ABSTRACT

Outdoor measurements of the surface flux density and dry deposition velocity of nanometer-size ($10^{-9}$ m) particles were made in the high desert terrain of central New Mexico, characterized by uncut grass and scattered shrubs, utilizing three independent methods – relaxed eddy accumulation (REA), modified Bowen ratio, and surface collection. The results from the above-the-vegetation-canopy REA and modified Bowen ratio methods were of similar magnitude while those from the below-the-vegetation-canopy surface collection method were significantly smaller. Using unattached-to-aerosol radon progeny [activity median diameter (AMD) of 1.5 nm] as a naturally existing tracer, the magnitude of the average inferred deposition velocity and its standard deviation of the mean for the combined REA and modified Bowen ratio measurements were $9.4 \pm 1.5$ cm s$^{-1}$ at a reference height of 4 m for an average horizontal wind speed of 4.8 m s$^{-1}$, an average vertical temperature gradient of 0.009 °C m$^{-1}$ (near neutral), and an average terrain roughness height of 19 cm. The REA and modified Bowen ratio results showed dry deposition velocity increasing with increasing horizontal wind speed on the order of 1 cm s$^{-1}$ per 1 m s$^{-1}$ increase in wind speed; but, because of data scatter, an exact quantitative relationship could not be established. Combined with previously reported preliminary results, these are the first successful above-canopy measurements of the dry deposition velocity using the REA method and indicate much higher dry deposition velocities than those theoretically predicted by some commonly used models. In contrast,
simultaneously performed surface collection measurements yielded deposition velocities approximately one seventh (0.14) those of the associated REA and modified Bowen ratio measurements. This difference had been anticipated since the REA and modified Bowen ratio methods are above-the-vegetation-canopy techniques, accounting for the effects of the surface roughness and aerodynamic turbulence, which are impossible to simulate with relatively smooth collecting surfaces located at ground level. Notably, approximately the same deposition velocity was obtained with the surface collection method whether the surfaces were oriented horizontally or vertically. The overall results suggest the need for improving existing dry deposition parameterization used in common atmospheric and air pollution models.
MEASUREMENTS OF THE SURFACE FLUX VELOCITY
OF NANOMETER-SIZE PARTICLES
OVER THE HIGH DESERT TERRAIN OF NEW MEXICO

by

Frederick Daniel Yarger

Submitted in Partial Fulfillment
of the Requirements for the

Doctor of Philosophy in Physics
with Dissertation in Atmospheric Physics

New Mexico Institute of Mining and Technology
Department of Physics

Socorro, New Mexico

May, 2003
ACKNOWLEDGEMENTS

I gratefully acknowledge the assistance provided on this project by my advisor, Dr. Steve Schery, New Mexico Institute of Mining and Technology; Dr. Piotr Wariolek, U. S. Department of Energy (DOE), NV; Bruce Nemetz; Dr. Stewart Whittlestone, ANSTO, Australia; Nathaniel Dale; and Dr. Suilou Huang, New Mexico Institute of Mining and Technology. Also, the support provided by Research Experience for Undergraduates (REU) summer students Jason Hartz (1996) and Susan Lenihan (1997) is acknowledged. I want to also thank Dr. Scott Zeman, New Mexico Institute of Mining and Technology, for providing an outside editorial review.

This research was supported in part under U.S. Department of Energy grant DEFG03-94ER6178. The REU summer program was supported by National Science Foundation grant ATM-9508621.
TABLE OF CONTENTS

List of Figures vi.
List of Tables xii.

Part 1 Introduction 1.
   Chapter 1 Importance of Research 2.

Part 2 Background 6.
   Chapter 2.1 Dry Deposition of Aerosol Particles 7.
   Chapter 2.2 Aerosol Particle Detection 20.
   Chapter 2.3 Radon and Radon Progeny 23.

Part 3 Site Descriptions 30.
   Chapter 3.1 Overall Site Locations 31.
   Chapter 3.2 SS Ranch Site Description 33.
   Chapter 3.3 Socorro Municipal Airport Site Description 39.

Part 4 Instrumentation 46.
   Chapter 4.1 Ultrasonic Anemometer 47.
   Chapter 4.2 Relaxed Eddy Accumulation (REA) System 51.
   Chapter 4.3 Interface Relay Control Box 55.
   Chapter 4.4 Alpha Counting System 57.
   Chapter 4.5 Miscellaneous Equipment 59.
Part 8  Combined Results

Chapter 8  Combined Data Results & Discussion

Part 9  Conclusions

Chapter 9  Conclusions

Bibliography

Appendix A  Data Forms

Appendix B  Data Processing Computer Software
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Figure Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1.1.</td>
<td>Particle Dry Deposition Velocity vs Particle Diameter on a Water Surface in a Wind Tunnel (Slinn et al., 1978; adapted from Seinfeld and Pandis, 1998).</td>
<td>9.</td>
</tr>
<tr>
<td>Figure 2.1.2.</td>
<td>Resistance Model for Dry Deposition (adapted from Seinfeld and Pandis, 1998).</td>
<td>11.</td>
</tr>
<tr>
<td>Figure 2.1.3.</td>
<td>Complex Resistance Model for Dry Deposition Showing Multiple Removal Paths (adapted from Wesely and Hicks, 2000).</td>
<td>12.</td>
</tr>
<tr>
<td>Figure 2.1.4.</td>
<td>Experimental Data and Theoretical Predictions for Particle Dry Deposition Velocities [adapted from National Center for Atmospheric Research (NCAR), 1982].</td>
<td>13.</td>
</tr>
<tr>
<td>Figure 2.1.5.</td>
<td>Predicted Dry Deposition Velocities at 1 m (adapted from Sehmel, 1980).</td>
<td>15.</td>
</tr>
<tr>
<td>Figure 2.1.6.</td>
<td>Deposition Velocities of Radon Progeny (adapted from Porstendörfer, 1994).</td>
<td>18.</td>
</tr>
<tr>
<td>Figure 2.2.1.</td>
<td>Particle Diameter Ranges for Common Aerosol Measurement Techniques (adapted from Schery, 2001).</td>
<td>21.</td>
</tr>
<tr>
<td>Figure 2.3.1.</td>
<td>Exhalation of Radon Gas into the Atmosphere (adapted from Porstendörfer, 1994).</td>
<td>24.</td>
</tr>
</tbody>
</table>
Figure 2.3.2. Atmospheric Cycle of Radon Progeny (adapted from Porstendörfer, 1994).

Figure 2.3.3. Size Distribution of Radon Progeny.

Figure 3.1.1. Locations of Sampling Sites.

Figure 3.2.1. SS Ranch Sampling Site Location (elevation contours in feet).

Figure 3.2.2. Three-dimensional Representation of SS Ranch Sampling Site.

Figure 3.2.3. Detailed Layout of SS Ranch Sampling Site.

Figure 3.2.4. 360º Panorama from SS Ranch Sampling Site.

Figure 3.3.1. Socorro Municipal Airport Sampling Site Locations (elevation contours in feet).

Figure 3.3.2. Three-dimensional Representation of Socorro Airport Sampling Sites.

Figure 3.3.3. Detailed Layout of Socorro Municipal Airport Sampling Sites.

Figure 3.3.4. 360º Panorama from Socorro Municipal Airport REA Sampling Site.

Figure 3.3.5. 360º Panorama from Socorro Municipal Airport Modified Bowen Ratio Sampling Site.

Figure 4.1.1. Ultrasonic Anemometer (SAM).

Figure 4.1.2. Close-up View of SAM Transducer Assembly.

Figure 4.1.3. Top View of SAM (adapted from Gill Instruments).

Figure 4.2.1. REA System Setup at SS Ranch.

Figure 4.2.2. Line Drawing of REA System (adapted from Schery et al., 1998).

Figure 4.4.1. Automatic Alpha Counting System.
Figure 4.5.1. Electro-Neutronics Model 2000 Air Sampler – Blower A.

Figure 4.5.2. Electro-Neutronics Model 8000 Air Sampler – Blower B.

Figure 4.5.3. Davis Portable Meteorological Station.

Figure 4.5.4. Datalogger.

Figure 4.5.5. Meteorological Instruments at SS Ranch (2 m, 5 m, and 10 m).

Figure 4.5.6. Meteorological Instruments at Socorro Airport (only instruments located at 8 m, 11.7 m, and 16 m are visible).

Figure 5.3.1. Preparing REA System for Operation at SS Ranch.

Figure 5.5.1. Combined Uncorrected REA Flux Velocity vs Horizontal Wind Speed Sorted by Year/Site Location.

Figure 5.5.2. Final Uncorrected REA Data Set Sorted by Site Location.

Figure 5.5.3. Final Uncorrected REA Data Set Sorted by Obstructed/Unobstructed Sectors.

Figure 5.5.4. Delay Correction Factor (DCF) vs Average Horizontal Wind Speed.

Figure 5.5.5. Delay-Corrected REA Flux Velocity vs Horizontal Wind Speed Sorted by Site Location.

Figure 5.6.1. Absolute Value of Vertical Wind Velocity vs Average Horizontal Wind Speed.

Figure 5.6.2. Vertical Wind Velocity Standard Deviation vs Average Horizontal Wind Speed.

Figure 5.6.3. SS Ranch REA Measurements Sorted by $|\mathbf{w}|$.

Figure 5.6.4. Socorro Airport REA Measurements Sorted by $|\mathbf{w}|$. 
Figure 5.6.5. Delay-Corrected REA Data Having $|w| \leq 3$ cm s$^{-1}$ and Sorted by Site Location.

Figure 5.6.6. Delay-Corrected REA Flux Velocity vs Average Temperature Gradient.

Figure 5.6.7. Delay-Corrected REA Flux Velocity vs Temperature Gradient Change.

Figure 5.6.8. Delay-Corrected REA Data Having $|w| \leq 3$ cm s$^{-1}$ and Sorted by Temperature Gradient Change.

Figure 5.6.9. Best-Fit Linear Curve to SS Ranch REA Data with 95% Mean Confidence Curves.

Figure 5.6.10. Best-Fit Linear Curve to Socorro Airport REA Data with 95% Mean Confidence Curves.

Figure 5.6.11. Best-Fit Polynomial Curve to SS Ranch REA Data.

Figure 5.6.12. 3D Scatter Plot of REA Measurements.

Figure 5.6.13. 3D Surface Plot of REA Measurements.

Figure 6.3.1. Modified Bowen Ratio Sampling Setup at Socorro Airport.

Figure 6.3.2. Blower A Located Upon 2 Meter Platform.

Figure 6.3.3. Placing Blower B Upon 8 Meter Platform.

Figure 6.5.1. Modified Bowen Ratio Flux Velocity Results vs Horizontal Wind Speed.

Figure 6.5.2. Final Modified Bowen Ratio Data Set vs Horizontal Wind Speed.

Figure 6.6.1. Average Vertical Wind Velocity vs Horizontal Wind Speed.
Figure 6.6.2. Vertical Wind Velocity Standard Deviation vs Horizontal Wind Speed.

Figure 6.6.3. Vertical-Wind-Corrected Modified Bowen Ratio Flux Velocity vs Average Temperature Gradient.

Figure 6.6.4. Vertical-Wind-Corrected Modified Bowen Ratio Flux Velocity vs Temperature Gradient Change.

Figure 6.6.5. Vertical-Wind-Corrected Modified Bowen Ratio Data Sorted by Temperature Gradient Change.

Figure 6.6.6. Best-Fit Linear Curve to Corrected Modified Bowen Ratio Data with 95% Mean Confidence Curves.

Figure 7.3.1. Sandpaper Collecting Surface Set Out For Exposure.

Figure 7.5.1. Combined Surface Collection Deposition Velocity Measurements.

Figure 7.5.2. Final Surface Collection Deposition Velocity Measurements Sorted by Site Location.

Figure 7.6.1. Surface Collection Deposition Velocity vs Average Temperature Gradient.

Figure 7.6.2. Surface Collection Deposition Velocity Measurements Sorted by Average Temperature Gradient.

Figure 7.6.3. Best-Fit Linear Curve to Surface Collection Data with 95% Mean Confidence Curves.

Figure 7.7.1. Exposure Arrangement of the Six Collecting Materials.

Figure 7.7.2. Normalized PAESC Results of 8 October 1996.

Figure 7.7.3 Normalized PAESC Results of December 2000.
Figure 8.1. Combined Flux/Deposition Velocity vs Horizontal Wind Speed Plot, Sorted by Method.

Figure 8.2. Combined REA/Modified Bowen Ratio Flux Velocity Measurements vs Horizontal Wind Speed.

Figure 8.3. Vertical Wind Velocity Standard Deviation vs Average Horizontal Wind Speed.

Figure 8.4. Best-Fit Linear Curve to Combined REA and Modified Bowen Ratio Data with 95% Mean Confidence Curves.

Figure 8.5. Surface Collection vs Concurrent REA/Modified Bowen Ratio Measurements.

Figure 8.6. Surface Collection to REA/Modified Bowen Measurement Ratio.
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Table Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.3.1</td>
<td>Radon Progeny Half-Lives and Alpha Energies.</td>
<td>27.</td>
</tr>
<tr>
<td>Table 5.1.1</td>
<td>Typical $\beta$ Values Reported by Katul <em>et al.</em>, 1996.</td>
<td>72.</td>
</tr>
<tr>
<td>Table 5.5.1</td>
<td>Breakdown of REA Flux Velocity Measurements.</td>
<td>97.</td>
</tr>
<tr>
<td>Table 5.5.2</td>
<td>REA Flux Velocity Measurement Error Sources.</td>
<td>98.</td>
</tr>
<tr>
<td>Table 5.6.1</td>
<td>Statistical Comparison of SS Ranch and Socorro Airport REA Flux Velocities.</td>
<td>129.</td>
</tr>
<tr>
<td>Table 6.5.1</td>
<td>Modified Bowen Ratio Flux Velocity Measurement Error Sources.</td>
<td>160.</td>
</tr>
<tr>
<td>Table 7.5.1</td>
<td>Breakdown of Surface Collection Deposition Velocity Measurements.</td>
<td>187.</td>
</tr>
<tr>
<td>Table 8.1</td>
<td>Typical Dry Deposition Velocities of Some Atmospheric Gases Over Land (adapted from Seinfeld and Pandis, 1998).</td>
<td>221.</td>
</tr>
</tbody>
</table>
PART 1

INTRODUCTION
CHAPTER 1

IMPORTANCE OF RESEARCH

The removal of trace gases and particles from the atmosphere is a key element of climate modeling. Wet and dry deposition are important processes by which removal is achieved. Dry deposition can account for a significant portion of the removal, depending on whether a species is present in a gaseous or particulate form, the solubility of the species, the amount of precipitation in a region, the terrain, and the type of vegetation (Seinfeld and Pandis, 1998). For example, it is estimated that 30% of sulfur emissions in the United States and Canada are removed by dry deposition, as are about 40% of NO$_2$-N emissions (Shannon and Sisterson, 1992; Wesely and Hicks, 2000). In arid regions the relative importance of dry deposition increases.

The common parameter used to estimate the rate of dry deposition in most models [e.g., the Acid Deposition and Oxidant Model (ADOM) (Pleim et al., 1984; Padro and Edwards, 1991; Padro, 1996); the Regional Acid Deposition Model (RADM) (Walcik et al., 1986; Chang et al., 1987); the European Centre Hamburg Model (ECHAM) (Ganjeveld and Lelieveld, 1995); the National Center for Atmospheric Research (NCAR) Regional Climate Model (Reg CM) (Giorgi and Mearns, 1999; companion articles in the same journal issue); and the Center for Climate System Research (CCSR), University of Tokyo/National Institute for Environmental Studies (NIES), Atmospheric General
Circulation Model (AGCM) (Numaguti et al., 1995; Takemura et al., 2000)] is deposition velocity, \( v_d \), whose product, along with concentration at a reference height, is the flux density. Wesely and Hicks (2000) noted, referring to the Dutch Aerosol Project conducted from 1991 to 1994, “Experimental evaluation of particle dry deposition models in a natural outdoor setting is difficult and is rarely done with thoroughness like that described by Erisman et al. (1997), Ruijgrok et al. (1997), and companion articles in the same journal issue.” The Dutch Aerosol Project [Erisman et al., 1997; reviewed by Wesely and Hicks (2000)] focused primarily on the deposition of acidifying compounds such as \( \text{NH}_3 \), \( \text{HNO}_2 \), and \( \text{HNO}_3 \) except for one paper that dealt with \( ^{214} \text{Pb} \) (Wyers and Veltkamp, 1997). Wesely and Hicks (2000) concluded, “Development of the parameterization and modeling of the deposition rates of particles has been slowly advancing. Measurements have been informative, but a comprehensive understanding of particle deposition has not been achieved. Innovative methods of measuring particle deposition need to be developed and applied to derive more universal parameterizations of deposition in natural settings outdoors.”

At the Fall 2001 American Geophysical Union (AGU) meeting, most of the work presented focused on \( \text{HNO}_3 \) and \( \text{NO}_x \). Comments made orally to myself at the meeting on our poster presentation (Yarger and Schery, 2001), which discussed preliminary results of the research presented in this dissertation, from researchers working with the Tropospheric Aerosol Program (TAP) (notably, S. Schwartz and B. Gintautas from Brookhaven National Laboratory and G. Shaw from the University of Alaska) highlighted the lack of reliable data on aerosol particles. One of the principal problems has been the discrepancy in reported deposition velocities, particularly between
laboratory measurements and those made outdoors (Wesely et al., 1977; Sehmel, 1980; Nicholson, 1988). Schery and Wasiolek (1993) noted the need for higher deposition velocities (5 to 10 cm s\(^{-1}\)) for nanometer-size particles in the development of their two-particle-size model of radon progeny near the Earth’s surface. Schery and Whittlestone (1995) reported high deposition velocities (mean \(v_d\) equaling 5.2 ± 0.9 cm s\(^{-1}\)) at the Mauna Loa Observatory (MLO) for unattached-to-aerosol radon progeny using a gradient analysis, which were disputed by Nicholson and Garland (1996) who expected values on the order of 1 cm s\(^{-1}\). Schery et al. (1998) reported preliminary results of 5 to 35 cm s\(^{-1}\) for unattached radon progeny in central New Mexico using the REA technique.

