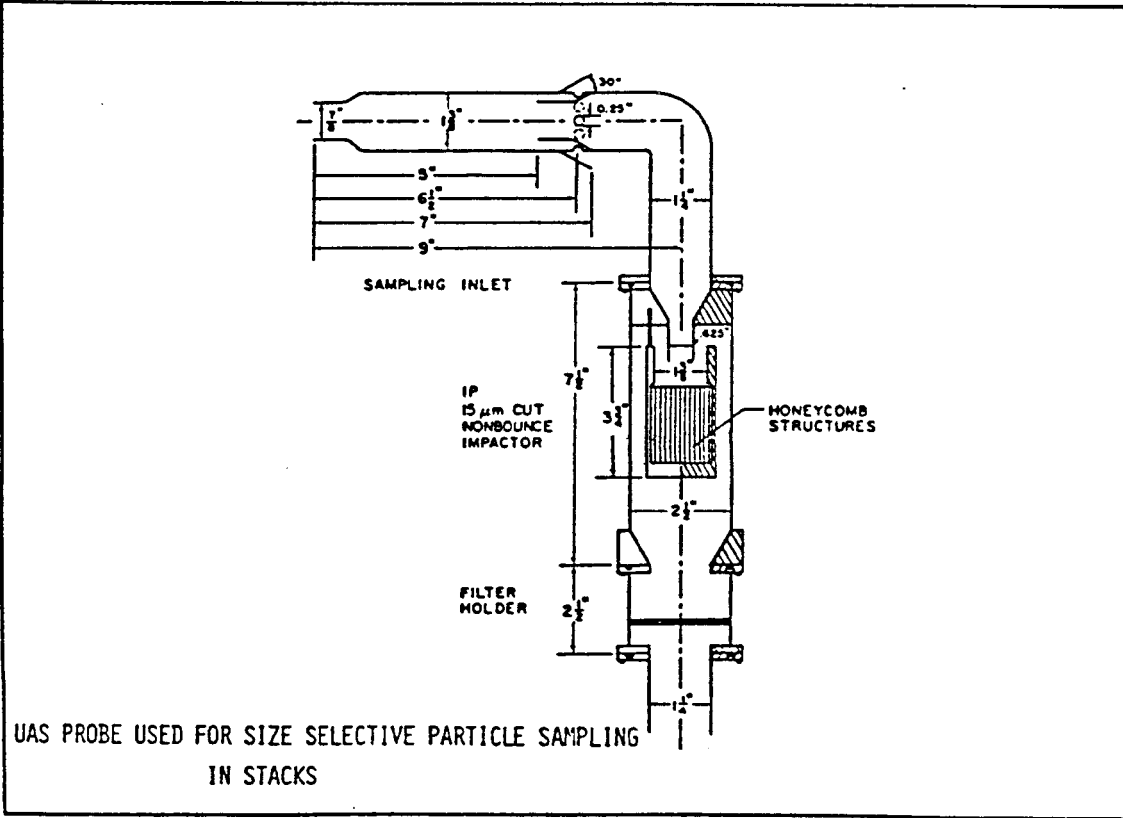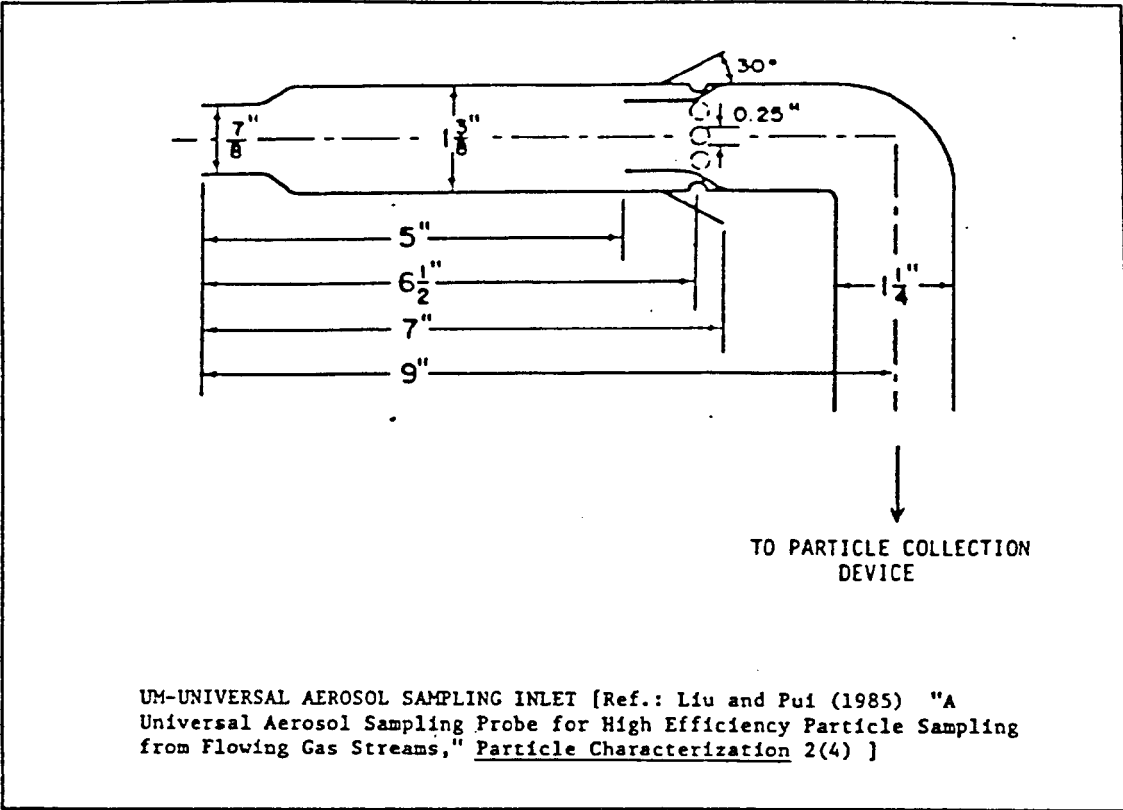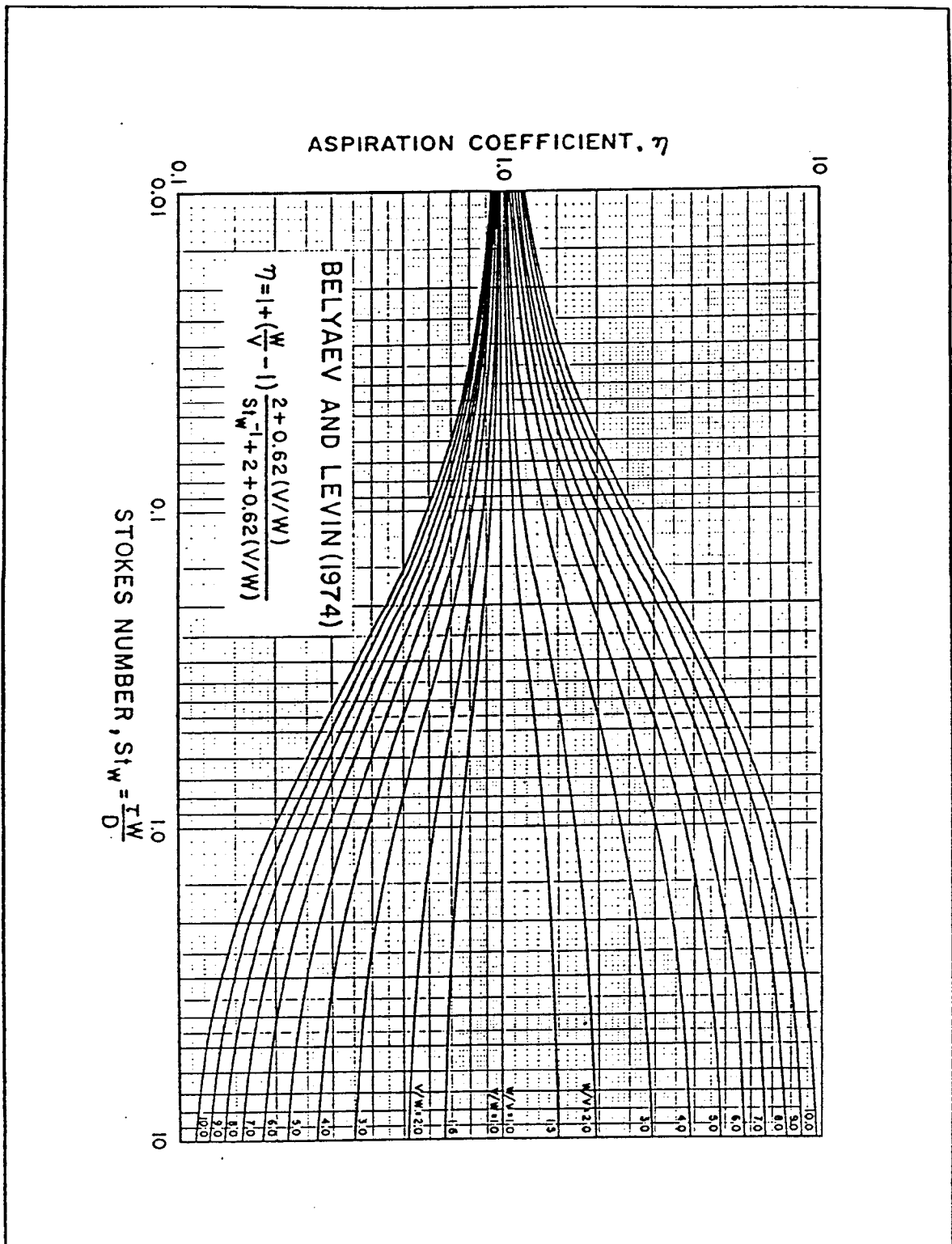
This is in contrast to what is used in stack sampling, which is to make use of button hook nozzle (Figure 30). The problem is how to make this match with the freestream when the stack flows are varying. In addition to that, there will be particle loss in the bend. We have developed a performance envelope for the button hook. This curve for isokinetic sampling with ± 10 percent of anisokinetic error. Within those two curves is an acceptable condition. Since there is particle loss in the bend, we impose additional constraints. With this button hook, you can really operate at very limited freestream velocity and sampling flowrate conditions in order not to have anisokinetic sampling error and particle loss in the bend.

Compare this with this shrouded probe (Figure 31). This is the performance envelope. So you can see that even at a freestream velocity over a wide range, you can still have a sample flowrate over a wide range without having particle loss due to anisokinetic sampling error or due to 90 degree bend here.

One other nice feature about this probe is that you can heat it up. The boundary layer will be sucked up from the outside. So this might be something you can use without heating up the airstream in the center yet prevent icing on the probe.

PERFORMANCE ENVELOPE OF THE "BUTTON HOOK" NOZZLE

[Figure 30]

166

PERFORMANCE ENVELOPE OF THE UNIVERSAL AEROSOL SAMPLING PROBE

[Figure 31]

167

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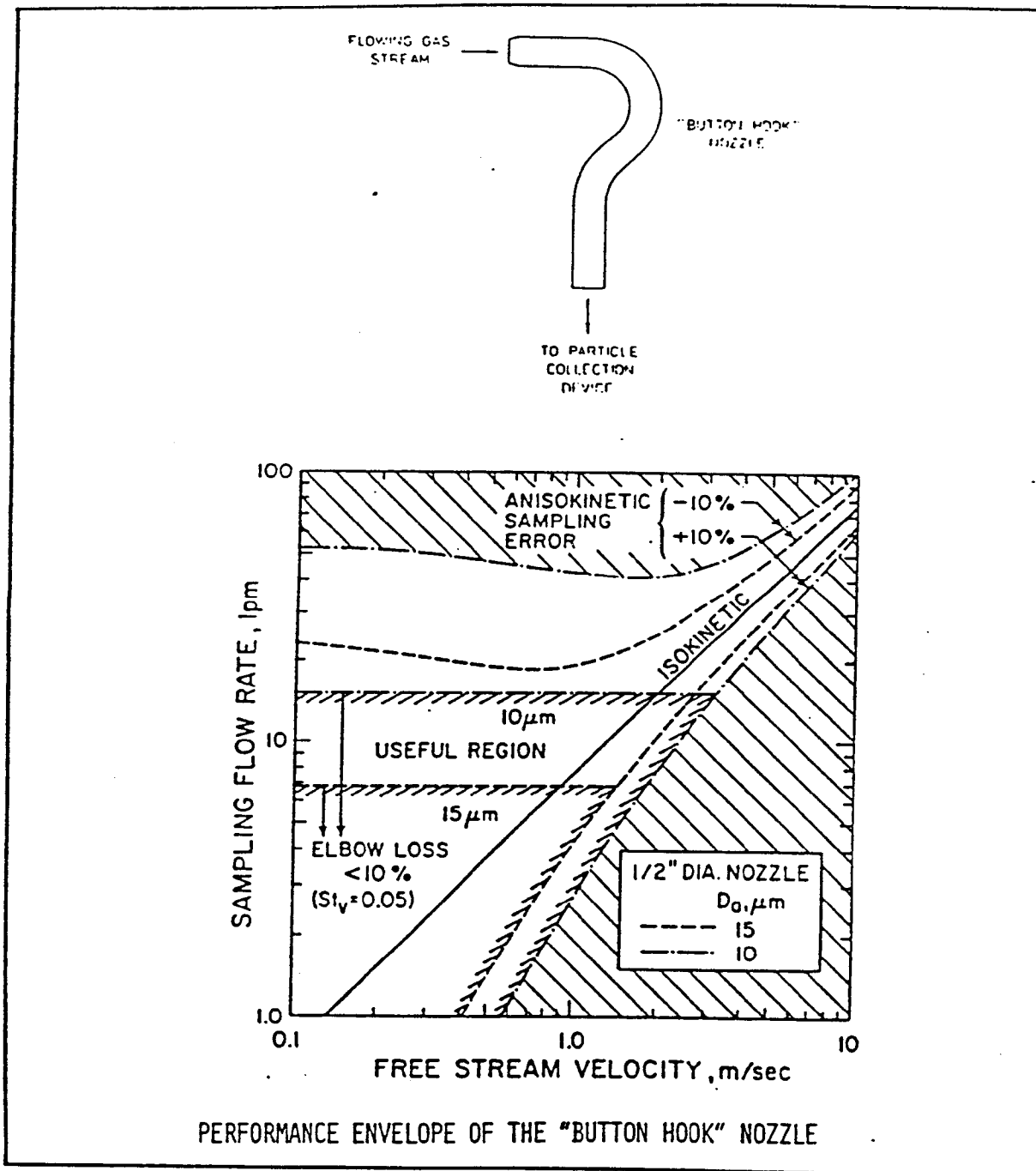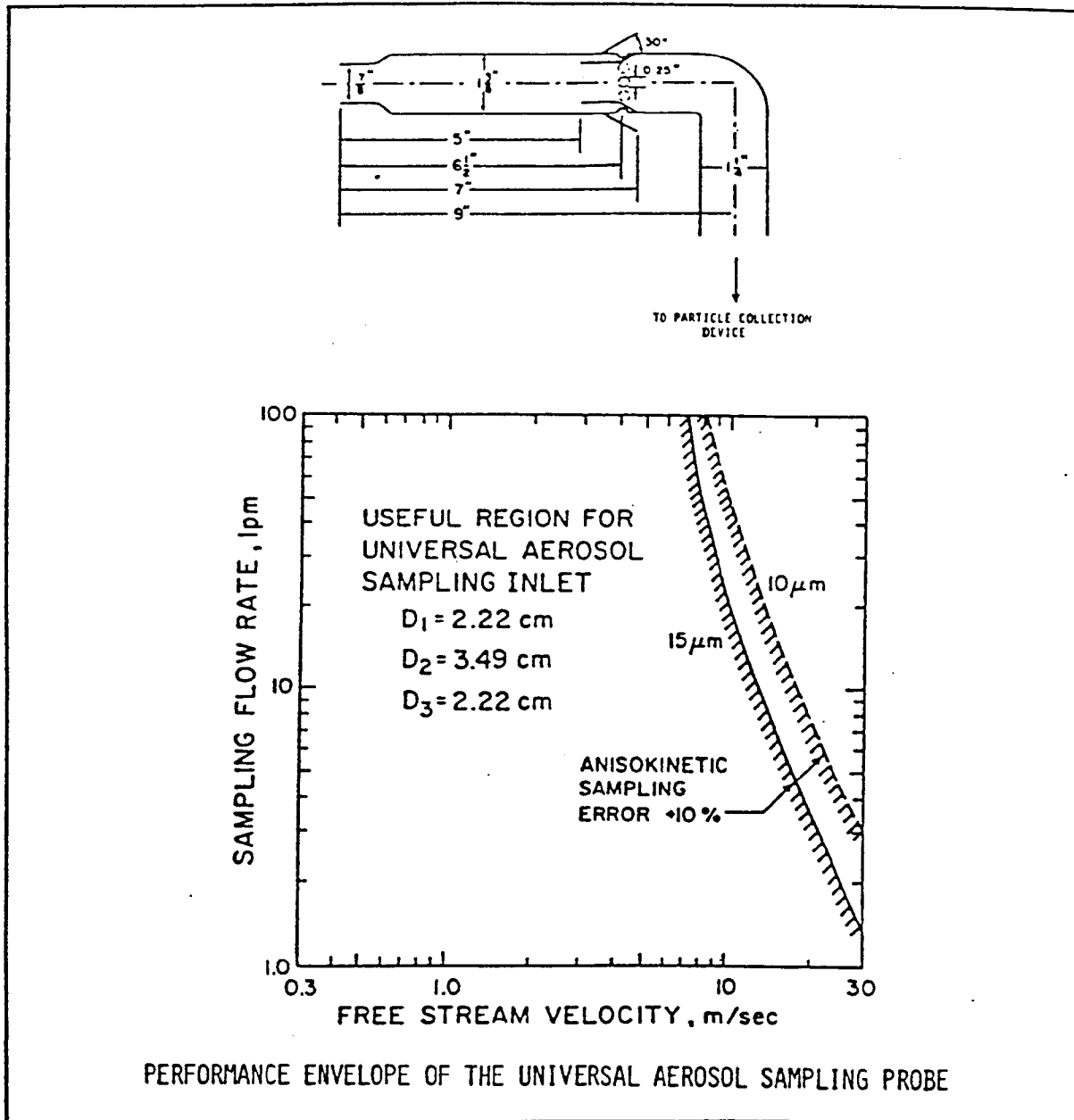
DISCUSSION

Clarke: Could you put your last slide up? Your sampling envelope when you start getting out there to 30 m/s is trying to crunch in on your sample flow. Do you have any feel for how you might have to change that to try to go up to 100 or 200 m/s? Would that effect the angles that you indicated in your shroud?

Pui: On this one, we basically tried to use this probe to compare with stack sampling conditions. I am trying to design a probe with a free steam typical of the stack condition. I see no problem with scaling it for the airborne application.

Clarke: How about the shape of your envelope? You want to maintain a high sample flow rate and at the same time a high diffusional velocity. What kind of modifications would be necessary, perhaps move the envelope up. It seems like of you want to go 30 m/s, you have to sample at ...

Pui: This probe is good for normally 30 m/m or 10 m/s, so if you were to try to develop a probe for airborne sampling, you would probably would want to do something with this way over on the right hand side.

Clarke: What does that mean physically in what you would change roughly. Is there a general trend?

Pui: First of all you have to try to make this shroud work. It is an isokinetic shroud. Jim, do you know if there are any limitations on this type of shroud as to how high a flow you can have while maintaining isokinetic conditions?

Willeke: I suspect because of the very large expansion, you may have to do that in a cascade fashion--have two or three of them. In other words, go down a decade in velocity and then another decade.

Pui: We published this work in 1985. Professor Sisson has a student that worked on this as a Master's thesis. I think that work will be almost complete. If you are interested in that, write Professor Sisson, and he can get you some more information.

            This work is verified experimentally, too. We have evaluated the data experimentally and confirmed some of this.

Huebert: I notice that you have a pretty sharp diffuser section here rather than a gradual diffuser. Is that, in fact, T° with a very sharp inlet ..

Pui: Initially we thought of having a diffuser here, but we though that maybe a little bit of turbulence may not hurt. It will help to make this particle concentration profile uniform in here. There will be some particle loss, but then the losses are on the wall.

Huebert: It seems to me that by establishing aircraft velocity, you really can get a uniform profile across the cross section.

Pui: I can tell you this. The reason that it is shaped like this is because it has a copper reducer here, another copper reducer here, and a copper reducer in the bend. It is something that we put together in one hour.

Soderman: It seems to me that you might have a pre-shear layer on that first corner which is going to be toward the center of the duct and mix.

Pui: This is not optimized for airborne studies. I am not too sure that it is even optimized for sack sampling. Professor Sisson's student has done some aerometric studies, so he would have more information.

Ram: Can you use heating to prevent particle deposition?

Pui: There are some people who have done studies on heat exchangers to see how temperature can minimize particle deposition.

Kritz: Have you ever applied the techniques that you've described this morning, including some of the newer ones that you have developed within the last few years to some of the samplers that Barry Huebert described washing out? In other words, applied your analysis to his samplers, and if you have done that, do your results predict the kind of depositions that he is finding?

Pui: Barry, I believe you have a copy of my report. Do you find in general that this theory applies to your bends?

Huebert: Yes, as a matter of fact, I did much better at predicting the deposition in bends than I did at predicting the deposition in the nozzle. For the very large particles, its possible to get in the right ball park.

Pui: Obviously the other thing you can put in here is the coil for the denuder, so you can make simultaneous particle gas measurements.

Clarke: Regarding the thermophoretic forces due to heating, they didn't seem to show very large effects for particles of under .1 of a micron. It seemed to have a strong effect even at 1 micron. Is that a consequence of the thickness of the layer you're looking at.

Pui: Remember for a clean room situation you have free stream flow of 100 f/m--a relatively low velocity. It's quite different from airborne situations. On the other hand, I'm seeing a lot higher temperature difference in the airborne case. Again, what I'm pointing out are things you might consider.

Clarke: Is there convective current in this?

Pui: No, there is no convection. Also in doing experiments, we are very careful not to have any convective buoyancy force.

On the Aerodynamic Design of Gas and Aerosol Samplers for Aircraft

By

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ABSTRACT

The aerodynamic design of airborne probes for the capture of air and aerosols is discussed. Emphasis is placed on the key parameters which effect the proper sampling such as inlet lip design, internal duct components for low pressure drop, and exhaust design. Inlet designs which avoid sonic flow conditions on the lip and flow separation in the inlet are shown. Cross-stream velocities of aerosols are expressed in terms of droplet density and diameter. Since flow curvature can cause aerosols to cross streamlines and impact probe walls, minimal flow curvature can be accomplished by proper inlet design, probe orientation, and the avoidance of bends upstream of the test section. A NASA panel code called PMARC has been used successfully to compute streamlines around aircraft and probes as well as the local velocity and pressure distributions in inlets. An NACA 1-series inlet with modified lip radius has been used for the airborne capture of ozone at high altitude and high flight speed. The device has a two-stage inlet which allows a large deceleration on the inflow with little disturbance to the flow through the test section. Diffuser design, exhaust hood design, valve loss, and corner vane geometry are discussed.

NOMENCLATURE

A_0	diffuser outlet flow area, m^2
A_i	diffuser inlet flow area, m^2
b	wing span, m
c	wing aerodynamic chord$=S/b$, m
C_L	wing lift coefficient
d	duct diameter, m
d_p	diameter of aerosol droplet or particle, m
k_v	total pressure loss coefficient, $\Delta p/q$
L_{dif}	streamwise length of diffuser, m
L	wing lift, N
q	dynamic pressure, N/m^2
r	distance from vortex core to induced streamline or distance from wing quarter chord to upwash location (Figure 1), m

M	Mach number
M_o	aircraft Mach number
M_d	average Mach number of airflow in duct
Re	Reynolds number based on duct diameter, $\rho V_d d/\mu$
S	wing area, m^2
V_o	velocity of aircraft, m/sec
V_1	velocity of sampler primary inlet, m/sec
V_2	velocity of sampler secondary inlet, m/sec
V_3	velocity in sampler test section, m/sec
V_d	average velocity in a duct, m/sec
V_r	particle velocity perpendicular to fluid streamline, m/sec
V_t	particle velocity tangent to fluid streamline, m/sec
w	wing upwash velocity, m/sec
W	aircraft weight, N
x	distance in boundary layer parallel to duct, m
α_i	angle of attack induced by wing upwash, rad
α_w	angle of one diffuser wall relative to duct centerline, deg
Δ_p	total pressure loss at duct component, N/m^2
Γ	vortex strength, m^2/sec
υ	viscosity of air, kg/m sec
ν	kinematic viscosity of air, m^2/sec
ρ	air density, kg/m^3
ρ_p	aerosol droplet or particle density, kg/m^3
θ	upwash angle (Figure 1), deg
ω	vortex rotation rate, rad/sec

INTRODUCTION

High altitude sampling of atmospheric chemistry has been accomplished for many years using rocket launched parachute drops and balloon drops (Anderson, 1975). More recently, the authors have been involved with airborne sampling using the NASA ER-2 aircraft, primarily to investigate the role of free radical CIO in ozone depletion in the stratosphere (Brune et al, 1988). Requirements for smooth, regulated airflow to the chemistry analysis section of the experiments have led to work in inlet and internal duct aerodynamic design. For example, it is often necessary in airborne experiments to decelerate the airflow smoothly so as to minimize turbulence in the sampled airstream. In an air sampler, turbulence could allow wall interactions that would alter the abundance of the gas being investigated. Similar flow constraints are required for aerosol sampling (Huebert et al, 1990).

Fortunately, there is a large body of literature on inlet and internal duct design. Aerodynamicists have been concerned for many years about aircraft aerodynamics related to smooth inflow to engines, flow separation, shock formation, boundary-layer control,

172

fuselage streamlines, wing upwash, internal duct losses, corner vane design, pressure probe design, and so on. All of these subjects are important to the design of airborne sampling systems for gas and aerosols and will be discussed.

With respect to aerosol sampling, the two most important aerodynamic constraints are a) minimization of the inflow streamline curvature since aerosols tend to cross curved streamlines because of inertia, an action which leads to inaccurate estimates of aerosol concentration, and b) elimination of turbulence because turbulence leads to wall collisions and removal of aerosols from the airstream (Huebert et al, 1990). It is also assumed that it is often necessary to decelerate the flow for the gas analysis system. This paper will focus on design ideas which affect those aerodynamic goals.

AEROSOL MOTION

Aerosols or particles following a curved streamline will experience a centrifugal force which tends to drive the particles across fluid streamlines. This is a common problem in laser velocimetry where flow velocities are deduced from particle motion and can be in error if the particles do not faithfully follow fluid streamlines. Likewise, curved streamlines can cause deposition of aerosols on probe walls and thereby lead to erroneous concentration measurements.

A curved streamline can be thought of as a rotational field like that induced by a vortex where all streamlines are circumferential. The tangential velocity is

$$V_t = r\omega \tag{1}$$

where ω is the vortex rotation rate necessary to product V_t, and r is the distance from the vortex center to the streamline. Thus, r is the radius of a circle tangent to the curved streamline at the region of interest. The centrifugal force creates a radial velocity experienced by a particle (Durst et al, 1976):

$$V_r = \frac{r\omega^2 d_p^2 \rho_p}{18\upsilon} \tag{2}$$

Thus, the radial velocity depends on the particle density and diameter squared. The radial displacement can then be computed for a given flow curvature. For high streamline curvature, particles must be very small to have a small radial velocity and displacement.

INLET DESIGN

Probes for airborne aerosol samplers must capture airflow smoothly over a small but significant range of inflow angles. Inflow angles change during flight because of changes in aircraft airspeed and angle of attack as fuel is burned or altitude is varied.

Probe orientation can be optimized to coincide with local streamlines. Estimates can be made of streamline direction anywhere near the aircraft knowing the aircraft geometry, airspeed, and wing lift. Estimates of wing upwash velocity, w, and induced angle of attack α_i, can be made using a simple vortex line modeling of the wing as illustrated in Figure 1. The vortex strength is

$$\Gamma = \frac{L}{\rho b V_o} \tag{3}$$

and the upwash velocity is

$$w = \frac{\Gamma}{2\pi r} \tag{4}$$

In level flight, aircraft lift equals weight, so the lift coefficient is given by

$$C_L = \frac{L}{qS} = \frac{W}{qS} \tag{5}$$

and the induced angle of attack is

$$\alpha_i = \frac{w}{V_o}\cos\theta = \frac{C_L c \cos\theta}{4\pi r} \tag{6}$$

for small values of w.

The above equation gave a value of $3.9°$ for the ER-2 wing pod station 3 m ahead of the wing quarter chord. Thus, a probe at that location would be oriented $3.9°$ downward for alignment with the local flow.

Detailed flow field streamlines are better computed using computer panel methods. We have used the NASA Ames PMARC code, which is a low-order potential flow panel code (Ashby et al, 1990). Figure 2 shows, for example, streamlines computed near the ER-2

174

Wing pod using PMARC which illustrate how far a given probe must project ahead of the pod to capture airflow upstream of flow curvature. The wing influence is not shown. For the probe location noted, the inlet was located 46 cm ahead of the wing pod to avoid flow curvature. Similar analyses can be used to estimate streamlines along the aircraft fuselage for various flight conditions.

The necessity to accept airflow over a range of inflow angles leads to the requirement of inlets with a finite lip thickness. This inlet lips function well for axial inflow, but off-axis inflow will separate at the probe leading edge. The NACA put considerable work into testing aircraft cowlings during the 40's, primarily to control velocities at engine inlets so as to avoid shock formations. This is also a problem for the ER-2 and other aircraft which must fly at high subsonic Mach numbers to attain high altitudes. Local flow accelerations around inlets can cause the flow to go supersonic even though the aircraft flight speed is subsonic. Shock waves on or near the inlet can adversely influence the flow into the inlet, especially if the shocks oscillate.

The stream tube captured by the probe will be smaller than the duct diameter if the duct velocity is lower than the flight speed, and the stream tube will be larger than the duct diameter if the duct velocity is greater than the flight speed as illustrated in Figure 3. In the first case, the stagnation point will be inside the inlet and the flow not captured will flow out around the lip. As the duct velocity increases, the stagnation point will move forward. Figure 4 shows various stagnation points on an inlet for several values of flight Mach number and a fixed duct Mach number of 0.85. At low flight Mach number and high duct speed, the captured flow along the surface must accelerate from the stagnation point high on the nose and flow around the lip and into the duct. This could lead to flow separation. Conversely, a high flight Mach number and low duct Mach number would force the non-captured air to flow from the stagnation point inside the inlet forward around the lip. Flow separation or sonic flow could result on a sharp or otherwise poorly shaped inlet.

Nichols et al (1949) and Baals et al (1948) generated a large data base which shows how NACA 1-series inlet shapes (Figure 5) delay sonic flow and flow separation for a range of flight Mach numbers and a range of duct-velocity to flight-velocity ratios. Re (1975) presents further performance studies of the NACA 1-series inlets. The NACA 1-55-100 inlet shape was chosen for the inlets of the stratospheric sampler used in ER-2 aircraft over Antarctica (Brune et al, 1989). However, the NACA lip radius was increased to 6.35 mm after discussions with an aircraft manufacturer[**]. The slightly thicker inlet lip is a more conservative design than the NACA lip in terms of prevention of flow separation from off-axis flow. The NACA 1-series geometry is given in Table 1. (The series designation code is explained in the table.) The NACA 1-55-100 inlet does not induce shock formation or flow separation even at the ER-2 flight Mach number of 0.7 and moderate angles of attack of the probe.