There has been little research done over the years involving aerosol particles in the size range presented in this dissertation (1 – 2 nanometers). Though the light scattering and absorption effects from ultrafine (less than 10 nanometers) particles are considered negligible, the fact that they grow into larger particles (accumulation mode) over time and their chemically active components are otherwise retained in the atmosphere for long periods does make their deposition rate important. Furthermore, in some sense, the theory of dry deposition for ultrafine particles is simpler than that for more chemically reactive species such as SO\(_2\) and NO\(_x\). Improved understanding of the dry deposition of ultrafine aerosol particles can isolate certain processes (e.g., aerodynamic resistance) that are important for reactive substances but are difficult to study directly by measurement of their dry deposition.

As a practical matter, uncertainty in the dry deposition of nanometer-size radon progeny has arisen as an important issue in interpreting the vertical distribution of the
radon progeny and their health-related dosimetry (Schery and Wasiolek, 1993; Wasiolek, James, and Yarger, 1996; Lupu and Cuculeanu, 2001).

The difficulty in detecting and making accurate measurements of the deposition velocity of nanometer-size particles probably accounts for the lack of research in this area. The dissertation research presented herein involved the use of a one-of-a-kind REA system capable of measuring the flux densities of nanometer-size particles containing radon progeny (molecular clusters unattached to larger aerosol particles). The results presented should improve the understanding of the dry deposition of nanometer-size particles in the outdoor environment.
PART 2

BACKGROUND
Dry deposition is the process by which gaseous and particulate species are transported from the atmosphere onto surfaces in the absence of precipitation. According to Seinfeld and Pandis (1998), important factors governing the dry deposition of aerosol particles are the level of atmospheric turbulence, the chemical properties of the aerosol, and the nature of the surface itself. In addition, the size, density, and shape of the aerosol particle play a key role. Brownian diffusion, gravitational settling, inertial impaction, and interception are other key elements that determine the rate of dry deposition. As noted in Chapter 1, dry deposition can account for almost half the removal for some species in comparison to wet deposition (the process by which gaseous and particulate species are scavenged from the atmosphere by rain, snow, and cloud and fog droplets).

The formulation generally used for dry deposition assumes that the dry deposition vertical flux density, $F$, is directly proportional to the atmospheric concentration, $C$, at some reference height above the ground,

$$F = -v_a C \quad \text{Eq. 2.1.1},$$

where $F$, the vertical flux density, is the amount of the atmospheric constituent of interest depositing onto or passing through a unit area per unit time [for the research presented
herein, involving radioactive radon decay products, a collective measure of the potential alpha particle decay energy (see discussion in Chapter 2.3) in nJ is used; so the units of $F$ are nJ m$^2$ s$^{-1}$, and $C$, the local concentration, is the amount of the atmospheric constituent of interest per unit volume (nJ m$^{-3}$ for the research presented). The proportionality constant, $v_d$, is referred to as the deposition velocity. $C$ is a function of height, $z$, above the ground; therefore, $v_d$ is also a function of $z$ and must be related to the reference height at which $C$ is specified. By convention, a downward flux density is negative such that $v_d$ is positive for an aerosol particle that is depositing. Thus defined, the dry deposition velocity represents a variety of physical and chemical processes and does not necessarily have a simple interpretation as the actual kinematic velocity of aerosol particles.

Dry deposition, particularly for small particles and under somewhat idealized conditions, consists of three major steps. The first step is the aerodynamic transport of the aerosol particle down through the atmospheric surface layer (on the order of 30 to 50 m) to the very thin (on the order of a few mm), stagnant air layer adjacent to the surface (called the quasi-laminar sublayer); the second step for small particles is the Brownian transport (diffusion) across the quasi-laminar sublayer to the surface; and the third step is attachment to the surface. The transport through the atmospheric surface layer frequently occurs by turbulent diffusion, commonly referred to as eddy diffusion, as a result of relatively large-scale random air motion near the surface of the Earth. Once at the quasi-laminar sublayer, small aerosol particles will cross the layer due to Brownian diffusion. If the particle is sufficiently large, gravitational settling may also contribute to the dry deposition. Figure 2.1.1 shows an example plot of deposition velocity versus
particle diameter for the simplified situation of a water surface in a wind tunnel. The curve reaches a minimum at a particle diameter of approximately 0.25 µm (250 nm). For particles larger than 0.25 µm, gravitational settling is generally an important factor in the dry deposition. For particles smaller than 0.25 µm, Brownian diffusion across the sublayer becomes progressively more important as a limiting factor.

Figure 2.1.1. Particle Dry Deposition Velocity vs Particle Diameter on a Water Surface in a Wind Tunnel (Slinn et al., 1978; adapted from Seinfeld and Pandis, 1998).
In Figure 2.1.1, the dashed curve shown for the deposition velocity of particles less than approximately 0.03 µm (30 nm) in diameter is predicted based on diffusion coefficients instead of empirical data. For particles 0.05 to 1 µm in diameter (what is commonly referred to as the accumulation mode), both Brownian diffusion through the quasi-laminar sublayer and gravitational settling are relatively ineffective for transport. Thus, aerosol particles in this size range can have atmospheric lifetimes on the order of days to weeks (Slinn et al., 1978; Prospero et al., 1983) until most likely scavenged by wet deposition.

Once at the surface, the attachment (or uptake) rate of the aerosol particle to the surface becomes important. For nanometer-size particles, the attachment rate is generally considered to be 100% (i.e., all the particles will attach to and remain on the surface if they reach it). This assumes that the nanometer-size particles are truly solids, approaching the surface with minimal kinetic energy (i.e., by Brownian diffusion), such that the interfacial energy (and, thus, the force of adherence) exceeds the force of repulsion (Fuchs, 1964). This was experimentally shown to be valid for unattached radon progeny by Porstendörfer and Mercer (1978). Though Porstendörfer and Mercer’s paper only presented results for particle sizes ranging from 9 nm up to 4 µm, it has since been shown using screen-type diffusion batteries that the size range of the unattached radon progeny (true solid particles) is between 1 – 2 nm (Reineking and Porstendörfer, 1986; Wasiolek, James, and Yarger, 1996). This is similar to highly reactive gases such as HNO₃.

The dry deposition process has been analogized in terms of a simplified model of electrical resistance, in which three “resistances” in series govern the transport process.
The total resistance, $r_t$, is the sum of the three resistances and is related to the deposition velocity as

$$v_d^{-1} = r_t = r_a + r_b + r_c \quad \text{Eq. 2.1.2.}$$

where $r_a$ is the aerodynamic resistance, $r_b$ is the quasi-laminar layer resistance, and $r_c$ is the surface resistance. As noted, for nanometer-size particles, the attachment rate is 100%, making the surface resistance, $r_c$, equal to zero ($r_c = 0$). The aerodynamic and quasi-laminar layer resistances are fundamentally dependent on horizontal wind speed, $u$. Based on this dependence, it is logical to correlate deposition velocity to horizontal wind speed. Figure 2.1.2 shows a basic resistance model for dry deposition.

![Species Concentration in Air](image)

**Figure 2.1.2.** Resistance Model for Dry Deposition (adapted from Seinfeld and Pandis, 1998).
Each of these resistances can be further subdivided, addressing the complexities of the atmospheric constituent of interest and the type of terrain and vegetation. Figure 2.1.3 is an example of a more complicated dry deposition resistance model for particulates and gases. Notably, even this more complicated model does not include corrections for plant canopy surface area and leaf area index (LAI), issues which proved relevant to the research presented. There are still many “unknowns” in terms of modeling the dry deposition of aerosol particles.

Figure 2.1.3. Complex Resistance Model for Dry Deposition Showing Multiple Removal Paths (adapted from Wesely and Hicks, 2000).
The goal of my research project was to measure the vertical flux density, $F$, and deposition velocity, $v_d$, of aerosol particles having diameters of approximately 1.5 nm (0.0015 µm), using the relaxed eddy accumulation (REA) method (the theory for this method is described in Chapter 5.1.1). Figure 2.1.4 shows another plot of experimental observations and model predictions for dry deposition velocity that extends to the nanometer-size range.

![Figure 2.1.4. Experimental Data and Theoretical Predictions for Particle Dry Deposition Velocities [adapted from National Center for Atmospheric Research (NCAR), 1982].](image)

The solid curve in Figure 2.1.4 represents the predicted deposition velocity considering the mechanisms of Brownian diffusion, gravitational settling, and inertial...
impaction, which, in some models, is also important for larger particles. Although this plot attempts to group together in one place data for a range of atmospheric and surface conditions, it is notable that no experimental data are presented in the nanometer-size range.

Since the 1970’s, a significant amount of research has been conducted regarding aerosol particles. Both wind tunnel and field experiments have been performed. Most of the research, though, has dealt with larger particles (greater than 10 nm in diameter). Wesely et al. (1977), measured deposition velocities of the order of 1.0 cm s\(^{-1}\), using eddy correlation, for particles 0.05 – 0.1 µm (50 – 100 nm) at a reference height of 5 m in light winds over a moderately rough surface. These measurements were in agreement with the predictions by Sehmel and Hodgson (1978). Figure 2.1.5 shows Sehmel’s (1980) predicted deposition velocity plot at a 1 m reference height for a stable atmosphere and a friction velocity, \( u_* \), of 30 cm s\(^{-1}\), using varying particle densities and roughness heights. \( u_* \) is a parameter at the reference height that depends on the horizontal wind velocity at that height and the surface roughness. It is defined for a neutrally stable (i.e., negligible temperature gradient in the vertical direction) atmosphere as

\[
u_* = \frac{k u(z)}{\ln \left( \frac{z}{z_0} \right)} \quad \text{Eq. 2.1.3.}
\]

where \( k \) is the von Karman constant (most generally accepted to be 0.4 in boundary layer atmospheric physics); \( u(z) \) is the mean horizontal wind velocity at the reference height, \( z \); and \( z_0 \) is the roughness height (also referred to as the roughness length) experimentally
derived from the vertical profile of the horizontal wind (Seinfeld and Pandis, 1998). Thus, in Figure 2.1.5, the $u^*$ of 30 cm s$^{-1}$ equates to an approximate horizontal wind speed of 2 m s$^{-1}$ at a roughness height of 10 cm.

Figure 2.1.5. Predicted Dry Deposition Velocities at 1 m (adapted from Sehmel, 1980).

Note that for a particle diameter of 1 nm ($10^{-3}$ µm) this model predicts a maximum deposition velocity of approximately 1 cm s$^{-1}$ at the upper limit, which is based
on there being no surface resistance below 1 m. The lower limits represent calculations based on there being only Brownian diffusion below the indicated height and both Brownian and atmospheric diffusion above it. The maximum roughness height, \( z_0 \), Sehmel presented calculations for was 10 cm, which is roughly the same order of magnitude as the average of the roughness heights measured at the SS Ranch and Socorro Airport (average roughness height was 19 cm).

Sehmel (1980) reviewed the reported deposition velocities for particles and gases up to that time. Most reported particle diameters were larger than 10 nm. Of interest, though, are the reported deposition velocities of 0.05 cm s\(^{-1}\) for RaB (\(^{214}\)Pb) and RaC (\(^{214}\)Bi) to filter paper (similar to the surface collection method reported herein) (Chamberlain, 1960), 0.05 – 0.5 cm s\(^{-1}\) for RaD (\(^{210}\)Pb) to a tank (Styro and Shalaveyus, 1966), and 3 cm s\(^{-1}\) for fission products to desert vegetation (Fuquay, 1957). Unfortunately, no particle diameters were reported for any of these observations (although being heavy metal atoms they were most likely attached to particles in the larger accumulation mode). At the time, Sehmel noted that the results of field measurements had not been generalized because of experimental uncertainties and limited data and that they ranged over three orders of magnitude. McMahon and Denison (1979) commented on variances of two orders of magnitude in deposition velocity. They also stated that deposition velocity “is approximately a linear function of wind speed and friction velocity.” Slinn et al., (1978) referred to deposition velocities between \(10^{-2}\) and \(10^{1}\) cm s\(^{-1}\) for 0.1 \(\mu\)m diameter particles. Nicholson (1988) listed deposition velocities of \(\leq 0.05\) cm s\(^{-1}\) for particle diameters of 0.09 to 0.1 \(\mu\)m [referencing Katen and Hubbe (1983), Sievering (1983), and Neumann and den Hartog (1985)]. Unfortunately, many of
these papers do not make clear whether or not they are dealing with below- or above-the-vegetation-canopy predictions.

Figure 2.1.6 shows Porstendörfer’s (1994) summary plot of results from papers in which radon and radon progeny were investigated. The majority of the deposition velocity measurements reported in Porstendörfer’s review were carried out in wind tunnels with deposition onto surfaces with the exception of the field measurements of Butterweck (1991). The plotted deposition velocities have been normalized to the friction velocity, $u^*$. For a typical $u^* = 40$ cm s$^{-1}$ (approximately 2 m s$^{-1}$ horizontal wind speed), Porstendörfer calculated average deposition velocities above the canopy (i.e., above the level of the highest surrounding vegetation) for a range of surfaces [aluminum foil (smooth) to wheat]. The unattached-to-aerosol radon progeny had calculated average deposition velocities ranging from 1.2 cm s$^{-1}$ (Al foil) to 15.7 cm s$^{-1}$ (wheat), approximately 100 times higher than those of the attached-to-aerosol progeny. Wyers and Veltkamp (1997) reported an average deposition velocity for attached $^{214}_{82}$Pb of 0.73 ± 0.10 cm s$^{-1}$ at the top of the canopy with a surface collection methodology using gamma emission vice alpha decay.

Comparable results have been reported for highly reactive gases such as HNO$_3$, which might be expected to have deposition velocities similar to nanometer-size particles. Hanson and Lindberg (1991) in a review of the dry deposition of reactive nitrogen compounds reported HNO$_3$ deposition velocities up to 26 cm s$^{-1}$ above the canopy and 1.2 cm s$^{-1}$ to leaf surfaces (below the canopy). More recently (AGU 2001 Fall Meeting), HNO$_3$ above-canopy deposition velocities peaking between 6 and 8 cm s$^{-1}$ have been reported (Horii et al., 2001).
Figure 2.1.6. Deposition Velocities of Radon Progeny (adapted from Porstendörfer, 1994).
As discussed, discrepancies between laboratory and field results have been a source of controversy regarding the “true” deposition velocity for various species and have raised the question as to whether or not it is physically meaningful to parameterize dry deposition in terms of a velocity. Sehmel (1980), Nicholson (1988), and Porstendörfer (1994) noted this deficiency. Accurate field measurements are routinely difficult to make due to the multitude of uncontrolled variables. Porstendörfer pointed out one field measurement (Butterweck, 1991) where the results were 10 times higher than those of wind tunnel experiments. Schery and Whittlestone (1995) reported a mean deposition velocity of $5.2 \pm 0.9 \text{ cm s}^{-1}$ for ultrafine ($< 10 \text{ nm}$) particles for a reference height of 18 m at the Mauna Loa Observatory (MLO), using gradient analysis. Nicholson and Garland (1996) were surprised by the high values reported by Schery and Whittlestone and found the methodology unconvincing. Recent developments in micrometeorological techniques (see discussion in Chapter 2.2) have allowed the measurement of the deposition velocities of nanometer-size particles under realistic field conditions. In a paper on experimental methods, we reported preliminary estimates for the deposition velocity of nanometer-size (approximately 1.5 nm in diameter) of 5 to 35 cm s$^{-1}$ at a 4 m reference height for horizontal winds ranging from 4 to 8 m s$^{-1}$ using an REA system built at New Mexico Tech (Schery et al., 1998). However, this preliminary work was primarily aimed at testing the new equipment and developing a precise sampling protocol and did not involve an adequate statistical sampling. This dissertation reports the results of intense use of this REA system, as well as independent auxiliary techniques, to study the dry deposition of nanometer-size particles at two locations in central New Mexico.
AEROSOL PARTICLE DETECTION

One of the major problems in measuring the deposition velocity, $v_d$, of nanometer-size aerosol particles has been the detection of the particles. Many commercially available detectors for smaller particles rely on electric mobility measurements (i.e., deflection of a particle in an electric field after charging) or vapor condensation (i.e., “growing” smaller aerosol particles to a size sufficient for detection by the scattering of light). Neither technique is suitable for the very small nanometer-size particles. For example, with vapor condensation, information on the original particle size is usually lost and only the presence and number of aerosol particles can be determined. Figure 2.2.1 shows the approximate size ranges for various techniques of aerosol particle detection. Some condensation nuclei counters (which rely on vapor condensation) tout particle detection capabilities down to diameters of 3 – 5 nm, but, in general, are not reliable for the detection of particles smaller than about 10 nm in diameter. Likewise, a recently advertised scanning mobility particle sizer by TSI Incorporated (Model 3936 series, TSI, Inc., P.O. Box 64394, St. Paul, MN 55164) claims detection down to 3 nm in diameter.
Thus, for nanometer-size particles, alternative methods for detection and quantification must be used. Due to the relatively high diffusion coefficient of nanometer-size particles, it is possible to selectively collect them on wire mesh screens (Fuchs, 1964). As air is drawn through the screen, the small aerosol particles will diffuse laterally, escaping the airstream and depositing on the wires of the screen. The larger aerosol particles pass through the screen. The “exposed” screen can then be analyzed by such techniques as viewing under an electron microscope, removing the collected particles in a washing process, or directly measuring the decay of the particles if they are radioactive. For the research presented herein, the latter technique was utilized.
aerosol particles of interest, containing the radioactive decay products of $^{222}\text{Rn}$, include alpha particles among their emissions, which can easily be detected directly.

There are a number of methods for detecting alpha particles. Due to the significant interaction of the positively charged alpha particle with surrounding atoms, large amounts of energy are deposited in a very small volume as the alpha particle slows down. One of the most important methods for detecting alpha particles is scintillation detection. Scintillation is the process whereby the light given off by the atoms excited by the passing alpha particle is detected as they de-excite and return to their ground state. Zinc sulfide is a commonly used scintillation material and the one contained in the alpha counting system detectors used in this research (see description in Chapter 4).
CHAPTER 2.3
RADON AND RADON PROGENY

The importance of radon and radon progeny to this research cannot be overemphasized. In order to make deposition velocity measurements on nanometer-size aerosol particles in the outdoor environment, a source of aerosols with such a size range (1 to 2 nm) must be readily available. Additionally, as noted in Chapter 2.2, the particles must be detectable by some means. Due to environmental considerations, introducing an unnatural aerosol particle was not considered a viable option. Fortunately, there is a natural tracer that can be used — radon gas and the radioactive decay products of radon (“progeny,” formerly called “daughters”). Due to the geology of the Earth, there are trace amounts of the primordial heavy elements in nearly all soils, including $^{238}_{92}$U, a precursor of $^{222}_{86}$Rn. Depending on the locale, the rocks present may contain higher concentrations of $^{238}_{92}$U. Therefore, there is widespread emanation of radon from the Earth’s surface.

There are three isotopes of radon that occur naturally in the environment — $^{222}_{86}$Rn, which is the most common, coming from the decay of $^{226}_{88}$Ra (starting from $^{238}_{92}$U); $^{220}_{86}$Rn (thoron) coming from the decay of $^{224}_{88}$Ra (starting from $^{232}_{90}$Th); and $^{219}_{86}$Rn (actinon) coming from the decay of $^{223}_{88}$Ra (starting from $^{235}_{92}$U). The isotope $^{219}_{86}$Rn has
such a short half-life (4 s) that it normally does not have time to escape from the soil. Therefore, it will not be discussed further. If, during the radioactive decay of radium into radon, the radon atom escapes the grain of soil in which the radium was located, then it can diffuse to the surface and escape into the atmosphere. Figure 2.3.1 shows this process.

Figure 2.3.1. Exhalation of Radon Gas into the Atmosphere (adapted from Porstendörfer, 1994).
Once in the atmosphere, radon, being an inert gas, freely mixes until it decays into \(^{218}\text{Po}\) (from \(^{222}\text{Rn}\)) or \(^{216}\text{Po}\) (from \(^{220}\text{Rn}\)). From this point on, the progeny are single atoms that are non-volatile and readily stick to surfaces. Most quickly grow to nanometer size clusters due to oxidation and hydration. This is referred to as the unattached-to-aerosol mode as a shorthand term for radioactive atoms that are a part of small molecular cluster particles rather than attached to the fairly pervasive larger aerosol particles. In this mode the radon progeny “clusters” will readily attach to any surface because of higher diffusion coefficients and strong chemical bonding. This attachment could be to water molecules, larger aerosol particles, or surfaces such as the ground and vegetation. If the attachment is to a larger aerosol particle, the radon progeny are in the attached-to-aerosol or accumulation mode. Most commonly, aerosol particles are in the accumulation size range. If the attachment is to a large surface (e.g., the ground, vegetation, or man-made surfaces) without the assistance of snow, rain, hail, or cloud/fog droplets, this is dry deposition. Figure 2.3.2 shows the atmospheric cycle of the radon progeny from the two principally occurring radon isotopes (\(^{219}\text{Rn}\) excluded). Note that wet deposition is not depicted in Figure 2.3.2 since that process was not investigated. The red “α” symbol denotes those steps where the primary emission during radioactive decay is an alpha particle. The decays of the final radionuclides shown in each chain are to stable isotopes of lead (\(^{206}\text{Pb}\) from \(^{222}\text{Rn}\) and \(^{208}\text{Pb}\) from \(^{220}\text{Rn}\)).
Figure 2.3.2. Atmospheric Cycle of Radon Progeny (adapted from Porstendörfer, 1994).

Table 2.3.1 lists the radioactive half-lives of the radionuclides in the decay chains of $^{222}_{86}$Rn and $^{220}_{86}$Rn where an alpha particle is the primary means of decay. The energy of the alpha particle emitted is listed in MeV.
Table 2.3.1. Radon Progeny Half-Lives and Alpha Energies.

<table>
<thead>
<tr>
<th>RADIONUCLIDE</th>
<th>HALF-LIFE</th>
<th>ALPHA ENERGY (in MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}_{86}$Rn</td>
<td>3.8 days</td>
<td>5.5</td>
</tr>
<tr>
<td>$^{218}_{84}$Po</td>
<td>3.05 min</td>
<td>6.0</td>
</tr>
<tr>
<td>$^{214}_{84}$Po</td>
<td>164 sec</td>
<td>7.7</td>
</tr>
<tr>
<td>$^{210}_{84}$Po</td>
<td>138.4 days</td>
<td>5.3</td>
</tr>
<tr>
<td>$^{220}_{86}$Rn</td>
<td>55.6 sec</td>
<td>6.3</td>
</tr>
<tr>
<td>$^{216}_{84}$Po</td>
<td>0.15 sec</td>
<td>6.8</td>
</tr>
<tr>
<td>$^{212}_{83}$Bi</td>
<td>60.6 min</td>
<td>6.1</td>
</tr>
<tr>
<td>$^{212}_{84}$Po</td>
<td>304 nsec</td>
<td>8.8</td>
</tr>
</tbody>
</table>

The remaining discussion focuses on the dry deposition of the progeny of $^{222}_{86}$Rn, since they typically have the highest activity concentrations in the lower atmosphere and are the most easily measured.

A special unit for quantifying radioactive aerosol particles of radon progeny is potential alpha particle energy, which is determined from the collective energy released by the alpha particles emitted by the radon progeny. This unit has evolved from the calculation of the radiation dose to the respiratory tract from radon progeny. The units for potential alpha particle energy are nanojoules (nJ). Thus, the units of concentration,
called the potential alpha particle energy per unit volume concentration (PAEC), are nJ m\(^{-3}\). Although individual activities of radon progeny could be reported in Bq m\(^{-3}\), the statistical fluctuations in these quantities would be greater than for the collective measurement in nJ m\(^{-3}\).

The general expression relating PAEC to the more common activity concentration units of Becquerels per cubic meter (Bq m\(^{-3}\)) for decay products of the primary radon isotope, \(^{222}\)Rn, is the following:

\[
\text{PAEC} = 0.58 (^{218}\text{Po}) + 2.86 (^{214}\text{Pb}) + 2.10 (^{214}\text{Bi}) \quad \text{Eq. 2.3.1},
\]

where the \(^{218}\)Po, \(^{214}\)Pb, and \(^{214}\)Bi are the concentrations of the controlling radionuclides in Bq m\(^{-3}\) and PAEC is in nJ m\(^{-3}\).

In order to better understand the unattached mode for radon progeny, it is helpful to look at plots of size spectra. Figure 2.3.3 shows the results of a series of outdoor activity-weighted size distribution measurements for radon progeny taken during the fall of 1995, using a screen diffusion battery, at a site just west of the New Mexico Tech campus (Wasiolek, James, and Yarger, 1996). From Figure 2.3.3 the activity median diameter (AMD) for the unattached-to-aerosol radon progeny was determined to be 1.5 nm. This diameter was utilized in calculating the screen collection efficiency, \(\kappa_c\), as part of the REA and modified Bowen ratio methods discussed later. This bimodal distribution is a well-established condition for radon progeny under 1 \(\mu\)m in diameter.
Though the aerosol particles investigated were radioactive, the flux measurements are expected to be applicable to most nanometer-size aerosol particles. There is little reason to suspect that the fact that the particles were radioactive influenced their attachment rate. Unattached radioactive aerosols can temporarily have a different charge distribution from that predicted by the equilibrium Boltzmann distribution, but for fair weather conditions, enhancement of the deposition rate due to the atmospheric electric field are typically small (Roffman, 1972; Shimo et al., 1985; Schery and Whittlestone, 1995).
PART 3
SITE DESCRIPTIONS
CHAPTER 3.1
OVERALL SITE LOCATIONS

The sampling sites were located approximately 130 km south/southwest of Albuquerque in Socorro County in central New Mexico, U. S. A. The terrain is semi-arid high desert, typical of the southwestern United States, covered with sparse grass, low brush/cactus, and an occasional tree. Figure 3.1.1 shows the two sampling sites – SS Ranch and Socorro Municipal Airport.

Figure 3.1.1. Locations of Sampling Sites.
Approximately 24 km separated the two sites. Detailed descriptions of each sampling site are provided in Chapters 3.2 and 3.3.
CHAPTER 3.2
SS RANCH SITE DESCRIPTION

The initial sampling site was located at the SS Ranch (owned at the time by Dr. Stephen Schery) off highway US 60 between the city of Socorro and the village of Magdalena in central New Mexico (see Figure 3.1.1). The sampling site latitude and longitude coordinates were 34° 07’ N, 107° 08’ W and the elevation was 1820 m. Figure 3.2.1 shows a larger scale map of the sampling site location. For reference, the square surrounding the site is one mile on each side. The elevation contour lines shown on Figure 3.2.1 are in feet above mean sea level.

Figure 3.2.2, in contrast, provides a three-dimensional representation of the SS Ranch sampling site, looking northwest from southeast of the site. The elevation scale is exaggerated to enhance the visualization of the local topography.
Figure 3.2.1. SS Ranch Sampling Site Location (elevation contours in feet).
Figure 3.2.2. Three-dimensional Representation of SS Ranch Sampling Site.

Figure 3.2.3 shows a detailed layout of the sampling site. The obstructed and unobstructed wind sectors are marked. The unobstructed wind sectors, those having stretches of relatively consistent terrain exceeding the standard 100z (z being the sampling reference height of 4 m) micrometeorological fetch requirement (Businger, 1985), ranged from approximately 230° to 030° and 135° to 180° (compass headings).

Due to nearby obstructions within 15 m, winds coming from the remaining directions were considered to be perturbed and likely to contain wake effects. The nearest
mountains to the site, the Magdalenas, rise to over 3000 m approximately 3 km to the west. The meteorological instruments were positioned up the southwest corner of the 10 m windmill derrick shown in Figure 3.2.3. Based on vertical profile measurements of the wind, the aerodynamic roughness height, $z_0$, for the unobstructed sectors was calculated at 30 cm.

Figure 3.2.3. Detailed Layout of SS Ranch Sampling Site.
Figure 3.2.4 is a composite 360° panorama photograph taken at the SS Ranch sampling site on 13 July 2000. Although some additional structures had been added to the site since sampling was conducted, the original features depicted in Figure 3.2.3 are still visible.

Testing and sampling were conducted at the SS Ranch beginning in the summer of 1995 and running through the summer of 1997. Only REA and surface collection measurements were performed there.
Figure 3.2.4. 360º Panorama from SS Ranch Sampling Site.
CHAPTER 3.3

SOCORRO MUNICIPAL AIRPORT SITE DESCRIPTION

The subsequent sampling location was at the Socorro Municipal Airport, west of Interstate 25/US 85, approximately 4 km south of the city of Socorro in central New Mexico (see Figure 3.1.1). Two sampling sites were located at the airport – one near the taxiway where REA measurements were performed and one near the aerobeacon where modified Bowen ratio measurements were performed. The REA sampling site latitude and longitude coordinates were 34° 01.3′ N, 106° 53.9′ W and the elevation was 1455 m. The modified Bowen ratio sampling site latitude and longitude coordinates were 34° 01.3′ N, 106° 53.8′ W and the elevation was also 1455 m. Figure 3.3.1 shows a larger scale map of the sampling site locations. For reference, the horizontal dimension of the rectangle surrounding the sites (but mostly to the south) is one mile. Also, the elevation contour lines shown on Figure 3.3.1 are in feet above mean sea level.

Figure 3.3.2, in contrast, provides a three-dimensional representation of the Socorro Municipal Airport sampling sites, looking northwest from southeast of the sites. The elevation scale is exaggerated to enhance the visualization of the local topography.
Figure 3.3.1. Socorro Municipal Airport Sampling Site Locations (elevation contours in feet).
Figure 3.3.2. Three-dimensional Representation of Socorro Airport Sampling Sites.

Figure 3.3.3 shows a detailed layout of the sampling sites. The obstructed and unobstructed wind sectors are marked with respect to each sampling location. The unobstructed wind sector for the REA sampling site, based on considerations similar to those outlined in Chapter 3.2 except as modified for building wake effects that are detectable 10 to 20 times the building height downwind (Arya, 1988), ranged from approximately $045^\circ$ to $033^\circ$ (compass headings, passing through $180^\circ$). The unobstructed wind sector for the modified Bowen ratio sampling site ranged from approximately $090^\circ$ to $270^\circ$ (compass headings). Due to nearby obstructions (within 30 m of the REA sampling site and 3 m of the modified Bowen ratio sampling site), winds coming from
the remaining directions in each case were considered to be perturbed and likely to contain wake effects. The nearest mountain to the sites, Socorro Peak (commonly referred to as M Mountain), rises to over 2000 m approximately 8 km to the west/northwest. The meteorological instruments were positioned up the southwest corner of the 17 m airport aerobeacon shown in Figure 3.3.3. Based on vertical profile measurements of the wind, the aerodynamic roughness height, $z_0$, for the unobstructed sectors was calculated at 7 cm, approximately a factor of 4 smaller than that calculated at the SS Ranch. This is due primarily to the much sparser and shorter vegetation surrounding the airport sampling sites.

Figures 3.3.4 and 3.3.5, following Figure 3.3.3, are composite 360° panorama photographs taken at the REA and modified Bowen ratio sampling sites. Key features are noted.

Sampling was conducted at the Socorro Municipal Airport beginning in the spring of 1998 and running through the summer of 2000. All three sampling techniques – REA, modified Bowen ratio, and surface collection – were performed there. REA and surface collection measurements were performed concurrently at the REA sampling site while modified Bowen ratio and surface collection measurements were performed concurrently at the modified Bowen ratio sampling site.
Figure 3.3.3. Detailed Layout of Socorro Municipal Airport Sampling Sites.
Figure 3.3.4. 360° Panorama from Socorro Municipal Airport REA Sampling Site.
Figure 3.3.5. 360º Panorama from Socorro Municipal Airport Modified Bowen Ratio Sampling Site.
PART 4

INSTRUMENTATION
CHAPTER 4.1
ULTRASONIC ANEMOMETER

A key instrument necessary for all the research presented here was the ultrasonic anemometer (SAM). Figure 4.1.1 shows the SAM installed atop the sampling tower.

Figure 4.1.1. Ultrasonic Anemometer (SAM).
Figure 4.1.2 below shows a close-up view of the SAM transducer assembly.

![Figure 4.1.2. Close-up View of SAM Transducer Assembly.](image)

The SAM is a commercially available product (Solent Research Ultrasonic Anemometer Model 1012) built by Gill Instruments, Ltd., Solent House, Cannon Street, Lymington, Hampshire, U.K. The New Mexico Tech Atmospheric Radioactivity Laboratory unit’s serial number is 0132R2. The unit was supplied by the manufacturer with a power supply and interface unit (PSIU), cabling, personal computer (PC) software, and a certificate of calibration. The software programs supplied with the SAM were FASTCOM.EXE and CONVERT.EXE. The first program, FASTCOM.EXE, managed instrument operation and data collection. The second program, CONVERT.EXE,
allowed conversion of the SAM output file into an exportable ASCI file. The unit could be run at a data output rate of 21 Hz (Mode 1) or 56 Hz (Mode 2). Unfortunately, when operated at 56 Hz, the $\mathbf{u}$ (horizontal), $\mathbf{v}$ (horizontal, perpendicular to $\mathbf{u}$), and $\mathbf{w}$ (vertical) wind components were unavailable due to the processing time required to calculate simultaneous wind components. Thus, the SAM was run in Mode 1, in which calibrated $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$ wind component information would be output. The SAM transducer head was oriented such that the one upper transducer was 30° to the west of true north. Figure 4.1.3 shows a schematic of the SAM transducer orientation. The SAM required that the one support arm be oriented to true north when the sampling tower was set up at the start of each sampling session.

![Figure 4.1.3. Top View of SAM (adapted from Gill Instruments).](image)

Figure 4.1.3. Top View of SAM (adapted from Gill Instruments).
The SAM operated on a basic sound wave time-of-flight principle to determine air
velocity. The analog outputs of the SAM were the air velocities in the \( u \), \( v \), and \( w \)
directions and the speed of sound. The air velocities were used to control the operation
of the solenoid valves of the REA system (see Chapter 4.2) and to calculate the average
measured horizontal wind speed and direction during each sampling run. The \( w \) velocity
played a critical role in the evaluation of the data as \( w \) turned out to be an important
factor in data scatter. The speed of sound was critical in calculating the covariance
between the vertical wind velocity and temperature for the modified Bowen ratio method.
Thus, the SAM output was important for all three methods used for determining the flux
velocity.

The SAM was provided with a certificate of calibration by the manufacturer,
indicating a less than 1% error in the wind magnitude at a 20 m s\(^{-1}\) wind speed from 0 -
360\(^{\circ}\). Because the SAM is a solid-state instrument, no verification testing was performed
upon receipt nor was the SAM tested for drift during or after the completion of data
collection. Normally, this type of testing requires the use of a wind tunnel, which was
not readily available. The SAM appeared to perform to specification throughout the
course of the research, giving no indication that testing and recalibration might be
required.
CHAPTER 4.2

RELAXED EDDY ACCUMULATION (REA) SYSTEM

The relaxed eddy accumulation (REA) system is a unique system designed and built at New Mexico Tech by the Atmospheric Radioactivity Laboratory of the Physics Department (Schery et al., 1998). The system consists of the following components:

- Ultrasonic anemometer (SAM) (see Chapter 4.1)
- Sampling assembly
- Blower
- Interface relay control box (see Chapter 4.3)
- Personal computer (PC)

Figure 4.2.1 shows the REA system as setup for testing at the SS Ranch while Figure 4.2.2 shows a simplified line drawing of the system. The physical and electronic connections will be briefly discussed here. The SAM and interface relay control box are described in different chapters and will only be discussed here as regards their connections with the remaining system components.
Figure 4.2.1. REA System Setup at SS Ranch.
Figure 4.2.2. Line Drawing of REA System (adapted from Schery et al., 1998).

The sampling assembly consists of the following components:

- Three screen/filter assemblies
- Three electromagnetic solenoid valves
- Polyvinylchloride (PVC) piping

The screen/filter assemblies contained a 10 cm diameter stainless steel wire mesh (635 or 400 wires per inch) diffusion screen (Tetko, Inc., P.O. Box 346, Lancaster, NY 14086) backed by a glass fiber filter (Gelman type A/E; Gelman Sciences, 600 S. Wagner
Rd., Ann Arbor, MI 48103-9019) of approximately the same diameter (actual diameter – 10.2 cm). The threaded cap holding the screen and filter in place reduced the air sampling opening diameter to 9 cm. The screens were assembled in the laboratory by taking cut circles of the stainless steel screen and gluing them to thin cross sections of PVC pipe.