[**] Conversation with Don Nelson of Lockheed Aircraft Co., 1986.

More recently, Luidens et al (1974) have done optimization studies aimed at finding the shortest, thinnest lip that will turn the flow into the inlet at low-speed conditions without flow separation anywhere in the inlet. This results in an elliptic lip shape. Figure 6 shows the important geometric parameters--fineness ratio and contraction ratio. At duct to free-stream velocity ratios of 1 the flow will stay attached to the lip up to an angle of 28° (Luidens and Abbot, 1976). At lower values of duct to free-stream velocity ratio, the separation angle is much lower (Baals et al, 1948).

To summarize this section, design guides exist for the design of inlet lips and diffusers for low-speed (elliptic lips) and high-speed flight (NACA 1-series). The design should result in this, but not sharp lips that can turn off-axis flow into the duct and decelerate the flow by diffusion as it moves downstream without any flow separation.

DUAL INTAKE

The design of the inlet shape for the CIO sampler flown on the ER-2 was complicated by the requirement to decelerate the flow smoothly from a flight velocity of approximately 200 m/s to a test-section velocity of 20 m/s. That large deceleration is equivalent to a blockage seen by the inflow that causes the air to spill out and around the inlet. Flow acceleration around the inlet outer surface would cause the flow to go sonic and thereby generate shock waves which could oscillate and perturb the flow into the duct. The studies of Nichols et al (1949) and Baals et al (1948) indicated that no inlet was found that could handle such a large flow deceleration and spillage without generating external shock waves at the aircraft flight speed of 200 m/s.

Therefore, a two-stage inlet was devised as shown in Figure 7. The idea is that the first (primary) inlet would capture and decelerate a stream tube to 30 percent of the free stream velocity or 60 m/s, and the second (secondary) inlet would capture the center core of the primary stream tube and decelerate it to 33 percent of the primary duct velocity, or a nominal 20 m/s. The excess flow from the primary duct bypasses the test section and is dumped. Because of the modest decelerations, shock wave generation on both inlets would be avoided. In addition, the boundary layer in the primary duct would not enter the secondary duct. At the secondary inlet, a new boundary layer would commence but would not have a chance to grow much in the short distance to the test section. The primary inlet was designed to accept off-axis flow of around 6° or less without flow separation so turbulence would not enter the center of the duct. (The actual off-axis flow angle that initiates flow separation has not been confirmed.)

Analysis of the two inlets in terms of velocity ratios V_d/V_o and critical Mach numbers (Baals et al, 1948) led to the adoption of the NACA 1-55-100 inlet shape with modified lip radius for both the primary and secondary inlets of the stratospheric sampling experiment. Although it was not possible to document the inlet flow fields in a wind tunnel, flight tests of the experiment aboard the ER-2 indicated that the aerodynamic performance of the two

stage inlet system was very good. Measurements involved wall heating of the entry portion of both inlets and evaluation of boundary-layer growth by means of low-mass thermistors arrayed at three downstream stations and at various distances off the walls. Both primary and secondary ducts were equipped with throttling valves and velocity sensors. In-flight testing at throttle settings appropriate for the design duct velocity, and at moderate variations of velocity, indicated no wall interaction with the core flow to a distance of at least 17 diameters down the secondary duct--past the test station.

The two-stage inlet design would also lend itself well to airborne aerosol sampling because the flow which enters the test section comes from the center of the primary duct. That portion of the flow does not pass close to the inlet lips and, therefore, does not experience much streamline curvature except for curvature caused by probe angle of attack relative to the flight direction. angle of attack can be minimized by anticipating local flow directions and orienting the probe close to streamwise as discussed above.

INTERNAL COMPONENTS

For aerosol sampling, flow curvature must be minimized since aerosols have inertia that cause them to cross curving streamlines as discussed above. This leads to the requirement of keeping a straight duct between the inlet and measurement station. The use of probes with elbows upstream of the measurement station will surely lead to the introduction of circulating flow in the elbow and possible wall contract by the gas or aerosols. Figure 8 shows typical flow patterns in elbows without turning vanes. The momentum of the flow will drive the flow outward across the core, which will establish secondary flow vortices which rotate as shown. The fluid elements follow a helical path while negotiating the corner. These general flow patterns exist in circular or rectangular corners, whether the flow is turbulent or laminar. Corner vanes can prevent this pattern, as is discussed below, but the vanes themselves could be contacted by the gas or aerosol.

Care must be taken with the internal duct design so as to minimize the pressure drops in all sections except at the regulator valve. Otherwise, mass flow may be retarded and back pressure may lead to flow separation and turbulence in the test section. In most flight cases, the system can be designed clean enough to pass adequate mass flow that is generated by ram pressure. In balloon drops with little forward speed, it has been necessary to incorporate a fan downstream of the test section so as to generate adequate mass flow rate in the test section (Weinstock et al, 1990).

Pressure drops occur all along the duct because of viscosity, but the primary pressure drops occur at corners, diffusers, junctions, area changes, and other perturbations in the duct. We have used the extensive data base of Idechik (1966) for pressure drop estimates, but there are numerous data sets in the literature on duct component pressure drop (see Blevins, 1984, and Miller, 1974).

177

Unobstructed diffusers should have wall angles less than 4° relative to the duct axis to prevent flow separation. With blockage in the diffuser, such as the secondary inlet shown in Figure 7, the wall angle can be increased because the effective wall angle is given by

$$\alpha_w = \tan^{-1}\left(\frac{\sqrt{A_o} - \sqrt{A_i}}{\sqrt{\pi}L_{dif}}\right) \qquad (7)$$

where the areas have been reduced by the cross-sectional area of the obstruction.

In a turbulent boundary layer, the flow mixes randomly and will contact the wall. Since wall contact affects gas and aerosol properties, it is often necessary to sample flow which is outside the boundary layer. Unless there is flow separation at the inlet, it will take some distance before turbulent pipe flow will be established in the duct. Figure 9 shows the velocity distribution for laminar flow in the inlet section of a channel. A fully developed laminar pipe flow velocity distribution does not develop until a distance of (Schlichting, 1979):

$$x = 0.03d \; Re \qquad (8)$$

so that for a Reynolds number, Re=5,000 to 10,000, x ranges from 150 to 300 pipe diameters. In higher Reynolds number flow, the boundary layer will become turbulent. Even then, it takes 25 to 100 pipe diameters to spread to the centerline as established pipe flow. The variation in distances depend on wall roughness and inflow smoothness.

On a flat plate, the flow will transition from laminar to turbulent flow at a distance from the start of the plate approximately equal to

$$x = 35,000\frac{\upsilon}{V_d} \qquad (9)$$

For the two stage inlet of Figure 7, the boundary layer was laminar the entire length of the primary inlet ($V_d = 60$ m/sec) and only 0.5 cm thick at the downstream end 46 cm from the inlet. The secondary inlet scooped off the flow outside the boundary layer and started a new laminar boundary layer. Thus, turbulence was not a problem for the flow conditions experienced in the flight test.

As discussed above, turning vanes are essential to controlling flow circulation in corners and the resulting pressure losses. Figure 10 shows typical corner vanes designed to subdivide the flow into separate channels so as to reduce pressure drop. Corner pressure drop with vanes

can be a third or less of the pressure drop without vanes depending on vane geometry. Airfoil vanes, for example, have less loss than thin vanes, though they are more expensive to fabricate. Blevins (1984) gives design information on vane geometry and spacing.

The largest pressure drop in the duct should occur at the regulator valve so that a range of mass flows can be controlled. Figure 11 shows total pressure loss coefficients for various valves as a function of valve position (Miller, 1974). Figure 12 gives the loss coefficients for a fully open butterfly valve as a function of valve thickness to duct-diameter ratio. These curves can be used as design guides, but the system should be calibrated in a laboratory to verify mass flow rate versus valve position.

Miller (1974) also presents empirical equations from Gardel which give the pressure loss associated with combining and dividing flows were recombined before being exhausted out of the wing pod. By designing the confluence so that the two flows merge nearly parallel, the pressure drop can be minimized, and a suction can be induced to aid pumping in one duct or the other.

EXHAUST

In the sampling system, the primary and secondary airflows were recombined and exhausted out the side of the ER-2 wing pod. A simple hole in the wing pod might have generated very unsteady flow that could have perturbed the entire duct system. Therefore, an exhaust hood was added as shown in Figure 13. The hood protects the exhaust from the airstream and turns the exhaust flow parallel to the airstream. This not only stabilizes the duct flow, but a small negative pressure can be created at the exhaust, which will contribute to the system pumping. The external drag and suction pressure of the hood can be estimated from the work of Hoerner (1965). The internal pressure drop of the hood can be estimated from the work of Rogallo (1940).

CONCLUDING REMARKS

The aerodynamic design of airborne probes for the capture of air and aerosols is discussed in terms of inlet lip design, internal duct components for low pressure drop, and exhaust geometry. Inlet designs which avoid sonic flow conditions on the lip and flow separation in the duct are shown. Cross-stream velocities of aerosols are expressed in terms of droplet density and diameter. A simple method for estimating wing upwash angles at probes is developed. A more elaborate method for flow computations, the NASA panel code called PMARC, has been used successfully to compute streamlines around aircraft and through probes, as well as to compute the local velocity and pressure distributions in inlets. This allows orientation of the probe so as to align with expected streamlines near the aircraft. An NACA 1-series inlet with modified lip radius used for a stratospheric sampling

179

experiment at high altitude and high flight speed is described. The device has a two-stage inlet which decelerates the inflow with little disturbance to the flow through the test section. Boundary-layer growth, diffuser design, exhaust hood design, valve loss, flow junctions, and corner vane geometry are discussed.

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180

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[Table 1]--NACA 1-55-100 Cowling Coordinates
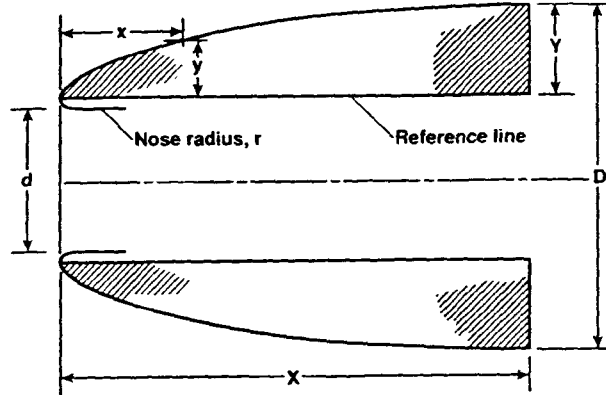
$$X = \left(\frac{X}{D}\right) D$$

$$Y = \frac{D-d}{2} - r$$

$$\text{For } r = 0.025 \text{ Y:Y} = \frac{D-d}{2.05} = \frac{D\left(1 - \frac{d}{D}\right)}{2.05}$$

x/X	y/Y	x/X	y/Y	x/X	y/Y	x/X	y/Y
0	0	13.0	41.94	34.0	69.08	60.0	89.11
.2	4.80	14.0	43.66	35.0	70.08	62.0	90.20
.4	6.63	15.0	45.30	36.0	71.05	64.0	91.23
.6	8.12	16.0	46.88	37.0	72.00	66.0	92.20
.8	9.33	17.0	48.40	38.0	72.94	68.0	93.11
1.0	10.38	18.0	49.88	39.0	73.85	70.0	93.95
1.5	12.72	19.0	51.31	40.0	74.75	72.0	94.75
2.0	14.72	20.0	52.70	41.0	75.63	74.0	95.48
2.5	16.57	21.0	54.05	42.0	76.48	76.0	96.16
3.0	18.31	22.0	55.37	43.0	77.32	78.0	96.79
3.5	19.94	23.0	56.66	44.0	78.15	80.0	97.35
4.0	21.48	24.0	57.92	45.0	78.95	82.0	97.87
4.5	22.96	25.0	59.15	46.0	79.74	84.0	98.33
5.0	24.36	26.0	60.35	47.0	80.50	86.0	98.74
6.0	27.01	27.0	61.52	48.0	81.25	88.0	99.09
7.0	29.47	28.0	62.67	49.0	81.99	90.0	99.40
8.0	31.81	29.0	63.79	50.0	82.69	92.0	99.65
9.0	34.03	30.0	64.89	52.0	84.10	94.0	99.85
10.0	36.13	31.0	65.97	54.0	85.45	96.0	99.93
11.0	38.15	32.0	67.03	56.0	86.73	98.0	99.98
12.0	40.09	33.0	68.07	58.0	87.95	100.0	100.00

Nose radius: 0.025Y

NOSE-INLET DESIGNATION

A designation system for nose inlets has been devised that incorporates the following basic proportions (see sketch in table I):

d inlet diameter
D maximun outside diameter of nose inlet
X length of nose inlet, measured from inlet to maximum-diameter station

The number designation is written in the form 1-40-150. The first number in the designation represents the series; the number 1 has been assigned to the present series. The second group of numbers specifies the inlet diameter in percent of maximum diameter d/D; the third group of numbers specifies the nose-inlet length in percent of maximum diameter X/D. The NACA 1-40-150 nose inlet, therefore, has a 1-series basic profile with $\frac{d}{D} = 0.40$ and $\frac{X}{D} = 1.50$.

Soderman-Table 1

182
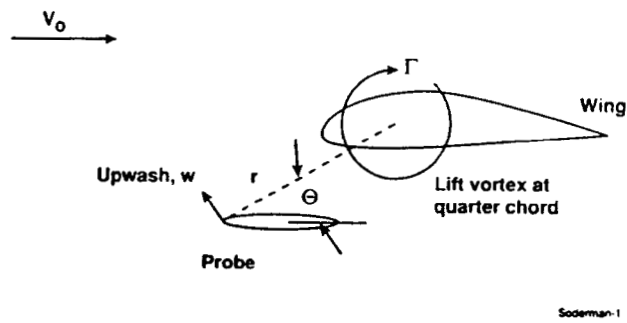
[Figure 1]--Geometry for wing upwash calculation using a lift vortex to simulate the wing.
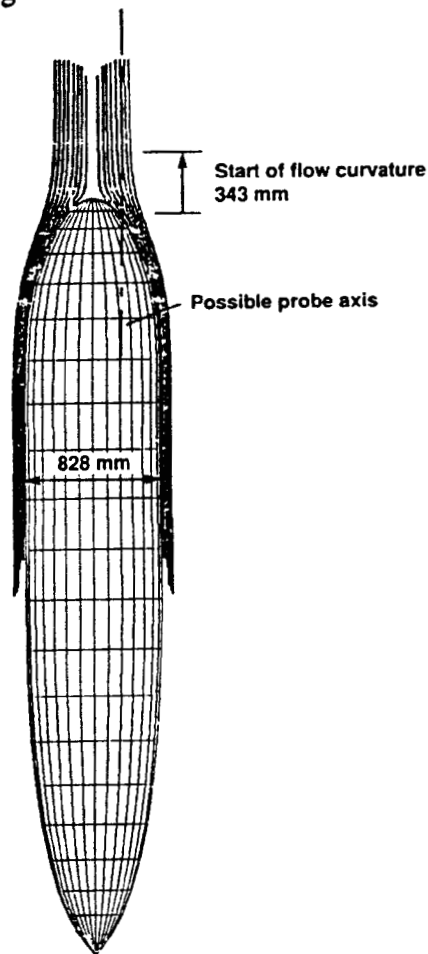
[Figure 2]--Predicted streamlines around the ER-2 spear pod nose using PMARC (Panel Method Ames Research Center); wing upwash not included.

183

Soderman-3
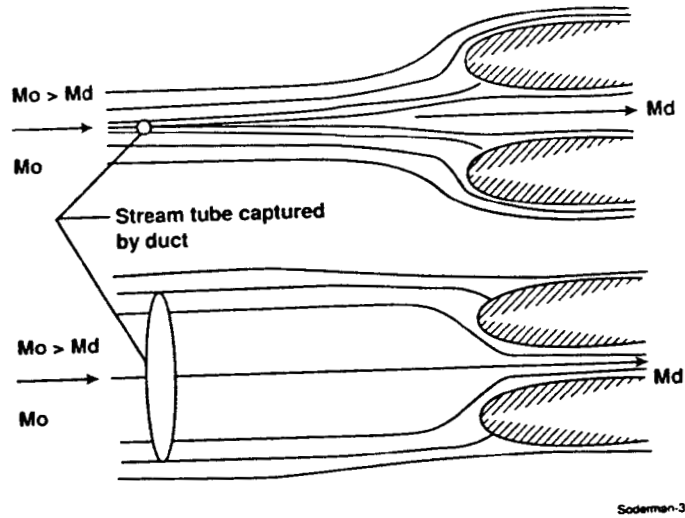
[Figure 3]--Inlet streamlines for flight Mach numbers greater or less than the duct Mach number.

Soderman-4
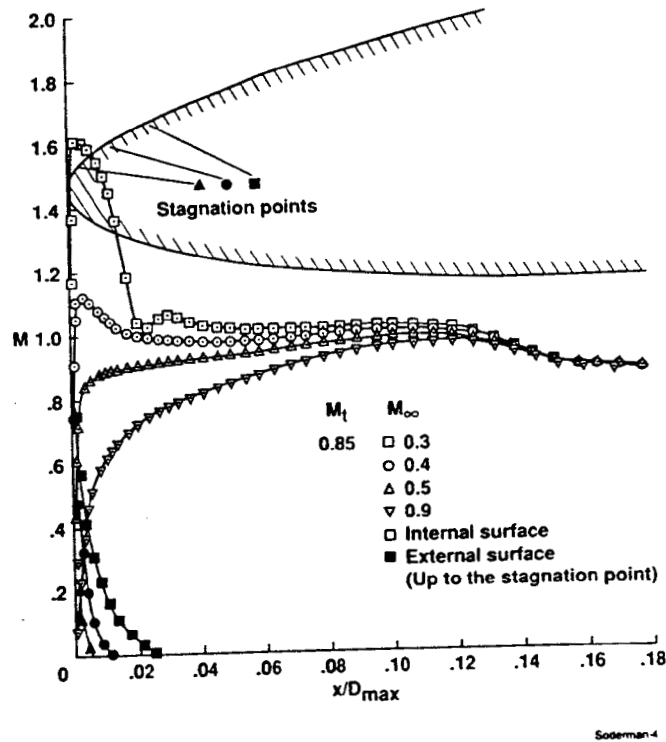
[Figure 4]--Effect of forward speed on lip surface Mach number distribution (ellipse ratio a/b 5, contraction ratio 1.15). (Seddon and Goldsmith, 1985).

184

P

1.0
.8
.6
.4
.2

+ Positive pressures
– Negative pressures

V_i/V_0
1.03
.69
.41

(a) NACA 1-55-100 cowling

1.0
.8
.6
.4
.2

.61
.80
.90

(b) NACA 1-85-050 cowling

1.0
.8
.6
.4
.2

.96
.68
.38

(c) NACA 1-70-100 cowling

1.0
.8
.6
.4
.2

.95
.68
.39

(d) NACA 1-70-050 cowling
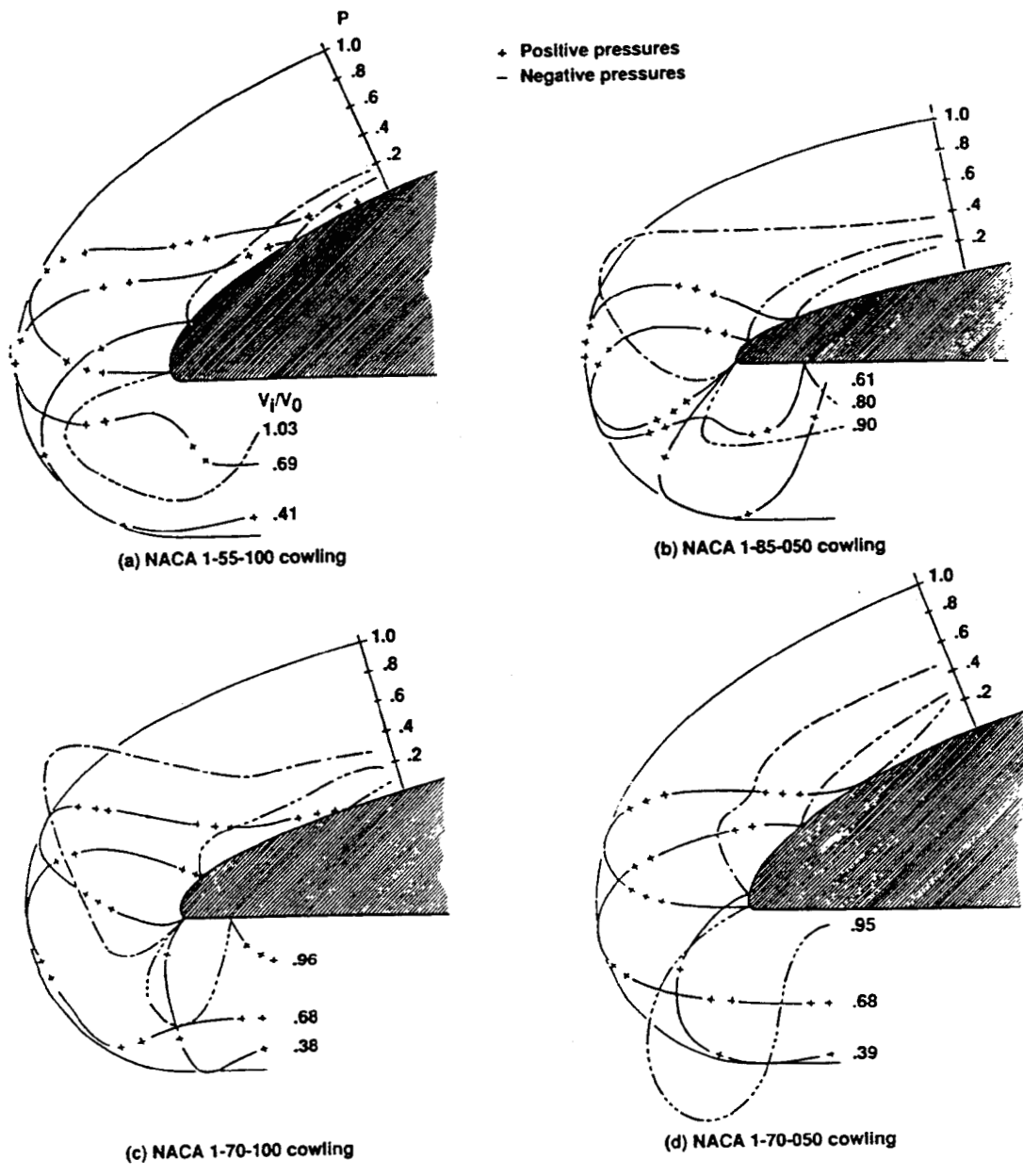
[Figure 5]--Static-pressure distributions around nose sections of representative NACA 1-series cowlings. Propeller removed; no spinner; $\alpha=0°$; M=0.13. (Nichols and Keith, 1949).

185

$(x/a)^p + (y/b)^q = 1.0$
Fineness ratio = a/b
Contraction ratio $CR = r_h^2 / r_t^2 = (r_t + b)^2 / r_t^2$
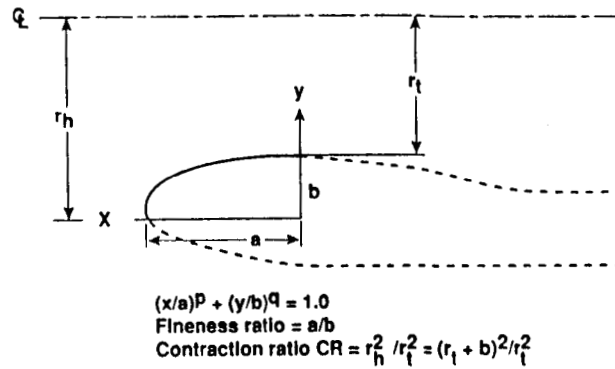
Soderman-6

[Figure 6]--Elliptical lip shape parameters. (Luidens et al, 1979)
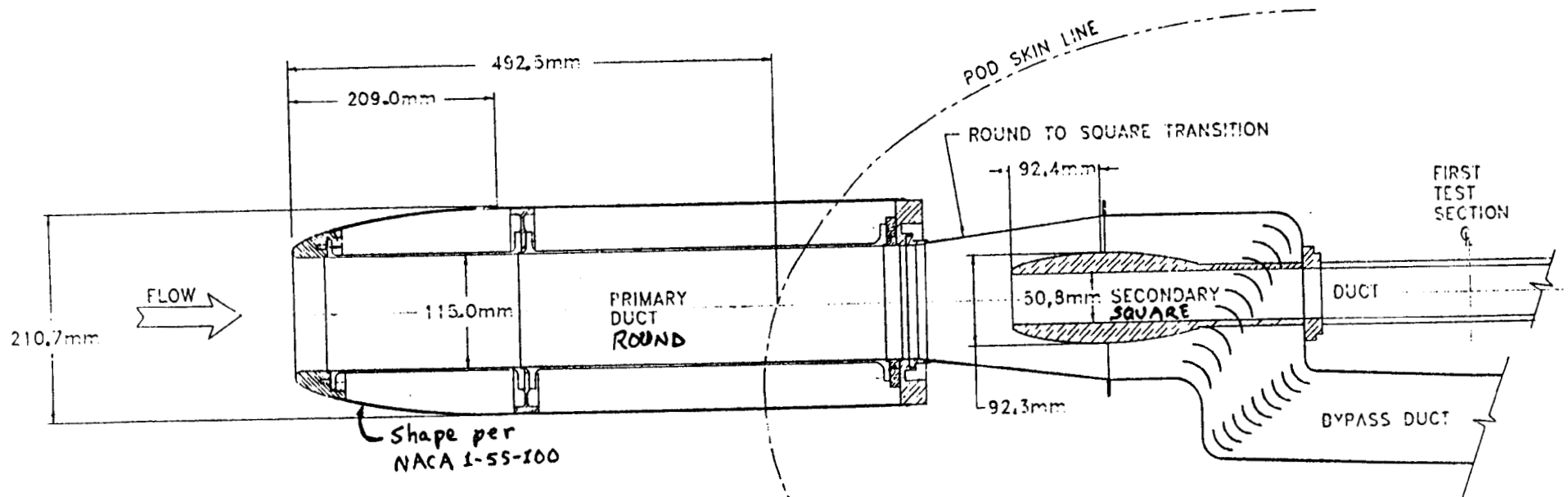
[Figure 7]--Two-stage inlet geometry using a NACA 1-55-100 cowling with modified lip radius.

a. Radial flow system

U_{max}

b. Contours of axial flow

Helical flow path

Flow direction
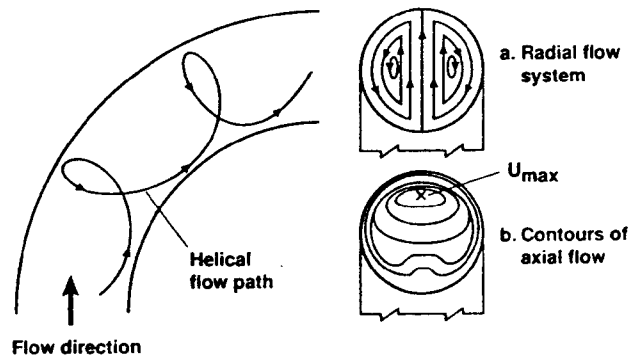
Soderman-8

[**Figure 8**]--Flow in a curved pipe showing the helical flow pattern of a fluid element and the two vortices created. (Blevins, 1984)
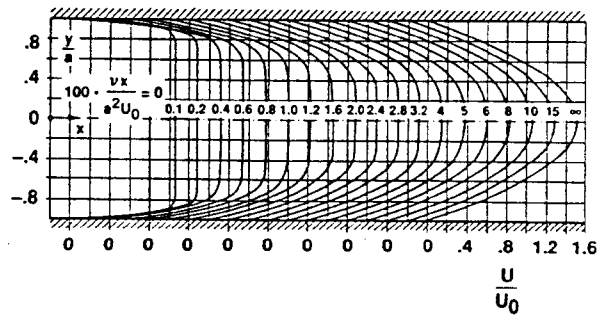
Soderman-9

[**Figure 9**]--Velocity distribution for laminar flow in the inlet section of a channel. (Schlichting, 1979)

187

a) Concentric
splitters

b) Circular arc
vanes
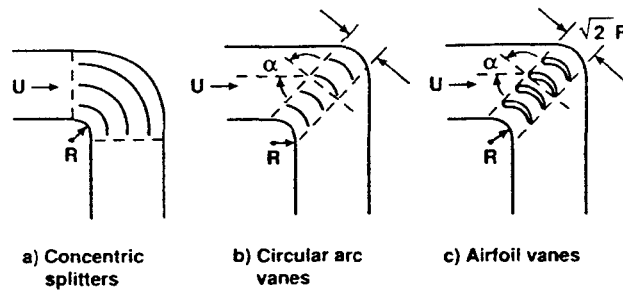
c) Airfoil vanes

Soderman-10

[Figure 10]--Three-vane systems for reducing pressure loss in sharp bends shown in a 90° bend. The angle of attack (α) is one-half the bend angle (θ) for circular arc vanes and slightly greater than this for profile and airfoil vanes. (Blevins, 1984)

A   Gate
B   Globe
C   Y
D   Angle
E   Butterfly
F   Diaphragm
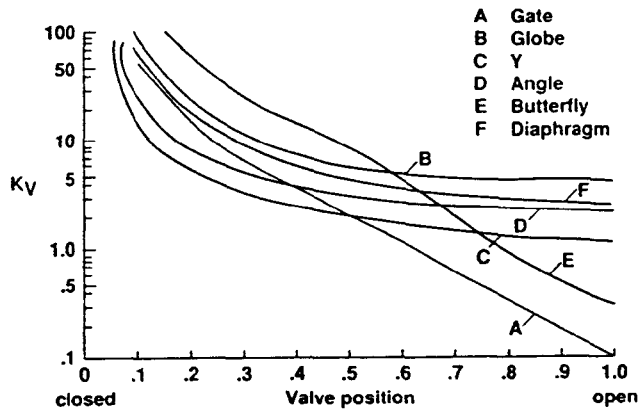
Soderman-11

[Figure 11]--Total pressure loss coefficients for several duct valve types. (Miller, 1974)

188

a) Concentric   b) Circular arc   c) Airfoil vanes
   splitters   vanes
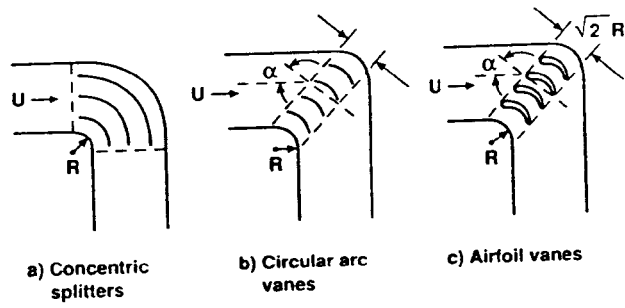
Soderman-10

[Figure 12]--Total pressure loss coefficients for fully open butterfly valves. (Miller, 1974)

A Gate
B Globe
C Y
D Angle
E Butterfly
F Diaphragm
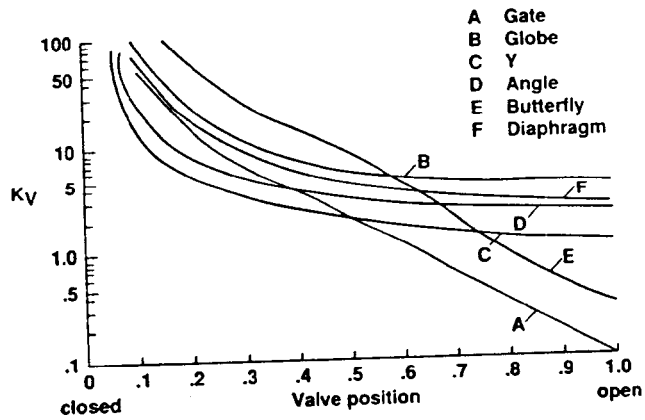
[Figure 13]--Exhaust hood geometry.