The screen/filter assemblies are connected to their respective solenoid valves (True Blue Model EASMT5V16W20-PV, Plat-O-Matic Valves, Inc., Totowa, NJ 07512) by a 3.8 cm inner diameter PVC pipe approximately 2.3 m in length such that there is no cross flow between the screen/filter and the solenoid valve. The outlets of the solenoid valves are connected to a common manifold, which in turn is connected via a hose to an oil-less air blower (Gast Model R3105-12, Gast Manufacturing Corporation, P.O. Box 97, Benton Harbor, MI 49022). The blower provides a constant flow rate of approximately 230 ℓpm through the screen/filter assembly when the solenoid valve is open. A flow gauge (AquaMatic, Inc., 2412 Grant Avenue, Rockford, IL 61103-3991) on the blower allows actual measurement of the flow rate through each screen/filter assembly, which can be corrected for the ambient temperature and barometric pressure using a correction formula supplied by the manufacturer. The flow can be adjusted, using a bypass valve. At 230 ℓpm, the collection efficiency, $\varepsilon_c$, for a 1.5 nm diameter aerosol particle is close to 85% for a 635 mesh screen, based on screen theory that assumes complete sticking of the particles to the screen wires (Cheng and Yeh, 1980).

Electronically, the solenoid valves are connected to the interface relay control box, which energizes the appropriate valve and, thus, opens it based on signal inputs from the SAM.
CHAPTER 4.3
INTERFACE RELAY CONTROL BOX

The interface relay control box was designed and built at New Mexico Tech by the Atmospheric Radioactivity Laboratory of the Physics Department. The interface relay control box is the “brains” of the REA system, taking inputs from the SAM and using them to open/close the appropriate solenoid valves to draw air through the screen/filter assembly. The discussion presented here will cover the basics of operation. A more detailed discussion can be found in Bruce Nemetz’s Masters thesis (Nemetz, 1997). Schery et al., 1998, presented a detailed electrical schematic drawing of the interface relay control box.

Taking the 0 to 5 V analog output of the SAM, corresponding to vertical wind speeds of -30 m s\(^{-1}\) to 30 m s\(^{-1}\) respectively, the interface relay control box was designed to open the “up” solenoid valve (for sampling the air while there existed an upward vertical wind, \(w^+\)) for input voltages greater than 2.5 V (0 m s\(^{-1}\)) and open the “down” solenoid valve (for sampling the air while there existed a downward vertical wind, \(w^-\)) for input voltages less than 2.5 V. This, however, is impractical for an operational system. Therefore, an adjustable dead band was also designed into the interface relay control box, creating a threshold value to be reached by the vertical wind speed before either the up or
down solenoid valve. This threshold value was nearly always set so as to have the dead band at -0.1 m s\(^{-1}\) to 0.1 m s\(^{-1}\).

The design also included the capability of shifting the dead band, called the offset, and calibrating the entire system. In the course of doing the REA measurements, there was never a time when the offset was utilized. Similarly, the interface relay control box proved sufficiently reliable that calibration was rarely required.

There are only two negatives regarding the current interface relay control box. First, the case in which the electronic circuitry is placed is flimsy and not suitable for long-term field use. Fortunately, through careful handling, it proved adequate for the duration of the fieldwork involved with this research. This could be easily rectified by placement in a sturdier case. Second, there is an inherent delay between the time when the SAM senses that the vertical wind velocity has reached or exceeded a threshold value and the time when the appropriate solenoid valve opens. This delay was measured at 125 ms. Chapter 5.2.2 contains a detailed discussion of the delay analysis.
CHAPTER 4.4
ALPHA COUNTING SYSTEM

The automatic alpha counting system was designed and built at New Mexico Tech by the Atmospheric Radioactivity Laboratory of the Physics Department using standard commercial components. Figure 4.4.1 shows the system located inside the Atmospheric Radioactivity Laboratory field trailer.

Figure 4.4.1. Automatic Alpha Counting System.
The automatic alpha counting system consists of the following components:

- Six ZnS(Ag) scintillation detectors with attached photomultiplier tubes (Ludlum Model 43-1, Ludlum Measurements, 501 Oak Street, Sweetwater, TX) (see Chapter 2.2 for discussion on alpha detection)
- Six counter-scalers (Ludlum Model 2000)
- Interface box
- Personal computer (PC)

This system has been used extensively and described in previous publications (Schery and Wasiolek, 1993; Wasiolek and Cheng, 1995; Wasiolek, James and Yarger, 1996; Schery et al., 1998). Therefore, the discussion here will be limited.

When energized, the scintillation detectors operate continuously, sending signals to their respective counter-scalers. The detector high voltage plateaus were rechecked in May 1998. The high voltages were adjusted as necessary. The counter-scalers output signals to an interface box that then provides count information to the PC via the serial port connection. The interface box also functions to provide power to two standard plug connectors as programmed into the PC.

The PC is loaded with the AC.EXE program that records the number of counts received from each counter-scaler each minute [see Appendix B]. The program also controls several other functions, the most important being power to the interface box plug connectors. This allows precise timing for blower operation during sampling runs. The alpha count data are saved to a file for future downloading and processing.
CHAPTER 4.5
MISCELLANEOUS EQUIPMENT

Several other pieces of equipment were used in data collection for the research presented herein. The most important of these are the two blowers (Blowers A and B) used for the modified Bowen ratio method. Figures 4.5.1 and 4.5.2 show the two blowers.

Figure 4.5.1. Electro-Neutronics Model 2000 Air Sampler - Blower A.
Blower A is a commercially purchased high volume air sampler (Model 2000) built by Electro-Neutronics, Inc., Tracy, CA. Blower B is another commercially purchased high volume air sampler (Model 8000) built by the same company as Blower A. Both have maximum volumetric flow rates around 400 ℓpm with a wire mesh screen and a glass fiber filter installed. The main difficulty experienced with these blowers was that they were sensitive to operation for long periods of time in warm weather. On occasion, in warm weather, one of the blowers would trip off due to thermal overload. A
sampling time of 30 minutes for the modified Bowen ratio method was selected partly on this basis.

Two other pieces of equipment were consistently used during sampling runs – the portable meteorological station (Perception II Model, Davis Instruments, 3465 Diablo Avenue, Hayward, CA 94545) and the datalogger (21X Micrologger Model, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). Figure 4.5.3 shows the portable meteorological station while Figure 4.5.4 shows the datalogger.

![Figure 4.5.3. Davis Portable Meteorological Station.](image)

Ambient temperature (°C), barometric pressure (mb), and relative humidity (%) were recorded with each sampling run from the portable meteorological station.
Meteorological instruments, including temperature sensors, cup anemometers, and wind vanes, were connected to the datalogger in Figure 4.5.4 and positioned on existing towers at the SS Ranch and Socorro Airport. The datalogger provided power to the instruments. At the ranch, the instruments were placed up one side of an old windmill derrick while at the airport they were placed up one side of the aerobeacon. Figure 4.5.5 shows the meteorological instruments at the SS Ranch. Figure 4.5.6 shows the instruments at the Socorro Airport. Three sets of three instruments each (a temperature sensor, a cup anemometer, and a wind vane) were positioned at heights of 2 m, 5 m, and 8 (or 10) m on the windmill derrick at the SS Ranch. Four sets were positioned at 2 m, 8 m, 11.7 m, and 16 m on the aerobeacon at the Socorro Airport. A pyrometer was also
placed atop the derrick (8/10 m) and the aerobeacon (16 m). It should be noted that the logarithmic mean of 2 m and 8 m is equivalent to the reference height for the REA and modified Bowen ratio measurements (4 m). Thus, the meteorological measurements were positioned so that they could also be used in calculating the flux velocities. Meteorological data were read out on the datalogger every 10 seconds. An average was calculated and permanently stored every hour. The stored data were periodically retrieved and stored in a computer file.

Figure 4.5.5. Meteorological Instruments at SS Ranch (2 m, 5 m, and 10 m).
Figure 4.5.6. Meteorological Instruments at Socorro Airport (only instruments located at 8 m, 11.7 m, and 16 m are visible).
PART 5

RELAXED EDDY ACCUMULATION

METHOD
CHAPTER 5.1

RELAXED EDDY ACCUMULATION THEORY

The relaxed eddy accumulation (REA) method of measuring dry deposition velocity, \( v_d \), as presented by Businger and Oncley (1990), derives from the eddy accumulation (EA) method suggested by Desjardins (1972), which in turn derives from eddy correlation (EC) theory. The derivation of REA from EC is outlined in the following paragraphs.

Eddy Correlation

The most direct micrometeorological method for measuring flux densities of atmospheric constituents (such as trace gases and aerosol particles) caused by turbulent diffusion is eddy correlation (EC). EC theory is extensively addressed in the literature and reviewed in particular detail by Stull (1993). EC is based on making simultaneous measurements of the values of two atmospheric variables. For determining the average vertical flux density, one variable is the vector quantity, vertical wind velocity (up or down only), \( w \), while the other variable is the scalar concentration, \( c \), of the atmospheric species of interest (e.g., carbon dioxide, water vapor, temperature, aerosol particles, etc.). A time series of measurements is generated for both variables over a sufficiently long
sampling period. For each time series measurement, both \( w \) and \( c \) can be represented as a sum of the mean value (\( \bar{w} \) and \( \bar{c} \)) and a perturbation value (\( w' \) and \( c' \), where \( \bar{w}' = \bar{c}' = 0 \)),

\[
\begin{align*}
    w &= \bar{w} + w' \quad \text{Eq. 5.1.1}, \\
    c &= \bar{c} + c' \quad \text{Eq. 5.1.2}.
\end{align*}
\]

Thus, the covariance, \( \bar{w}c \), following the Reynolds averaging rules (Arya, 1988; Kaimal and Finnigan, 1994), can be written as

\[
\begin{align*}
    \bar{w}c &= (\bar{w} + w')(\bar{c} + c') = \bar{w}c + w'c' \quad \text{Eq. 5.1.3}.
\end{align*}
\]

The term \( \bar{w}c \) represents the mean transport (i.e., the transport resulting from the mean vertical motion) and the term \( w'c' \) represents the turbulent transport. The latter term, also referred to as the turbulent flux, usually is dominant (Arya, 1988; Seinfeld and Pandis, 1998); and, particularly if \( \bar{w} = 0 \), the \( \bar{w}c \) term can be dropped. Thus, the average vertical turbulent diffusion flux density, \( F_{EC} \), as measured using the EC method, is given by (with appropriate units for the research presented here),

\[
F_{EC} = \bar{w}c' \quad \text{[\text{nJ m}^{-2} \text{s}^{-1}] = \left[ \text{m s}^{-1} \text{(nJ m}^{-3}) \right]} \quad \text{Eq. 5.1.4}.
\]

EC has long been recognized as a powerful approach for measuring the atmospheric flux densities of sensible heat, water vapor, and carbon dioxide. However, in order for it to work, sensors capable of instantaneously and simultaneously measuring both \( w \) and \( c \) are required. Turbulent eddies typically have frequencies between 0.3 Hz.
and 0.0003 Hz (Stull, 1993); and wind measurement devices with frequency responses of 10 Hz or greater are needed to ensure that the eddies will be sampled quickly enough to be considered “instantaneous.” The current technology in sonic anemometers (with response times on the order of 10 Hz or greater) makes it possible to measure $w$ quickly enough to be considered “instantaneous.” Unfortunately, it has frequently been difficult, if not impossible, to similarly measure the concentration, $c$, of many species. This is especially true for very small aerosol particles, such as unattached radon progeny, as there are currently no sensors or measuring techniques capable of rapidly detecting them – especially at 10 Hz or greater.

**Eddy Accumulation**

Based on the lack of quick-responding sensors for EC, Desjardins (1972) suggested an alternative method, eddy accumulation (EA), to overcome this limitation. The EA method relies on sampling the air at a rate proportional to the vertical wind velocity, $w$, bypassing the need for quick-responding sensors. This is achieved by obtaining a statistically meaningful air sample and making the measurement of $c$ later. Different valves in a sampling system are opened, directing air to independent reservoirs, depending on the vertical wind direction ($w^+, w \geq 0$ (up); $w^-, w \leq 0$ (down)). The valves are adjusted to sample at a rate proportional to the absolute magnitude of the vertical wind velocity, $|w|$. After a sufficiently long sampling period, the independent reservoirs contain air proportional to $w^+ c$ and $w^- c$. The net vertical flux density, $F_{EA}$, is found by summing the two quantities,

$$F_{EA} = w^+ c + w^- c \quad \text{Eq. 5.1.5.}$$
Using Equation 5.1.2 again to represent the concentration, \( c \), as a sum of the mean value and a perturbation term (similar to the procedure used in the EC method), Equation 5.1.5 becomes, assuming that \( \bar{c} \) is a constant (which is generally true for relatively short sampling periods),

\[
F_{EA} = (\overline{\text{w}^+} + \overline{\text{w}^-})\overline{c} + \left(\text{w}^+ c' + \text{w}^- c'\right) \quad \text{Eq. 5.1.6.}
\]

For a properly aligned measurement system, the mean vertical wind velocity should be zero. Thus,

\[
\overline{\text{w}^+} + \overline{\text{w}^-} = \overline{\text{w}} = 0 \quad \text{Eq. 5.1.7.}
\]

Therefore, after a sufficiently long sampling period (approximately 30 minutes to 1 hour), Equation 5.1.6 becomes,

\[
F_{EA} = \overline{\text{w}^+} c' + \overline{\text{w}^-} c' \quad \text{Eq. 5.1.8.}
\]

The vertical winds (\( \text{w}^+ \) - up; \( \text{w}^- \) - down) can, in turn, be expressed as sums of their mean values and their perturbations,

\[
\text{w}^+ = \overline{\text{w}^+} + w^+ \quad \text{Eq. 5.1.9},
\]

\[
\text{w}^- = \overline{\text{w}^-} + w^- \quad \text{Eq. 5.1.10}.
\]

Substituting Equations 5.1.9 and 5.1.10 into Equation 5.1.8 and rearranging terms, Equation 5.1.8 becomes, assuming \( \overline{\text{w}^+} \) and \( \overline{\text{w}^-} \) are constants (which follows from Eq. 5.1.7),
\[ F_{EA} = \overline{(w'^+ + w'^-)}c' + \overline{w'^+}c' + \overline{w'^-}c' \quad \text{Eq. 5.1.11.} \]

The first term equals zero from Equation 5.1.7. Once again, as with the mean vertical wind velocity, after a sufficiently long sampling period, the mean perturbation of the vertical wind velocity should also be zero,

\[ \overline{w'^+} + \overline{w'^-} = \overline{w'} = 0 \quad \text{Eq. 5.1.12.} \]

Thus,

\[ F_{EA} = \overline{w'^+}c' + \overline{w'^-}c' = \overline{w'^+}c' + \overline{w'^-}c' = \overline{(w'^+ + w'^-)}c' = \overline{w'c'} \quad \text{Eq. 5.1.13.} \]

Though Equations 5.1.4 and 5.1.13 are the same, the sampling methodology is quite different. While EC relies on the actual measurement of \( w' \) and \( c' \) to directly obtain \( \overline{w'c'} \) (and, thus, \( F \)), EA actually uses Equation 5.1.5, measuring the proportionally sampled concentrations (based on the magnitude of the vertical wind velocity, \( |w'^+| \) or \( |w'^-| \)), \( \overline{w'^+c} \) and \( \overline{w'^-c} \), to obtain \( F \). EA is potentially more useful than EC for certain atmospheric constituents, but it is still difficult to execute experimentally. Businger (1986) points out two major difficulties with EA. First, due to a bias in the vertical wind measurement or to the presence of a heat and/or water vapor flux density, it is possible that \( \overline{w} \neq 0 \). If this is true, there are other terms required in Equation 5.1.13. These extra terms can be corrected for, if they are known. Usually, though, they are unknown. Second, both \( \overline{w'^+c} \) and \( \overline{w'^-c} \) are individually much larger in magnitude than the net flux
density, meaning that the measurements must be made with exceptional accuracy. Thus, EA requires the ability to precisely control the proportional valves.

**Relaxed Eddy Accumulation**

Businger and Oncley (1990) outline a method whereby the requirement for the proportional valves in the EA method is relaxed. This “relaxed” eddy accumulation (REA) method requires only that the sampling be determined by the presence, but not the magnitude, of an up or down vertical wind and that the air be sampled at a constant flow rate. Thus, the measurements are simply the average concentrations of the atmospheric constituent being investigated in the upward \( w > w_0 \) vertical wind reservoir, \( \overline{c^+} \), and in the downward \( w < -w_0 \) vertical wind reservoir, \( \overline{c^-} \), where \( w_0 \) is a positive threshold value that typically ranges between zero and one standard deviation in the vertical wind speed, \( \sigma_w \). In the atmospheric surface layer, Businger and Oncley (1990) show that the flux density is obtained by,

\[
F_{REA} = \overline{w'c^+} = \beta (\zeta) \sigma_w \left( \overline{c^+} - \overline{c^-} \right) \quad \text{Eq. 5.1.14},
\]

where \( \beta (\zeta) \) is a dimensionless coefficient determined by experiment or theoretical calculation. This coefficient is assumed to be a function of atmospheric stability as characterized by

\[
\zeta = \frac{z}{L} \quad \text{Eq. 5.1.15},
\]

where \( z \) is the height above the earth’s surface and \( L \) is the Obukhov length. The value of \( \beta \) has been determined from a number of experiments using the REA method and has
been found to be so weakly dependent on $\zeta$ that it is close to being a constant. Values of $\beta$ (ranging from 0.51 to 0.62), measured using different atmospheric constituents, are listed below in Table 5.1.1.

<table>
<thead>
<tr>
<th>Measured Quantity*</th>
<th>$\beta$</th>
<th>$w_0$ (m s$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>T and q</td>
<td>0.6</td>
<td>not given</td>
<td>Businger &amp; Oncley (1990)</td>
</tr>
<tr>
<td>q, CO$_2$, and T</td>
<td>0.57 – 0.60</td>
<td>0</td>
<td>MacPherson &amp; Desjardins (1991)</td>
</tr>
<tr>
<td>q and CO$_2$</td>
<td>0.56</td>
<td>0</td>
<td>Baker et al. (1992)</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.57</td>
<td>0.0 – 0.4</td>
<td>Pattey et al. (1993)</td>
</tr>
<tr>
<td>T and q</td>
<td>0.57 – 0.62</td>
<td>0</td>
<td>Katul et al. (1994)</td>
</tr>
<tr>
<td>T and q</td>
<td>0.51 – 0.61</td>
<td>0</td>
<td>Gao (1995)</td>
</tr>
</tbody>
</table>

* T = temperature; q = water vapor concentration

At least two theoretical parameterizations of $\beta$ are presented in the literature (Businger and Oncley, 1990; Pattey et al., 1993). Based on numerical simulations, Businger and Oncley (1990) proposed that $\beta$ be described by

$$\beta \cong \beta_0 \exp \left( -0.75 \frac{w_0}{\sigma_w} \right) \quad \text{Eq. 5.1.16},$$

where $\beta_0 = \beta(w_0 = 0) \approx 0.6$ and $w_0$ is the threshold vertical wind velocity at which the sampling valves actuate. Using air temperature, carbon dioxide, and water vapor flux densities; Pattey et al., (1993), derived a phenomenological model for $\beta$ represented by
\[ \beta = \beta_0 \left[ 1 - b_0 \left( 1 - \exp \left( -b_1 \frac{w_0}{\sigma_w} \right) \right) \right] \]  

Eq. 5.1.17,

where \( b_0 \) and \( b_1 \) are empirically determined coefficients of the nonlinear model having values of 0.427 and 2.010, respectively.