Soderman-11

189

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DISCUSSION

Huebert: I would like to know what the aerosol physicists think about a sampler like this where you essentially have a sequence of two non-isokinetic situations. Does this sound like a reasonable approach?

Vincent: My first thought was, until I came to this meeting, I'd never ever design a probe with a blunt edge for this purpose, but I can see the reasons that Paul is getting at is a problem of separation. That's the problem he is addressing, the question of separation at the leading edge, whereas in most of the applications where I have been concerned before, you use a sharp edged probe because you know the direction of flow. It just occurs to me, though, I wonder if in the atmospheric case, there is a thing called a tunnel sampler, which has been developed for the ambient atmosphere, which is not unlike the thing that Paul is describing, but it has a vane on it so it can always orient itself to face in the wind. In a sense it is kind of self-orienting so that the air is always coming into the sampler tunnel where the conditions are well-defined. Then you sample isokinetically back inside the tunnel. That flow through the tunnel is driven by a fan, and the orientation is driven by the wind direction.

I wonder if there is any mileage in this application for having some continuously controllable orientation, by using a vane or something a bit more high tech like a little robot and some sensors. I don't like the idea of blunt entrance to be honest.

Soderman: Why do you like sharp inlets? What does that do for you?

Vincent: You can define isokinetic conditions in principle without any losses.

Soderman: Yes, but if you have the wrong mass influence your inlet, you have more curvature even on a sharp inlet. In other words if I have velocity in my inlet, I'm going to get this type of curvature whether it's sharp, round, or whatever. The flow will have to adjust.

Vincent: I am assuming that inside the duct you aren't controlling your flow.

Soderman: You're going to control it so that these two come straight into your sharp inlet.

You put a different filter in and what happens?

190

Vincent: You're still controlling the flow so the mass flow through the system is kept constant.

Soderman: If you change the filter, there is more blockage.

Vincent: Then you adjust the pump speed.

Soderman: How do you assure yourself that you have done that properly?

Vincent: You calibrate before you go up.

Wilson: Do you believe that the curvature suffered by streamlines in the center of the inlet are quite different from the ones suffered out near the edge so that we could hope that our average calculations for this would be completely wrong for the streamlines which we ultimately sampled.

Soderman: The answer is yes, If a particle goes down the center there is no curvature. There must be a gradient at the curvature between the center and its magnition point. The actual distribution of particles measured out is computed.

Pui: Chuck, has anybody intentionally made this anisokinetic sampling and then try to do it at the flat region and then just correct the data by this velocity ratio.

Wilson: We just saw that the enhancement by the virtual impactor yesterday would essentially do this.

Clarke: But the problem is that it is only good if you are doing size-resolved sampling. If you are doing filter or bulk sampling, you don't know how to interpret that. You can't make the correction. You can make a size-resolved correction based upon this, then you could in principle correct this correction of size.

Kritz: I see the concept of using the blunt nozzle to give a sort of phantom diffuser is really an intriguing thing, because what we're doing is we get a sharp-edged orifice and that can allow us when it's isokinetic to really characterize what's going in, but then when we have any departure from the ideal because of misalignment, it goes to hell in the diffusing section. So you get rid of all of that with this blunt entrance. Of course you pay a price maybe with impaction of some of the streamlines on the surface, but the way around you showed us is just to put a secondary inlet to skim off the center a little further down. It seems to me we are practically home free that way.

Soderman: Might be. It should be checked experimentally.

Pueschel: Regarding the upwash around the wing tips, what do aircraft designers do to minimize it, and how small can it be made.

Soderman: That is a function of the lift to the wing, you can't minimize it. It's related to the weight of the aircraft, because for a level flight, the weight equals the lift, and that determines the upwash. The farther away from the wing, the weaker it is.

Clarke: Going back to your discussion of your exhaust port that you used. You oriented it the same way we had in the system on the DC-8 downstream basically. The suction coefficient for that is not very high. I found it to be somewhat limiting. I don't have a filter, don't have a pump, I used that to obtain isokinetic flow. I looked in some of the earlier flight test basically during the war (WWII), and they show the orientation if you cut the section off parallel to the stream you get a suction coefficient about three times higher. Is there some trade off where you can orient it at some different angle and improve the suction?

Soderman: For it to get into the hole you can get a steady flow, but there may be a variety of geometries that prevent that. I would tend to have the opening point downstream, though, otherwise you might get separation.

Pueschel: Following on my earlier question, if you are at the wing tip, how far away from the tip do you have to get to minimize the upwash?

Soderman: The wing tip is probably a bad place to be because of the vortex roll up there. The upwash along the wing is pretty constant, I think. Until you get to the tip region, and I don't know how close that is. But when you get to the tip region you get into complex flow. You have to do a panel method I guess to find the distribution of velocities.

Seebaugh: Ames has done some work flying Leer jet and tip vortices of C-5 aircraft which is a little bigger than a DC-8. I think it's something along the line of the fuselage diameter of the Leer jet which is six feet.

Kritz: Paul, with respect to the Anderson inlet that you have been describing you mentioned how you adjusted the angle to compensate for the wing roll. Did that change at all during the flight of the plane?

Soderman: I'm sure it did. I don't know that we went through that calculation.

Baumgardner: How insensitive actually is its angle of attack? What sort of range are we talking about?

Soderman: That depends on the relative velocity inside and outside the duct. If you have 1:1 if you're sucking in at the same speed you are flying it is very intolerant to angles more than 20 or 30°. If you're at 30% of the flow inside, it might be only a few degrees before you have separation. You're very dependent on your conditions. You should be able to get one that is insensitive to at least 6°.

Applications of Principles of Aerodynamics to Inlet/Diffuser Design

By

W. R. Seebaugh

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The primary function of an inlet/diffuser system is to provide the proper amount of air flow to a device located downstream of the diffuser at the desired velocity or pressure, generally at the highest possible efficiency. Additional requirements placed on the inlet/diffuser system depend on the application.

The major applications with large performance data bases are inlet/diffuser systems for aircraft propulsion and for closed or ducted flows such as in wind tunnels. Ducted systems have developed flows at the entrances in contrast to propulsion systems, which have essentially freestream flows at the entrances (except for inlet systems for supersonic aircraft, which are essentially ducted systems). For aircraft propulsion systems, the amount of diffusion (as measured by the ratio of outlet area to inlet area) is usually relatively low; however, severe limitations on the distortion of the flow at the exit are imposed. Achieving this requirement may be made more difficult by the need to turn the diffuser while meeting constraints on overall diffuser length. Ducted systems usually operate at larger area ratios than propulsion systems; however, length, flow distortion, and turning requirements are less stringent.

Inlet/diffuser systems for airborne aerosol measurements exhibit some of the characteristics of those for aircraft propulsion systems--essentially freestream flow at the entrance and the possibility of turns in the diffuser. The major differences are related to the amount of diffusion in aerosol measurement systems, which greatly exceeds that in propulsion diffusers. This is a problem because most of the data for moderate to high area ratio diffusers apply to ducted systems.

This paper addresses the effects of the aforementioned design parameters on the performance of diffuser systems. The approach is from the point of view of one who has designed a number of diffuser systems for aircraft and wind tunnels, but has never considered (until now) the demanding requirements of inlet/diffuser systems for airborne aerosol measurements. We first present the overall approaches and measures of performance for inlet/diffuser system design for aircraft propulsion and ducted systems. We then relate the performance to the details of the flow within the internal passage, considering the following: isentropic compression of the main flow; boundary layer effects including separation and transition from laminar to turbulent flow in the boundary layer;

turbulence and recirculating flow; effects of Mach and Reynolds numbers; and effects of specific requirements for airborne aerosol systems such as precise alignment with the external flow, isokinetic sampling, entry geometry (sharp vs. blunt lip), and extreme diffuser area ratio. We then recommend a process to be followed in the design of inlet/diffuser systems for airborne aerosol measurements. The paper concludes with a qualitative analysis of the flow problems to be anticipated in a sharp lip conical inlet/diffuser operating at high subsonic entrance Mach numbers with an extreme internal area ratio and a right-angle turn, and a discussion of potential means of addressing these problems including boundary-layer control. Figure 1 summarizes the coverage of the paper.

DEFINITIONS

The definitions of several important terms, as used in this paper, are presented in Figure 2. An important feature of diffusers is that they are always used in conjunction with other equipment. In general, the performance of a diffuser depends strongly on the characteristics of the air stream at the diffuser entrance and to a lesser extent on the behavior of other system components that follow the diffuser exit.

Two important dimensionless parameters that affect the performance of diffusers are the Mach and Reynolds numbers. Figure 2 stresses that these parameters are determined at local points in the flow. For compressible flows, the temperature is also a local variable. Since the sound speed depends on the local temperature, variations in Mach number relate to variations in both the local temperature and velocity. Values of Mach and Reynolds numbers may also be defined based on constant properties such as the freestream velocity of an aircraft and the diameter of an inlet.

Diffuser performance is highly dependent on the characteristics of the boundary layers that develop on the internal surfaces. Boundary-layer behavior in diffusers is a major subject of this paper.

INLET/DIFFUSER SYSTEMS FOR AIRCRAFT PROPULSION

One obvious source of performance data for diffusers is the literature on aircraft propulsion systems. For subsonic flight conditions (freestream Mach number less than unity) the entrance flow is at nearly freestream conditions (except for modifications due to the presence of the other components of the aircraft) and there is no boundary layer at the entrance.

The purpose of an inlet system for an aircraft is to provide the proper amount of air flow to the engine while increasing the air pressure (and reducing its velocity) at the highest possible efficiency. Additional pressure increase (and velocity reduction) is provided by the

compressor stages at the front end of the engine. As flight speeds increase, an increasing fraction of the overall pressure increase is provided by the inlet system.

Figure 3 shows a cross-sectional view of the inlet and diffuser for an early model of the Boeing 747 aircraft (from Viall, 1969). The definitions used in the aircraft propulsion community are as indicated on the sketch.

One major concern in propulsion inlets is that they must function at airspeeds from zero to the maximum achievable airspeed of the aircraft. This accounts for the use of a blunt lip and blow-in doors around its periphery (Figure 3). This is not a concern with airborne aerosol inlets which operate only at aircraft cruise conditions (assuming that a retractable cover is used). Another reason for using a blunt lip, as recognized by Huebert, et al., (1990) is that the blunt lip permits essentially automatic flow adjustment as the attitude of the inlet with respect to the incoming airstream changes. This is also a concern with airborne aerosol inlets. A third reason for using a blunt lip on aircraft is that the forebody portion of the outer cowl provides thrust. This is not a design factor for airborne aerosol inlets.

Aircraft inlets nearly always provide some degree of geometric contraction between the highlight and the throat. This is a natural outcome of using a blunt lip. It also provides some length for development of the boundary layer on the duct wall before imposing the adverse pressure gradient present in the diffuser on the flow (see discussion of boundary layer flows below). One adverse consequence of the converging section upstream of the throat is that the flow accelerates to higher Mach numbers in this region. Diffuser performance deteriorates rapidly as the Mach number exceeds 0.8. This is one factor that limits the true airspeed of the aircraft. This is not an issue with aerosol inlet systems flown on lower speed aircraft such as the Electra. For higher speed aircraft, the limit on throat Mach number might be important if an inlet with a minimum area throat is used.

The size of the inlet is determined by the air flow required by the engine. For the 747, this criterion is applied at the highest true airspeed at cruise altitudes. In propulsion inlets, the suction provided by the engine can increase the air flow, thus increasing the flow velocity throughout the inlet system. This is an undesirable situation, as the Mach number limits at the throat and engine face might be exceeded, causing extreme losses in system performance. This flow matching problem also exists in aerosol inlet systems.

INLET/DIFFUSER SYSTEMS FOR WIND TUNNELS AND OTHER DUCT SYSTEMS

The other major source of data for inlet/diffuser systems relates to closed or ducted flows such as in wind tunnels and water distribution systems. The use of diffusers in these applications predates aircraft applications by thousands of years.

The purpose of an inlet/diffuser system for a wind tunnel or other duct system is to recover the maximum possible fraction of the dynamic pressure Q_1 of the entrance flow (equal to

one-half of the product of the air density and the square of the velocity for incompressible flow and including higher order terms for compressible flow). The inlet portion of the system is the exit of some upstream component, so that the entrance flow has a pre-existing boundary layer on all surfaces. For the purposes of this paper, an inlet/diffuser system for a supersonic aircraft is included in this section, with the concepts and data presented applicable to the subsonic flow portion of the overall system.

Figure 4 shows sketches of the two primary diffuser types, flat or two-dimensional and conical (White, 1986). Diffusers with flat walls often have variations in both dimensions (width and height), and designs with six or eight flat walls are common. Transitions between rectangular and circular cross sections also are used, particularly in air handling systems in buildings.

The variables used in data presentations for diffusers are the divergence angle, which is usually given as the total angle (as shown in Figure 4), the axial length, and a length characteristic of the cross-sectional size (width or diameter). The total angle ranges to 100 degrees or more. As shown later, performance deteriorates rapidly above 40 degrees.

The variations in entrance conditions for a particular ducted system are generally less extreme than for aircraft propulsion systems. Ducted systems must operate through transients such as starting and stopping; however, the performance of the diffuser is generally not critical during such transients. The size of the entrance section is determined by the air flow provided by the upstream component.

Data on diffusers for ducted systems are generally more accessible and somewhat more general in application than for aircraft systems. It is, therefore, useful to present some of these data and to discuss some of the details of the flow in these systems. Figures 5 and 6 give representative characteristics of flat diffusers. In Figure 5 (replotted from White, 1986, in terms of area ratio rather than length) the domain is divided into several flow regimes based on stall characteristics. The stall phenomenon is discussed in detail below; for purposes of Figures 5 and 6, stall can be equated to boundary-layer separation. The stall characteristics for conical diffusers are not identical to those given in these figures; however the trends of the available data are similar (insufficient data were available for conical diffusers to complete the performance map shown in Figure 5).

In regime A (Figure 5), no appreciable stall occurs, which means that the boundary layers remain attached throughout the diffuser. Diffuser designs for most applications in which the absence of separated flow is more critical than the performance (in terms of C_p which is defined in Figure 4) will be in regime A. Regime B is the region of transitory stall, which means that a separated region wanders around the diffuser in an unsteady manner. Limiting the total divergence angle to 7 degrees will place diffusers with area ratios greater than about 3 in regime B. The designs shown by Huebert, et al., (1990) fall into this category. Full stall in flat diffusers, regime C, is characterized by nearly steady asymmetric separated flow. This condition may not occur in conical diffusers. In the worst condition, regime D,

the flow does not reattach to the diffuser surface, but continues down the center of the duct as if the surfaces were not present. This condition occurs in conical diffusers.

Figure 6 shows the variation of pressure coefficient with divergence angle. The maximum value of C_p, which occurs at approximately 9 degrees, corresponds to the curve labeled "Maximum C_p" in Figure 5. The performance in regime A, as measured by C_p, decreases with decreasing divergence angle as the boundary layer fills more of the duct. The performance also falls off with increasing angle (regime B), but not as rapidly.

It should be noted here that the pressure coefficient C_p is important for diffusers used in pressure recovery applications, where transitory stall may not be relevant. C_p is not necessarily a good indicator of performance for airborne aerosol inlet systems, where separated flow, either transitory or steady, may have undesired effects on particulates in the flow.

BOUNDARY-LAYER PHENOMENA

Figure 7 shows the growth of the boundary layer on a flat plate. The initial boundary layer is laminar. At some distance from the leading edge which depends on the freestream flow conditions (primarily the Reynolds number) turbulent patches form at the surface, beginning the transition process (Schlichting, 1960). These patches, which propagate out to the edge of the boundary layer, eventually merge to form a fully turbulent boundary layer.

The turbulent boundary layer grows faster as a function of distance than the laminar boundary layer. The velocity profiles have different shapes. In the laminar case, the profile is approximately parabolic. The turbulent profile is much steeper, with higher velocities much closer to the surface.

In an adverse pressure gradient ($dP/dX > 0$ and $dU/dX < 0$) the velocity at a given height from the wall decreases with distance as a result of the pressure gradient. This leads to the appearance of an *inflection point in the velocity profile* (lower part of Figure 7). At some critical value of dP/dX, the shear stress at the surface equals zero. This condition of incipient separation can be maintained essentially indefinitely. Larger pressure gradients cause the flow to separate from the surface, with a region of reversed flow between the edge of the boundary layer and the surface.

The shape of the velocity profile has a large effect on the tendency of the boundary layer to separate when an external pressure gradient is imposed on it. At a given distance from the surface, the velocity is lower in a laminar boundary layer than in a turbulent boundary layer. As a result, the laminar boundary layer separates much more readily than the turbulent boundary layer. By definition, adverse pressure gradients exist in diffusers. Too large gradients will cause boundary-layer separation or stall. Most diffuser data correspond to turbulent boundary-layer conditions at the diffuser entrance.

199

BOUNDARY-LAYER SEPARATION AND RECIRCULATING FLOW

The upper sketch in Figure 8 illustrates the ideal desired flow within a diffuser typical of that used for an airborne aerosol inlet system (no initial boundary layer). The flow remains attached to the surface for the entire length of the diffuser and the boundary layer grows gradually with distance from the entrance. The velocity reduction is inversely proportional to the change in area. The lower sketch shows a high divergence diffuser with a region of separated flow. This could be a snap-shot of a transitory stall pattern in a diffuser. At a cross section that contains the separated flow region the centerline velocity is higher than desired, while a substantial region of reversed flow exists near the surface. If sufficient length of straight duct is attached to the exit of the diffuser, the flow reattaches to the surface. The velocity near the centerline remains higher than the desired ideal velocity, while the velocity near the surface is lower than the ideal velocity.

OTHER FLOW ISSUES

Another type of flow separation occurs when a sharp-edged surface (a flat plate or a sharp-edged inlet) is misaligned with the flow (Figure 9). This is the so-called leading edge separation which occurs when the flow cannot negotiate the abrupt turn at the sharp edge. Although leading-edge separation occurs with essentially zero boundary-layer thickness, a separated or reversed flow region exists downstream of the leading edge. When a sharp-edged inlet is misaligned with the approach flow, leading-edge separation occurs over approximately half of the inlet circumference. The flow may reattach in the manner shown in Figure 8, or may remain separated for the entire length of the diffuser. A leading-edge separation may also couple with a transitory stall to produce a separated region that fluctuates with time.

The occurrence of turbulence is discussed above in the context of transition within a boundary layer. Turbulence also exists in the freestream flow as a result of wind gusts and, for locations within the region of influence of the aircraft structure, as a result of disturbances created by the aircraft itself. Mathematically, turbulence is represented in Figure 9 by a mean velocity plus a fluctuating component (it is easier to view the velocity in a frame of reference attached to the aircraft). The magnitude of the turbulent velocity fluctuations is represented by the intensity (root mean square) or the relative intensity, which is the ratio of the RMS value to the mean velocity (Schlichting, 1960). The turbulence scale is a measure of the size of turbulent eddies.

The freestream turbulence discussed above may be a factor in the performance of diffusers for airborne aerosol inlet systems. The analogous turbulence parameters in wind tunnels and internal flow systems definitely affect diffuser performance. A potential problem in applying the existing data base is that turbulence intensities in pressure or fan driven flow systems are much higher than in the atmosphere.

200

As discussed above, turbulence also originates in the boundary layer in and downstream of the transition region. This type of turbulence, which is what causes the air noise heard in the cabins of aircraft, may affect the behavior of particulates in diffuser flows.

The unsteady transitory stall regions in diffuser flows have many of the characteristics of turbulence. This unsteady flow, which is intermittent at any position within the affected region of the diffuser, is probably the most important unsteady flow phenomenon in diffuser flows. It is possible that investigators in the airborne aerosol research community are attributing the effects of transitory stall to turbulence.

EFFECTS OF FLOW PARAMETERS ON DIFFUSER PARAMETERS

Figure 10 presents a summary of the effects of the various flow parameters discussed above on diffuser performance (Cockrell and Markland, 1974). The performance parameter is the pressure recovery C_p, which, as noted above, is probably not the best parameter to describe the overall performance of airborne aerosol inlet systems. C_p is, however, the standard measure of diffuser performance in the fields responsible for essentially all of the existing data base for diffusers.

FLOW THROUGH BENDS

Some airborne aerosol inlet systems require that the captured air and particulates negotiate bends of up to 90 degrees between the entrance and exit stations. Sharp bends are always problems in internal flow systems because they cause secondary flows even when the approaching flows are fully attached ("good" upstream flow in Figure 11). When the approaching flow is separated, near separation, or a reattached flow following a separated region ("poor" upstream flow in Figure 11), the flow separates from the convex surface. This separated flow interacts with the secondary flows in the bend, producing disturbances in the flow similar to those associated with stalled diffusers. If the diffuser and bend are too closely coupled, the entire flow in the diffuser-bend combination may exhibit stall characteristics.

Much effort has been expended on this issue in the aircraft propulsion community since many aircraft inlet systems have short diffusers with sharp bends (the center inlet of the Boeing 727 is typical). Essentially all aircraft inlet systems integrate the diffuser and the bends. This approach can markedly improve the flow in the vicinity of the bends. In some cases, residual separated regions remain. Vortex generators provide very effective means of correcting this problem. These are pairs of airfoils that extend from the surface into the flow to about the edge of the boundary layer. The vortices shed from the tips of these small wings interact to produce trailing vortex systems that mix the higher speed flow from the center of the duct with the low energy flow in the boundary layer. This energizes the boundary lay and prevents flow separation.

Another technique used to prevent boundary-layer separation that is often employed in subscale testing of aircraft models in wind tunnels is tripping the laminar boundary layer to promote early transition. This is necessary to provide an accurate simulation of the flow over the full-scale aircraft on which transition typically occurs close to the nose of the fuselage or the leading edge of the wing. Trips could also be used to promote early transition in the internal flow in airborne aerosol inlet systems; however, a performance improvement cannot be predicted with confidence for these systems, especially when the Reynolds number is low.

Another very effective means of preventing boundary-layer separation is to remove the low energy portion of the boundary layer through holes or slots in the surface. This technique is used in virtually all high-performance military aircraft. Since the secondary flow in a bend is affected by the state of the boundary-layer, suction can also be effective in suppressing this adverse effect. In typical aircraft inlet systems, removal of a total of about 1-2 percent of the inlet flow suppresses the adverse effects of flow separation. Great care is required in applying boundary-layer suction techniques to aircraft because a large drag penalty is associated with bringing air into the inlet system and then throwing it overboard as waste. This would not be an issue with airborne aerosol inlet systems because of the low inlet flow rate. Minor additional drag would be associated with the shroud needed to provide a region of low pressure for the suction flow to exit the diffuser.

AIRBORNE AEROSOL SAMPLING ISSUES

Huebert, et al. (1990) thoroughly address most of the issues in Figure 12. In applying the data bases developed for aircraft propulsion and ducted flow applications, the analyst must be aware that the typical internal area ratios for airborne aerosol inlet systems far exceed those used to generate the data bases. In almost all cases, the designs fall into the transitory stall regime. Problems arising from this unsteady flow phenomenon are aggravated if a sharp bend follows the diffuser exit. Bends with large radii of curvature may be tolerable, depending on whether the stall effects have damped out prior to the bends.

Many variations in diffuser design have been attempted in order to eliminate the adverse effects of diffuser stall. The use of contoured rather than straight walls permits adjustment of the pressure gradient to match the state of the turbulent boundary layer (Childs, et al., 1981). Unfortunately, this method has not been extended to laminar and transitional boundary layers. A variation on this technique that is used in the subsonic diffuser portion of inlet systems for supersonic aircraft is to begin the diffuser with a slightly diverging section (total angle of less than 2 degrees), followed by a transition to a more conventional divergence angle (6-7 degrees). This permits the boundary layer to develop in a region of essentially zero pressure gradient before being subjected to an adverse gradient (for compressible flows, it is necessary to provide some divergence, otherwise the flow will accelerate due to the presence of the thickening boundary layer). Boundary-layer suction can then be applied to suppress residual separated flow regions.

202

DESIGN PROCESS

Figure 13 is a suggested design procedure for inlet/diffuser systems for airborne aerosol research. An iterative design procedure is almost mandatory since it is unrealistic to expect that the first attempt will provide an optimum or even satisfactory result. A combination of calculational and experimental approaches should provide the best design in the shortest time. With modern calculational techniques, it is possible to screen a number of possible designs and to refine the contours of the one or two best candidates. Unfortunately, some of the flow phenomena, such as boundary-layer transition, that strongly affect the success of a diffuser are not amenable to solution using current computational methods. A test is usually needed to confirm the design. In determining whether steady separation exists, pressure distributions, exit velocity profiles, and flow visualization are usually sufficient. More elaborate techniques include measuring of skin friction to determine the location of separated regions. Transitory stall is more difficult to detect; dynamic instrumentation is usually required. Boundary-layer control may be necessary to suppress any residual stall effects.

ANALYSIS OF A SPECIFIC AEROSOL INLET/DIFFUSER SYSTEM

The inlet described in Figure 14 was provided by J.C. Wilson. It is a simple conical diffuser with an internal area ratio of 47.3, which places it in the transitory stall regime. Pressure distributions were determined using one-dimensional compressible flow theory for a constant inlet total (stagnation) pressure of one atmosphere (this is the situation that would occur if the inlet were tested in a simple suction driven wind tunnel). At the lowest inlet Mach number, the pressure distribution is nearly linear and the overall pressure rise is small. Larger adverse pressure gradients occur in the first 10 percent of the diffuser at the higher Mach numbers. Because of the large area ratio, extensive stall is possible in this diffuser for inlet Mach numbers greater than about 0.3. This graph also illustrates the importance of proper simulation of inlet Mach number in a test. For comparison purposes, a linear pressure distribution for an inlet Mach number of 0.7 is shown (dashed line). The corresponding contour is compared to the conical diffuser contour (with an expanded scale for radius) on the graph to the left. This is not a practical configuration due to the trumpet-like contour at the exit. Obviously, an intermediate contour could provide lower pressure gradients while retaining a practical shape.

BOUNDARY-LAYER CONTROL

Figure 15 shows a possible installed arrangement of the inlet from Figure 14. It includes a sharp right-angle bend immediately downstream of the diffuser exit. Suction holes are provided near the separation point in the diffuser (determined by calculation or experiment) and at the approach to the convex wall of the bend. As indicated on Figure 15, suction

holes can be designed to provide relatively high suction flow rates when the velocity distribution is approaching separation and relatively low rates otherwise (McLafferty and Ranard, 1958). The flow through the holes is actually self-adjusting. The suction holes near the bend would be designed to provide higher suction rates at all times. The shroud that surrounds the inlet provides the low back pressure required for the suction flow.

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OUTLINE OF PRESENTATION

DEFINITIONS--DIFFUSER, MACH NUMBER, REYNOLDS NUMBER, BOUNDARY LAYER

INLET/DIFFUSER SYSTEMS FOR AIRCRAFT PROPULSION--GEOMETRY, PERFORMANCE MEASURES, LIMITS OF GEOMETRIC PARAMETERS IN DATA BASE

INLET/DIFFUSER SYSTEMS FOR WIND TUNNELS AND OTHER DUCT SYSTEMS--GEOMETRY, PERFORMANCE MEASURES, LIMITS OF GEOMETRIC PARAMETERS IN DATA BASE

BOUNDARY-LAYER PHENOMENA--LAMINAR/TURBULENT/TRANSITION, SEPARATION, RECIRCULATING FLOW, TURBULENCE

EFFECTS OF BOUNDARY-LAYER SEPARATION IN DIFFUSERS--EFFECTS OF PRESENCE OF INITIAL BOUNDARY LAYER

EFFECTS OF FLOW PARAMETERS ON DIFFUSER PERFORMANCE--SUMMARY

FLOW THROUGH BENDS--SECONDARY AND SEPARATED FLOWS

AIRBORNE AEROSOL SAMPLING ISSUES--ALIGNMENT, ISOKINETIC SAMPLING, ENTRY GEOMETRY, AREA RATIO

DIFFUSER DESIGN PROCESS

ANALYSIS OF A SPECIFIC AEROSOL INLET/DIFFUSER SYSTEM--BOUNDARY LAYER CONTROL

[Figure 1]

DEFINITIONS

DIFFUSER:

A FLUID FLOW DEVICE USED TO REDUCE THE VELOCITY AND INCREASE THE PRESSURE OF THE FLUID WHICH ENTERS THE DEVICE, GENERALLY AT THE HIGHEST POSSIBLE EFFICIENCY.

MAY BE ATTACHED TO AN INLET WHICH ALLOWS THE FLUID TO ENTER THE FLOW SYSTEM (A TYPICAL EXAMPLE IS PROPULSION INLET FOR AN AIRCRAFT).

MAY BE ONE OF A SERIES OF DEVICES ARRANGED IN SERIES IN AN OPEN OR CLOSED DUCT SYSTEM (A TYPICAL EXAMPLE IS A WIND TUNNEL).

MACH NUMBER:

A DIMENSIONLESS PARAMETER EQUAL TO THE RATIO OF THE LOCAL SPEED OF FLOW TO THE LOCAL SPEED OF SOUND.

REYNOLDS NUMBER:

A DIMENSIONLESS PARAMETER EQUAL TO THE RATIO OF THE PRODUCT OF THE FLUID DENSITY, FLUID VELOCITY, AND A LENGTH CHARACTERISTIC OF THE FLOW TO THE FLUID VISCOSITY.

BOUNDARY LAYER:

THE REGION OF FLOW ADJACENT TO A SOLID SURFACE WHERE THE SHEAR STRESSES ARE PRESENT (EXCEPT FOR VERY LOW DENSITY FLOWS, THE VELOCITY OF THE FLUID AT THE SURFACE EQUALS THE VELOCITY OF THE SURFACE).

[Figure 2]

INLET/DIFFUSER SYSTEMS FOR AIRCRAFT PROPULSION
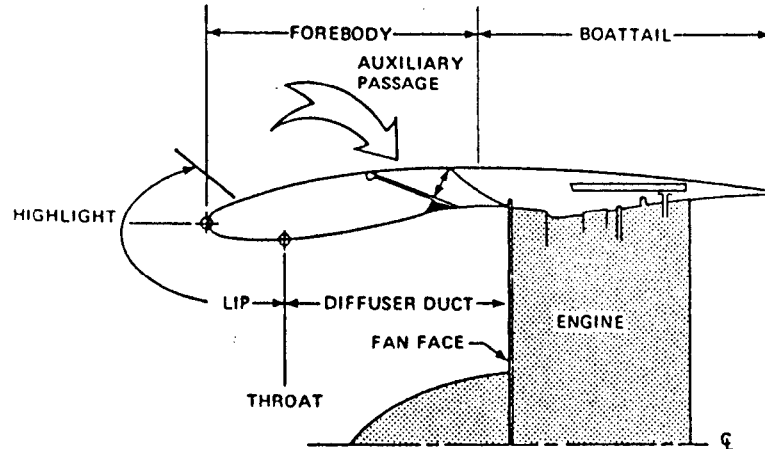
SIZE DETERMINED BY:
    MAXIMUM THRUST AT MAXIMUM
    ALTITUDE

ENTRANCE CONDITION:
    MAXIMUM MACH NO. < 0.9

EXIT CONDITION:
    MAXIMUM MACH NO. = 0.5-0.6

PERFORMANCE MEASURES:
    TOTAL PRESSURE RECOVERY
    DISTORTION

LIMITS OF GEOMETRIC PARAMETERS IN
DATA BASE:
    AREA RATIO < 1.6
    FAIRLY BLUNT LIP

FEATURES OF ALTERNATIVE SYSTEMS:
    TRANSITIONS IN CROSS SECTION
    TURNS
    OFFSETS (EXIT PARALLEL TO
    ENTRANCE)

[Figure 3]

INLET/DIFFUSER SYSTEMS FOR WIND TUNNELS AND OTHER DUCT SYSTEMS
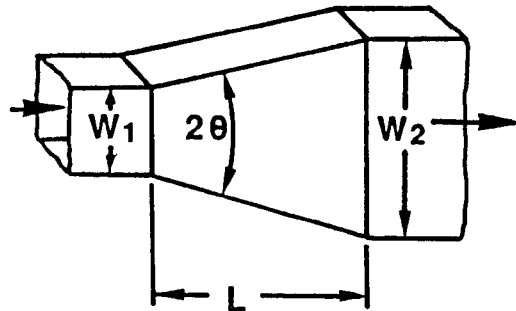
FLAT DIFFUSER
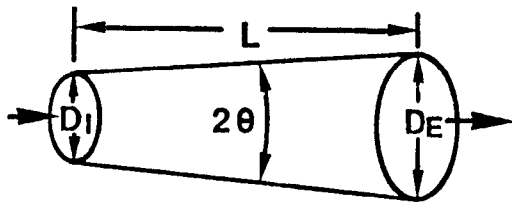
CONICAL DIFFUSER

ENTRANCE CONDITIONS:
INCOMPRESSIBLE FLOW TO MACH NO. = 0.95

EXIT CONDITIONS:
INCOMPRESSIBLE FLOW TO MACH NO. = 0.5-0.6

PERFORMANCE MEASURES:
EXIT PRESSURE OR VELOCITY
PRESSURE RECOVERY COEFFICIENT = $C_P = (P_E - P_I)/Q_I$
PRESSURE LOSS COEFFICIENT = $1 - C_P/[1 - (A_E/A_I)^2]$
DISTORTION
STALL MARGIN

LIMITS OF GEOMETRIC PARAMETERS IN DATA BASE:
INCLUDED ANGLE 5 TO 100 DEGREES
AREA RATIO < 40
THIN TO FULLY DEVELOPED INITIAL BOUNDARY LAYER

VARIATIONS IN GEOMETRY:
CONICAL
RECTANGULAR, HEXAGONAL, ETC
ANNULAR
TRANSITIONS IN CROSS SECTION
TURNS

[Figure 4]

DIFFUSER FLOW REGIMES
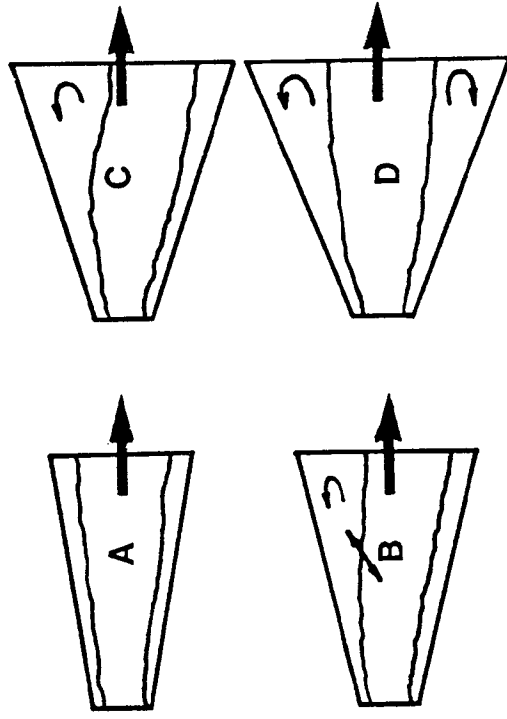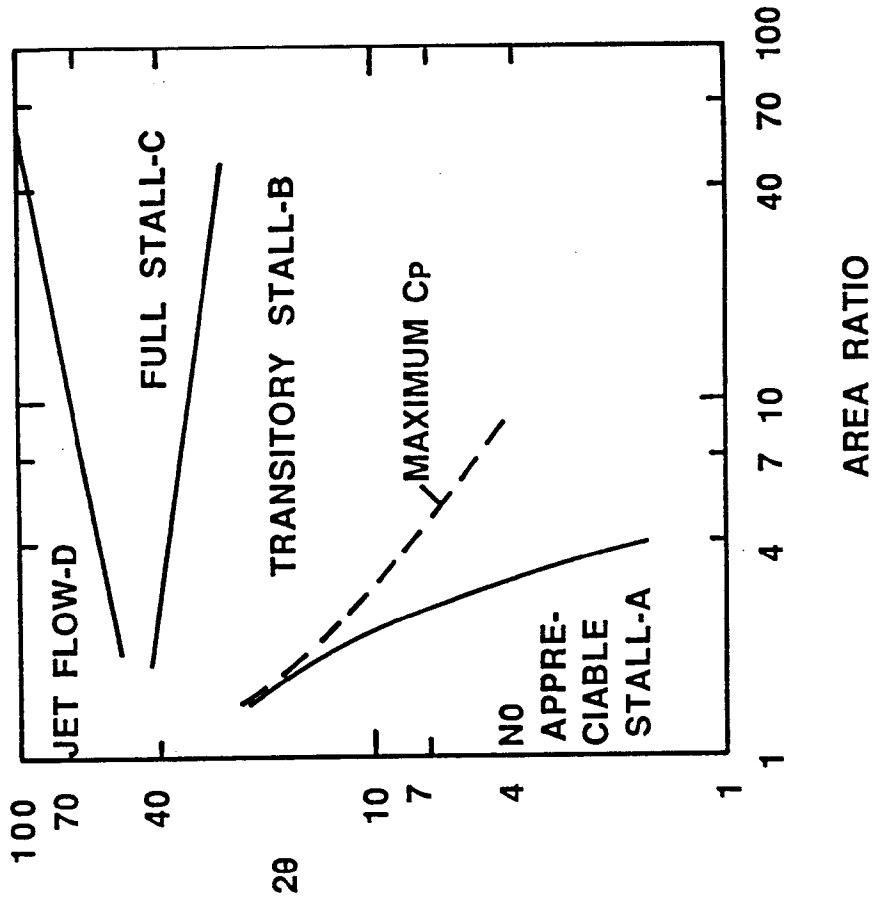
[Figure 5]

DIFFUSER FLOW REGIMES
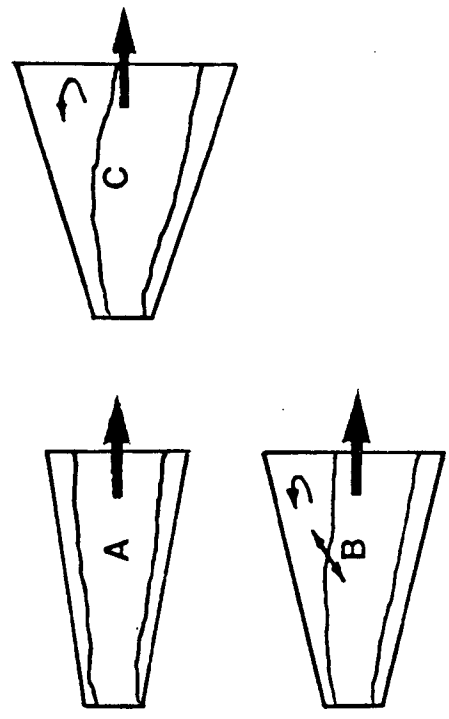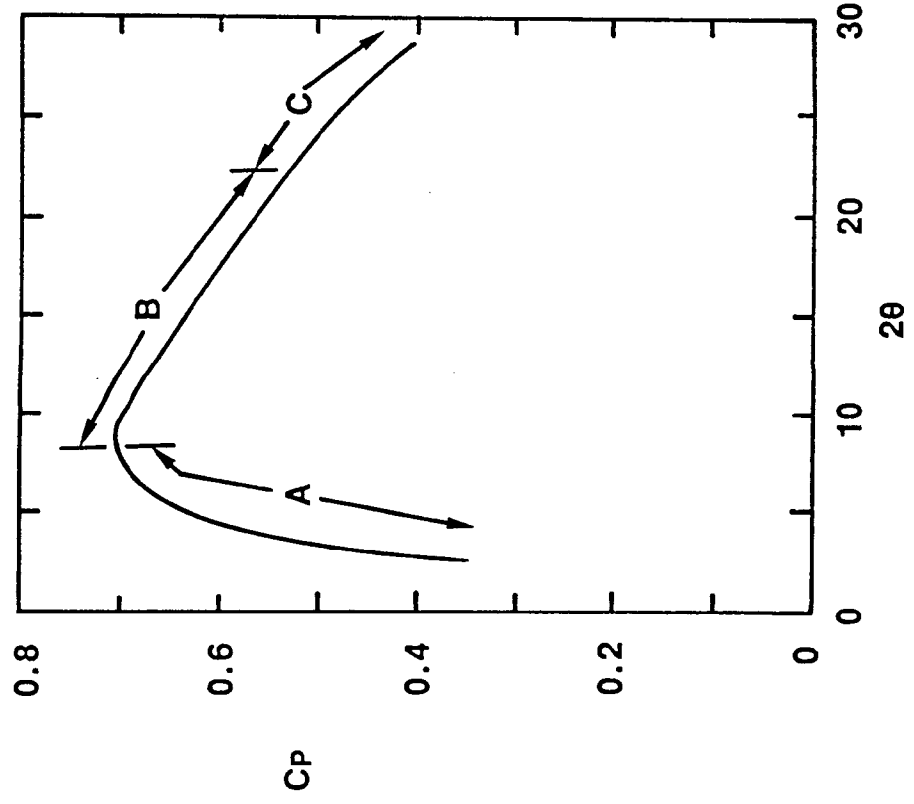
[Figure 6]

BOUNDARY-LAYER PHENOMENA

BOUNDARY-LAYER GROWTH WITH ZERO PRESSURE GRADIENT:

U▶

LEADING EDGE

LAMINAR BOUNDARY LAYER   TRANSITION   TURBULENT BOUNDARY LAYER
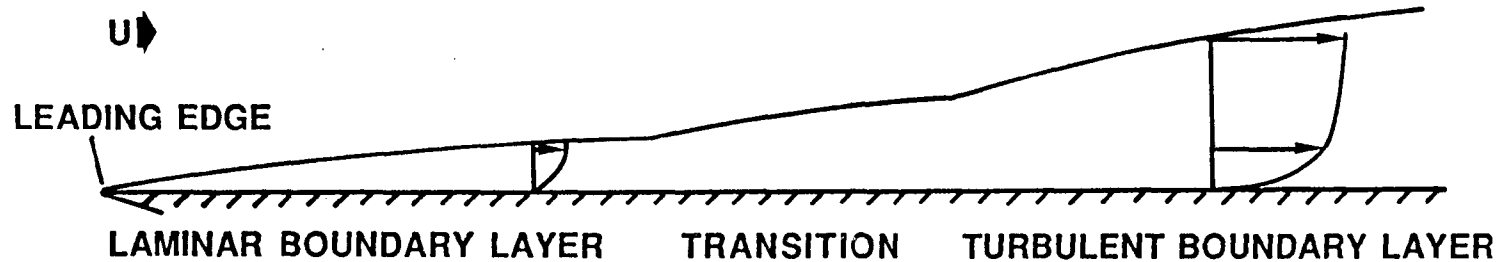
BOUNDARY-LAYER SEPARATION IN ADVERSE PRESSURE GRADIENT:

U   U   U   U

u   u   u   u

                           — INFLECTION   — INFLECTION

             — INFLECTION ZERO SHEAR STRESS   —— REVERSED FLOW

ZERO GRADIENT	WEAK ADVERSE GRADIENT	CRITICAL ADVERSE GRADIENT	EXCESSIVE ADVERSE GRADIENT
$dU/dX = 0$	$dU/dX < 0$	INCIPIENT	SEPARATED FLOW
$dP/dX = 0$	$dP/dX > 0$	SEPARATION	REVERSED FLOW REGION
NO SEPARATION			NEAR SURFACE
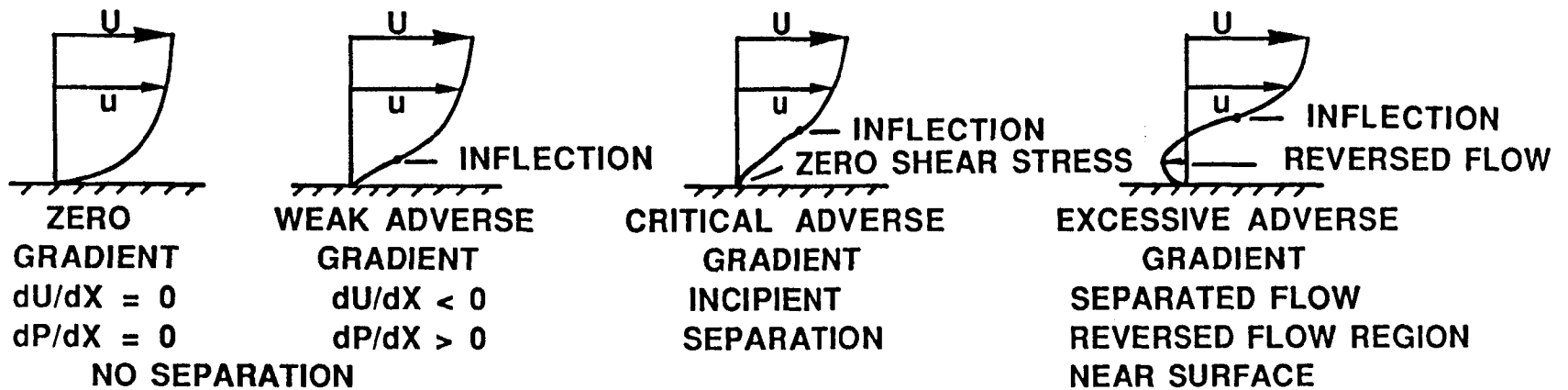
[Figure 7]

BOUNDARY-LAYER SEPARATION AND RECIRCULATING FLOW

IDEAL FLOW WITH FULLY ATTACHED BOUNDARY LAYER:

NO INITIAL BOUNDARY LAYER

THIN BOUNDARY LAYER

LOW VELOCITY,
HIGH PRESSURE

U ▶

CENTERLINE
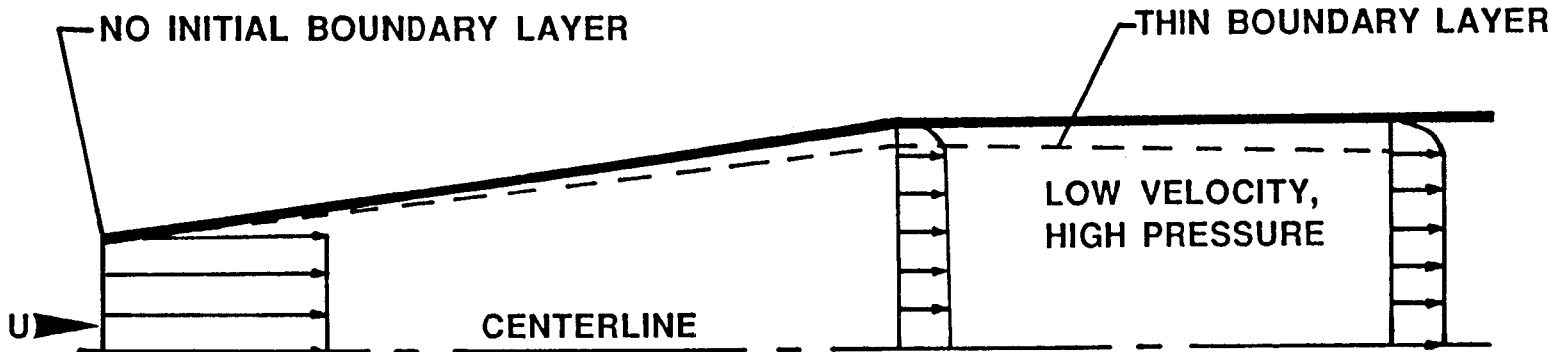
SEPARATED FLOW WITH REATTACHING BOUNDARY LAYER:

NO INITIAL BOUNDARY LAYER

REATTACHMENT POINT

SEPARATION POINT

BACKFLOW

HIGH VELOCITY,
LOW PRESSURE

SOME
RECOVERY

U ▶

CENTERLINE

IDEAL VELOCITY
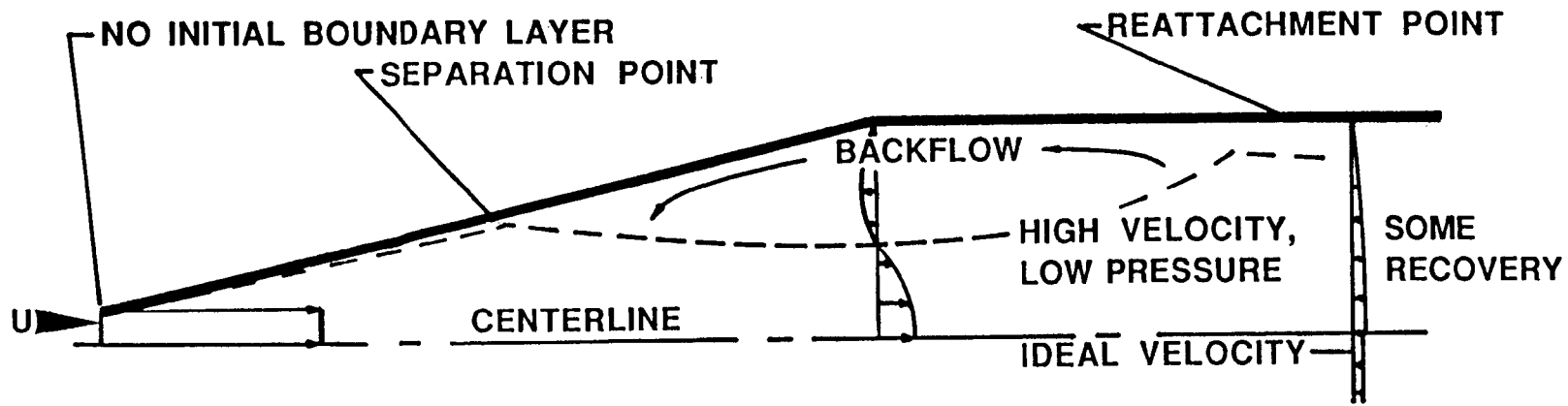
[Figure 8]

OTHER FLOW ISSUES

LEADING-EDGE SEPARATION:

U

TURBULENCE: DEFINITIONS

VELOCITY FLUCTUATIONS $U = \bar{U} + u$

INTENSITY $u' = \sqrt{\overline{u^2}}$

SCALE

"TYPES"

FREESTREAM TURBULENCE

BOUNDARY-LAYER TURBULENCE-NOISE

UNSTEADY FLOW-TRANSITORY STALL

[Figure 9]

EFFECTS OF FLOW PARAMETERS ON DIFFUSER PERFORMANCE

PARAMETER (INCREASING)	NO EFFECT	INCREASE IN C_P			DECREASE IN C_P		
		HIGH	MOD.	LOW	HIGH	MOD.	LOW
ENTRANCE BOUNDARY-LAYER THICKNESS					X		
REYNOLDS NO. (OTHER THAN BL THICKNESS)							
IF TURBULENT BL	X						
IF LAMINAR/TRANSITIONAL BL			X			X	
ROUNDING OF LIP							
IF TURBULENT BL			X				
IF LAMINAR/TRANSITIONAL BL						X	
MACH NO. AT ENTRANCE*			X			X	
TURBULENCE INTENSITY AT ENTRANCE			X				
TURBULENCE SCALE AT ENTRANCE			X				

*ALSO SHIFTS ONSET OF STALL TO LOWER ANGLES

[Figure 10]

FLOW THROUGH BENDS

"GOOD" UPSTREAM FLOW:

    NO SEPARATION IN BEND
    SECONDARY FLOW PRESENT IF BEND IS TOO SHARP
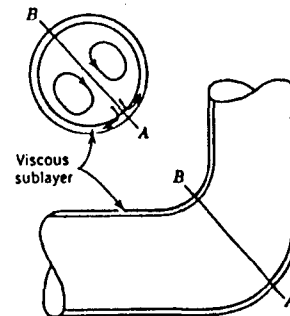
"POOR" UPSTREAM FLOW:

    SEPARATED FLOW ON CONVEX SURFACE
    SECONDARY FLOW ALSO PRESENT

POSSIBLE SOLUTIONS TO PROBLEMS:

    INTEGRATION OF BEND WITH DIFFUSER

    BOUNDARY-LAYER CONTROL:
        VORTEX GENERATORS (BOEING 727 CENTER INLET)
        BOUNDARY-LAYER TRIPS (PROBABLY NOT COMPLETE
        SOLUTION)
        BOUNDARY-LAYER SUCTION

[Figure 11]

AIRBORNE AEROSOL SAMPLING ISSUES

ALIGNMENT:

    REFERENCE LINE ON AIRCRAFT
    VARIATIONS IN FLOW ANGLE WITH AIRCRAFT ANGLE OF ATTACK
    FLOW ANGLE CAN BE MEASURED FOR ALL FLIGHT CONDITIONS

ISOKINETIC SAMPLING:

    FLOW RATE MATCHED AT DESIGN CONDITION
    CORRECTIONS NECESSARY AT OTHER CONDITIONS

ENTRY GEOMETRY:

    ROUND LIP DECREASES PROBE SENSITIVITY TO MISALIGNMENT
    STREAMLINE DIVERGENCE INCREASES WITH LIP THICKNESSES
    DIFFUSION REQUIRED INCREASES WITH INCREASING LIP THICKNESS

AREA RATIO:

    EXTREME VALUES ARE MAJOR DEPARTURE FROM DATA BASE
    TRANSITORY STALL IS LIKELY
    PROBLEM IS AGGRAVATED BY CURVED DIFFUSERS OR TUBES
    REQUIRES CAREFUL DESIGN FOR MAXIMUM AREA RATIOS

[Figure 12]

DESIGN PROCESS

ASCERTAIN FLIGHT CONDITIONS

ASCERTAIN REQUIREMENTS OF INSTRUMENT

PERFORM PRELIMINARY DESIGN:

MASS FLOW REQUIREMENT
EXIT FLOW VELOCITY--AREA RATIO
INLET LIP GEOMETRY
DIFFUSER CONTOUR
FLOW METERING

CALCULATE INTERNAL FLOW
↕
REFINE DIFFUSER CONTOUR

TEST:

PRESSURE DISTRIBUTION ⎤
VELOCITY PROFILE AT EXIT ⎥ SEPARATION?
FLOW VISUALIZATION ⎦

IMPROVE (IF NECESSARY):

BOUNDARY-LAYER CONTROL

[Figure 13]

ANALYSIS OF SPECIFIC AEROSOL INLET/DIFFUSER SYSTEM

INLET DIAMETER: 0.277 CM
EXIT DIAMETER: 1.905 CM
LENGTH: 13.310 CM
CONTOUR: CONICAL
INTERNAL ANGLE: 7 DEG
AREA RATIO: 47.3

0.1
0.3   INLET MACH NO.
0.5
0.7

TOTAL PRESSURE = 1 ATM
— — — LINEAR PRESSURE DISTRIBUTION
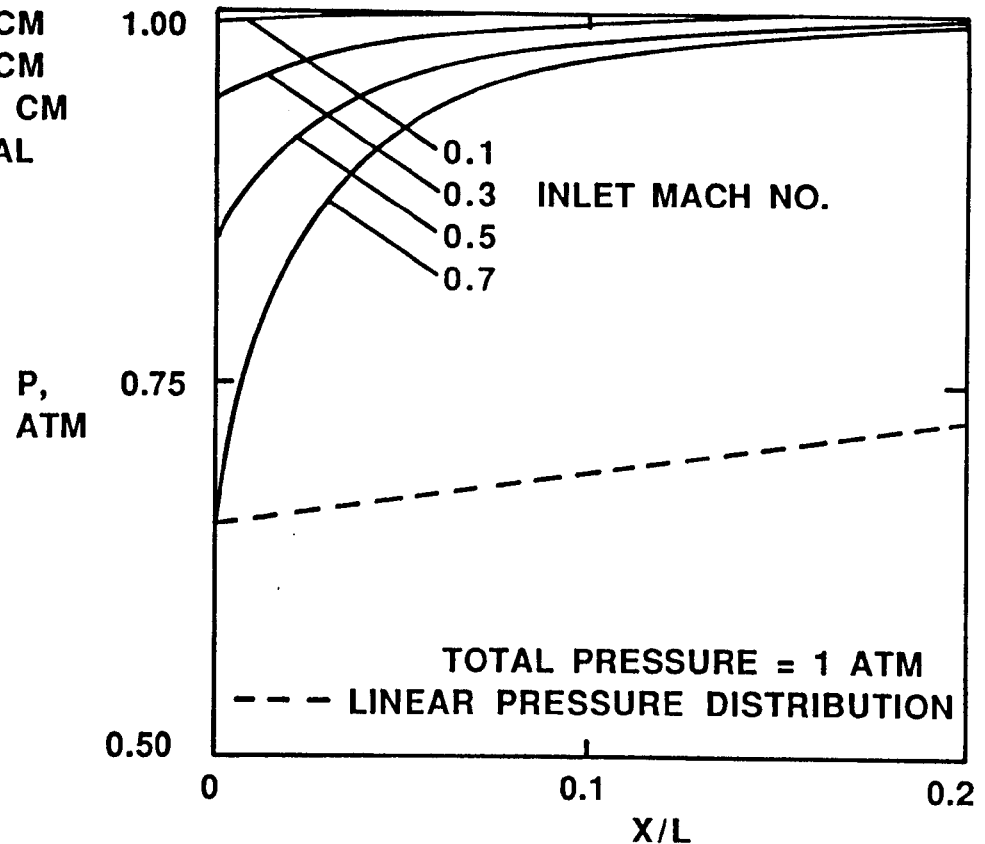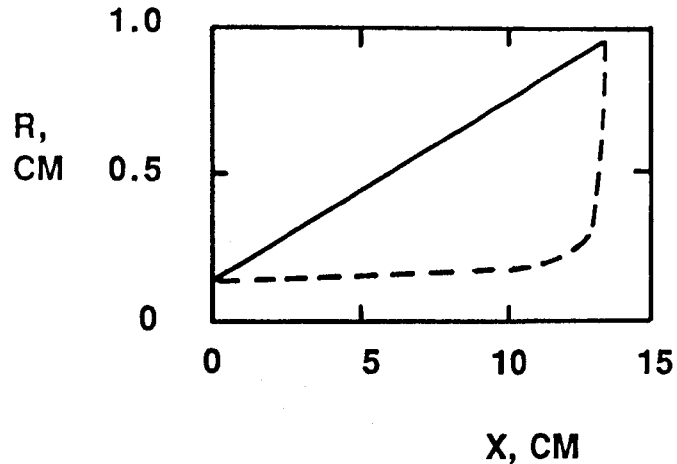
ANALYSIS:
    TRANSITORY STALL LIKELY
    EXTENSIVE STALL POSSIBLE

RECOMMENDATIONS:
    CODE CALCULATION
    TESTING AT FLIGHT MACH NO.
    BOUNDARY-LAYER CONTROL

[Figure 14]

BOUNDARY-LAYER CONTROL

TRIPS: PROMOTE EARLY TRANSITION FROM LAMINAR TO TURBULENT
BOUNDARY LAYER

NOT EFFECTIVE AT LOW REYNOLDS NUMBERS

SUCTION:

LOCATED IN REGIONS OF FLOW SEPARATION WITHOUT SUCTION

HOLES CONTOURED TO INCREASE SUCTION FLOW WHEN INLET FLOW
IS TENDING TO SEPARATE, REDUCE SUCTION FLOW WHEN INLET
FLOW IS ATTACHED

FLOW RATE--MAXIMUM 1-2 PERCENT OF INLET FLOW

HOLES LOCATED AT SEPARATION
LOCATION WITH NO SUCTION

U

SUCTION FLOW

SHROUD
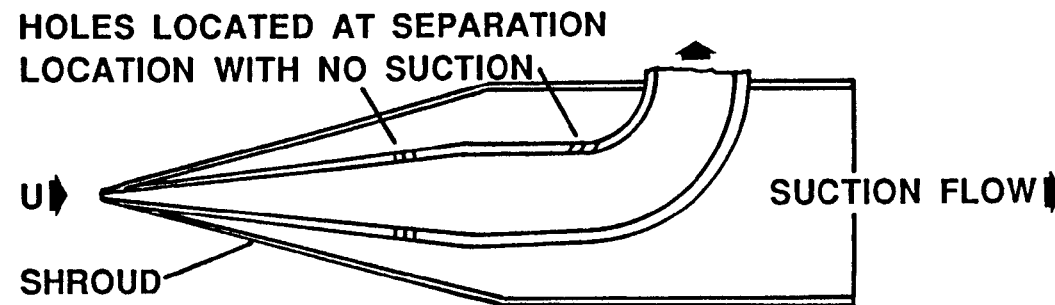
[Figure 15]

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DISCUSSION

There was no Discussion after this presentation.

Computations of Particle Flows Around Simple Inlets, Wings, and Fuselages

By

Daniel J. Rader, A.S. Geller, and S.N. Kempka

Daniel Rader earned his doctoral degree in mechanical engineering in 1985 at the University of Minnesota's Particle Technology Laboratory. The focus of his dissertation was the development of a technique that uses two differential mobility analyzers to accurately measure minute changes in particle size during particle evaporation or growth. Since graduating, Dan has been a Senior Member of Technical Staff in the Fluid, Thermal, and Structural Sciences Department at Sandia National Laboratories in Albuquerque. His research activities have included the measurement of high-velocity uranium combustion aerosol, fluid dynamic modeling of particle-laden flows, and studies the generation of particulate contamination by mechanical wear. Much of this work has required characterization and calibration of a wide range of sampling and in situ aerosol sizing instrumentation.

Recent work at Sandia has focused on the design and placement of an airborne sampler that accurately collects particles at aircraft speeds of about 100 m/s. An extensive review of the literature on particle sampling was conducted first, and the salient results are summarized here. Of particular interest are sampling errors induced by velocity and angle of attach mismatches. A brief review of the author's earlier work on anisokinetic sampling is included, which used a finite difference technique to calculate sampling errors for a straight cylindrical probe as a function of velocity mismatch, particle Stokes and Reynolds Numbers and probe wall thickness. Simple analytic correlations are presented which can be used to estimate sampling errors. A few special topics are touched on, including the use of the effective Stokes Number, and the effects of gas compressibility and turbulence.

Additional sampling errors can result from improper placement of the sampler on the aircraft. The need to avoid mounting a sampler in the turbulent boundary layer adjacent to aircraft surfaces is well known. Less understood, however, is that the disturbance to the flow field caused by the aircraft can extend much farther than the relatively thin boundary layer. Even such far field disturbances in the flow field can alter local particle concentrations. A numerical simulation was performed to explore the magnitude of these concentration effects. For this work, the flow around the aircraft was assumed to the inviscid and irrotational (potential). In this limiting case, analytic flow field solutions exist for several simple geometries. Two geometries with analytic solutions wee studies: a 10:1 prolate ellipsoid (to approximate an aircraft fuselage) and a Joukowski airfoil (to

approximate a wing). Using the analytic flow fields, particle trajectories were obtained by a time integration of the forces acting on the particle. Using a scheme proposed by Fernandez de la Mora, particle concentration along these trajectories are obtained by additional integrations. The calculations reveal that the stand-off distances required to mount a sampler in undisturbed flow are many times larger than required to avoid the turbulent boundary layer.