If \( w_0 \neq 0 \) in the REA method, a “dead band” is created. The dead band is an interval defined in terms of \( w \), centered around \( w = 0 \), in which no air is collected into either the up- or down-reservoir (Pattey et al., 1993) or the air is collected into a neutral-reservoir, \( c^0 \), to ensure that no back pressure builds up in the sampling lines. Having a dead band prolongs the valve life in the REA system and increases the difference between the up and down concentrations, \( \overline{c^+ - c^-} \), of the atmospheric constituent of interest. With a dead band, the atmospheric constituent is sampled when \( w > w_0^+ \), where \( w_0^+ \) is a fixed positive offset for the up-vertical wind, and when \( w < w_0^- \), where \( w_0^- \) is a fixed negative offset (usually of equal magnitude as the positive offset; so \( |w_0^-| = w_0^+ = w_0 \) in the notation presented earlier) for the down-vertical wind.

Since an “accumulated” concentration is required vice the direct covariance, \( \overline{w'c'} \), of the EC method, slower responding sensors and/or bulk laboratory measurements can be utilized. However, other requirements (e.g., sampling rates, switching response lag time, bias to the mean vertical wind velocity, and vertical wind velocity dead band) and technical difficulties play critical roles in the design and operation of the instrumentation used in the REA method (Katul et al., 1996). Regardless, the ability to sample at a constant flow rate and determine the concentration later, after collecting the sample, make REA an excellent method for investigating the flux densities of atmospheric constituents such as aerosol particles.
Equation 5.1.14, as modified by Pattey et al. (1993), served as the basis for calculating the atmospheric flux density with the Atmospheric Radioactivity Laboratory REA system. For $\beta_0$, a fixed value of 0.57 from Table 5.1.1 (Pattey et al., 1993) was utilized in Equation 5.1.17,

$$\beta = 0.57 \left[ 1 - b_0 \left( 1 - \exp \left( -b_1 \frac{w_0}{\sigma_w} \right) \right) \right] \text{ Eq. 5.1.18.}$$

PAEC results calculated from the alpha counting system data files with the EXMAXDP.EXE program (a program which curve fits radon progeny concentrations and decay rates to the minute-by-minute alpha counts) (Maher and Laird, 1985; Knutson, 1989) [see Appendix B] were inserted for the concentrations, $c^+$ and $c^-$, in Equation 5.1.14. Specifically, the PAEC results for the up and down screens (unattached-to-aerosol radon progeny) of the REA system, corrected for the screen collection efficiency and normalized to the average of the up and down filter PAEC results (attached-to-aerosol radon progeny), were used [see Chapter 5.5 for a more detailed explanation of these corrections]. The value for $\sigma_w$ in Equations 5.1.14 and 5.1.18 came from processing the SAM data files using the program NSA2.EXE (a program which averages and statistically analyzes the SAM wind data) (Nemetz, 1997) [see Appendix B] while the remaining variable, the vertical wind velocity threshold, $w_0$, was a control setting on the interface relay control box. For nearly all of the REA measurements, $w_0$ was set at 0.1 m s$^{-1}$.
Dry Deposition Velocity

To deduce the dry deposition velocity, \( v_d \), from the flux density is not a trivial matter. It is possible to define a quantity, \( v \), with units of velocity [m s\(^{-1}\)], which is proportional to the flux density. This “flux velocity” (with appropriate units for the research presented here) is given by

\[
v = \frac{F}{c} \left[ \frac{m}{s} \right] = \left[ \frac{nJ m^{-2} s^{-1}}{nJ m^{-3}} \right] \text{ Eq. 5.1.19,}
\]

where \( F \) is the flux density at the reference height (4 m for the research presented) above the earth’s surface calculated from Equation 5.1.14 and \( c \) is the total mean concentration (\( \bar{c} \) from Equation 5.1.2) of the atmospheric constituent of interest at the same reference height. Based on standard convention, this means that a negative flux velocity, \( v \), is towards the ground.

Under ideal conditions just above the earth’s surface (i.e., when \( \bar{w} = 0 \) and the only removal (sink) process of the atmospheric constituent of interest is dry deposition), the magnitude of the flux velocity should be the same as that of the dry deposition velocity and, to make a positive deposition velocity (i.e., towards the ground) [see definition on pp. 7-8],

\[
v_d = -v \text{ Eq. 5.1.20.}
\]

For the research herein presented, radon progeny (both unattached- and attached-to-aerosol) were the atmospheric constituents of interest. Since the dry deposition velocity, \( v_d \), of attached-to-aerosol radon progeny (the source of the majority of the alpha
activity collected on the glass fiber filters) is normally negligible (smaller by over a factor of 100) compared to that of unattached progeny (the source of the majority of the activity collected on the wire mesh screens) (Schery and Whittlestone, 1995); comparison of the flux densities for both provides a powerful technique for inferring the $v_d$ of the unattached radon progeny. The negligible deposition velocity of the attached-to-aerosol progeny is theoretically predicted by their larger diameter, which makes their Brownian diffusion through the quasi-laminar sublayer at the earth’s surface much slower (Sehmel, 1980; Nicholson, 1988). If the dry deposition velocity of the attached-to-aerosol radon progeny is essentially zero, the up and down concentrations should be the same. Experimental measurements support this assumption (Schery and Wasiolek, 1993; Schery and Whittlestone, 1995). If the up and down attached-to-aerosol concentrations are not the same, it is assumed that there is some system bias, although under some conditions (e.g., a sudden atmospheric pressure drop that causes a sudden exhalation of radon from the ground) this may not be a valid assumption. A system bias is most likely associated with small differences in flow rates when sampling. Again, it is assumed that the up and down attached-to-aerosol concentrations are equal to the average of the two concentrations. Taking this average and dividing it by either the up or down concentrations creates correction factors, which, in turn, are applied to the up and down unattached radon progeny concentrations, respectively, to normalize them. Therefore, some of the REA system’s bias can be eliminated. Additionally, at the high flow rates of the REA system, the wire mesh screens do not capture 100% of the unattached radon progeny. Some portion of the unattached radon progeny is, therefore, collected on the glass fiber filters, reducing the PAEC results of the screens and increasing the PAEC
results of the filters. The PAEC results can be corrected by running the program ALLSCR.EXE. ALLSCR.EXE calculates the collection efficiency of the wire mesh screen based on the screen mesh number (number of wires per inch), sampling flow rate, flow-opening diameter (i.e., the screen diameter), air temperature, barometric pressure, and aerosol particle diameter. ALLSCR.EXE was developed by the Atmospheric Radioactivity Laboratory and uses the algorithm developed by Y. S. Cheng and H. C. Yeh (1980). The corrected PAEC results for the up and down unattached radon progeny, thus, become $c^+$ and $c^-$ in Equation 5.1.14. The total mean unattached radon progeny concentration, $c$, for Equation 5.1.19 is determined by,

$$c = c^+ \frac{t^+}{T} + c^- \frac{t^-}{T} + c^0 \frac{t_0}{T} \quad \text{Eq. 5.1.21},$$

where $c^+$, $c^-$, and $c^0$ are the corrected unattached radon progeny concentrations (PAECs) associated with the up, down, and neutral vertical winds; $t^+$, $t^-$, and $t_0$, are the actual sampling times associated with the up, down, and neutral vertical winds; and $T$ is the total sampling time. In practice, the neutral vertical wind velocity component, $c^0$, was excluded to allow more optimal use of the alpha counting system (i.e., allow counting of concurrent surface collection samples). This exclusion was determined to have an acceptably small (less than 10%) effect on the resultant measurements of $v$. Thus, the $v$ for the unattached radon progeny is obtained by inserting the results of Equations 5.1.14 and 5.1.21 into Equation 5.1.19.

In summary, the accuracy of the REA method for deducing deposition velocity depends upon the extent to which the following assumptions are met:
1. $\overline{w} = 0$;

2. Vertical atmospheric conditions are homogeneous with no significant sources or sinks above the quasi-laminar sublayer, particularly non-homogeneous sources and sinks; and

3. The only significant sink process is dry deposition.

Assumptions 2 and 3 warrant elaboration and some special comments. For unattached radon progeny, there normally exists a source above the surface, i.e., radon gas, and also a sink of non-radioactive aerosol particles in the accumulation mode. Assumptions 2 and 3 can still be met provided that the radon gas and accumulation mode aerosol distributions are vertically homogeneous through the measurement height and that the time scales for radioactive decay and attachment are small compared with the time scale for deposition. Fortunately for radon progeny, this is typically true (Schery and Whittlestone, 1995). Perhaps the strongest experimental evidence of this is that the vertical concentration of the attached radon progeny, subject to minimal dry deposition, is, on average, homogeneous over the heights of interest here ($\leq 4$ m) (Schery and Wasiolek, 1993; Schery et al., 1993; Schery and Whittlestone, 1995).
CHAPTER 5.2
REQUIRED DATA FOR
RELAXED EDDY ACCUMULATION METHOD

The following are the data requirements for computing the flux velocity, $v$, by the REA method:

1. The background activity of the three wire mesh screens and three glass fiber filters prior to installation in the up, down, and neutral vertical wind velocity sampling heads of the REA system (using the lowest of either the counter-scaler or alpha counting system data file) in total counts over a ten minute period;

2. The actual flow rate in cubic feet per minute (CFM) through each sampling head with the wire mesh screen and glass fiber filter in place as measured by the blower flow gauge;

3. The ambient air temperature in degrees Celsius (°C) as measured by the portable meteorological station;

4. The ambient atmospheric pressure in millibars (mb) as measured by the portable meteorological station;

5. The wire mesh screen gauge in wires per inch;
6. The dead band (i.e., vertical wind velocity threshold) setting, \( w_0 \), on the interface relay control box in m s\(^{-1}\);

7. The vertical wind velocity offset setting on the interface relay control box in m s\(^{-1}\);

8. The actual amount of time that each valve of the REA sampling system (up, down, and neutral vertical wind velocity) was open during the sampling period in minutes as calculated from the SAM data file using the NSA2.EXE program;

9. The PAEC results of the individual wire mesh screens and glass fiber filters in nJ m\(^{-3}\);

10. The standard deviation of the vertical wind velocity, \( \sigma_w \), in m s\(^{-1}\), during the sampling period as calculated from the SAM data file using the NSA2.EXE program;

11. The counting efficiencies, \( \varepsilon_{\text{Counter}} \), for each counter-scaler of the alpha counting system used to count the alpha activity on the wire mesh screens and glass fiber filters;

12. The diameter of the exposed wire mesh screen in the REA system sampling head, which is the airflow opening diameter (referred to as the opening size by the ALLSCR.EXE program) in cm.

The horizontal wind speed and direction are required for additional analysis. They are obtained from the processed SAM data file.
CHAPTER 5.3
RELAXED EDDY ACCUMULATION
SAMPLING TECHNIQUE

Sampling by the REA method began with identifying the wire mesh screens that would be placed in each sampling head (up, down, or neutral vertical wind velocity) of the REA system. Each screen had a serial number written on it so as to ensure that an individual screen was not used twice in succession. Otherwise, the buildup in the alpha activity by successive usage could mask the activity collected during subsequent samples. Generally, there were a sufficient number of 635 mesh screens (12 total) to run four consecutive samples without reusing any screens. Both 635 and 400 mesh screens were available, but the 635 mesh screens were preferred due to the higher collection efficiency, $\varepsilon_{Collection}$, for the unattached-to-aerosol radon progeny. Additionally, the identification of the screens by serial numbers ensured that they would be switched between the sampling heads for subsequent measurements rather than reused in the same position over multiple samples. This intentional randomization of the wire mesh screen usage between the sampling heads over multiple samples was intended to eliminate any bias that might be introduced by a particular screen/sampling head combination.

Three unused glass fiber filters were removed from their plastic pouch and marked with a U(p), D(own), or N(eutral). The markings were placed on the rough side
of the filters to facilitate their proper placement in the sampling heads (rough side facing into the air flow). The selected wire mesh screens and marked glass fiber filters were then counted for background activity on the alpha counting system. The counter-scaler used to count each particular screen and filter was carefully noted so that, after sampling, the same counter-scaler would be used for the final collected activity count. If a surface collection measurement was being taken concurrently with the REA sample, then the wire mesh screen and filter that were to be placed in the neutral vertical wind velocity sampling head were not counted for background activity. Rather, the surface collection materials were counted for background activity. The up, down, and neutral screens and filters were placed under different counter-scalers each sampling set (i.e., for one sampling set, the up screen might be counted for both background and collected activity on counter-scaler number 1; whereas for the next sampling set, the up screen might be counted for background and collected activity on counter-scaler number 6). Again, this intentional randomization in the usage of the counter-scalers for counting the up, down, and neutral screens and filters was intended to eliminate any bias that might be introduced by counting the same screen or filter (up, down, or neutral) on the same counter-scaler every sample. The counter-scalers were set to take ten-minute background activity counts, which were later compared to the total counts recorded in the alpha counting system data file for the same period. The background activities recorded by the counter-scalers and alpha counting system data file could be different because the counter-scalers, when started, would begin to count immediately whereas the alpha counting system data file would record the total alpha counts detected each minute. Since radioactive decay is a random process, unless the two methods overlapped exactly
in time, the background counts would likely be different. The lowest ten-minute count from either source was used in calculating the PAEC. All the information was recorded on a sampling run data sheet (sample copy in Appendix A).

While the background activity of the wire mesh screens and glass fiber filters was being counted, a five-minute test run was conducted with the SAM at the sampling site. The SAM data file was then processed using the NSA2.EXE program to evaluate the tilt of the REA system tower. The calculated “tilt” (in degrees) was really a measure of the amount by which the tower was misaligned with the vertical wind velocity ($w$), resulting in $\bar{w} \neq 0$, and, therefore, not perpendicular to the horizontal wind versus perpendicularity with the ground (i.e., gravitational vertical). If the calculated tilt from the vertical wind for the five-minute test run was greater than two degrees ($2^\circ$), the REA system tower was adjusted in a direction to reduce the tilt (the NSA2.EXE program output included the direction in which to tilt the tower). Due to the rudimentary nature of the inclinometers attached to the REA system tower, adjustments of less than $2^\circ$ were considered impractical. In the case that an adjustment was made, a second (and more, if necessary) five-minute test run was conducted to ensure that the tower tilt was reduced to less than $2^\circ$. This process was repeated until the desired tilt was achieved. These preliminary SAM tests ensured that the REA system tower was close to being perpendicular with respect to the horizontal wind at the start of each sampling run set, hopefully resulting in $\bar{w} = 0$.

Once the tower tilt was less than $2^\circ$ and the background checks were completed, the wire mesh screens and glass fiber filters were installed in the appropriate sampling heads of the REA system. With the sampling portion of the REA system still resting on
the ground, each valve (up, down, and neutral vertical wind velocity) was manually opened, in turn, using the interface relay control box. With one of the three valves open, the blower was manually started. As soon as the airflow through the blower flow gauge stabilized, the flow rate (in CFM) was recorded and the blower was stopped. The valve was then shut. This was repeated until the actual flow rate through each individual sampling head, with the screen and filter (upon which the radon progeny would be collected) installed, was measured and recorded. The process of obtaining the individual flow rates generally took significantly less time (10 – 15 seconds) than the overall time that each valve was open during sampling (typically 600 – 900 seconds), therefore, introducing negligible errors in the PAEC results.

Figure 5.3.1. Preparing REA System for Operation at SS Ranch.
With the preliminary measurements completed, the sampling portion of the REA system was hung vertically on the tower (see Figure 5.3.1). The only computer set up with an RS-232 connection to run the SAM was an IBM Personal System/2, Model P70 386 (Model No. 8573-061, International Business Machine Corporation, New Orchard Road, Armonk, NY 10504). It was generally programmed to take 50,400 wind measurements, equaling 40 minutes at a 21 Hz sampling rate. The valve control switches on the interface relay control box were set to AUTO so as to be controlled by inputs from the SAM. The vertical wind velocity threshold ("deadband") setting, $w_0$, on the interface relay control box was verified to be properly positioned (almost exclusively at 0.1 m s$^{-1}$). Likewise, the vertical wind velocity offset setting on the interface relay control box was verified at 0.0 m s$^{-1}$.

The alpha counting system was then set to provide power to the REA system blower for forty minutes from the computer interface box. When all the previously noted settings were completed, the alpha counting system was programmed to start the blower, which occurred within a minute once entered. With the blower set to start, it was necessary to get back to the SAM computer (sometimes over 100 m away) to “enter” the total number of wind measurements to be recorded as the blower started running. This started the SAM operating program, which, in turn, began opening/closing the up, down, and neutral wind velocity valves of the REA system via the interface relay control box.

Once started, the REA system ran independently without the necessity for operator intervention. The blower and SAM would automatically shut down after the set times had elapsed. While the REA system was sampling, the meteorological conditions were recorded, including the ambient temperature (in °C), barometric pressure (in mb),
and relative humidity (%) from the portable meteorological station, as well as the cloud cover (%) and type of clouds. At periodic intervals during sampling (usually three times, roughly ten minutes apart, starting about ten minutes into a sampling run), the readings from the meteorological instruments located at 2 and 8 m (or 10 m, depending on the site/year) on the nearby tower were recorded as a backup for the SAM. The readings included the temperature (in °C), wind speed (in m s⁻¹), and wind direction (compass heading) at the two heights.