****

DISCUSSION

Huebert: That horseshoe vortex is frightening. A lot of us have put samplers/inlets back on the fuselage. The size of the vortex is so large that it means you shouldn't use any location.

Rader: It is a disturbed region. How intense is the disturbance? It grows but it sort of diminishes I think as you go down. We have flowrate data for the location that is near the wing and one on the aircraft where it is much forward. The entrance coefficient changes significantly. We suspect it might be because of the presence of the horseshoe vortex. The problem is that folks always want to be a little more quantitative. It is hard to be when this thing is off and on. It is not stationary, kind of moves around the tube, sort of like a tornado growing, unsteady turbulence is a problem. There is something there to be worried about, and I don't know how to quantify that.

Seebaugh: What aircraft was that for?

Rader: The calculation was on a WC135. The calculations were real simplified flat geometry with a standard NACA-20 Airfoil. Again, that's why we're being careful to be quantitative. I's been shown experimentally.

Kritz: I think it might be useful to compare those calculations with the ones they generated for the DC-8, where we have the flow fields of the skin. I don't know, John, what do you think? We've looked at those together, and I didn't see anything over the wing that suggested...

Reller: It wouldn't have shown that anyway.

Soderman: Your comments about compressibility, I'm not sure whether you meant trajectory or flow prediction, but flow, I think, you can predict quite well--compressibility, you have a full-blown Navier Stokes' code or Euler code, but it takes a lot of computer power and it's complicated.

Rader: I should be more specific, I'm speaking from the background of Sandia. The sort of intermediate Mach number between .3 and 1 code. We don't really have anything that works very well.

Vincent: Can I comment on your blunt sampler results, which if I recall for the subisokinetic case, you showed that as you increase the blockage, you've brought the curve closer to what appeared to be aspiration efficiency of unity. If you increase the blockage further, it actually brings the curve below the line of the line and back up again. As you increase the blockage to a very large blockage, it drops right back down. I don't think we should assume that just by increasing the blockage more and more, you're going to get better and better.

Aerosol Sampling and Transport:
Recent Findings at the Universities of
Cincinnati (USA) and Odessa (USSR)

By

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Sergey Grinshpun*, Gennady Lipatov, and Taras Semenyuk (USSR)

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SUMMARY

An unified model for tubular inlets sampling at small angles of pitch (vertical plane) and yaw (horizontal plane) has been developed for horizontal aerosol flows. Convenient charts have been prepared for use in the field. A new non-dimensional parameter couples the external flow to the internal flow for determining the overall sampling efficiency.

The effect of secondary aspiration, due to particle interaction with the outer surface of the thin walled cylindrical sampler in the down-ward wind was quantified experimentally for isoaxial and non-isoaxial conditions. The transmission efficiency and the particle retention coefficient were quantified for isoaxial conditions.

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UNIVERSITY OF CINCINNATI STUDIES

Inlet sampling studies were carried out in the wind tunnel facility shown in Fig. 1. This facility is a horizontal aerosol flow wind tunnel which measures the particle concentration dynamically and quickly for various particle sizes and angles.

Experimental data on sampling efficiencies have shown that for many sampling configurations most of the losses occur just downstream of the inlet face (Tufto & Willeke, 1982b). Figure 2 illustrates the mechanisms that affect the overall efficiency of a sampling inlet. The losses in the inlet section cannot be explained by the equation of fully developed pipe flow (Okazaki & Willeke, 1987).

A unified model for the overall efficiency of inlet sampling has been developed (Hangal & Willeke, 1990), based on a large set of sampling efficiency data obtained in the wind tunnel facility over a period of several years. The inlets
ranged in size from 0.32 to 1.59 cm in diameter, the aerosols from 5 to 40 μm, at wind velocity U_w and inlet velocity U_i of 125 to 1000 cm/sec, and sampling angles θ from 0 to 90°. The transmission efficiency may significantly affect the overall sampling efficiency due to direct wall impaction inside the inlet, gravitational settling loss and aerosol deposition inside the vena contracta region which forms when the sampling velocity exceeds the wind velocity.

Figure 3 illustrates the particle loss due to gravitational settling in the inlet's developing boundary layer. For non-isoaxial conditions, the pathway of the particle settling is determined by settling velocity component, $V_s\cos\theta$, where V_s is the gravitational settling velocity. Taking the angle effect, the model which was previously developed for isoaxial conditions (Okazaki. et al., 1987) has been extended to non-isoaxial conditions (Hangal and Willeke, 1990).

$$Z_\theta = (L/U_i)\ (D_i/V_s\ \cos\theta)^{-1} = Z\ \cos\theta \tag{1}$$

where Z_θ expresses the gravitational settling in the boundary layer, L is the length of the sampling tube, and D_i is inlet diameter. At non-isoaxial conditions, the boundary layer development and inertial penetration are expressed by the same Reynolds number, Re, and Stokes number, Stk, as expressed for isoaxial conditions. Thus, the gravitational settling parameter has been expressed for all angles as

$$K_\theta = [(Stk\ Z_\theta)\ Re^{-0.5}]^{0.5} = K(\cos\theta)^{0.5} \tag{2}$$

$$K_\theta = [d_p^2\ \rho_p\ U_w\ L\ V_s\ \cos\theta\ (18\ D_i^{2.5}\ U_i^{1.5}(\rho_a\ \mu)^{0.5})^{-1}]^{0.5} \tag{3}$$

where d_p is the particle diameter, ρ_p and ρ_a are the densities of the particle and air, respectively. The gravitational settling component E_{ts} of the transmission efficiency which was developed from our experimental data has been expressed for all sampling angles

$$E_{ts} = \exp{(-4.7\ K_\theta^{0.75})} \tag{4}$$

The particle losses due to direct wall impaction vary with the orientation of the inlet to the wind direction. During upward sampling, the particle will impact onto the lower wall of the inlet and for downward sampling onto the upper wall. Gravity tends to pull the particle away from the wall during downward sampling. This decreases the amount of impaction. We have introduced gravity effect angle α, which - when added or subtracted to physical angle θ - takes into account gravity .

The impaction component E_{ti} has been expressed as a function of a wall impaction parameter, I_w, and a vena-contracta impaction parameter I_v.

$$E_{ti} = \exp{[-75\ (I_w + I_v)^2]} \tag{5}$$

$$I_w = Stk\ R^{0.5}\ \sin(\theta \pm \alpha)\ \sin((\theta \pm \alpha)/\ 2) \tag{6}$$

$$I_v = 0.09\ [(1-R)^{-1}\ Stk\ \cos\theta]^{0.3} \qquad for\ R < 1 \tag{7}$$

$$I_v = 0\ for\ R \geq 1 \tag{8}$$

where $R = U_w/U_i$. The results obtained from the experimental data are shown in Figure 4 for small sampling angles. Using the above developed relations, several charts which are easy to use in the field have been prepared to determine the overall sampling efficiencies of inlets at several operating conditions. Figure 5 illustrates one of the charts for overall sampling efficiency at different yaw orientations and sampling ratios as a function of non-dimensional particle size.

UNIVERSITY OF ODESSA STUDIES

To describe sampling errors for disperse flows, it is common to use the external aspiration coefficient E_e, which is the ratio of the mean inlet flow concentration of mono-disperse particles to the true concentration upstream. The aspiration efficiency E_a does not consider the interaction of the particles with the external surface of the sampler. Even for sharp-

edged inlets facing the wind, the particles may interact with the external surfaces of the inlet, i.e., secondary aspiration may occur due to inward bounce, blow-off, and re-entrainment under anisokinetic conditions. This is especially important for high-speed aspiration of coarse aerosols. This particle-wall interaction process has been investigated extensively during the past five years. The efficiency of such a process is characterized by the secondary aspiration coefficient E_r which is (Grinshpun. et al., 1990)

$$E_r = E_e / E_a \qquad (9)$$

where E_e is the experimentally determined external aspiration coefficient. The values of E_a was determined separately for each set of conditions were found. For isoaxial sampling E_a was measured by the Limiting Trajectory Method, realized through the "thread-of-droplets" technique (Lipatov et al., 1986). For non-isoaxial sampling this coefficient was either calculated theoretically or measured under the condition of absolute particle retention.

Figure 6 illustrates the effect of the wind velocity on the secondary aspiration efficiency at wind velocity of 90 - 450 cm/s, inlet diameter of 0.56 cm. and spherical spore diameter of 30 μm. The influence on the secondary aspiration is significant at R $\leq$ 0.1 which resulted in a rapid decrease of E_r when the velocity ratio was increased. Experiments were also conducted which showed the decrease in E_r with the increase in inlet diameter from 0.3 - 1.5 cm for the same conditions. Figures 7a & b illustrates that for non-isoaxial sampling at R=1, E_e decreases monotonically with increase in Stk for a "high" Reynolds numbers, and E_e changes non-monotonically for the same Stk for "small" Re -values. The external aspiration coefficient for thin-walled nozzles facing the wind was found to be independent of Reynolds number while non-isoaxial sampling has a complicated dependence of E_e on θ, Stk and R at Re = 100 - 1000 .

The wind tunnel was also used to study the interaction of particles with the inner wall of a sampling nozzle. Two identical samplers - one with and one without the greased inner walls - were placed in the wind tunnel, and exposed to monodisperse aerosols of constant concentration. The transmission efficiency values were determined for each sampler by gravimetric techniques. The ratio of these values is the overall coefficient of particle retention by the surface. It consists of protracted retention due to absolute adhesion, and transitory retention which depends on particle drift. Figure 8 illustrates the setup to find the dependence of the corresponding adhesion number (Zimon, 1976) which was obtained by the method of direct observation over a segment of the inner surface of the test duct. Copper nozzles with diameters of 0.4 - 1.2 cm and Lycopodium spores were employed in the experiments. The temperature was 15° C and kept constant, the relative humidity was 20 - 30 %. The suction velocity U_i in the inlet was 40 - 1000 cm/s. For $U_i < 150$ - 200 cm/s absolute particle retention was observed. For U_i = 300 - 450 cm/s, the rebound coefficient varied from 0.65 to 0.80. The range of U_i = 200 - 300 cm/s is characterized by a considerable particle blow-off and drift.

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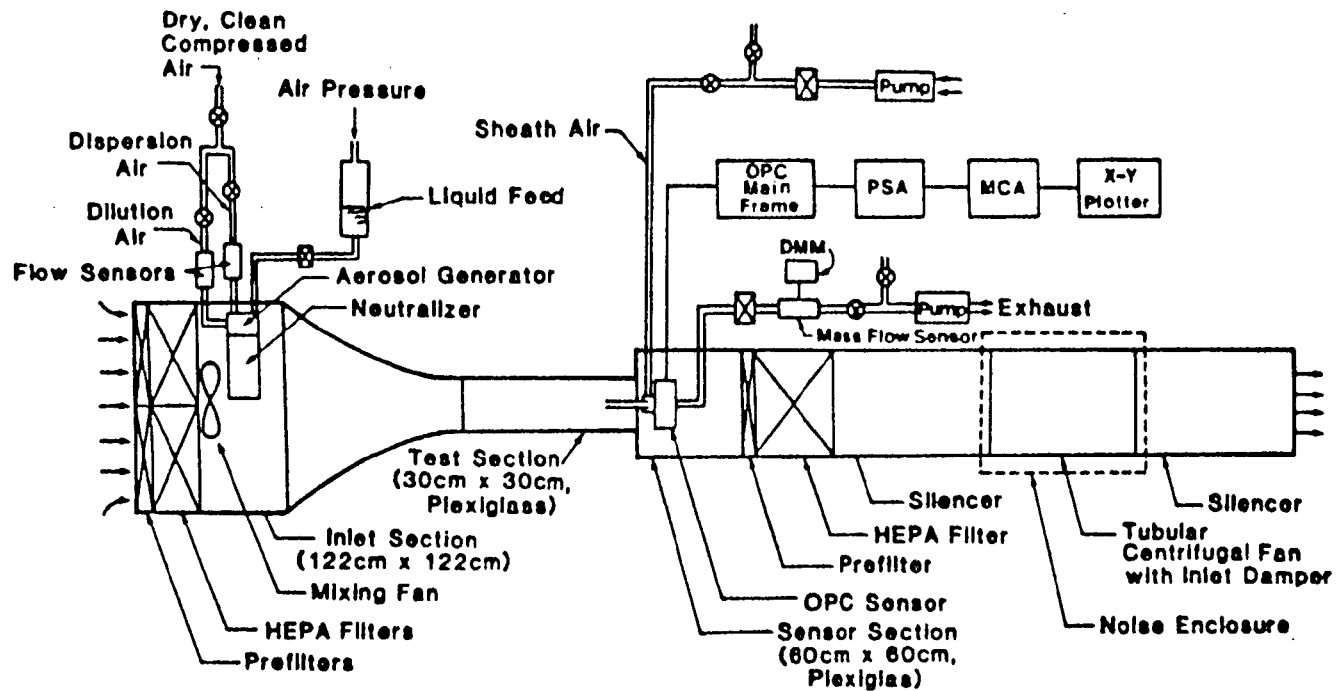
OPC = Optical Partical Counter.   MCA = Multi Channel Analyzer.
PSA = Pulse Shaping Amplifier.   DMM = Digital Multi-Meter.

[Figure 1]--Schematic diagram of the University of Cincinnati wind tunnel facility
(modified from Tufto & Willeke, *Environ. Sci. Technol.*, 16, 607-609, 1982)
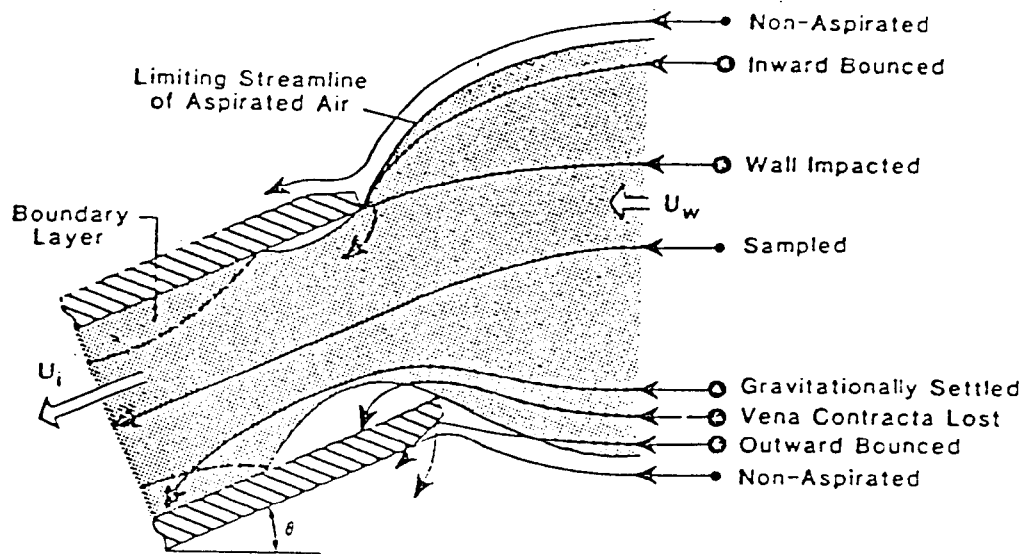
[Figure 2]--Schematic representation of the mechanisms that affect the overall efficiency of a sampling inlet (Hangal & Willeke, *Atmospheric Environment*, 24A, 2379-2386, 1990).
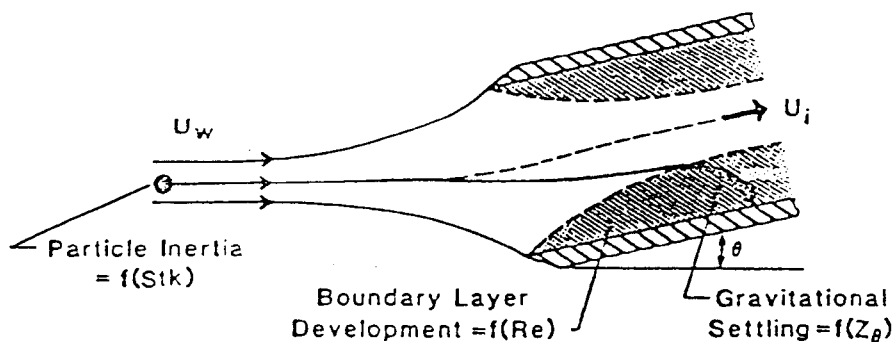
[Figure 3]--Schematic represnetation of the coupling between external flow and gravitational settling in the inlet (Hangal & Willeke, *Atmospheric Environment*, 24A, 2379-2386, 1990).

$$I_w = Stk \ R^{0.5} sin(\theta - a) \ sin((\theta - a)/2)$$

$$I_v = 0.09[(1-R)R_i^{-1}Stk \ cos\theta]^{0.3}$$
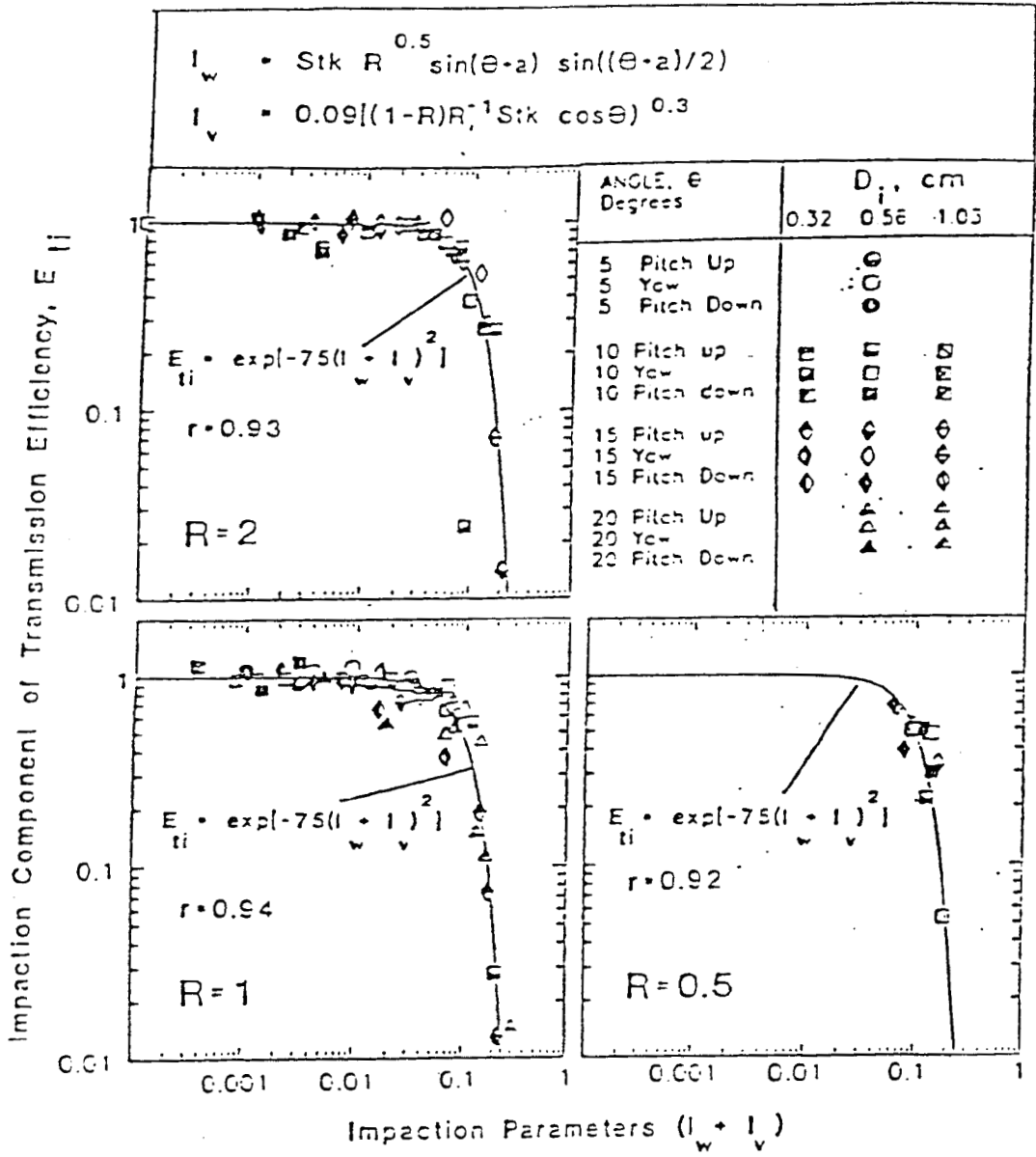
[Figure 4]--The impaction component of the particle transmission efficiency (Hangal & Willeke, submitted to AtmosphericEnvironment, 1991).

234
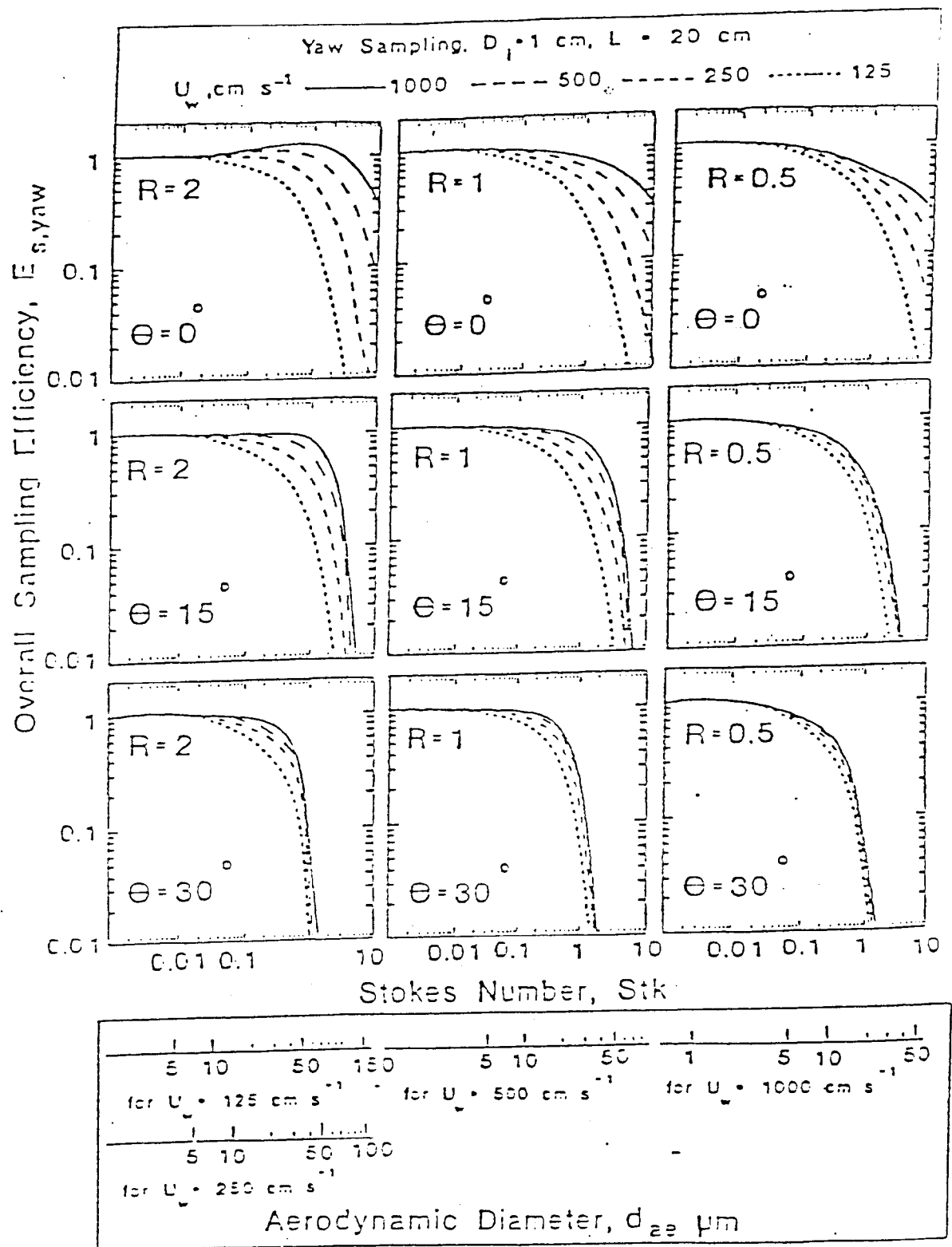
[Figure 5]--Overall sampling efficiency for several angles (Hangal & Willeke, submitted to *Atmospheric Environment*, 1991).

Isoaxial sampling for Downward Flows.

	U_w cm/s
■	90
□	150
▲	240
△	450
D_i	0.56 cm
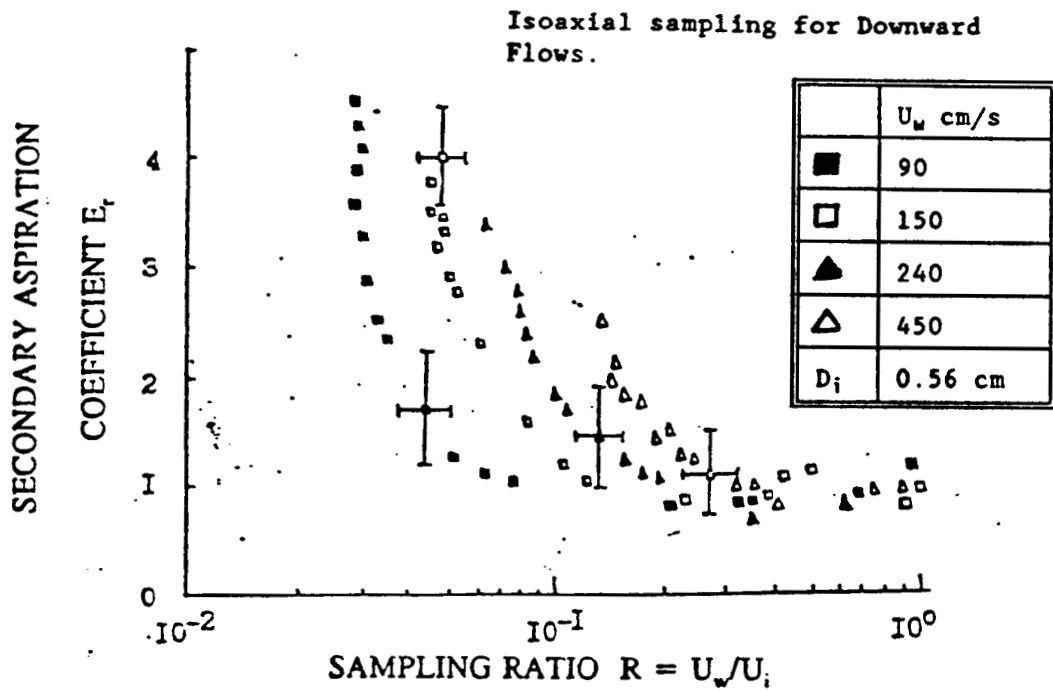
[Figure 6]--Effect of wind velocity on aspiration efficiency (Lipatov et al., *Atmospheric Environment*, **22**, 1721-1727, 1988).
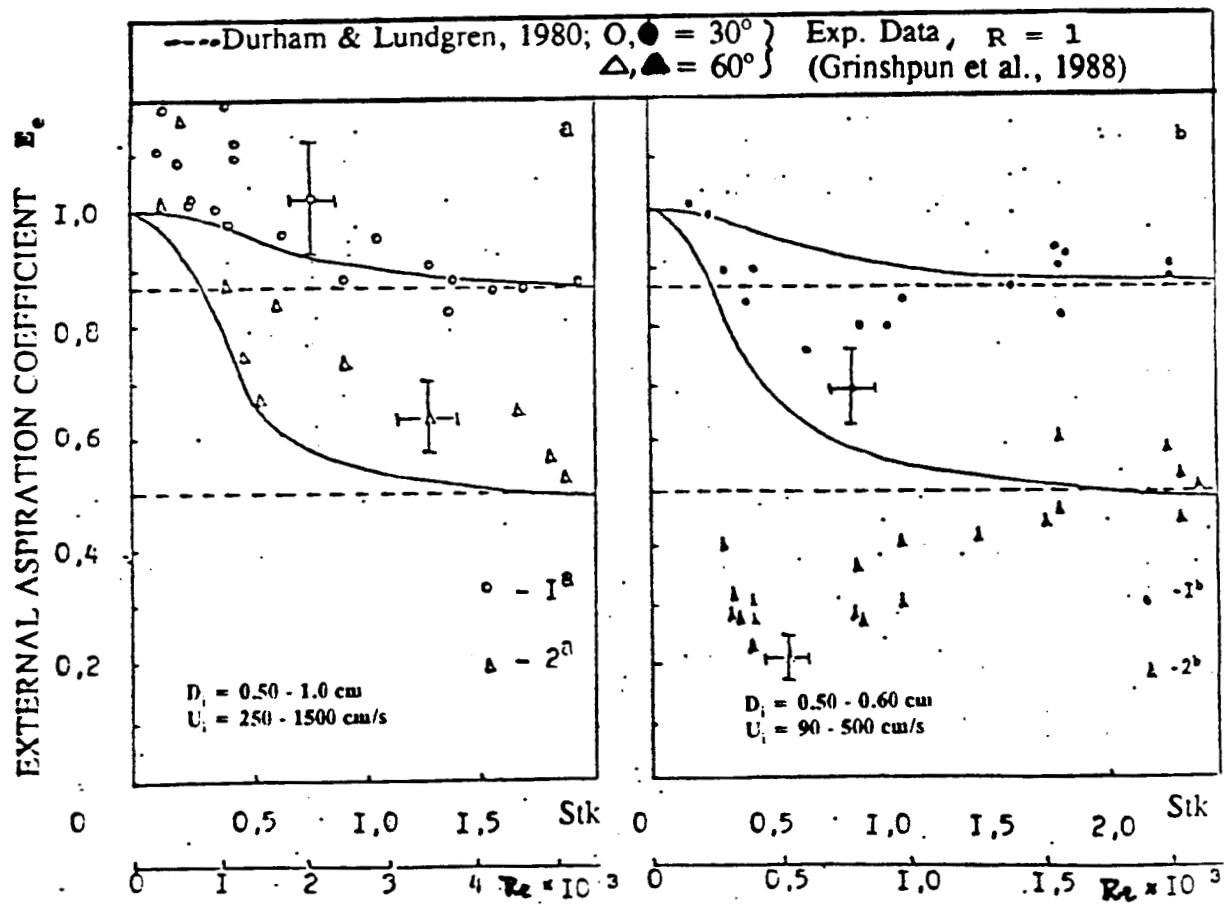
[Figure 7]--Effect of Stokes and Reynolds numbers on external aspiration coefficient (Grinshpun et al., *Meteorologia i Hydrologia*, 127-133, 1988).
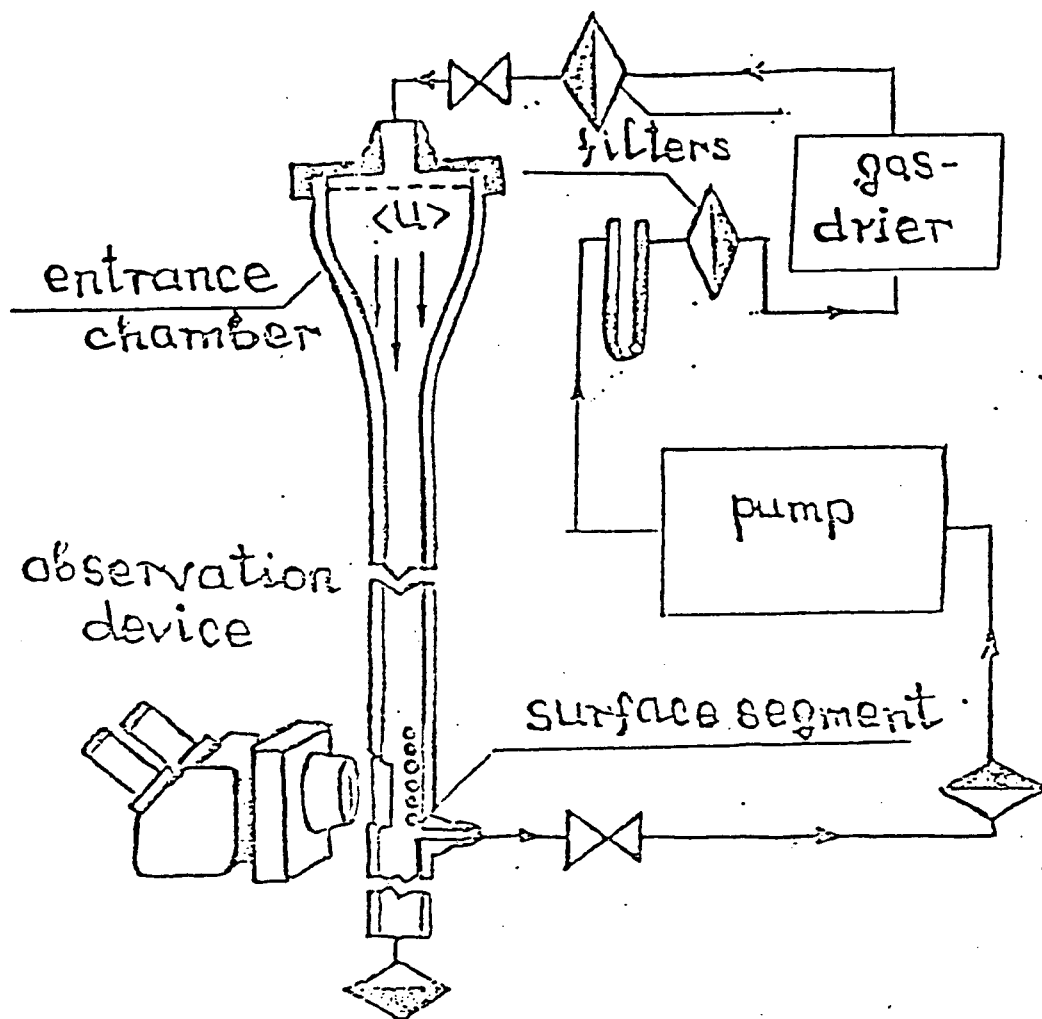
[Figure 8]--Experimental facility at the University of Odessa for the measurement of particle bounce and transmission efficiency (Lipatov, Grinshpun et al., *J. Aerosol Sci.*, 20, 929-941, 1989).