As the blower shut down, the sampling portion of the REA system was taken down and the wire mesh screens and glass fiber filters were immediately removed. Within two minutes, they were placed on the same counter-scalers used for determining their background activity. The serial numbers on the screens and the markings on the filters facilitated their proper placement. The counter-scalers were set to count the alpha activity for fifty minutes as a backup to the alpha counting system data file. Though the screens and filters were counted on the alpha counting system for about an hour, only fifty-eight minutes were utilized in the COUNTER.EXE (a program which divided the alpha counting system data file into individual minute-by-minute alpha count files for each counter-scaler, beginning with a specified start time and concluding at the number of minutes specified) [see Appendix B] and EXMAXDP.EXE programs for calculating the PAEC results.

While the filters and screens were being counted, the SAM data file was processed with the NSA2.EXE program to calculate the times (both as percentages and number of minutes) that the individual valves (up, down, and neutral wind velocity) were open, the wind parameters (u, v, and w magnitudes and their corresponding standard
deviations, \( \sigma_u \), \( \sigma_v \), and \( \sigma_w \), and tower tilt. The NSA2.EXE results were recorded on the sampling run data sheet as a backup to the electronic data file.

Depending on the conditions and available time, more (generally up to two) REA sampling runs were performed, repeating the process outlined.
CHAPTER 5.4

RELAXED EDDY ACCUMULATION

DATA PROCESSING

The following outlines the major points regarding the processing of the REA data and calculating the flux velocity. The investigator:

1. Processed the alpha counting system data file using the COUNTER.EXE program, SYS.EML files (information files containing REA sampling data used in the EXMAXDP.EXE program) [see Appendix B], and EXMAXDP.EXE program to obtain the PAEC results for the wire mesh screens and glass fiber filters for the REA sampling run, using the corrected flow rates through each sampling head;

2. Processed the SAM data file using the NSA2.EXE program;

3. Corrected the PAEC results for the wire mesh screens and glass fiber filters for the collection efficiency, $\varepsilon_{\text{Collection}}$;

4. Entered the corrected PAEC results and processed SAM data onto the Deposition Velocity Calculation form (see sample copy in Appendix A);

5. Calculated the vertical flux density, $F_{\text{REA}}$, and flux velocity, $v$, per Equations 5.1.14, 5.1.18, and 5.1.19. In addition to manually calculating $F_{\text{REA}}$ and $v$ on
the Deposition Velocity Calculation form, the same data were input into the VDEP.EXE program, which also calculated $F_{REA}$ and $v$ [see Appendix B]. The results from the Deposition Velocity Calculation form and VDEP.EXE program were compared to verify the correctness of the results;

6. Plotted $F_{REA}$ and $v$ from the REA method versus the average horizontal wind speed.
Several corrections were applied to the REA flux velocity results during their calculation. These corrections are outlined below.

**Screen Mesh Correction**

Using the corrected flow rates, in ℓpm, through the REA system sampling heads (and, thus, the wire mesh screens and glass fiber filters) along with the screen mesh (wires per inch), number of screens, diameter of the sampling system opening (cm), ambient air temperature (°C), barometric pressure (mb), and aerosol particle diameter (nm); the ALLSCR.EXE program calculated collection efficiencies, $\varepsilon_{\text{Collection}}$, for the wire mesh screens (as percentages). These percentages represent the amount of the total unattached radon progeny in the air actually captured on the wire mesh screens. Thus, the EXMAXDP.EXE program PAEC results (representing the unattached radon progeny alpha activity collected on the up, down, and neutral vertical wind velocity screens) were lower in value than the true unattached radon progeny alpha activity in the air (up, down, and...
neutral vertical wind velocity air “parcels”). The wire mesh screen PAEC results were corrected as follows:

\[
\text{Screen - Mesh - Corrected Screen PAEC} = \left( \frac{1}{\varepsilon_{\text{Collection}}} \right) \text{Eq. 5.5.1.}
\]

Similarly, the EXMAXDP.EXE PAEC results for the glass fiber filters, primarily representing the attached-to-aerosol radon progeny alpha activity, were higher in value than the true attached-to-aerosol radon progeny alpha activity in the air (up, down, and neutral vertical wind velocity air “parcels”) due to the inclusion of that fraction of the unattached radon progeny \((1 - \varepsilon_{\text{Collection}})\) that passed through the wire mesh screens. Thus, the glass fiber filter PAEC results were corrected as follows:

\[
\text{Screen - Mesh - Corrected Filter PAEC =}
\]

\[
\left( \frac{1}{\varepsilon_{\text{Collection}}} \right) \left( \frac{1}{\varepsilon_{\text{Collection}}} \right) \text{Eq. 5.5.2.}
\]

**Filter Correction**

As discussed in Chapter 5.1, the present REA method assumes that the attached-to-aerosol radon progeny are minimally removed from the atmosphere by attachment to surrounding surfaces. Thus, the alpha energy concentration of
the attached-to-aerosol radon progeny should be the same in the up, down, and neutral vertical wind velocity air samples for ideal vertically homogeneous atmospheric conditions as discussed in Chapter 5.1. As the PAEC results of the up, down, and neutral vertical wind velocity glass fiber filters primarily represent the attached-to-aerosol radon progeny alpha energy concentration; once the filter PAEC results were corrected using Equation 5.5.2, they ideally should have been exactly the same. If the screen-mesh-corrected PAEC results for the up, down, and neutral vertical wind velocity glass fiber filters were not equal; they were assumed to be equal to their average as outlined in Chapter 5.1 and were, therefore, adjusted to their combined average. Normalizing the filter PAEC results should correct for any potential system bias due to small differences/fluctuations in the sampling flow rate and certain violations of the vertically homogeneous atmospheric conditions.

In practice, in normalizing to the filters, only the screen-mesh-corrected PAEC results of the up and down vertical wind velocity filters were utilized. This was done for the following reasons:

1. The neutral vertical wind velocity sampling valve was generally open for the shortest period of time of any of the three valves during sampling with the REA system.
2. The average of the screen-mesh-corrected PAEC results for the up and down vertical wind velocity glass fiber filters was considered to be accurate enough for calculating the correction. An evaluation of the
average filter PAEC, including and excluding the neutral vertical wind velocity filter PAEC, was conducted on the final set of REA measurements (i.e., after exclusion for other reasons as discussed later). The difference between the average filter PAEC including the neutral vertical wind velocity filter and the average excluding it was less than 10% in all but one case where it was 12%. The majority of the differences were approximately 5% or less.

3. The neutral vertical wind velocity wire mesh screen and glass fiber filter were often not counted for alpha activity so as to allow two counter-scalers and channels of the alpha counting system to be utilized for counting concurrently taken surface collection samples.

The screen-mesh-corrected screen PAEC results were normalized to the filters as follows:

\[
\text{Filter - Normalized - Screen PAEC (unattached)} = \frac{\text{Screen - Mesh - Corrected Screen PAEC (unattached)}}{\frac{\text{Corrected Up Filter PAEC (attached) + Corrected Down Filter PAEC (attached)}}{2 (\text{Corrected Up/Down Filter PAEC (attached)})}}
\]

\text{Eq. 5.5.3},
where the divisor (up or down filter PAEC) matched the screen PAEC (up or down, respectively) and the Screen-Mesh-Corrected PAEC results from Equations 5.5.1 and 5.5.2 were used.

**Delay Correction**

Inherent to any REA system is the delay between the time a certain vertical wind velocity is detected and the time when the appropriate valve is opened. This delay introduces a potential error into the calculated flux (underestimating it) because some amount of the up vertical wind velocity “parcels” is sampled through the down vertical wind velocity sampling head and vice-versa. The REA system built by New Mexico Tech is no different. In other REA systems, different methods have been employed to correct for this delay. Baker *et al.* (1992), derived an approximate mathematical formula based on the actuation time of the valves, the response time of the sonic anemometer, and the eddy reversal frequency to determine the percentage of the true concentration that was actually being measured. The eddy reversal frequency is defined as the mean frequency with which the vertical wind reverses direction (up/down). Baker *et al.* (1992), reported that the measured concentration values ranged from 60 % to 93 % of the true concentration. Majewski *et al.* (1993), and Nie *et al.* (1995), compared their REA measurements to EC measurements for the same atmospheric constituent. Their solution was to scale the $\beta$ in Equation 5.1.13 in order that the REA measurements matched the EC measurements. Since the correction to $\beta$ is dependent on the particular sample, extrapolating these
corrections to an REA system, which is not being correlated to an EC system, is difficult. Oncley et al. (1993) measured the delay \([0.30 \pm 0.05 \text{ s}]\) of their REA system experimentally.

The delay of the New Mexico Tech REA system was measured using an oscillation experiment. The sonic anemometer sensor head was enclosed in a cardboard funnel. The screen/filter assemblies were removed from the up and down vertical wind velocity sampling heads so that flexible hoses could be directly connected to the PVC piping. The flexible hose connected to the up vertical wind velocity intake was connected to the cardboard funnel so as to “create” a “down” vertical wind across the sonic anemometer sensor head. Similarly, the hose connected to the down vertical wind velocity intake was connected so as to “create” an “up” vertical wind. The hoses used were less than 1 m in length such that their contribution, based on the pressure pulse moving close to the speed of sound, would be negligible. With the blower turned on, a “vertical” wind was generated in the cardboard funnel enclosing the sonic anemometer sensor head. An “up” wind would cause the up vertical wind velocity valve to actuate, resulting in a “down” wind; and a “down” wind would cause the down vertical wind velocity valve to actuate, resulting in an “up” wind. This resulted in periodic oscillations of the air in the funnel surrounding the sonic anemometer sensor head. The frequency with which the up or down vertical wind velocity valves were opening and closing was measured. From this frequency the oscillation period was calculated. This oscillation period is a measure of the system delay. For the New Mexico Tech REA system the system delay was
measured at 125 ± 25 ms (Schery et al., 1998). This result included a correction for the hose lengths. The delay was then used in an experimentally based algorithm to correct for the delay-related error in the PAEC results (Nemetz, 1997). Essentially, in the algorithm, the recorded vertical wind was analyzed retrospectively to determine whether or not the vertical wind was actually up or down at the time that a given valve was open. The measured PAEC corresponding to a given valve was then adjusted (higher or lower) a small amount in proportion to the true time that the valve should have been open. The details regarding the delay correction algorithm are provided in Appendix B. The delay correction was applied to the final REA data set (after the exclusions discussed below were made).

128 REA equivalent flux velocity measurements were obtained, broken down by year and location, as listed in Table 5.5.1. The number of measurements excluded and the reason for the exclusion are included.
Table 5.5.1. Breakdown of REA Flux Velocity Measurements.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Measurements (No. Excluded in Final Set)</th>
<th>Site Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>13 (13 *)</td>
<td>SS Ranch</td>
</tr>
<tr>
<td>1996</td>
<td>64 (36 *; 3 **)</td>
<td>SS Ranch</td>
</tr>
<tr>
<td>1997</td>
<td>17 (8 **)</td>
<td>SS Ranch</td>
</tr>
<tr>
<td>1998</td>
<td>17 (4 **)</td>
<td>Socorro Airport</td>
</tr>
<tr>
<td>1999</td>
<td>17 (1 **)</td>
<td>Socorro Airport</td>
</tr>
</tbody>
</table>

* Data unavailable to make screen mesh correction.

** Tilt from true vertical wind direction exceeded acceptable tolerance.

Error Analysis

The error sources associated with the individual REA measurements were evaluated. Table 5.5.2 identifies the source and magnitude of each error while the notes below discuss how each error was corrected for or its impact on the measurement error depicted by the error bars on the subsequent plots.
Table 5.5.2 REA Flux Velocity Measurement Error Sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Method of Determination</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAEC Error*</td>
<td>Random</td>
<td>EXMAXDP.EXE Program</td>
<td>1 Sigma [7% (average)]</td>
</tr>
<tr>
<td>Tilt **</td>
<td>Random</td>
<td>NSA2.EXE Program</td>
<td>Not evaluated**</td>
</tr>
<tr>
<td>Screen Mesh† Correction</td>
<td>Systematic</td>
<td>ALLSCR.EXE Program</td>
<td>17% (average)</td>
</tr>
<tr>
<td>Filter Correction†</td>
<td>Random</td>
<td>Average of filter PAEC’s</td>
<td>Note 1.</td>
</tr>
<tr>
<td>Delay Correction††</td>
<td>Systematic</td>
<td>DELAY.CPP Program</td>
<td>31% (average)</td>
</tr>
</tbody>
</table>

Note 1. The magnitude of the Filter Correction is included in that of the Screen Mesh Correction.

* This error was carried through in the flux velocity calculation using standard error propagation as shown on the sample Deposition Velocity Calculation form (Appendix A). This was the principle contributor to the measurement error bars.

** This error was not evaluated with respect to the REA measurements and could not be corrected for. Based on the modified Bowen ratio Vertical Wind Velocity Correction, this error is likely to be around 12% on average.

† These errors were corrected for during the calculation of the flux velocity as shown on the sample Deposition Velocity Calculation form (Appendix A) and did not contribute to the overall measurement error.

†† An adjustment for the delay was applied to the original flux velocity error (resulting from the PAEC Error) when correcting the flux velocity for the system delay, thus, contributing to the measurement error bars.
All 128 REA measurements (before exclusion and uncorrected for delay) are plotted versus the average horizontal wind speed in Figure 5.5.1. The data are broken down as listed in Table 5.5.1.

(Intentionally Blank)
Figure 5.5.1. Combined Uncorrected REA Flux Velocity vs Horizontal Wind Speed Sorted by Year/Site Location.
Of the 128 REA measurements, **only 63 were included in the final data set.**

The following REA measurements were excluded:

1. **49 REA measurements were excluded because the screen mesh correction had not been (and could not be) applied.** The principle reason for not being able to apply the correction was the fact that the actual flow rate through each sampling head was not determined or recorded for those measurements. It was identified during the summer of 1996 that the flow rates were neither identical through each sampling head nor equal to the laboratory measurements. This correction is critical to the accuracy of the flux velocity calculation.

2. **16 REA measurements were excluded because the tilt exceeded 2.0 degrees.** The accuracy of the REA system in terms of sampling the up/down vertical wind velocity parcels depended on the SAM being aligned with the vertical wind, $w$, and perpendicular to the direction of the rolling eddies (i.e., the horizontal wind). Proper orientation should hopefully result in a zero average vertical wind velocity ($\bar{w} = 0$) during sampling. Unfortunately, the proper alignment of the system could not be assured for all possible wind speeds/directions that might arise during sampling after the initial alignment testing/adjustment. Therefore, for some REA measurements the tilt exceeded 2.0 degrees.
The 63 REA measurements included in the final data set are plotted versus the average horizontal wind speed in Figure 5.5.2. The delay correction has not yet been applied. The data have been sorted by site location.

Consideration was also given to excluding REA measurements for which the horizontal wind originated from a direction considered obstructed (i.e., having uncharacteristically large obstacles closer than 100 m upwind of the REA system intakes). Figure 5.5.3 shows the final 63 REA measurements sorted by whether or not the wind direction was considered obstructed.

Analysis of the data in Figure 5.5.3 indicated that the data points from obstructed wind directions have little systematic difference from the overall data set. Therefore, they were not excluded.

(Intentionally Blank)
Figure 5.5.2. Final Uncorrected REA Data Set Sorted by Site Location.
Figure 5.5.3. Final Uncorrected REA Data Set Sorted by Obstructed/Unobstructed Sectors.
Delay corrections were calculated for the final REA data set. As the oscillation amplitude and frequency of the vertical wind, $w$, increase with increasing horizontal wind speed; it is reasonable to expect the system delay to have a greater impact at higher wind speeds. Therefore, the delay correction factors (DCF) were plotted versus horizontal wind speed. Figure 5.5.4 shows the calculated DCFs for the final 63 REA measurements plotted versus the average horizontal wind speed. The DCF plot shows a linear response to the horizontal wind speed up to approximately $7 \text{ m s}^{-1}$ where it begins to level off (excluding the two outlier data points). The specific causes for the system response seen in Figure 5.5.4 were not investigated as part of this research and remain undetermined. Further investigation is recommended. From Figure 5.5.4 the maximum error of the New Mexico Tech REA system appears to be approximately 50%.

The DCFs were applied to the final 63 REA measurements, which were then plotted versus the average horizontal wind speed. Figure 5.5.5 shows the delay-corrected flux velocities sorted by site location (as in Figure 5.5.2). The REA results were then analyzed (see Chapter 5.6).
Figure 5.5.4. Delay Correction Factor (DCF) vs Average Horizontal Wind Speed.
Figure 5.5.5. Delay-Corrected REA Flux Velocity vs Horizontal Wind Speed Sorted by Site Location.
As discussed in Chapter 5.5, a total of 128 REA flux velocity measurements were made. Figure 5.5.1 shows all 128 REA flux velocity results plotted versus the average horizontal wind speed. Results are identified by year and sampling site location at which they were taken. The error bars represent the cumulative error calculated (see Table 5.5.2). The primary error included is the PAEC counting error determined by the EXMAXDP.EXE program when processing the alpha counting system data file. Only 63 REA flux velocity measurements were selected for further analysis (see Chapter 5.5). Figure 5.5.5 shows the final 63 delay-corrected REA flux velocity measurements plotted versus the average horizontal wind speed. The cumulative error for the final 63 measurements increased due to the 125 ms delay inherent in the New Mexico Tech REA system. Figure 5.5.5 separates the final data set between the two sampling site locations, the SS Ranch and the Socorro Municipal Airport. The reason for this separation is discussed later.

Figure 5.5.5 exhibits significant data scatter. Statistical analysis of the data indicated that an important source of the data scatter was having a non-zero average vertical wind velocity (i.e., $\bar{w} \neq 0$). The absolute value of the average vertical wind
velocity, $|\bar{w}|$, as calculated by the NSA2.EXE program for the 63 final data points, is plotted versus the average horizontal wind speed in Figure 5.6.1. The data are separated by site location. Trendlines are provided only for the purpose of identifying possible differences, if any, between the values from the two site locations.

From Figure 5.6.1 it is evident that $|\bar{w}|$ and the scatter of $|\bar{w}|$ increase with increasing horizontal wind speed. Statistically, the larger the value of a fluctuating variable, the larger the absolute variation; so, this is not unexpected. It also appears from the trend lines that possibly the terrain roughness height, $z_0$, has different effects on $|\bar{w}|$ at the two site locations. The roughness height at the SS Ranch was calculated to be 30 cm, while at the Socorro Airport it was calculated to be 7 cm. This terrain effect is even more evident when the standard deviation of the vertical wind velocity, $\sigma_w$, is plotted versus the average horizontal wind speed as in Figure 5.6.2.
Figure 5.6.1. Absolute Value of Vertical Wind Velocity vs Average Horizontal Wind Speed.
Figure 5.6.2. Vertical Wind Velocity Standard Deviation vs Average Horizontal Wind Speed.
Because of the apparent difference in the relationship of the vertical wind velocity to the average horizontal wind speed between the two site locations (validated statistically), the data from the two sites were analyzed separately.