237

DISCUSSION

McFarland: What's the ratio of wall thickness to diameter in the tubes that you used in your experimental setup?

Grinshpun: The bulk of the sampling tubes were thin-walled. The ratio was less than 1.01. Regarding the thick-walled sampling tubes, not more than 2.

McFarland: What is the leading edge of your probe look like? Is it a sharp-edged probe or is the edge rounded?

Grinshpun: No, it is not sharp edged. It is a thin-walled probe.

McFarland: Thin-walled--the edge would be rounded instead of angled?

Grinshpun: It is pure cylindrical surface and flat. The thick-walled samplers like this develop sharp edges. For thin walled like this tube, the ratio is very close to being good.

Huebert: Most of the effects that you saw were at large angles, and when you get down to angles less than 5°, which is probably what we're worrying about here, is that there wasn't very much impact of being non-isoactive.

Willeke: Yes, I think that is roughly correct. In terms of gravity, though, as you saw, the effect of gravity upward was the strongest but for high speed aircraft sampling, I assume that gravity is a minor effect.

Pueschel: Where you have separation of liquids vs solids, at what Stokes' number does collection efficiency occur?

Willeke: I will make that information available to you.

Design and Testing of Aerosol Inlets and Transport Systems

By

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AEROSOL TRANSPORT THROUGH STRAIGHT TUBES

Aerosol losses in straight tubes take place primarily through the mechanisms of gravitational settling, turbulent diffusion and thermal diffusion. numerical analyses have been performed to predict the losses as functions of flow rate, tube orientation, tube length, tube diameter and particle size. With reference to Figure 1, the tube is assumed to be oriented at an angle ϕ with respect to the vertical direction. An aerosol particle is subject to two velocity components; namely, that due to gravitational settling, V_g, and that due to the combined effects of thermal turbulent diffusion, V_d. In the calculations, the model of Beal (1970) was used to predict the losses due to turbulent and thermal diffusion.

Typical results obtained from the calculations are shown in Figure 2, wherein the penetration of 10 μm aerodynamic equivalent diameter (AED) aerosol particles is shown as a function of tube diameter for a flow rate of 100 L/min and for various tube lengths. It may be noted that there is a well-defined optimal tube diameter, D_{opt}, for which the penetration is a maximum. The optimal diameter is independent of tube length. The results given in Figure 2 suggest that for design purposes, the actual tube diameter should be selected somewhat greater that D_{opt} since the penetration decreases dramatically on the left side of D_{opt} (controlled by turbulent deposition) and only gradually on the right side of D_{opt} (controlled by gravitational settling). Flow rates higher than the design rate have the equivalent effect of moving the operating point to the left on the penetration curve.

AEROSOL TRANSPORT THROUGH A TUBING SYSTEM

A user friendly computer program has been developed to characterize aerosol penetration through a tubing system comprised of an inlet, elbows and straight sections. The model of Vincent et al. (1986) is used to calculate aerosol aspiration efficiency, the model of Okazaki and Willeke (1987) can be used to characterize losses in the inlet section of horizontal pipes, the model of Beal (1970) is used to determine losses due to turbulent and thermal diffusion, the model of Pui et al. (1987) is used to calculate losses in bends, and the model of Anand and McFarland (1989) is used to estimate losses due to gravitational settling.

The efficacy of the model was experimentally evaluated by constructing an aerosol transport system and testing it in an aerosol wind tunnel. With reference to Figure 3, the transport system is composed of 26,7 mm inside diameter tubing and has an inlet, three straight sections of tubing (horizontal, inclined and vertical), and two elbows (90° and 45°). An example of the results is shown in Figure 4, the penetration through the system is plotted as a function of aerodynamic particle diameter for a flow rate of 70 L/min and an inlet oriented parallel to the flow stream. The experimental results and numerical predictions compare favorable--the experimentally determined cutpoint (particle size for which the penetration is 50 percent) is 16.2 μm AED predicted by the model. Similar results were obtained at other flow rates and inlet orientations.

SHROUDED AEROSOL SAMPLING PROBE

Torgeson and Stern (1966) employed a shroud about an aerosol sampling probe in order to negate angle of attack effects on a WB-50 aircraft. McFarland et al. (1989) employed the shroud principle in the sampling of aerosols from flow ducts to reduce wall losses on the internal surfaces of the probe. The device developed by McFarland et al., shown in Figure 5, utilizes the shroud to decelerate the flow to approximately 1/3 of the free stream velocity. This permits the use of a larger diameter probe which, in turn, will have lower internal losses. With reference to Figure 6, the results from wind tunnel tests with a shrouded probe and an isokinetic probe are compared. The wind tunnel was operated at a range of speeds from 2 to 14 m/s and the flow rate was set at 170 L/min through both types of probes. A particle size of 10 μm AED was used for these experiments. In Figure 6, the concentration ratio denoted as T is the transmission efficiency and the concentration ratio denoted as A is the aspiration efficiency. The difference between A and T are the wall losses. It may be noted from Figure 6 that the wall losses of 10 μM AED particles at a wind speed of 14 m/s are approximately 35 percent for the isokinetic probe and approximately 17 percent for the shrouded probe. For this particular design, the transmission efficiency is within ±10 percent of unity for the range of wind speeds of 2 to 14 m/s.

HELICOPTER-BORNE AEROSOL SAMPLING SYSTEM

A sampler was developed for collecting fly ash particles from the vicinity of a coal-fired power plant. The sampler, Figure 7, was mounted under a Bell UH1-B helicopter, and the device was fitted with a dual shrouded probe. It was designed to sample at a flow rate of 9 m³/min and it includes provisions (a horizontal elutriator) for fractionating the aerosol at a particle size of 10 μm AED (to remove non-inhalable aerosol). Particles with sizes $\leq$ 10 μm AED are collected on a set of hi-vol filters. The system was wind tunnel tested at a wind speed of 48 km/h to characterize penetration of aerosol from the free stream to the filter collectors. The results are shown in Figure 8 together with curves which predict

penetration of aerosol to the filters based on the assumptions of laminar and turbulent flow in the elutriator. Good agreement was obtained between prediction and experiment which suggests the shrouded probe permitted passage of a representative sample of aerosol.

ACKNOWLEDGEMENTS

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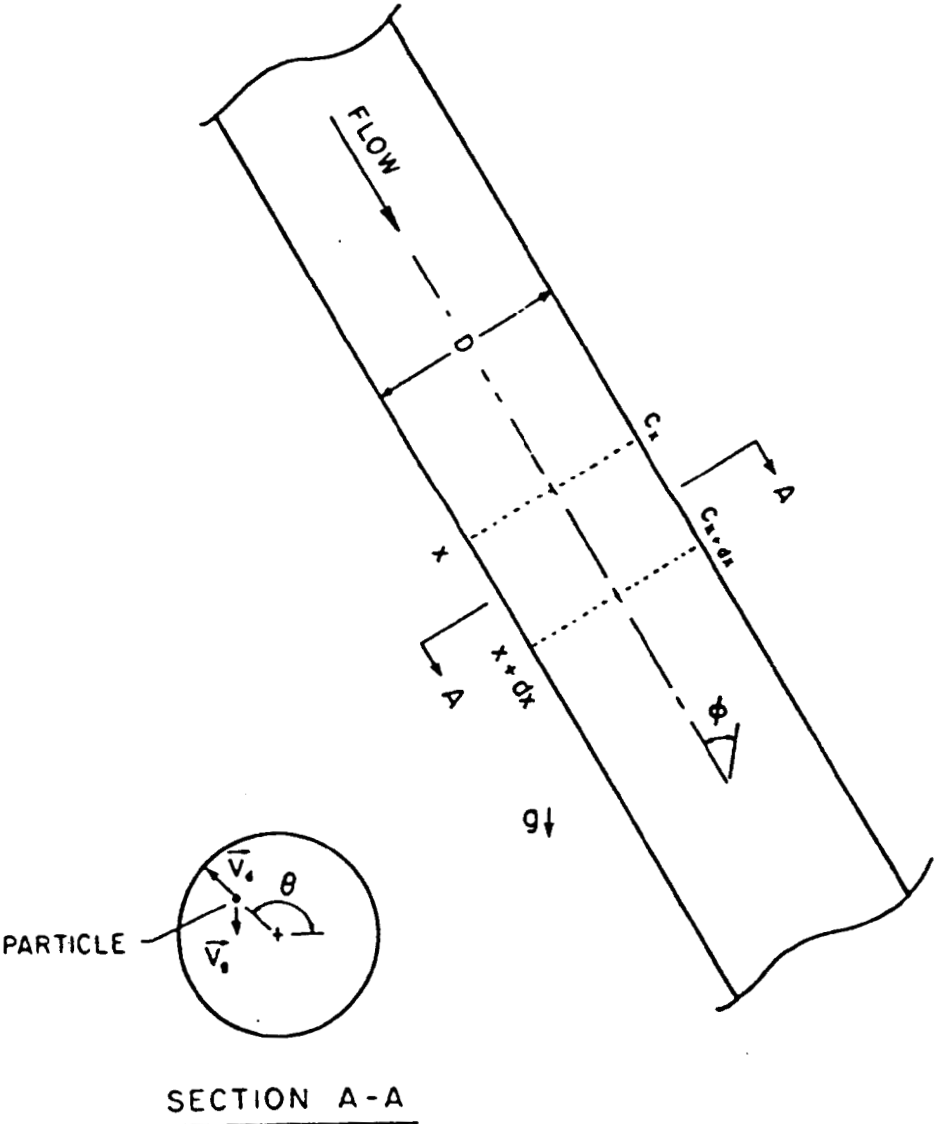
[Figure 1]--Model of tube used for calculation of aerosol penetration.
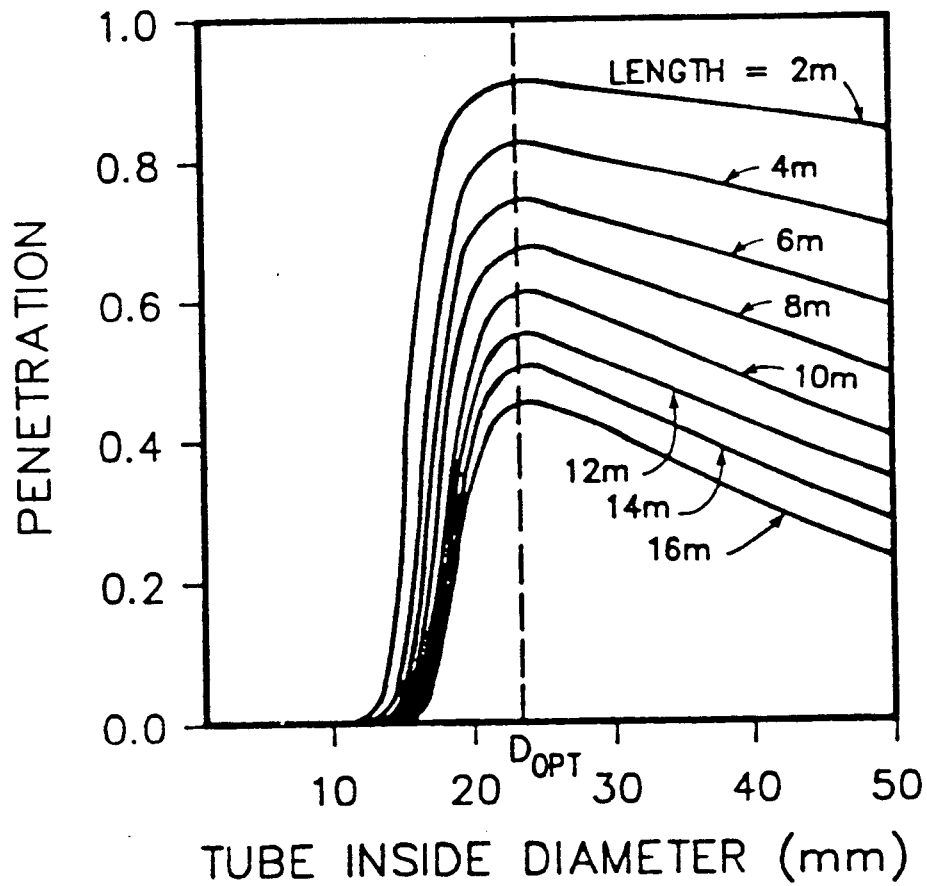
[Figure 2]--Penetration of 10 μm AED aerosol particles through horizontal tubes. Flow rate = 100 L/min.

243
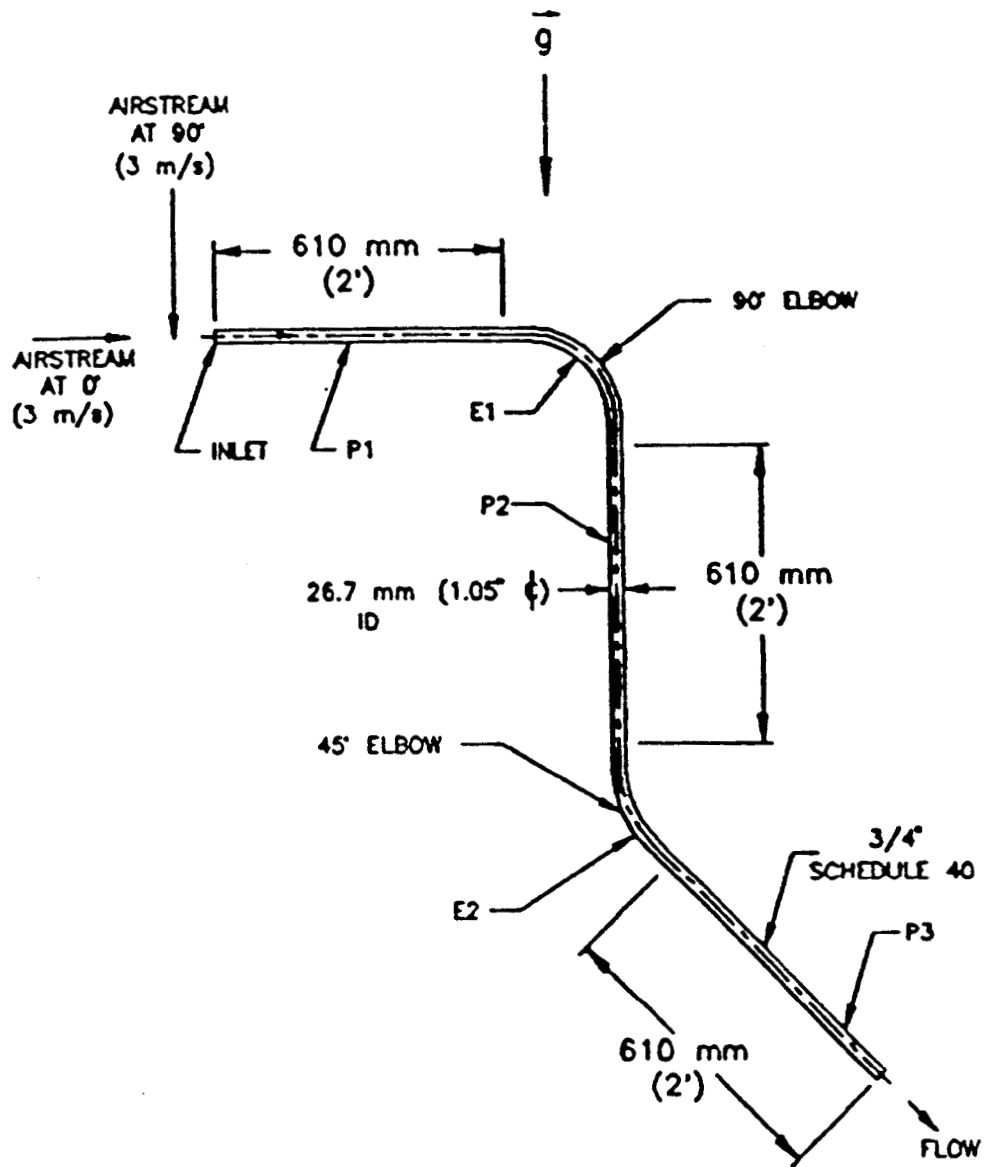
[Figure 3]--Aerosol transport system which was tested in a wind tunnel to determine penetration characteristics.
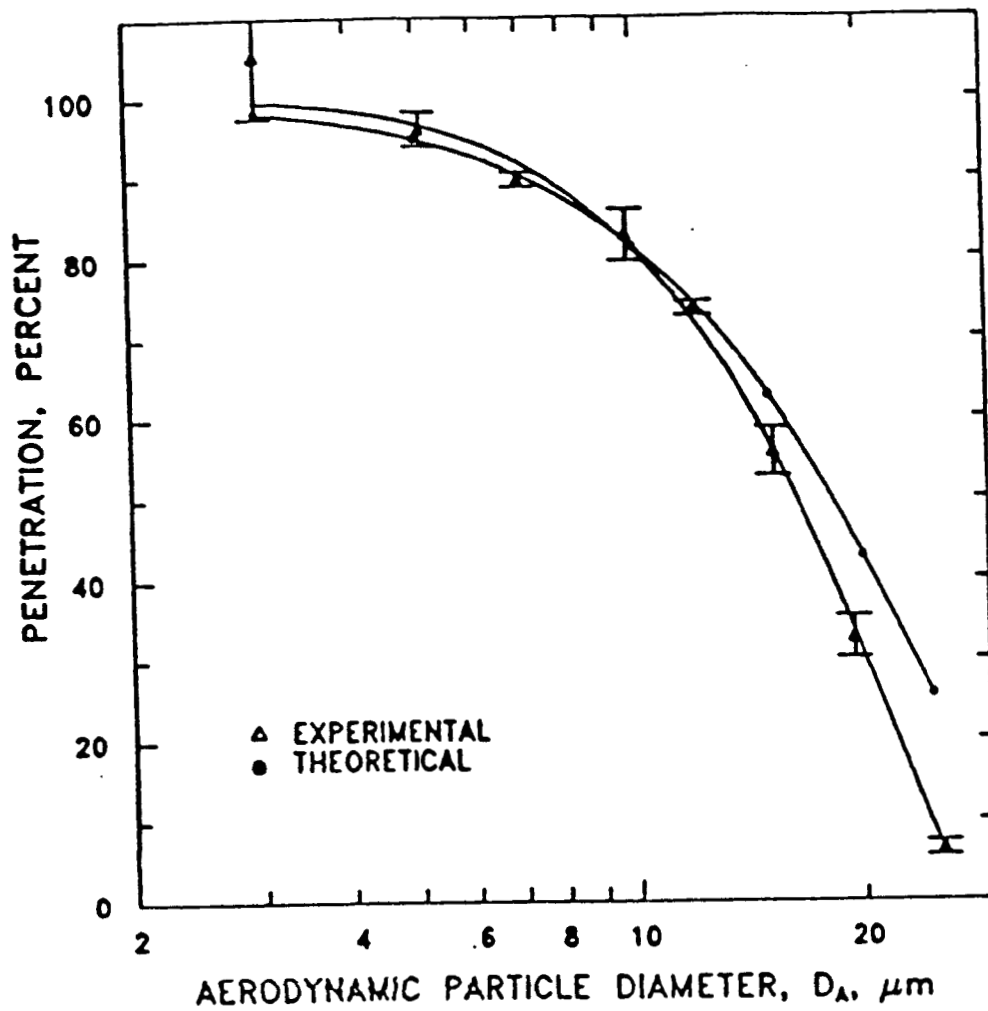
[**Figure 4**]--Aerosol penetration through the model transport system. Flow rate = 70 L/min, inlet orientation is parallel to the flow field.
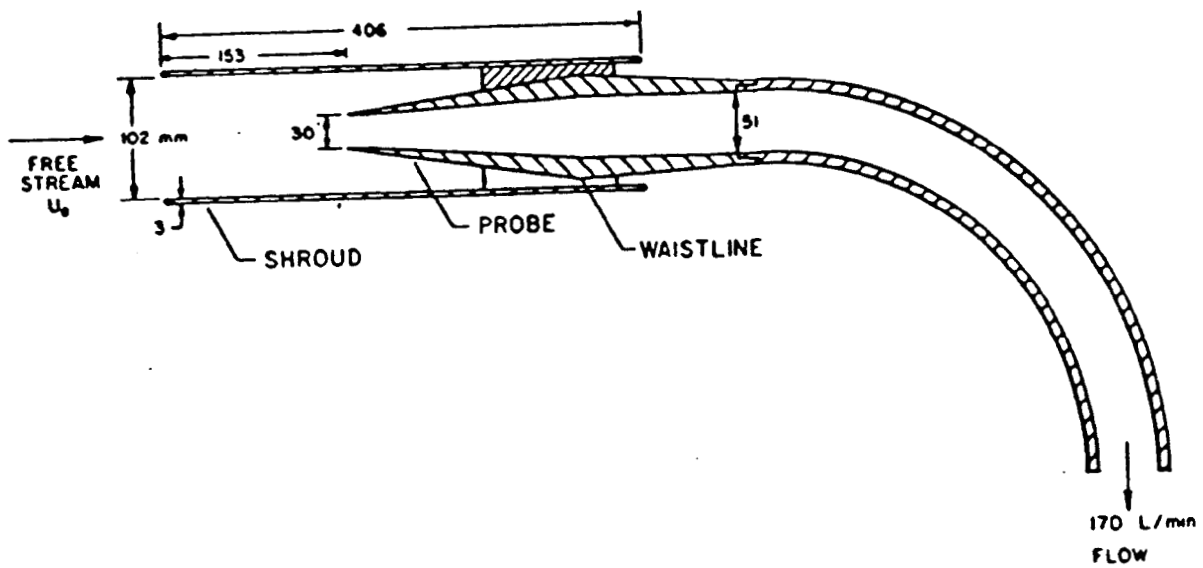
[**Figure 5**]--Shrouded probe aerosol sampler. The system is designed to operate at a flow rate of 170 L/min in air speeds of 2-14 m/s.
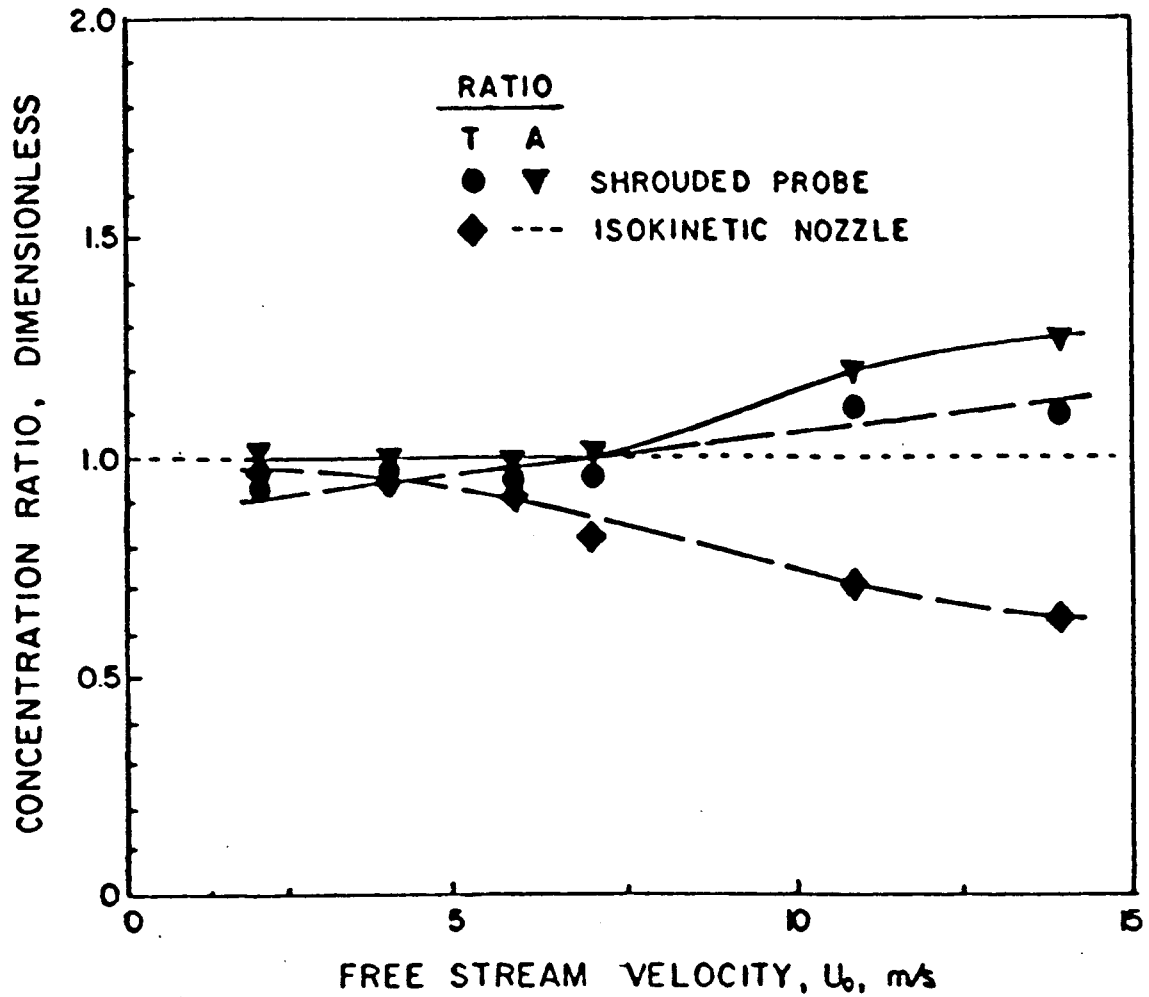
[Figure 6]--Comparison of sampling characteristics of a shrouded probe and isokinetic probe. T = transmission efficiency, A = aspiration efficiency. Flow rate - 170 L/min, particle size = 10 μm AED.

247
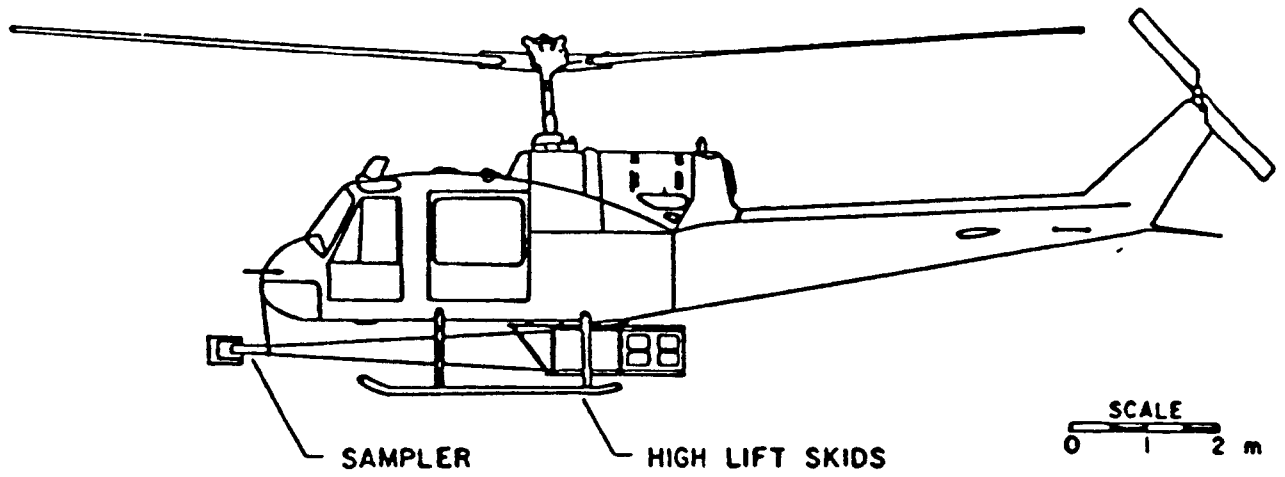
[Figure 7]--Helicopter-borne, shrouded probe aerosol sampling.

248
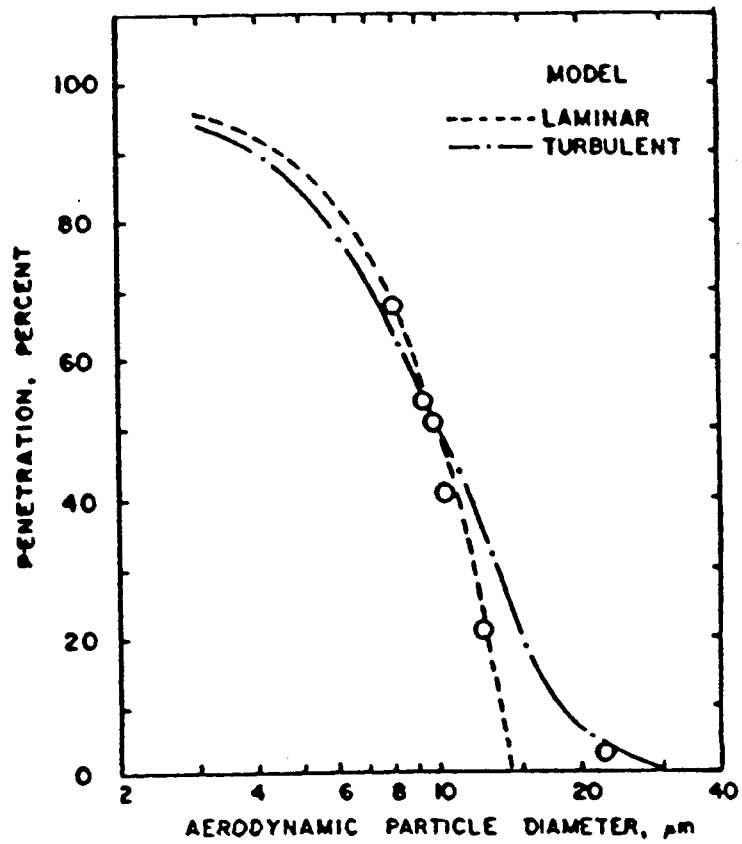
[Figure 8]--Results from wind tunnel tests with the helicopter-borne aerosol sampling system.

DISCUSSION

Huebert: Could you put up the slide where you have a cylinder of air along the axis going into your shroud.

McFarland: You know that that's an artist's conception.

Huebert: I know, but I want to talk about what the artist had in mind. As I looked at that, it occurred to me that if you were in fact slowing the air down even along the axis, the cross-sectional area of that air that's coming in there has to increase.

McFarland: Oh, definitely.

Huebert: What the shroud and some of the other schemes accomplish is to get you away from wall effects, but they don't get you away from virgin streamlines because lower air has got to occupy a larger cross-section. I thought about that fact and the fact that your performance looks pretty good, and it occurred to me that it's essentially the enhancement that the virgin streamlines there give you in the aspiration coefficiency. Which they offset by transmission losses of the larger particles. Those two factors are really counteracting one another.

McFarland: Let's come back to what you first me, the artist's conception. It's an artist's conception because with our streak lines that we took experimentally in wind tunnels didn't really show up well enough to photograph. But good lighting and all we could get in there and make certainly qualitative and to a certain extent quantitative measurements. The curvature of the streamlines--it's not just the fact that the bottom of the streamlines may increase the cross-sectional area, it's really the radius of curvature at entrance. If we have a very long radius of curvature, we will not effect the concentration. Here where the radius of curvature is very abrupt the concentration is substantial. What you see as an artist's conception is pretty true.

Clarke: You referred to an isokinetic probe, but I wasn't sure if that was the same probe without the shroud or is that some other probe? Did you compare them with or with a shroud?

250

McFarland: Yes, we compared them with and without the shroud. We couldn't use exactly the same probe for the same conditions because we have a velocity difference. We have say 14 m/s here. With the isokinetic probe, you have to have a smaller cross-sectional area. We did do the same thing by using this as an isokinetic probe and comparing it with what it would equivalently do as a shrouded probe.

Clarke: What is that?

McFarland: It is exactly as you'd expect. The shrouding does help reduce wall loss.

Wilson: Are the wall losses reduced as a mechanism of turbulent deposition.

McFarland: The answer is yes, yes, and then from Dr. Willeke's work there is also a yes for the gravitational settling components in the developing boundary layer. There are a number of factors. Again, what the Environmental protection agency has had in mind for use of this probe for the most part no problem. They do some size work these days where there's a desire to make a fractionation of 10 μm and things are getting a little fuzzy there, but if you look strictly at the methods, you don't see too much of a problem with the sharp-edged inlet.

Wilson: Given Professor Willeke's mechanism, can you explain why the shroud reduces losses on the inside of the tube?

McFarland: I think I would look at it from a different perspective. The Reynolds' numbers that we are dealing with with these probes typically are in the range of maybe 2,000 to 10,000. The factors that you mentioned might be more at work at the higher levels.

Vincent: Could there also be dropped upon on that point, that would the shroud have some effect that would prevent the penetration of large curvident eddies into the region where you are actually doing the sampling?

McFarland: We are just doing those types of studies right now.

Wilson: If we took your graphs and had wind speeds on the x axis and put a 0 behind each of those numbers so that we were talking about 50, 100, and 150, what kind of confidence would you have in being able to design a shrouded inlet to work in those kinds of velocities?

McFarland: First of all let me make a comment that primarily the work that we are doing is in this range of velocities of 5 to 20 m/s. I must say that we genuinely appreciate the area the realm of interest of our particular endeavors, it is a much easier realm to work with than the high-speed realm. To answer your question, when you look at the alternatives for collecting samples from the freestream in an aircraft, what choice do you have? You need to do some deceleration, clearly you do. If you don't, what isn't lost in the probe is lost on the walls. Clearly something has to be done. The question is how do you do the deceleration? You do it with the freestream doing its deceleration such as we have done here, you decelerate internally, but clearly to reduce the losses for the models that we look here, with the sizes that we are considering, you really need to get down to the velocities that we're looking at. If you change the range of sizes, you are looking at an order of magnitude lower than any you can look at a much higher rate of velocity. In general, I think our interests would overlap in the size spectrum, and I think we could deduce from that the types of numbers that we look at here for velocities, sizes, and so forth are the types of numbers that you would probably also use.

Design and Test of Sampling Inlets for Airborne Aerosol Spectrometer

By

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Aerosol particles are important natural and anthropogenic constituents of the atmosphere. Their role in air chemistry, especially in heterogeneous reactions, and their influence on climatic changes is hardly known due to the lack of in-situ measurements. Nevertheless, a key role in ozone depletion, global warming, and nuclear winter scenario is scientifically expected. Therefore in-situ measurements of the vertical concentration profile, the physical and chemical characterization by airborne platforms are required. Similar sampling techniques for balloons, rockets and various aircraft are already in the stage of development. Optical particle counters, mass monitors, condensation nuclei counters and impactors are in use, but differ in flow rate and size ranges. Appropriate inlets carry the polydisperse aerosol inside the platform where the measurements are performed. Especially large particles like those of PSC's require fairly isokinetic sampling whereas nucleation/accumulation particles need high sampling volumes due to their low particle mass.

According to the requirements of the German governmental air traffic regulations, we started the tests with modified Rosemount inlets which have the official installation certificate. The efficiency has been tested with pyrotechnical generated polydisperse aerosols in a wind tunnel at different velocities. The results are a comparison of the Rosemounts with an isokinetic inlet directly faced to the air stream. Additionally the effect of different tubings and various tubing length are measured, too. Finally, from the results a single inlet has been designed as an "ideal entrance" working isokinetically. The inlet diameter increases by an angle of seven degrees to reduce the speed for the appropriate intake velocity of the various instruments.

DISCUSSION

Huebert: Before you take that off, I am fascinated to see that you are seeing losses at the sub micron particle mode. It's a pretty small spectrum.

Georgi: It might be that we are two low for the flow. We have rectangular input, you see we have this Rosemount and they have to suck in this direction. But you have a stagnation here, and I think we might change it a little bit, but we are limited to these changes. It would be much better if you could have real sampling like a diffuser.

Clarke: Is your impactor heater to the same temperature as the Rosemount?

Georgi: Yes.

Kritz: In the wind tunnel tests, you heated it also just like in the air flight?

Georgi: No. Of course, this airflow is fairly dry. It's got generated pyrotechnically in the wind tunnel. We achieved concentrations about 500 micrograms per cubic meter in tunnel, and at all times circulating, and we can keep it for about a half an hour--this concentration in the tunnel. You have a fairly stable distribution; therefore, we can check this variation of distribution according to different sampling efficiencies of different inlets.

Pui: If the RAM is intended to reject the big particles, do you have to make any modifications?

Georgi: Yes, we made complete modifications. We have tube from beneath and put it directly on the same level as the Rosemount.

Pui: Then the tube stays in the inlet?

Georgi: No. You see, you have a fairly enlarged entrance, and you get, again, a very small hole in the Rosemount, and you start sampling in the middle.

Pui: But does the Rosemount probe have the RAM intended to reject the ice particles from getting into the ....

Georgi: Outside, yes, outside RAM's it has reject, but this time we are using a different type of Rosemount. The type we are using is the type which is being used for temperature and humidity measurements, not for velocity.

Pui: I'm familiar with the total temperature sensing probe, but one of the reasons they have the RAM is to reject the ice particles from getting in the sensor.

Georgi: Ice particles cannot get in because even if you have a certain angle, they can't follow according to its sampling velocity.

Pui: That RAM doesn't effect your sampling efficiency apparently.

254

Radke: I think the RAM is not present on the deiced version of the Rosemount probe. I think you're thinking of a different total temperature probe.

Georgi: The normal Rosemount has a sensor inside. We have removed completely the inner part and put a tube inside. This tube is then directly connected to the inside. There we have a tube in for the impactor.

Clarke: So you have a large opening in the Rosemount and a small tube perpendicular to it.

Georgi: You have a 8mm diameter of the tube and the entrance is about 12mm to 10mm.

Clarke: It's still a right angle sampling?

Georgi: Yes, it's still a right angle. That's the best thing, but you can't avoid it. All the Rosemounts compare fairly well with each other. All the variations within the wind tunnels are fairly low, but we now have different tubing, and we've got a reduction, which is not so high of a reduction.

             For example in this case where here is the direct Rosemount and have plastic tubing 1m long with a diameter of 25mm, you get some losses which are not so drastic, but you get a higher variation within the sample.

             If you are coming through the stainless steel tubes, the first one has a 25mm diameter, and the lower one has a 10mm diameter. Here you have higher velocities, you've got higher sampling efficiency in the small particle range.

             This is a teflon diffuser on top of the Rosemount. You see that the Rosemount has collected more particles than its diffuser. This diffuser has a rectangular entrance into the place, and then we have an impactor. If you put the impactor directly after the diffuser, you get a much higher sampling efficiency.

Willeke: What does stage four represent science-wise?

Georgi: It's a Berne Impactor.

Baumgardner: What is the maximum speed you can get on your wind tunnel?

Georgi: 55 m/s.

Clarke: How far away are your inlets from your skins of the aircraft?

Georgi: 11 cm.

Clarke: Are you concerned about that? Have you tested that?

Georgi: We asked the company, and they say ok.

Clarke: Do you maintain these at isokinetic based upon the wind speed in determined by some other measurement?

Georgi: The idea I think would be if you had an online sensor--any optical particle counter--move it out move it in to experiment at the plane. Fly up to 500 k/h maximum. Then we can get real measurements. In a wind tunnel we are limited in this case.

An Aircraft Aerosol Inlet for Operation at Mach 0.7
At Altitudes from 8km to 20km

By

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ABSTRACT

An inlet was developed to sample aerosol on a NASA ER-2 aircraft. The inlet is used with a PMS Passive Cavity Aerosol Spectrometer. The objective was to achieve quantitative sampling of aerosol in the diameter range from 0.1μm to 3μm. The development process involved internal flow studies, instrumentation of the inlet, flight studies and monitoring of inlet performance in flight. We could not afford wind tunnel studies at the Mach numbers and Reynolds numbers of interest.

We believe that the inlet enhances particle concentrations due to inertia and evaporates particles due to compressive heating. However, it was possible to account for these factors quantitatively and to correct for them. Calculated correction factors are presented for both effects.

Some problems remain to be solved. Orientation of the inlet axis parallel to the streamlines in the local flow must be assured. Protection must be provided against flow separation in the event that misalignment of the inlet is unavoidable. And particle losses in diffusers of this type must be investigated. If unanticipated loss mechanisms are not causing unanticipated particle losses in the diffuser, then inlet performance should meet expectations.

INTRODUCTION

The NASA ER-2 aircraft operated by NASA Ames Research Center often carries a PMS Passive Cavity Aerosol Spectrometer (PCAS), operates at altitudes up to 20 km and at Mach .7. The PCAS sample flow rate ranges from 8 to 16 cm^3/s and the sample flow stream velocity is about 1.5m/s at the inlet to the instrument. In order to sample aerosol quantitatively, it is necessary to slow the sampled flow from 200m/s in the free stream to 1.5 m/s at the instrument without subjecting the aerosol to loss mechanisms which can not be calculated.

In order to interpret the measurements correctly it is necessary to account for the effects of heating on the aerosol. Compressive heating resulting from the deceleration of the flow increases the sample temperature by approximately 20K. In addition, the sample is heated by conduction by another 50K as it passes through the instrument case into the passive cavity where it is sized. The 20K temperature increase occurs for approximately 0.2s and the 50K increase occurs for approximately 0.01s.

The inlet development occurred under time and resource constraints. We did not have access to a low pressure wind tunnel. Therefore, flow sensors were built into the inlet so that its performance could be monitored in flight. The sensors were calibrated in the lab at the appropriate Reynolds and Mach numbers. The sensors permitted the flows to be measured and the effects of anisokinetic sampling to be calculated. Correction factors were less than two for submicron particles.

The evaporation of particles in the inlet was calculated from theory. The particle composition was assumed to be sulfuric acid in equilibrium with water at ambient temperatures. The effects of evaporation are strongly size dependent.

Additional work needs to be done on this inlet. The inlet is mounted on a wing tank and it is aligned parallel with the wing tank surface and in a plane parallel to the ER-2's water line. The flow around the wing tank is unknown, thus the inlet axis may not be aligned with the local streamlines. Therefore, it is necessary to measure the actual wind vector at the location of the inlet in order to align the inlet correctly. Even with improved alignment, angle of attack can vary in flight. Therefore, the leading edge of the inlet should be shaped to minimize the likelihood of flow separation in the inlet.

PERFORMANCE OF THE INLET

Figure 1 shows the inlet. It consists of a main diffuser, an exit flow meter and an internal sample extractor with a second diffuser. The main diffuser is a sharp edged cone with an included angle of 6.7°. The diameter of the inlet opening is 0.737 cm. Under isokinetic conditions, the flow into the inlet is about 8520 cm^3/s. Less than 20 cm^3/s is extracted from this flow at the internal sample extractor. The rest of the flow exits the exit flow meter. The sample can be biased due to flow mismatch at the entrance to the main diffuser and at the entrance to the internal sample extractor.

The flow mismatch at the main inlet is determined using the exit flow meter, the true air speed, ambient pressure and temperature. The exit flow meter permits the mass flow out of the inlet to be determined. Since the flow to the instrument is small compared to the flow through the inlet, the exit flow is essentially equal to the flow into the main diffuser. The pressure drop across the exit flow meter is constantly monitored in flight. The mass flow out of the flow meter is calculated from this pressure drop, the pressure and temperature in the inlet, and the discharge coefficient of the exit flow meter.

258

The discharge coefficient was determined in laboratory studies. In these studies, the internal flows were maintained at the Reynolds numbers and Mach numbers encountered in flight. The discharge coefficient is a function of Reynolds number and varies from 0.71 to 0.81. These measurements were made with the main diffuser in place so that the flow profile would approximate that encountered in flight.

The flow determined from the exit flow meter was compared to the mass flow through an area equal to the inlet opening in the free stream. The ratio of these mass flows is shown in Figure 2 as a function of Ambient Pressure and is shown in Figure 3 as a function of aircraft Mach number. The flow into the inlet is less than isokinetic, but the mismatch is less than 25% over a wide range of pressures and Mach numbers. This flow mismatch leads to an enhancement of particle concentration and this enhancement is discussed below. It seems likely that the mismatch can be reduced by enlarging the exit diameter of the exit flow meter.

The flow mismatch at the internal sample extractor is determined from the measured mass flows leaving the PCAS and the estimated center line velocities in the inlet. The flow profile was measured in the laboratory over a range of Reynolds numbers at low pressure and found to be approximately 1.5 times the mean velocity. This flow profile was also measured in flight on the NCAR Sabreliner. The center line velocity can be estimated from the exit flow meter measurements and the flow profile. The flow velocity in the internal sample extractor was found to be a factor of two less than the velocity in the inlet on the center stream line. Design changes should also permit this mismatch to be reduced.

The effect of these mismatches on sampling efficiency is shown in Figure 4. The results of Belyaev and Levin (1974) were adapted to compressible flow and used in these calculations. Sampling efficiency is plotted as a function of particle size for typical operating conditions. In practice, corrections of this type were calculated from the measured conditions for each size distribution and the corrections were applied to the data.

The effect of evaporation on particles was also estimated. The particles are assumed to be super cooled sulfuric acid and water droplets in equilibrium with the ambient relative humidity. The results of Steele and Hamill (1981) permit the composition of the particles and vapor pressure of the water vapor to be determined. Heat and mass transfer calculations permit the evolution of the particle properties to be tracked during transport to the laser. Figure 5 shows the results of such calculations for a relatively dry case (5a) and a relatively wet case (5b).

It has not been possible to verify the predictions of particle sampling efficiency with direct measurements in wind tunnels. It has been assumed that well behaved flow in the diffuser implies reasonable particle trajectories. There is no literature on particle deposition in diffusers. Therefore, the particle loss in the diffusers has been estimated to be negligible based on rules of thumb for particle motion. If these estimates are wrong, then the design is flawed.

CONCLUSIONS

It seems possible to build a passive aerosol inlet which minimizes anisokinetic sampling over a wide range of pressures and Mach numbers. Such an inlet can be designed and built using internal flow studies and flow monitoring transducers.

The inlet described here can be improved based on the housekeeping data acquired in flight. Additional improvements would include determining the actual wind vector at the location of the inlet on the aircraft so that alignment could be verified. In addition, transducers permitting the center line flow velocity to be monitored and permitting separation to be studied would be helpful.

Flow separation at the sharp edged inlet may have occurred and not been detected. The inlet edge contour can be changed to reduce the probability of this occurring. And flow can be monitored in such a way as to provide assurances that flow is not separating.
Studies are needed to determine if unexpected particle losses are occurring in the diffuser. If particle transport through diffusers of this type were generally understood, then it is likely that inlet performance could be monitored by monitoring flow in flight.

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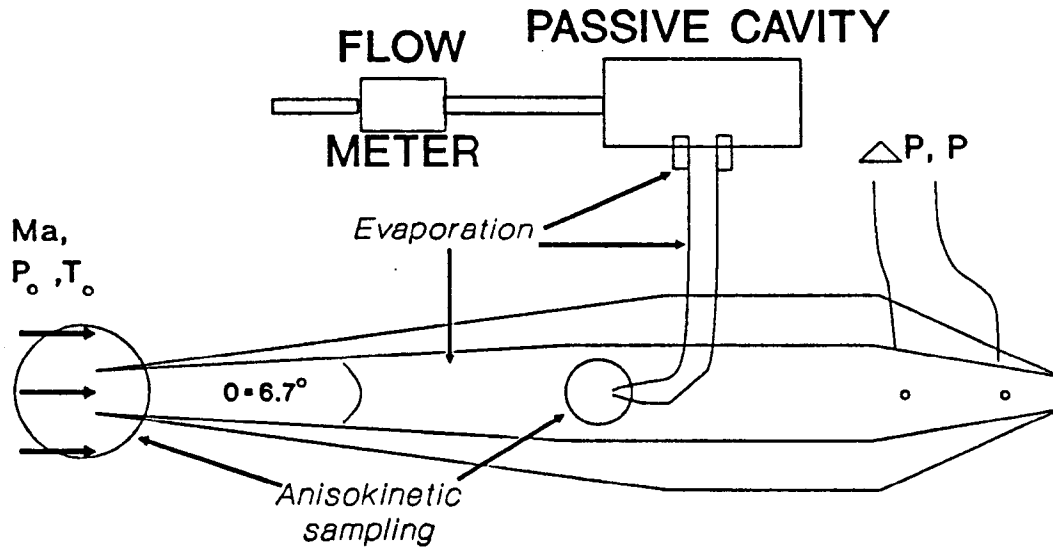
[Figure 1]--Diagram of the PCAS inlet on the ER-2. The inlet to the main diffuser is on the left. The exit flow meter is on the right. The sample extractor is in the center.
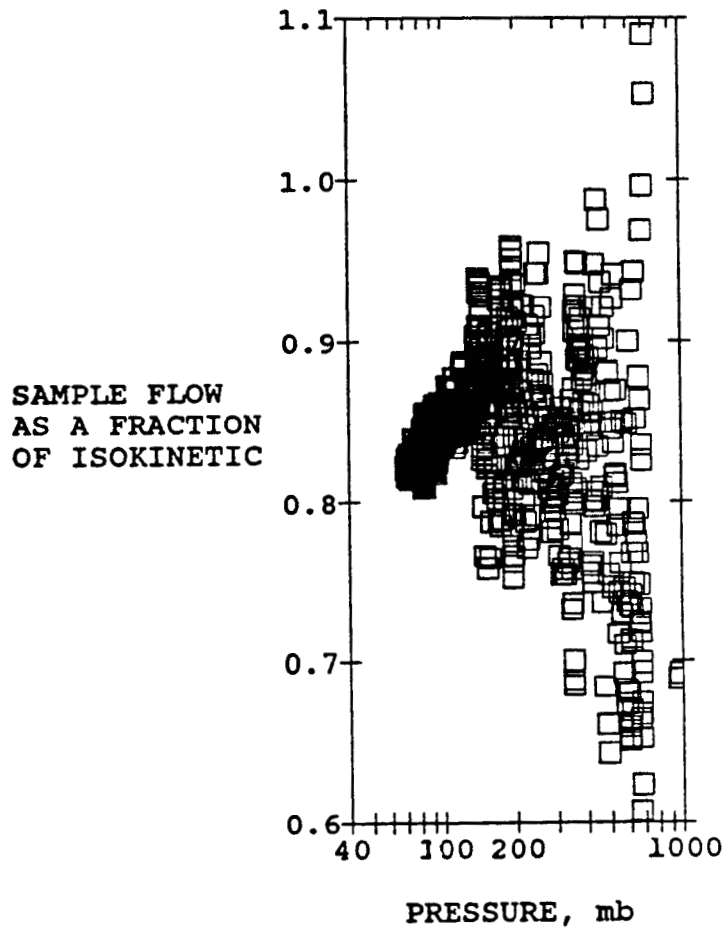
[Figure 2]--Ratio of mass flow into the main diffuser to the mass flow through an equal area in the free stream. Two flights.

262
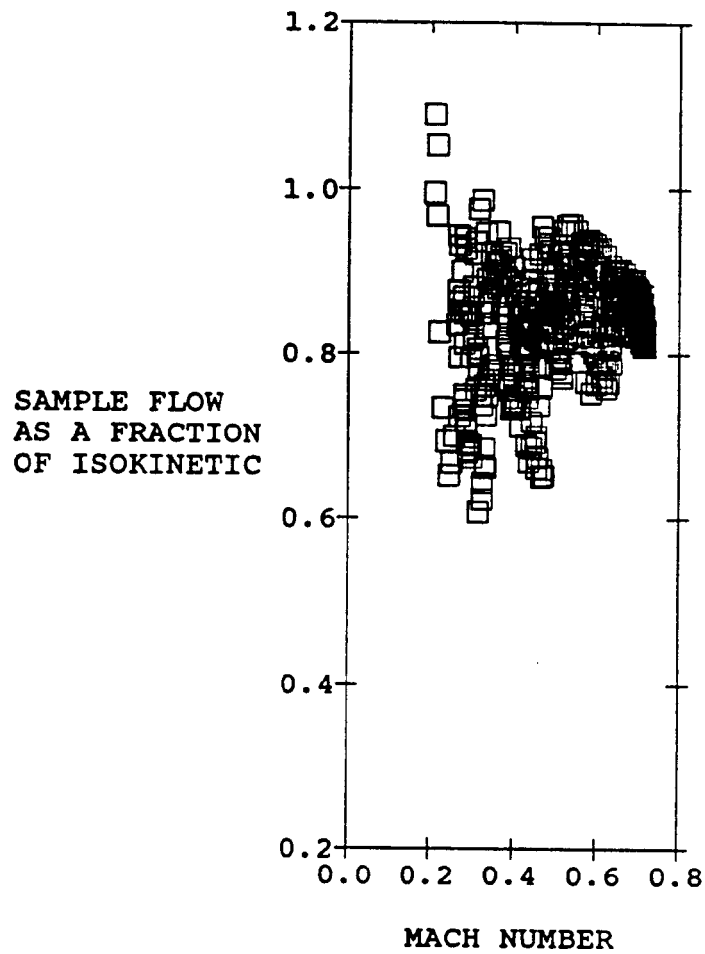
[Figure 3]--Ratio of mass flow into the main diffuser to the mass flow through an equal area in the free stream. Two flights.
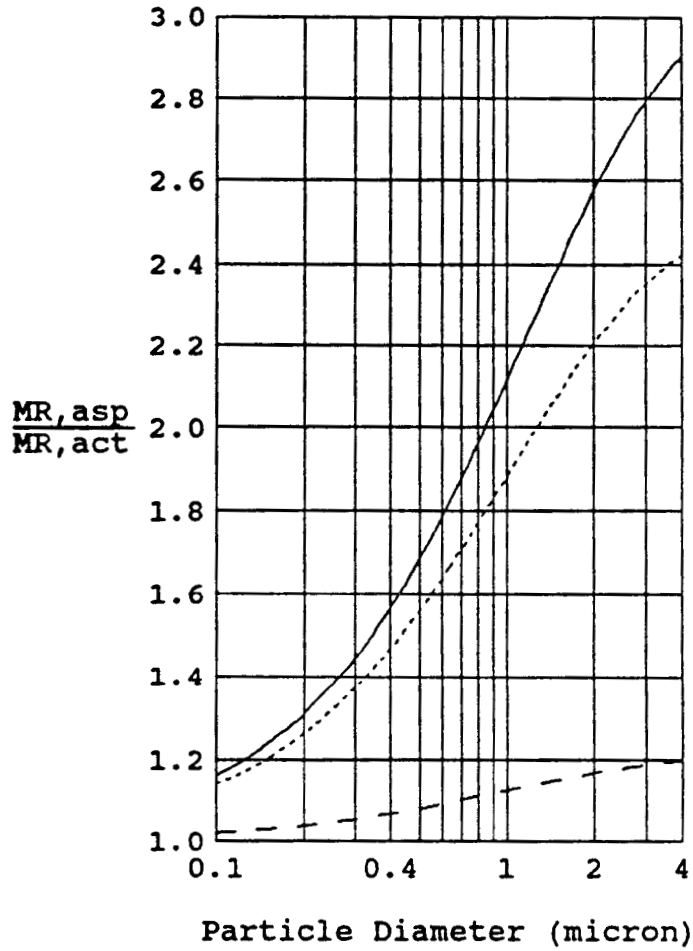
[**Figure 4**]--Dashed line is enhancement at the main diffuser entrance. Dotted line is enhancement at inner diffuser entrance. Solid line is the net enhancement. Most of the enhancement is due to the velocity mismatch at the inner sample extractor.

264
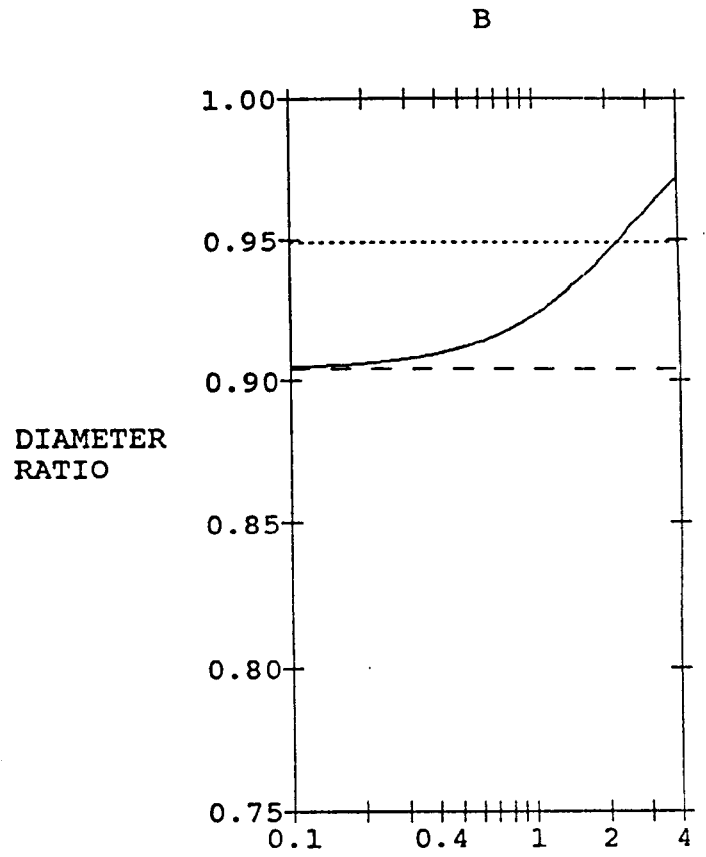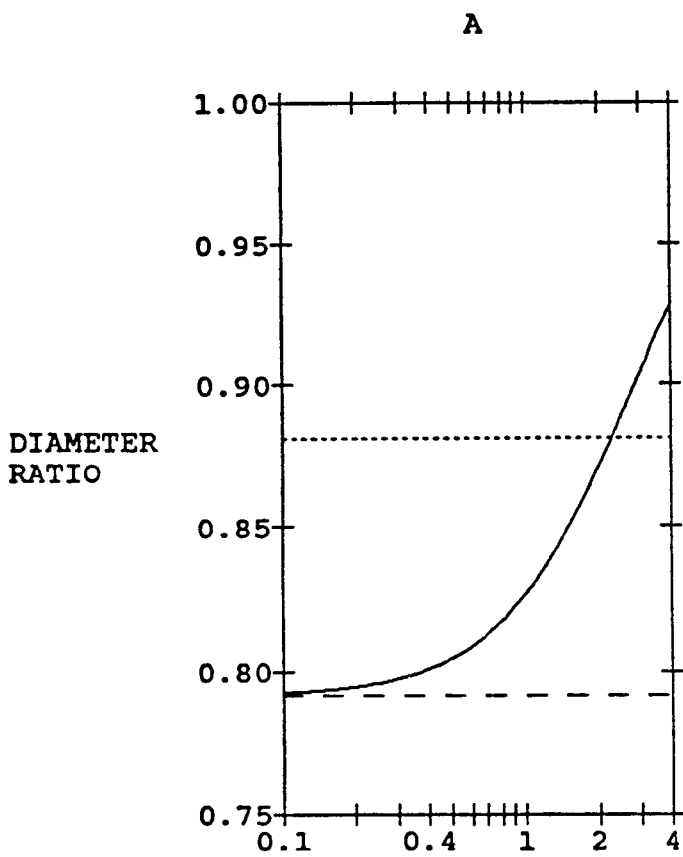
[Figure 5]--Diameter at laser, microns.

_____ Ratio of diameter at laser to ambient diameter
..... Equilibrium ratio at RAM temperature
---- Equilibrium ratio at cavity temperature

DISCUSSION

Radke: Do you intend to remount the exhaust of your decelerator to make it work right or will you live with the handicap

Wilson: We don't intend to live with this handicap; we intend to create whole new handicaps. What we would like to do is round the front edge. We would like to discipline our diffuser. We would like to make the match on the inside. We would like to learn whether or not shrouds could perhaps do some of the diffusing for us. This is not set in concrete.

Georgi: Why can't you go outside the cavity and avoid this 90 degrees?

Wilson: There are plumbing arrangements that would allow us to avoid the 90 degrees. We have diffused that slowly enough to where we can make it for our 1 to 2 micron particles. We're not permitted to place on the airplane that would allow us to avoid the 90 degree.

Brock: How do you make your hot wire measurements? Were they inflight or in a wind tunnel?

Wilson: They were in both.