For ideal REA measurements directed at deducing dry deposition due to eddy diffusion alone, it is desirable to have the average vertical wind speed as small as possible. Thus, the REA flux velocity data from the two sites were evaluated with respect to the absolute value of the vertical wind velocity, $|w|$, by successively excluding the data points having larger absolute vertical wind velocities for the SS Ranch and Socorro Airport, respectively. The data were divided into the following categories:

- All REA flux velocity data (each site)
- REA flux velocity data having $|w| < 10$ cm s$^{-1}$ (each site)
- REA flux velocity data having $|w| < 5$ cm s$^{-1}$ (each site)
- REA flux velocity data having $|w| \leq 3$ cm s$^{-1}$ (each site)

Three cm s$^{-1}$ was selected as the minimum value for $|w|$ in the analysis because it was considered low enough so as not to mask the underlying flux velocity (which appears to be on the order of 10 cm s$^{-1}$). Figures 5.6.3 and 5.6.4 show the results of this graphical analysis.
Figure 5.6.3. SS Ranch REA Measurements Sorted by $|w|$.
Figure 5.6.4. Socorro Airport REA Measurements Sorted by $|w|$. 
The analysis showed that excluding the data having larger absolute vertical wind velocities does not significantly impact the resulting best-fit linear curve for each site when analyzed separately with one exception. For the case of $|\vec{w}| < 5 \text{ cm s}^{-1}$ in Figure 5.6.4, one apparent outlier at an approximate horizontal wind speed of 13 m s$^{-1}$ results in a notably different best-fit linear curve. But, as is also shown in the same figure, the best-fit linear curves for $|\vec{w}| < 10 \text{ cm s}^{-1}$ and $|\vec{w}| \leq 3 \text{ cm s}^{-1}$ are very similar. These graphical results were confirmed with statistical t-tests of the data. Statistical analyses on the combined data from the two site locations proved unacceptable, further indicating a distinction between the two sites. The delay-corrected REA flux velocity data having $|\vec{w}| \leq 3 \text{ cm s}^{-1}$ are plotted versus the average horizontal wind speed and by site location in Figure 5.6.5. The best-fit linear curves are included in Figure 5.6.5 to highlight the apparent differences between the two sites.

Excluding the data points having $|\vec{w}| > 3 \text{ cm s}^{-1}$ significantly reduced the data scatter, resulting in a more apparent correlation between the flux velocity and horizontal wind speed.
Figure 5.6.5. Delay-Corrected REA Data Having $|w| \leq 3 \text{ cm s}^{-1}$ and Sorted by Site Location.
Other possible sources for the data scatter were investigated. Particularly, the average temperature gradient and the change in the temperature gradient (over the time period during which the REA measurement was conducted) were investigated. The average temperature gradient (in units of degrees C per meter) is the temperature difference, $\Delta T$, between the temperature sensors located at 2 and 8 (or 10) m on the meteorological instrument tower divided by their height difference in meters. The temperature gradient change was calculated by subtracting the temperature gradient calculated at or near the start of the sampling run from the temperature gradient calculated at or near the end of the sampling run and dividing by the total time in between, giving units of degrees C per meter per minute. A positive gradient (where the temperature increases as altitude increases) is usually found during nighttime hours, while a negative gradient (decreasing temperature as altitude increases) is usually found in the daytime. A positive temperature gradient is usually indicative of a stable air layer, having little mixing and high concentrations of radon progeny. A negative temperature gradient is generally unstable with significant mixing and lower concentrations of radon progeny. For the small vertical distance involved with this research, the error in the temperature gradient due to the dry adiabatic lapse rate, $\Gamma$, is not significant in comparison to the instrument error. Five of the final set of 63 REA measurements did not have temperature data available for calculating gradients. Figures 5.6.6 and 5.6.7 show the 58 REA flux velocity measurements plotted versus the average temperature gradient and the temperature gradient change, respectively.
Figure 5.6.6. Delay-Corrected REA Flux Velocity vs Average Temperature Gradient.
Figure 5.6.7. Delay-Corrected REA Flux Velocity vs Temperature Gradient Change.
Although the scatter is significant, Figure 5.6.6 weakly suggests that more stable atmospheric conditions tend to result in smaller magnitude flux velocities. This is an important result that is expected with eddy diffusion theory and addressed in the literature; it will be discussed later. Figure 5.6.8 shows the same data as Figure 5.6.5, but separated by data having a negative temperature gradient change from those having a positive or zero temperature gradient change.

From Figure 5.6.8 it is evident that excluding the unstable/negative temperature gradient change data does further reduce the scatter and may be a key contributor. But unstable conditions are valid atmospheric conditions. Thus, separate analysis, vice exclusion, may be warranted. This will be discussed in more detail later.

The delay-corrected REA data for each site location (without excluding for atmospheric stability) were analyzed using the linear regression packages found in Microsoft Excel and Number Cruncher Statistical Software (NCSS) (NCSS Statistical Software, 329 North 1000 East, Kaysville, UT 84037) for a linear best-fit curve (of the type \( y = ax + b \)). Figures 5.6.9 and 5.6.10, respectively, show the data for the SS Ranch and Socorro Airport, including error bars, with the best-fit linear curves and the 95% mean confidence level boundaries.
Figure 5.6.8. Delay-Corrected REA Data Having $|w| \leq 3$ cm s$^{-1}$ and Sorted by Temperature Gradient Change.
Figure 5.6.9. Best-Fit Linear Curve to SS Ranch REA Data with 95% Mean Confidence Curves.
Figure 5.6.10. Best-Fit Linear Curve to Socorro Airport REA Data with 95% Mean Confidence Curves.
The data for each site location were further analyzed for other possible curve fits. The following families of equations were evaluated:

- \( y = ax^2 + b \) (quadratic)
- \( y = ax^2 + bx + c \) (second order polynomial)
- \( y = ae^{bx} + c \) (exponential)
- \( y = ax^b + c \) (power)

Figure 5.6.11 shows one of the more interesting results. Although the goodness-of-fit indicator, \( R^2 \), does not suggest decisively that a non-linear function is superior to a simple linear fit, there is some evidence that the flux velocity increases more rapidly with increasing horizontal wind speed than implied by a simple linear fit. There is no particular physical basis, though, for the application of a non-linear function to the flux velocity measurements.

Because the REA flux velocity exhibits a potential dependence on both the average horizontal wind speed and the average temperature gradient, a multilinear analysis was performed on the 58 flux velocity measurements for which the average temperature gradient was available. Figure 5.6.12 shows a three-dimensional (3D) scatter plot of the flux velocity versus the average horizontal wind speed and temperature gradient. The orange plane outlined in Figure 5.6.12 is a planar fit to the data as determined by NCSS. Figure 5.6.13 shows the same data, but as a 3D surface plot. Note that the aspect has been rotated 180º between Figures 5.6.12 and 5.6.13 so as to view more clearly those data points having particularly negative flux velocities.
Figure 5.6.11. Best-Fit Polynomial Curve to SS Ranch REA Data.

SS RANCH
DELAY-CORRECTED REA FLUX VELOCITY
vs HORIZONTAL WIND SPEED
(Best-Fit Polynomial Curve)

Flux Velocity = -0.007 (Horizontal Wind Speed)^2 + 0.04 (Horizontal Wind Speed) - 0.09
R^2 = 0.25
Figure 5.6.12. 3D Scatter Plot of REA Measurements.
Figure 5.6.13. 3D Surface Plot of REA Measurements.
Figures 5.6.12 and 5.6.13 both show a relatively strong correlation between the flux velocity and horizontal wind speed (increasingly negative with increasing wind speed) and a weak correlation between the flux velocity and average temperature gradient (increasingly negative with increasingly negative [unstable] temperature gradient). A simple multilinear regression was performed using NCSS with similar results. This does not preclude the possibility that a more complex nonlinear correlation might exist, but there is no physical basis for drawing such a conclusion.

For the SS Ranch site the magnitude of the average flux velocity, $v$, and its standard deviation of the mean (including all data regardless of atmospheric stability or vertical wind velocity) were $8.5 \pm 2.2 \text{ cm s}^{-1}$ for an average horizontal wind speed of $3.2 \text{ m s}^{-1}$ and an average vertical temperature gradient of $0.03 ^\circ \text{C m}^{-1}$ (near neutral). For the Socorro Airport site the average magnitude of $v$ and its standard deviation of the mean (again, including all the data) were $11.1 \pm 2.7 \text{ cm s}^{-1}$ for an average horizontal wind speed of $6.6 \text{ m s}^{-1}$ and an average vertical temperature gradient of $0.02 ^\circ \text{C m}^{-1}$ (near neutral).

Since a difference between the two sampling site locations would not be unexpected, the resulting linear best-fit curves shown in Figures 5.6.9 and 5.6.10 were evaluated to determine whether or not the difference was statistically significant. Table 5.6.1 shows the results of a statistical comparison between the SS Ranch and Socorro Airport REA flux velocities.
Table 5.6.1. Statistical Comparison of SS Ranch and Socorro Airport REA Flux Velocities.

<table>
<thead>
<tr>
<th>Sample Portion</th>
<th>SS Ranch</th>
<th>Socorro Airport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Data Pts.</td>
<td>Mean $\nu$</td>
</tr>
<tr>
<td>Middle 50%</td>
<td>16</td>
<td>-6.30 cm s$^{-1}$</td>
</tr>
<tr>
<td>Lower 25%</td>
<td>9</td>
<td>-25.30 cm s$^{-1}$</td>
</tr>
<tr>
<td>Upper 25%</td>
<td>9</td>
<td>4.33 cm s$^{-1}$</td>
</tr>
</tbody>
</table>
From Table 5.6.1 it is clear that there is no statistically significant difference between the REA flux velocity results from the SS Ranch and the Socorro Airport as measured by this type of test. This, though, does not necessarily explain away the difference in the linear best-fit curves shown in Figures 5.6.9 and 5.6.10.

Overall, averaging the results from both sites yielded a $v$ of $9.7 \pm 1.7 \text{ cm s}^{-1}$ for an average horizontal wind speed of $4.7 \text{ m s}^{-1}$ and an average vertical temperature gradient of $0.03 \degree \text{C m}^{-1}$ (near neutral). This result is consistent with more recent results found in the literature for both nanometer-size aerosol particles and HNO$_3$ (Schery and Whittlestone, 1995; Schery et al., 1998; Horii et al., 2001). It also appears that terrain roughness might play a role in the flux velocity, though the difference in roughness between the two sampling sites was too small to establish a quantitative relationship. However, terrain roughness obviously plays a role in increasing the vertical wind velocity and its standard deviation. Data scatter significantly increases with horizontal wind speed, particularly above $7 \text{ m s}^{-1}$. Excluding those data points having higher vertical wind velocities can reduce the data scatter. Likewise, changes in the temperature gradient during sampling also appear to have a measurable effect on the data scatter. The exclusion of those data points having negative temperature gradient changes further reduces the scatter. Alternatively, though, it may be the case that positive temperature gradient changes make the flux velocity more negative (note Figure 5.6.8). These effects should be quantified and the exact relationships modeled in future research.

Additional measurements, increasing the statistical database, would likely improve the overall quality of the results from the REA method. Also, longer sampling times, especially at the higher horizontal wind speeds (above $7 \text{ m s}^{-1}$), would hopefully
result in $\bar{w}$ being closer to zero, reducing the data scatter and, again, improving the data quality.

After consideration of the above factors with respect to the data scatter, there still remains a part of the scatter that cannot be explained by the variables so far measured. If interpreting $v$ as the negative of the deposition velocity (see p. 77), clearly the positive values presented are impossible. One likely explanation is a violation of the ideal conditions for the REA method presented in Chapter 5.1. While, on average, there is experimental evidence that these conditions are met; for individual measurements, it is certainly possible to have radon gas concentrations (sources) and accumulation mode aerosol particle concentrations (sinks) that are not uniform with height. These factors alone could lead to a few anomalous positive deposition velocities.
PART 6

MODIFIED BOWEN RATIO

METHOD
CHAPTER 6.1
MODIFIED BOWEN RATIO THEORY

The modified Bowen ratio method for measuring dry deposition velocity, $v_d$, is presented by Businger (1986) in his evaluation of current micrometeorological techniques. He notes that turbulence indiscriminately transfers any scaler quantity, resulting in mean concentration profiles that are similar to each other. As a consequence, if the flux density, $F_{e_1}$, and gradient of one quantity, $c_1$, are known; then only the gradient of another quantity, $c_2$, need be known in order to determine the flux density, $F_{e_2}$, of the second quantity. Simply, this is

$$F_{e_2} = F_{e_1} \frac{\Delta c_2}{\Delta c_1} \text{ Eq. 6.1.1,}$$

where $\Delta c_1$ and $\Delta c_2$ are the concentration differences of the first and second quantities, respectively, over the same vertical distance.

The turbulent flux density of a trace constituent can also be determined by eddy correlation theory from the covariance of the perturbation value of the vector quantity, vertical wind velocity, $w'$, and the perturbation value of the scalar concentration, $c'$, of the atmospheric species of interest (e.g., carbon dioxide, water vapor, temperature, aerosol particles, etc.) (see Chapter 5.1)
Therefore, as Businger (1986) suggests, using the Bowen ratio similarity, one way Equation 6.1.1 can be written, using Equation 6.1.2, is

\[ F' = \frac{w'c_1'}{\theta} \quad \text{Eq. 6.1.2}, \]

where \( \theta \) (replacing \( c_1 \)) is potential temperature, \( \theta' \) is its perturbation about the mean, and \( c \) (replacing \( c_2 \)) is the unattached radon progeny concentration.

Potential temperature, \( \theta \), and actual temperature, \( T \), are related by

\[ \theta = T \left( \frac{1000}{P} \right)^{R/c_p} \quad \text{Eq. 6.1.4}, \]

where \( P \) is barometric pressure (in mb), \( R \) is the specific gas constant, and \( c_p \) is the specific heat at constant pressure. If pressure changes little with height, as is true for the small heights involved in the measurements presented here, then \( T \) can replace \( \theta \) in Equation 6.1.3.

Thus, Equation 6.1.3 can be rewritten, using the parameters measured by the SAM and other equipment, as

\[ F' = \frac{w'T'}{\Delta T} \quad \text{Eq. 6.1.5}, \]

where \( w'T' \) is the covariance of the perturbation values of the vertical wind velocity and temperature (\( w' \) and \( T' \) are the perturbation values about the mean values, \( \bar{w} \) and \( \bar{T} \)), \( \Delta c \).
is the difference between the unattached-to-aerosol radon progeny concentration (PAEC results) for air samples collected at 2 and 8 meters, and $\Delta T$ is the average of the temperature differences between 2 and 8 meters recorded during sampling.

$\overline{w'T'}$ was determined by running the CONVERT.EXE program (a program supplied with the SAM which converts the SAM ASCI file into a standard text file) on the SAM data file and then importing the resultant text file (containing the values of the vertical wind velocity, $w$, and speed of sound, $v_s$, recorded at 21 Hz) into Microsoft Excel where the covariance could be automatically computed using the resident statistical data package. The temperature was calculated from the speed of sound recorded in the SAM data file by rewriting

$$v_s = \sqrt{\frac{\gamma RT}{M}} \quad \text{Eq. 6.1.6,}$$

the speed of sound equation for an ideal gas, where $\gamma$ is a constant (equal to 1.40 for air), $R$ is the gas constant, $T$ is the temperature, and $M$ is the average molecular mass of air ($28.8 \times 10^{-3} \text{ kg mol}^{-1}$). $w'$ and $T'$ were calculated by taking the mean values of the SAM vertical wind velocity and temperature, $\overline{w}$ and $\overline{T}$, and then calculating the perturbations from the mean for each recorded set of SAM vertical wind and temperature values.

The PAEC results for the wire mesh screens from the two blowers located at 2 and 8 meters above ground level were calculated from the alpha counting system data files using the EXMAXDP.EXE program. After correcting for screen collection efficiency and adjusting the PAEC results to the average side-by-side sampling run screen PAEC ratio, the screen PAEC results were used to calculate $\Delta c$. 

135
The discussion of the measurement techniques in Chapter 5.1 applies here as well with the exception of the method for determining the mean concentration of the unattached-to-aerosol radon progeny, \( c \). Since two different blowers were utilized for the modified Bowen ratio method, the wire mesh screen PAEC results were not only corrected for collection efficiency, \( \epsilon_{\text{Collection}} \), but were also adjusted based on the results of side-by-side sampling runs performed prior to and after each modified Bowen ratio up/down sampling run. In these side-by-side runs the ratio of the wire mesh screen PAEC result (corrected for collection efficiency) of one blower to that of the other was recorded. An average ratio was calculated from the “before” and “after” ratios. Then, one of the wire mesh screen PAEC results from the actual up/down sampling run was multiplied by the average side-by-side screen ratio. This, in effect, corrected for any flow rate differences between the blowers.

As also discussed in Chapter 5.1 for the REA method, a quantity, \( v \), with units of velocity \([\text{m s}^{-1}]\), proportional to the flux density was defined, having the standard convention that a negative flux velocity, \( v \), is towards the ground. In the modified Bowen ratio method, if the covariantly-determined flux density is accurate and the only process affecting the concentration gradients and flux densities is dry deposition, the magnitude this flux velocity for the unattached radon progeny will be the same as that of the dry deposition velocity and, to make a positive deposition velocity,

\[
v_d = -v \quad \text{Eq. 6.1.7.}
\]

However, there are additional issues besides those presented at the end of Chapter 5.1, related to the structure of gradients and their measurement, which must be considered:
1. The ratio of the two sampling heights, $z_2/z_1$, should be between 2 and 4 (for the modified Bowen ratio method measurements presented here, the ratio was 4). If the ratio is too large, some of the basic approximations of the gradient method become invalid; but, if it is too small, the differences between the vertical wind velocities, $w$, and temperatures, $T$, at the two heights may not be resolvable (Arya, 1988).

2. The lowest sampling height should satisfy the criterion $z/z_0 >> 1$ (Businger, 1986; Seinfeld and Pandis, 1998) (for the research presented, the lowest sampling height ($z = 2$ m) and terrain roughness ($z_0 = 7$ cm) result in a ratio of 28.6). This criterion can be difficult to achieve over extremely rough surfaces, placing the measurements above the constant-flux layer.