Using Simultaneous Radon Gas and Radon Daughter Measurements to Evaluate Sub-Micron Aerosol Sampling Efficiencies of Airborne Sampling Systems

By

Mark A. Kritz

Mark A. Kritz is a staff scientist at the Atmospheric Sciences Research Center, State University of New York at Albany, with a Bachelor of Science in Mechanical Engineering from Cornell University, and a Doctorate in Geology and Geophysics from Yale. His research activity has been somewhat bipolar, with the stratosphere as one pole (his thesis was on the origin and mechanism of formation of the background stratospheric aerosol layer, and has been a PI in several aerosol sampling experiments flown on NASA U-2 and ER-2 high altitude research aircraft), and the marine boundary layer as the other (he has been a participant or a PI in several shipboard and airborne experiments studying the halogen and sulfur chemistry of the marine atmosphere.). In recent years, his interests have expanded to include the atmospheric geochemistry of natural radionuclides (e.g., radon, pb-210, and Be-7), and in particular their use as tracers in airborne atmospheric science experiments, and as indicators of large-scale dynamics in mesoscale and global modeling studies. As most of the radionuclides of interest in our work are attached to aerosols, and essentially all of our research projects are conducted from aircraft, this has necessitated a continuing involvement with the development, evaluation, and use of airborne aerosol sampling systems.

Radon (Rn-222) enters the atmosphere from the crust, where it is produced by the decay of trace quantities of its parent, Ra-226. As radon is a noble gas, and is relatively insoluble in water, its only significant atmospheric sink is in its own radioactive decay, which occurs with a half-life of 3.8 days. For these reasons, radon is an excellent tracer of the presence of air of recent continental origin over the oceans, and has been used for this purpose in a wide range of atmospheric science experiments by ourselves and others (e.g., Prospero and Carlson, 1970; Wilkness, et. al., 1973; Kritz and Rancher, 1980).

The decay of radon leads to the formation of a series of short-lived daughter products, as shown in the abbreviated radon decay chain in Figure 1. Unlike radon, which is a noble gas, all of the radon daughters are metals, which in the atmosphere are quickly and irreversibly scavenged by sub-micron sized particles of the ambient atmospheric aerosol. Because the lifetimes of these daughters are short relative to that of radon and of the particles to which they are attached, these daughters are in secular equilibrium with their parent and with one another. We, and others, have used this fact to determine atmospheric radon concentrations

by capturing the short lived daughters (together with the aerosols to which they are attached) on filters, and measuring the resultant (radio)activity (e.g., Larson, et. al., 1972; Andreae, et. al., 1988; Kritz, et. al., 1990)

In practice, application of this technique (known as the active daughter technique) to make radon measurements from an aircraft requires a filter sampling system and an on-board counting system to determine, in flight, the activity of the short-lived radon daughters collected on the filter. Figure 2 plots this activity as a function of time for a representative filter collection. The left hand, rising portion of the curve represents the increasing activity on the filter during sampling, taken to be 10 minutes in this example. Following collection, the filter is placed adjacent to the radiation detector, and the alpha (or beta) activity of the collected radionuclides determined. The right hand, falling portion of the curve in Figure 2 represents the decreasing alpha activity on the filter during counting. The numbers in parentheses are representative of the nominal number of net counts registered by the detector for four successive ten minute counting periods, for a ten minute sampling period, and a sampling flowrate of 0.75 m^3(STP)/min, and an ambient radon concentration of 20 pCi/m^3 (STP). (This value is representative of radon concentrations in lower mid-continental troposphere, or just off the east coast of North America; c.f. Liu, et. al., 1987).

The number of net counts recorded in any counting period is related to the ambient radon concentration by Equation 1, shown in Figure 3. Here [Rn] is the radon concentration in pico-Curies per STP cubic meter, K is a unit-matching constant, Ct is the net number of counts registered during the counting period (total less background), ϕ the sampling flowrate, υ the overall system efficiency, and f(Ts, Td, Tc) follow the methods developed by Evans (1955), Polian (1984) and others.

The overall efficiency, υ, is the product of the several terms, each representing the efficiency of portion of the measurement system or of the sampling process. For purposes of the present discussion, these terms (listed in equation 2 of Figure 3) would comprise a sampling system efficiency υ_s, (which is of primary interest here); and several internal efficiency terms; a filter retention efficiency, υ_f; a filter absorption efficiency, υ_a, (accounting for the absorption of alpha particles emitted from radon daughters imbedded deep in the filter matrix); and a detector geometrical efficiency, υ_g, (accounting for the fact that some alpha particles emitted from daughters captured by the filter will not be directed towards the detector surface); and an air path absorption factor, υ_p, accounting for the loss of alpha particle energy due to collisions with gas molecules in the gap between the filter and the detector.

Thus, the application of the approach requires that the above system parameters (i.e., υ_* in equation 2) be known and invariant within acceptable limits during a given flight or sampling run. In addition, the approach requires that the ambient radon concentration and the sampling flowrate be constant during the sampling period, that the daughters be in

equilibrium with their parent, that the background count rate of the detector be small compared to the count rate resulting from the activity of the radon daughters on the filter, and that the corresponding radon gas measurement can be accurate.

While this list may appear daunting, similar lists of requirements and assumptions underlie essentially all aerosol measurement and analytical chemical procedures. In point of fact, experience has shown that all of these factors can be accurately determined, and that those subject to variation can be monitored. For example, the variance of the ambient radon concentration during the filter sampling period can be tested by collecting two successive gas samples during the filter sampling period; any disequilibrium between radon and its daughters will be result in a departure of the rate of decay of the daughters in successive counting periods from that predicted by Equation 1 (see Figure 2); we have developed anti-coincidence techniques to identify and discard spurious counts, and to monitor net background count rates; and so forth.

The radon gas measurement would be made in a ground laboratory following each flight, on pressurized whole air grab samples collected at the same time as the aerosol filter samples. The aircraft sampling system consists of an inlet, compressor, pressure monitoring sensors and relief valves, and a suitable number of steel sample bottles. The bottles in our system have a volume of 2.5 liters and a DOT rating of 1800 psig, and when fully pressurized hold approximately 300 STP liters of ambient air. The nominal bottle fill time at altitude is less than two minutes, though this time can be increased to coincide with the filter sampling times. The number of sample bottles carried depends the space and weight available, and is usually between 16 and 32.

After a flight, the filled sample bottles are removed from the aircraft and brought to a laboratory, where the radon they contain is stripped out by cold trapping on charcoal, and transferred to individual counting cells. The design of our trapping/transfer system and the counting system follows closely those developed at the Lamont-Doherty Geological Observatory for use in the GEOSECS program (c.f. Broecker, 1965; Broecker and Peng, 1971). We routinely intercalibrate with other laboratories by exchanging standards and samples; internal quality control is effected by taking duplicate samples, running blanks, operating traps in series, and so forth.

For ambient radon concentration of 20 pCi/m^3 (STP) (the value used in compiling Figure 2), approximately 4,000 counts would be registered during our standard three hour counting period, resulting in a 2 sigma counting uncertainty for the gas phase measurement approximately 3.2 percent. For the active daughter, this same radon concentration would result in approximately 745 counts being registered during the four 10-minute counting periods (see Figure 2), resulting in a 2 sigma counting uncertainly of approximately 7.3 percent. In practice the effect of background counts and other random factors (as opposed to systematic errors, which would cancel) would increase these uncertainties somewhat, to about 5 percent for the gas phase measurement, and to about 10 percent for the active daughter measurement.

To evaluate aerosol sampling efficiencies on aircraft, simultaneous collections of filter and whole air gas samples would be made for various aerosol sampling systems, system operating parameters (e.g., sampling flowrate), and flight conditions (e.g., angle of attack). The ambient radon concentrations derived from the gas samples will be used to compute the resultant ambient daughter concentrations, which in turn will be compared with the quantity of daughter products actually captured on the filter. If the other efficiencies are known, then Equation 3 can be solved to obtain a quantitative evaluation of the sampling system efficiency, v_s.

While the approach described here can be used in laboratory, wind tunnel, and aircraft studies, its principal advantage will be on aircraft, as an alternative to determining internal aerosol losses by washing out the system ducting after each test run. The radon daughter approach will allow a substantial number of test runs per flight to be made on a given sampling system; for example, at various airspeeds, trim conditions and/or degrees of departure from isokinetic flow. The principal disadvantage of the method is that it is limited to sub-micron sized aerosols, which in general are less susceptible to losses and sampling artifacts than are the larger particles. However the increasing need to sample sub-micron sized particles aboard high-speed aircraft makes it important to verify performance in this size range as well.

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271

$$\xrightarrow{\hspace{1cm}} {}^{222}\text{Rn} \xrightarrow{\alpha} {}^{218}\text{Po} \xrightarrow{\alpha} {}^{214}\text{Pb} \xrightarrow{\beta} {}^{214}\text{Bi} \xrightarrow{\beta} {}^{214}\text{Po} \xrightarrow{\alpha} {}^{210}\text{Pb} \xrightarrow{\hspace{0.5cm}}$$

| 3.8d | 3.0m | 27m | 19.7m | <1s | 22y |
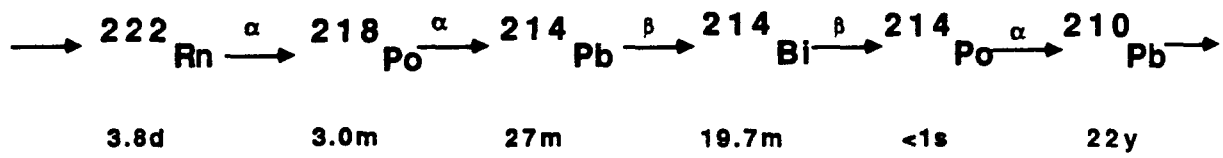
[Figure 1]--Abbreviated radon decay chain, shows the short-lived daughters.
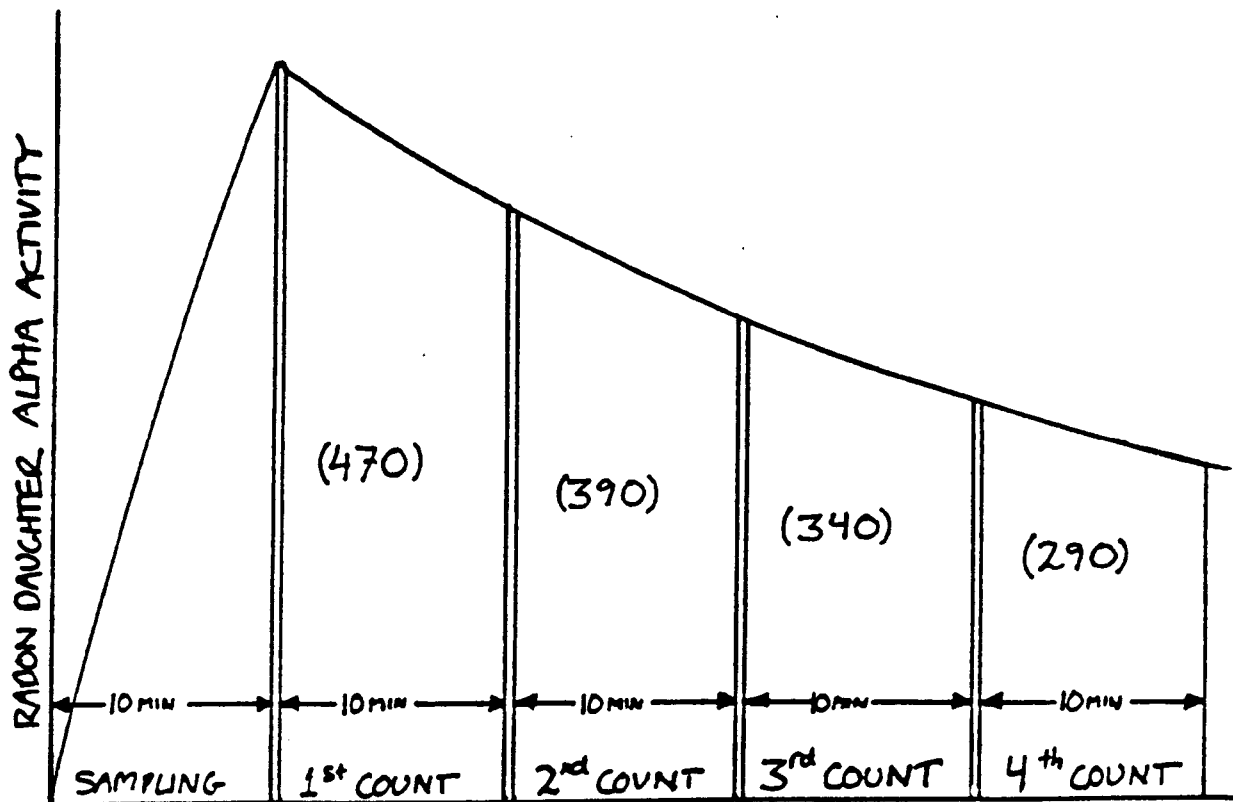
[Figure 2]--Representative plot of radon daughter alpha activity on sample filter versus time. A 10 minute sampling period and four 10 minute counting periods are shown. Also shown are representative numbers of net counts recorded during each counting period, for a system flowrate of $0.75m^3$ (SCM)/min and an ambient radon concentration of 20 pCi/SCM. See text.

$$[R_n] \;=\; K \; C_t \; f \, (t_s, \, t_d, \, t_c) \, / \, \phi \, \eta \qquad\qquad (1)$$

$$\eta \;=\; \eta_s \, \eta_f \, \eta_a \, \eta_g \, \eta_p = \eta_s \, \eta* \qquad\qquad (2)$$

$$\eta_s \;=\; K \; C_t \; f \, (t_s, \, t_d, \, t_c) \, / \, \phi \; [Rn] \; \eta* \qquad (3)$$

[Figure 3]--Equations for radon concentration and sampling system efficiency. See text.

DISCUSSION

Radke: Why do we believe radon measurement is absolute?

Kritz: That's true. Naturally, there are uncertainties there as well. But the gas measurement can be done pretty well. In the area that we are going to be doing this work, it is not the remote marine atmosphere where the concentrations are very low, we are going to be over the continents or downstream of the continents where the concentrations are high.

Radke: We're not worried about the radon participating on sticking on the ducts sticking in your whole air sample can?

Kritz: Radon is a noble gas, like helium, and is absolutely bullet-proof.

Radke: Well helium isn't bullet-proof.

Kritz: Well yes, strictly speaking, you're right. Bullet-proof is probably too strong a word.   What I mean to say is that the gas phase radon measurement technique we would use is straightforward, well-established and reproducible. It was developed at Lamont (the Lamont-Doherty Geological Observatory of Columbia University) in the 60's for the GEOSECS program and has stood the test of time. You do have to work carefully, as you do with any other analytical technique, but if there are any glitches, by bet would be that they are second order.

Daum: Some of the most careful chemistry and chemical procedures that have ever been developed have been developed to analyze things like this. This is something that is really well-established.

Ram: You use radon to distinguish between continental stuff and ocean stuff, but you may have radon coming from the continent but no sulfate, not much. You can't tell what is the proportion of the ocean sulfate. You have a method?

Kritz: I can refer you to our manuscript. There is a lot of discussion to be made about the use of radon as a tracer and radionuclides in general, but that isn't why I was asked to come here today.

Ram: I am asking you a question. How is it done? Separation?

275

Kritz: In the interest of time, Michael, I really don't want to get involved into the geochemistry of radon, because we are talking about aerosol ducts. We can discuss this at break.

Sheridan: What kind of flow rates do you get from that?

Kritz: We're talking about .75 standard m^3/min.

Proposed Development and Testing of Insoluble Particle Collectors

By

Michael Ram

Michael Ram is currently associate professor of physics at the State University of New York at Buffalo. He received his BSc and MSc in physics from the Technion, Haifa, Israel, and his PhD in physics from Columbia University. At present, Dr. Rams primary interests are insoluble atmospheric aerosols and paleoclimates. He is a principal investigator in Gisp 2 (Greenland Ice Sheet Project 2).

It is generally assumed that, since the large polar ice sheets of Greenland and Antarctica are remote, high altitude locations where ice experiences little melting, dust found in ice cores retrieved from the ice sheets reflects past insoluble atmospheric dust levels and size distributions going back more than 200,000 years BP.

We[1,2] have measured the size distribution of insoluble particles retrieved from polar ice cores by filtration of ice meltwater through 0.08 μm pore diameter Nuclepore filters. Our size distributions cover the radius range 0.05 - 1.31 μm which is the range of greatest interest with regard to the effect of atmospheric aerosols on incoming solar radiation. To give a simple indication of size distribution, we divided the measured radius range into three subranges: "small" (0.05 - 0.13 μm), "medium" (0.13 - 0.38 μm), and "large" (0.38 - 1.31 μm). Our measured size distributions were characterized by the percentage of particles in each of the subranges. We wish to point out that the decision to break up the distributions into these three size ranges was made during the analysis period, after the data had already been taken. Consequently, because of our choice of measured radii, it was only possible to get approximately equal radii ratios for the limits of the three intervals. One of the most interesting features of our measurements is that they reveal the size distribution of the insoluble background aerosol and that this size distribution does not seem to change with time.

Another important feature of dust in polar ice is that it's concentration exhibits seasonal variations with large concentration peaks in the spring[3]. Since it is well known that severe dust storms occur in the Asian deserts, the Sahara and the southwestern United States in the spring, it is not surprising that dust found in polar ice should show such prominent spring concentration peaks.

Even though it is of great importance for paleoclimate reconstruction, the assumption that dust in polar ice is representative of dust in the atmosphere at the time of the snow deposition has never been directly demonstrated. In an effort to compare the dust in the atmosphere over the central Pacific with dust found in Greenland ice, I proposed to NSF

to carry out size distribution measurements of dust over the central Pacific during the dusty spring periods. For a clear-cut and unambiguous comparison of Greenland and Pacific results, it is essential that dust measurements in the atmosphere mimic as much as possible those carried out in the ice (particle size distribution measurements have been carried out[4] at a central Pacific location but they also included water soluble particles which are not present in filtered polar ice meltwater. Also, the sizing technique used in these measurements is very different from the one used for dust in polar ice). Thus, I proposed to collect atmospheric dust particles on the same 0.08 μm pore diameter Nuclepore filters that were used to filter the polar ice meltwater. Since the concentration of dust in the mid and upper troposphere is low, I proposed to collect the particles on large, 90 mm diameter filters and redeposit them on similar, but smaller, 13 mm diameter filters after submerging the particles in a very mild Tween 80 solution to lift them off the filter surface. This would achieve two important objectives:

(i) Discard all water-soluble material so that only insoluble particles are sampled.

(ii) Give us a concentration factor of approximately 50.

I have proposed to build an insoluble particle collector with the highest possible efficiency. Since particles sticking to the inside walls of the collector will be redeposited on the filter when the latter is submerged, I am not concerned with particles hitting and sticking to the inside wall of the probe. I am, however, concerned that the design of the probe be such that particles enter the probe without any size bias. I believe I can achieve this if the airflow into the probe is undistorted (laminar) so that all particles, irrespective of size, follow the wind stream as they enter the probe. To attain this goal, I have proposed to

(a) Use a shrouded probe[5] similar to the one shown very schematically in Figure 1. Note that the figure is not drawn to scale and that details of the filter support are not indicated. One of the advantages of the shrouded probe is that it is not sensitive to changes in angle of attack[5]. I also feel that, to a certain extent, the shroud will isolate the probe from outside disturbances. Another advantage of the shrouded probe is that it slows the air entering the probe[5] so that one can use an inlet with a larger opening (3.0 cm diameter would be perfectly reasonable). Note that the inlet to the diffuser incorporates a straight section which will reduce the bluntness of the probe entrance and help in achieving laminar flow into the probe. We also do not show the special cover that will be used to seal the probe when not sampling. Preferably, we would like to install this device so that it seals the shroud entrance and does not in any way interfere with the flow of air into the probe during sampling. A. McFarland has informed us, however, that he used a sealing mechanism that could close the probe inlet directly without interfering significantly with the airflow.

(b) As mentioned above, the design of the shrouded probe will be such that airflow into the probe inlet is laminar and as parallel to the probe axis as possible. The necessary

278

dimensions, pumping rates and shroud exhaust will be determined by air flow simulation studies that will be carried out in collaboration with Dale Taulbee of our mechanical and aerospace engineering department. Such simulation studies are the most effective and economical means of determining the proper parameters for the probe.

(c) Once the proper probe design is determined, it will be built at NCAR with the assistance of Jack Fox. The use of the NCAR shop facilities is made possible by my collaboration with Gregory Kok of NCAR (RAF). To achieve the smoothest possible probe surfaces (inside and outside), the probe will be built using electroforming techniques[6].

(d) The airflow into the probe will be tested at the Calspan wind tunnel facility in Buffalo prior to mounting on the aircraft. These wind tunnel tests will also determine how sensitive the device is to changes in angle of attack. We will have two pairs of pressure ports on the perimeter of the shroud entrance connected to a series of pressure transducers. Under computer control, this will allow us to properly align the system into the streamlines at all altitudes and aircraft speeds. If, however, the air tunnel measurements show that the probe is very insensitive to the kind of variations in angle of attack that might be encountered in flight, we could decide to dispense with the servo mechanism.

Airborne testing of the shrouded probe will be carried out in King Air flights at Mount Lemon, Arizona, (9,300 ft asl). A platform will be built there housing a similar shrouded probe for simultaneous ground based aerosol measurements. This will allow us to compare the extent to which airborne particle recovery is representative of particles collected on stationary, high elevation platforms.

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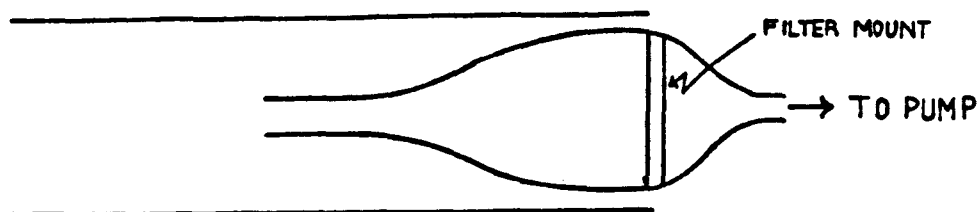
[Figure 1]

DISCUSSION

Sheridan: Your drawing isn't very clear, but it doesn't look like your inlet would be very accommodating for a probe cap. I think you might want to consider a probe cap.

Ram: We'll have cap. I didn't show you all the details, but we haven't yet come up with the best design for the cap.

Sheridan: It looks like it would be difficult to put it over a shrouded inlet.

Ram: It's not impossible to put it in there, but it sort of violates my feeling for aerodynamic smoothness. Another possibility would be to cap the shroud, which presents some technical difficulties, but I don't think they're insurmountable. I think its pretty feasible, and I'm not worried about the details yet.

Vincent: In your Greenland Ice experiments and in the proposed new one, you do quite a lot of fairly aggressive processing of the deposited aerosol. In doing that, are you in any danger of changing the size distribution? For example, the particles are either delicate or in the form of aggregates.

Ram: When I do it in the ice, it is very gentle because I use plain water. It doesn't do much. When I look at the particles through the ice particle analyzer, they seem to be pretty integral particles. There are no aggregates. I have never seen an aggregate in all my measurements, and I'm the person who has been doing this analysis. You're measuring from an ice particle analyzer, and it is very difficult to describe to someone else exactly.

Vincent: When you look at the particles in the microscope, what is your definition of size for non-circular or spherical?

Ram: We have seen some spherical, but they're very rare. Most of them have odd shapes. The criteria for particle size is that you take a particle and you match its area to the area of a round spot of light.

Radke: One thing that I found in airborne sampling of large particles in polar regions is that the particles are remarkable in that they are largely 2 dimensional particles. They have been assorted for non-sphericity. You find plates. You find flat structured particles, so the equivalent diameter is not achieved by rotating the way they would sit on a filter or an impactor.

Ram: Well, we've looked at a lot of particles, and we've tried to shadow some of them to see what is the dimension. I wouldn't say that a majority of the particles are flat.

Radke: I think that Pat Sheridan and I would agree that over in the Polar regions, today, the large particles are flat particles.

Ram: Why would the particles over the Polar regions be flat? Is it a matter of altitude?

Sheridan: That's where we sampled.

Radke: Why are they flat?

Ram: If it's a question of transport, that it is easier to transport large particles over long distances.

Radke: It is easier to transport large, flat particles.

Ram: That's a possibility; however, when we end up doing our measurements over the Pacific, these particles will be sampled at altitudes of 7 or 8 km. This is the kind of particle that will reach Greenland. Whatever we're sampling over the Pacific at high altitude is what is likely to be found in Greenland ice. Maybe what you are trying to say is that this is not representative of gentle aerosol. However, what we are ultimately interested in is the aged aerosol, something that has spent a lot of time in the upper troposphere.

Rader: If you are looking for large particles, it seems like in your sampler in the shroud design, the large particles are going to be enhanced in concentration relative to the small ones. Am I just missing the boat on this?

Ram: That's another thing Tony Clarke and I were talking about. We may not necessarily use the same sampler for the large particles. Tony suggested that it might be better to use a virtual impactor for large particles.

Rader: The really large particles are not going to follow the flow stream because of the presence of the shroud, so they're going to go straight through and you essentially have created a virtual impactor. Your present system is going to enhance those particles to be very size dependent.

Ram: No, No. It's true there are other particles that will end up on the filter. I'm not saying that when I do this thing, I collect particles from .1 to 2.6, what I'm saying I will only measure for my size distribution those particles in .1 to 2.6. When we look at the filter, we see particles that are larger and smaller. We have limited ourselves to this size range.

McFarland: I have a comment on the question on some sort of a cover for the actual inlet. In the work that Torgeson did for the sampler for the WD-50, he put an inlet cover and mounted it on the inside of the shroud.

Ram: As I said, I look at this as a technical matter.

Georgi: I have one difficulty. If you are using a nuclepore in this size, how are you going to mount it? With high speed, it will be blown off completely.

Ram: No, No. This is just a schematic. The thing will have a backing.

Aircraft Electrical Charge: An Aerosol Inlet Issue

by

Lawrence F. Radke and James E. Dye

Lawrence F. Radke is currently the Manager of the Research Aviation Facility of the National Center for Atmospheric Research and Affiliate Professor of Atmospheric Sciences at the University of Washington. He received a Bachelor of Science in Physics, Master's and PhD in Atmospheric Sciences from the University of Washington in 1964, 1966, and 1968 respectively. His research interests include cloud and precipitation physics, atmospheric chemistry, and air pollution, with emphasis on airborne instrumentation and the development of specialized instrumentation.

James E. Dye has a joint appointment with the Mesoscale and Microscale Meteorology Division and the Research Aviation Facility of the National Center for Atmospheric Research. His research has been directed toward the better understanding of the physical processes of precipitation formation, cloud electrification, chemical production in cumulus clouds, and the formation of polar stratospheric clouds. He has been active in the evaluation and development of improved airborne particle measurement techniques.

Most airborne scientists are well aware of the large variations which occur in the atmosphere's electric field and of aircraft electrification by collision with cloud elements and hydrometers. These charges are reduced on aircraft by using static discharge wicks on trailing surfaces which provide a comparatively low threshold for corona discharge, but still leave a substantial charge on the aircraft, particularly when the aircraft is flying in cloud or in precipitation. Historically, aerosol scientists have generally assumed that aircraft induced charging effects are small and assert that their work is always done in the "fair weather field," clear of clouds and precipitation and, hence, dismiss the effects of charge and electric fields.

However, it is less well known that aircraft separate charge in the process of propulsion with large variations in efficiency and by mechanisms that are not well understood (Bent and McKinley, 1981). Charge separation is thought to be associated with particulate collisions in engine exhaust (Hallet, personal communication), and inductive feedback enhancements of the ambient electric field (Moore et al, 1989). It is known that considerable variation in charging rates are found between aircraft types and for some aircraft, engine power levels. Generally, older, less efficient engines produce more self-charging.

This charge can lead to electric fields of a few hundred KV per meter at the surface of the aircraft. Thus, we assert that the combination of induction, collision, and exhaust charging

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will always leave the aircraft platform charged with respect to its environment and that on many aircraft this charge might have a potentially large and uncharacterizable effect on aerosol sampling. One would expect knife edge inlets, inlets at the extremities of the aircraft, inlets with large protrusions from the aircraft, and inlets which are not bonded electrically to the aircraft or composites of insulators and conductors to be particularly susceptible to electrically induced aerosol sampling loses. Teflon which is sometimes used as a coating has strong triboelectric characteristics which could create large charge transfer during particle collisions.

Because it is so difficult to characterize the sampling loses due to aircraft charging and because additional research is necessary before we can successfully neutralize charge on an aircraft, we suggest:

1. The charge on an aircraft be monitored. The technology for doing this is well established (Stimmel, et al, 1946, Vonnegut, 1961, and Jones, 1990).

2. At an early time, tests be carried out by charging an aircraft on the ground (electrically insulated) and experimentally observe changes in sampling efficiencies as a function of electrical charge.

3. Kel-F, a dielectric used by most "atmospheric electricians" or other suitable dielectric be utilized instead of teflon, when an inert lining is needed.

The first of these suggestions would provide both quantitative data about aircraft charging rates and charge equilibria as well as a red flag for experimenters who will know they have taken data under anomalous conditions. The second suggestion, while hardly realistic, would provide quickly an order of magnitude assessment of the problem. The third would reduce local triboelectric effects.

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DISCUSSION

Wilson: Would you expect this to be an oscillating phenomena or would you expect things to happen in a way like this on the airplane where we can look at the data for those kinds of oscillations and changes?

Dye: The charge accumulated on the aircraft is governed by two factors. One is the rate of charging which can be a function of power setting and whether the aircraft is in cloud, and the other thing is how fast the charge is bleeding off, usually by engine exhaust.

Georgi: If you have an aircraft on the ground, it should be equally charged. Then you are flying through the air, and there are a lot of particles with nitrate in them and deposited on the surface. If you are then flying through a cloud, you have high humidity and a wet surface. You should be again uniformly charged, but this is not the case?

Dye: In clouds, some of our observations show that charge changes very dramatically because conditions in the cloud are changing. In clear air, conditions are not changing as dramatically so I would expect that, unless you have an aircraft like the Electra where charge changes with power settings and altitude, things would be pretty much the same. The time scale of changes would be slower.

Radke: Incidentally, the engine on a CV-580 and the electra are identical. There are just twice as many on the electra.

Dye: You talked about uniform potential on the aircraft. One of my colleagues as been working with Walter Strapp to put electrical field meters on their CV-580 for a winter experiment. They had their aircraft on the ground and put

high potential on the aircraft to try to check operation before flight, and someone was able to actually draw a spark from the wing of the aircraft. The difference in the potential between the wing and the fuselage electrical bond was 2,000 volts. There are things that go on that we don't always understand.

Seebaugh: The aluminum turns out to corrode rather effectively. As an aircraft gets older, it is going to get more and more susceptible to that problem. You actually loose electrical contact between the panel of the airplane.

Vincent: In clear air, there are well-defined levels of ions. So presumably even in clear air there will be a mechanism for continuous charging. I imagine that an airplane is moving through and picking up this charge, it would accumulate to a level where it would then balance by the amount the charge removed by corona.

Radke: Precisely our point, Jim. We maintain that you will always find the airplane charged. We don't know exactly what the charge will be, but you'll always find it charged.

Vincent: On you point about the charging of aerosols at the tip of the sampler, we observed something like that in our studies of electric charge in work places. Where we have put a charge on the sampler to simulate the charge of somebody walking around a work place and found that there was significant modification of the performance of the sampler which we attributed to discharge from sharp tips around the edge of the sampler to modify the charge on the aerosol.