Methods involving flux gradients are most applicable to neutral or unstable atmospheric conditions (for the modified Bowen ratio measurements presented here, the atmospheric conditions were unstable) and are generally considered difficult to apply and interpret under stably stratified conditions (Arya, 1988; Businger and Delany, 1990; Schery and Whittlestone, 1995).
CHAPTER 6.2
REQUIRED DATA FOR
MODIFIED BOWEN RATIO METHOD

The following are the data requirements for computing the flux velocity, $v$, by the modified Bowen ratio method:

**Blower Flow Check**
1. The average of two flow rate measurements using the dry flow test meter for each of the two blowers with wire mesh screens and glass fiber filters installed.

**Side-by-Side Sampling Runs**
1. The background activity of the two wire mesh screens prior to installation into the sampling heads of the two blowers (using the lowest of either the counter-scaler or alpha counting system data file) in total counts over a ten minute period;
2. The actual amount of time that the two blowers were running as programmed into the alpha counting system computer and shown on the alpha counting system data file;
3. The ambient air temperature in degrees Celsius (°C) as measured by the portable meteorological station;
4. The ambient atmospheric pressure in millibars (mb) as measured by the portable meteorological station;
5. The wire mesh screen gauge in wires per inch;
6. The diameter of the wire mesh screen which is also the air flow opening diameter, referred to as “opening size” in the ALLSCR.EXE program, in cm;
7. The counting efficiencies (ε\text{Counter}) for the counter-scalers of the alpha counting system used to count the activity on the wire mesh screens;
8. The PAEC results of the individual wire mesh screens used in the two blowers in nJ m\(^{-3}\).

**Up/Down Sampling Run**

1. The background activity of the two wire mesh screens prior to installation into the sampling heads of the two blowers (using the lowest of either the counter-scaler or alpha counting system data file) in total counts over a ten minute period;
2. The actual amount of time that the two blowers were running as programmed into the alpha counting system computer and shown on the alpha counting system data file;
3. The ambient air temperature in degrees Celsius (°C) as measured by the portable meteorological station;
4. The ambient atmospheric pressure in millibars (mb) as measured by the portable meteorological station;

5. The wire mesh screen gauge in wires per inch;

6. The diameter of the wire mesh screen which is the air flow opening diameter, referred to as “opening size” in the ALLSCR.EXE program, in cm;

7. The counting efficiencies ($\varepsilon_{\text{counter}}$) for the counter-scalers of the alpha counting system used to count the activity on the wire mesh screens;

8. The PAEC results of the individual wire mesh screens used in the two blowers in nJ m$^{-3}$;

9. The average ratio of the wire mesh screen PAEC results (corrected for screen collection efficiency, $\varepsilon_{\text{collection}}$) for the two blowers for the two side-by-side sampling runs, using the PAEC result for the blower placed at 8 m during the up/down sampling run over the PAEC result for the blower placed at 2 m during the up/down sampling run;

10. The average temperature difference in degrees Celsius (ºC) between the temperature sensors at 8 m and 2 m on the meteorological instrument tower as calculated from several recorded measurements made during the up/down sampling run;

11. The perturbation value of the vertical wind velocity, $w'$, in m s$^{-1}$, as calculated from the SAM data file using the CONVERT.EXE program;

12. The perturbation value of the speed of sound, $v_s'$, in m s$^{-1}$, as calculated from the SAM data file using the CONVERT.EXE program.
The horizontal wind speed and direction are required for additional analysis. They are obtained from the processed SAM data file.
CHAPTER 6.3

MODIFIED BOWEN RATIO

SAMPLING TECHNIQUE

Sampling by the modified Bowen ratio method began with measuring the flow rates through each individual blower (designated as Blower A and Blower B) using the dry test meter (Model DTM-325-4, American Meter Company, 13500 Philmont Avenue, Philadelphia, PA 19116). Each blower was connected to the trailer power source, as it would be for the main up/down sampling run. This meant that the extension cord, required to allow one blower to reach a height of 8 m (up) on the meteorological instrument tower (the airport aerobeacon), was used. This was necessary to ensure that any voltage drops, and resultant flow rate reductions, due to the long power cable runs were present during the flow rate measurements. Into each blower’s sampling head a wire mesh screen and glass fiber filter were installed, again to ensure flow rates equal to those of the actual sampling runs. A funnel, outfitted with a rubber seal and connected to a hose, was connected to the inlet sampling head of the blower. The other end of the hose was connected to the outlet of the dry test meter. Thus, the blower would draw air through the dry test meter. Two flow measurements were taken for each blower, running the blower for 5 minutes each time. The actual time during which air was being drawn through the dry test meter was measured using a stopwatch. This ensured that the times
during which the blower motor was coming up to full speed and slowing down were included in the measurement since the blower was still drawing a small amount of air during these short periods of time. The dry test meter measured the total flow to one hundredth of a liter. A typical test volume was approximately 1600 ℓ. The flow rate, in liters per minute (ℓpm), was calculated by dividing the total flow volume, in liters (ℓ), by the total time, in minutes, recorded on the stopwatch. The two flow rate measurements were averaged. For the highest precision, the dry test meter’s rated capacity was 153 ℓpm, meaning that, for the flow rates of Blowers A and B (~ 400 ℓpm), some sort of correction was required. Therefore, the average flow rate measured for each blower was corrected later while processing the data, based on laboratory experiments conducted with the dry test meter using a balloon (see discussion in Chapter 6.5).

While the flow rates for the blowers were being measured, two wire mesh screens were selected for the first side-by-side sampling run. The serial numbers of the screens were recorded so as to ensure that an individual screen was not used twice during a modified Bowen ratio sampling set because the buildup in alpha activity from one usage could mask activity collected during subsequent samples (until it had decayed away). There were a sufficient number of 635 mesh screens to perform all three sampling runs required for a modified Bowen ratio sampling set without reusing any screens (8 of a total of twelve available 635 mesh screens). Both 635 and 400 mesh screens were available, but the 635 mesh screens were preferred due to the higher collection efficiency, $\varepsilon_{Collection}$, for the unattached radon progeny. Additionally, the identification of the screens by serial number ensured that they would be switched between blowers for subsequent sampling runs rather than reused in the same blower. This intentional randomization of
the wire mesh screen usage between the blowers over multiple samples was intended to eliminate any bias that might be introduced by a particular screen/blower combination.

Additionally, two unused glass fiber filters were marked A (Blower A) or B (Blower B) with the markings placed on the rough side to facilitate their proper placement in the blower sampling heads (rough side facing into the air flow).

The selected wire mesh screens and marked glass fiber filters were then counted for background activity on the alpha counting system. The counter-scaler used to count each screen and filter was carefully noted so that, after sampling, the same counter-scaler would be used for counting the collected alpha activity. The Blower A and B screens and filters were placed under different counter-scalers each sampling set (i.e., for one sampling set the Blower A screen might be counted for both background and collected activity on counter-scaler number 1; whereas during the next sampling set the Blower A screen might be counted for background and collected activity on counter-scaler number 6). Again, this intentional randomization in the usage of the counter-scalers for counting the Blower A and B screens and filters was intended to eliminate any bias that might be introduced by counting the same screen or filter (Blower A or B) on the same counter-scaler every sample. The counter-scalers were set to take a ten (10) minute background activity count, which was compared to the alpha counting system data file for the period during which the background was being taken. The lowest number of counts in ten minutes from either source was then used in calculating the PAEC. All the information was recorded on a sampling run data sheet (see sample copy in Appendix A).

Once the background checks and the flow rate measurements were completed, the wire mesh screens and glass fiber filters were installed in the appropriate sampling heads
of Blowers A and B. The screens and filters used in the blowers for the flow rate measurements were removed and set aside, not to be reused for the rest of the modified Bowen ratio sampling. The two blowers were set side-by-side at a height of approximately 1 meter above the ground. The alpha counting system was then set to connect power from its interface box to the two blowers for thirty minutes. Then the alpha counting system was set to start the blowers, which occurred at the next program download of data from the counter-scalers.

Once started, the two blowers ran independently without the necessity for operator intervention. The blowers would automatically shut down after the set time had elapsed. While the side-by-side sampling run was in progress, the meteorological conditions were recorded, including the ambient temperature (in °C), barometric pressure (in mb), and relative humidity (%) from the portable meteorological station. At periodic intervals during sampling (usually three times, roughly ten minutes apart, starting a few minutes into the sampling run), the readings from the meteorological instruments located at 2 m and 8 m on the meteorological instrument tower were recorded. The readings included the temperature (in °C), wind speed (in m s⁻¹), and wind direction (compass heading) at the two heights. The geometric mean of the two heights is 4 m, the reference height at which the SAM would be located during the up/down sampling run.

As the blowers shut down, the sampling heads were taken off and the wire mesh screens and glass fiber filters were immediately removed. Within two minutes, they were placed on the same counter-scalers used for determining their background activity. The serial numbers on the screens and the markings on the filters facilitated their proper placement. The counter-scalers were set to count for fifty minutes. Though the screens
and filters were counted on the alpha counting system for about an hour, only fifty-eight minutes were utilized in the COUNTER.EXE and EXMAXDP.EXE programs for calculating the PAEC results.

While the screens and filters were being counted, preparations were begun for the up/down sampling run, including setting up the SAM. Two more unused wire mesh screens were selected along with two unused glass fiber filters. As before, the serial numbers of the screens were recorded and the filters were marked A and B. When the counting of the side-by-side sampling run filters and screens was completed and all appropriate data recorded, the new set of wire mesh screens and glass fiber filters were placed on the alpha counting system to count them for background activity. The same procedures used for the background activity checks in the side-by-side sampling run were repeated for the up/down sampling run.

The SAM was raised into position near the meteorological instrument tower (the airport aerobeacon) and connected to the IBM 386 computer that would control it. This new location was chosen to be adjacent to the tower where the two blowers could be placed up/down vertically. Since the output of the SAM was not being used for controlling the solenoid valves as with the REA method, the interface relay control box was not installed. Figure 6.3.1 shows the relative locations for the two blowers during the up/down sampling run and the SAM.
Figure 6.3.1. Modified Bowen Ratio Sampling Setup at Socorro Airport.
Once the background activity checks of the two wire mesh screens and filters were completed, they were installed in the sampling heads of the appropriate blowers (A or B). The blowers were then placed on the platforms at 2 m and 8 m on the meteorological instrument tower shown in Figure 6.3.1 (see Figures 6.3.2 and 6.3.3).

Figure 6.3.2. Blower A Located Upon 2 Meter Platform.

Figure 6.3.3. Placing Blower B Upon 8 Meter Platform.
The alpha counting system was set to connect power to and run the blowers for thirty minutes as done in the side-by-side sampling run. Likewise, the computer program controlling the SAM was set to take 37,800 readings (equaling 21 Hz for 30 minutes). SAM sampling was initiated at the same time the two blowers started.

As with the side-by-side sampling run, the blowers and SAM ran independently without operator intervention and would shut down automatically after the set time had elapsed. While the up/down sampling run was in progress, the meteorological conditions were recorded, including the ambient temperature (in °C), barometric pressure (in mb), and relative humidity (%) from the portable meteorological station. Five times during the sampling run the readings from the meteorological instruments located at 2 m and 8 m on the meteorological instrument tower were recorded, including the temperature (in °C), wind speed (in m s⁻¹), and wind direction (compass heading). The temperature readings were of particular importance since they were used in the calculation of the flux/dry deposition velocity.

As done in the REA procedure, as the blowers shut down, the sampling heads were taken off and the wire mesh screens and glass fiber filters were immediately removed. This required two people since one blower was located on the platform located at 8 meters. The wire mesh screen and glass fiber filter from the “UP” blower were dropped to the ground in a packet and, within two (2) minutes, the two screens and filters were placed on the same counter-scalers used for determining their background activity. The counter-scalers were set to count for fifty minutes. The screens and filters were counted on the alpha counting system for about an hour. Again, only fifty-eight minutes
were utilized in the COUNTER.EXE and EXMAXDP.EXE programs for calculating the PAEC results.

While the filters and screens from the up/down sampling run were being counted, the SAM data file was processed, using the NSA2.EXE program, to provide the averages of the orthogonal wind parameters \( u, v, \) and \( w \) magnitudes and directions and their corresponding standard deviations, \( \sigma_u, \sigma_v, \) and \( \sigma_w, \) and the average speed of sound, \( v_s, \) and its corresponding standard deviation). The SAM data file was later converted to a text file by the CONVERT.EXE program such that it could be imported into Microsoft Excel and used for calculating the covariance between the perturbation values of the vertical wind velocity, \( w', \) and temperature, \( T', \) \( (w'T'). \)

The blower located on the 8 m platform was brought back down for a second side-by-side sampling run while the wire mesh screens and glass fiber filters from the up/down sampling run were being counted for collected alpha activity. The same procedure was followed for this second side-by-side sampling run as had been followed for the first one. Thus, to perform a complete modified Bowen ratio sampling set took between seven and eight hours.
CHAPTER 6.4
MODIFIED BOWEN RATIO
DATA PROCESSING

The following outlines the major points regarding the processing of the modified Bowen ratio data and calculating the flux velocity. The investigator:

1. Processed the alpha counting system data file, using the COUNTER.EXE program, SYS.EML files, and EXMAXDP.EXE program, to obtain the PAEC results for the wire mesh screens and glass fiber filters for all the modified Bowen ratio sampling runs (including the two side-by-side and the up/down), using the corrected flow rates through the two blowers;

2. Corrected the PAEC results for all the wire mesh screens for the collection efficiency, $\epsilon_{\text{Collection}}$, and compared the side-by-side sampling run wire mesh screen PAEC results. A ratio of the corrected PAEC result of the screen in the blower placed at 8 m for the up/down run to the corrected PAEC result of the screen in the blower placed at 2 m was calculated for each side-by-side sampling run. The average of the two ratios was taken. Since the two blowers were running for the same amount of time side-by-side, the PAEC results of the wire mesh screens should be equal after accounting for the flow
rate differences (using the corrected flow rates in the EXMAXDP.EXE and correcting for the collection efficiency, $\varepsilon_{\text{Collection}}$). Correcting the wire mesh screen PAEC results from the up/down sampling run using this average ratio eliminated potential errors induced by any system bias, any flow rate differences/fluctuations that occurred during sampling and were not previously accounted for, and any unaccounted for changes in atmospheric conditions;

3. Processed the SAM data file using both the NSA2.EXE and CONVERT.EXE programs and Microsoft Excel to obtain the average horizontal wind speed (and other wind components) and the covariance ($\overline{w'T'}$) between the perturbation values of the vertical wind velocity, $w'$, and temperature, $T'$;

4. Calculated the average temperature difference between the temperature readings recorded during the up/down sampling run of the 2 and 8 m temperature sensors located on the meteorological instrument tower;

5. Calculated the vertical flux density, $F_c$, and flux velocity, $v$;

6. Plotted $F_c$ and $v$ from the modified Bowen ratio method versus the average horizontal wind speed.
Several corrections were applied to the modified Bowen ratio flux velocity results during their calculation. The corrections are outlined below:

**Flow Rate Correction**

Laboratory experiments, using a balloon, were conducted with the dry test meter February 8 – 9, 2000. The dry test meter was known to be unreliable at flow rates well above its rated capacity of 153 ℓpm (9200 ℓph). Thus, for the flow rates of the two blowers that were used for the modified Bowen ratio sampling (each approximately 300 – 400 ℓpm), a correction factor was required. A controllable low flow rate source was built - a vacuum cleaner controlled by a dimmer switch. The dimmer switch was adjusted such that the vacuum cleaner’s flow rate was as low as possible. A total flow volume of 100 ℓ, as measured using the dry test meter, was timed using a stopwatch. The average flow rate for the vacuum cleaner was calculated at 165 ℓpm. The flow rates of the two blowers were also measured using just the dry test meter. With the dimmer switch maintained in the same position, the vacuum cleaner was connected to the inlet of
the dry test meter so as to exhaust through the meter into a large rubber balloon. Knowing the flow rate of the vacuum cleaner, the balloon was filled with 800 ℓ of air (by both the dry test meter and the expected time required to fill the balloon based on the vacuum cleaner’s flow rate). Once filled, the hose to the balloon was “kinked” so as not to allow the balloon to lose its contents. The balloon was then connected to the dry test meter’s inlet and one of the blowers was connected to the outlet of the meter. The blower was started at the same time as the hose to the balloon was “unkinked,” resulting in the blower drawing suction on the balloon. The time required to empty the balloon was measured using the stopwatch. The flow rate of the blower was calculated based on the known air volume of the balloon and the time required to empty the balloon. This process was repeated for the other blower. The flow rates measured using the dry test meter alone and the flow rates calculated from emptying the balloon were compared. In this manner, correction factors were derived for both blowers.

<table>
<thead>
<tr>
<th>Blower A: Dry Test Meter</th>
<th>402.6 ℓpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon Test</td>
<td>470.5 ℓpm</td>
</tr>
<tr>
<td>Correction Factor</td>
<td>1.169 (17%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blower B: Dry Test Meter</th>
<th>397.9 ℓpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon Test</td>
<td>467.2 ℓpm</td>
</tr>
<tr>
<td>Correction Factor</td>
<td>1.174 (17%)</td>
</tr>
</tbody>
</table>
At the airport, though, the flow rates of both blowers were reduced due the voltage drop caused by the length of the power cables. As a result, an additional correction was necessary. Assuming that the dry test meter was reading accurately (around 1%) at the low flow rate of the vacuum cleaner (proven in the laboratory experiment) and that the correlation of the balloon test to dry test meter flow measurements was linear from the 165 ℓpm of the vacuum cleaner to the laboratory flow rates of the blowers, then a revised correction factor for the reduced flow rates seen at the airport could be calculated as follows:

\[
\text{Revised Correction Factor} = 1 + x \quad \text{Eq. 6.5.1,}
\]

where \( x \) is,

\[
x = \left( \frac{(\text{Laboratory Derived Correction Factor} - 1)}{(\text{Airport Measured Dry Test Meter Flow Rate-165ℓpm})} \right) \times \frac{(\text{Laboratory Measured Dry Test Meter Flow Rate-165ℓpm})}{(\text{Laboratory Measured Dry Test Meter Flow Rate-165ℓpm})} \quad \text{Eq. 6.5.2.}
\]

This resulted in approximately a 10% correction being applied to the measured flow rates from the modified Bowen ratio sampling runs.
**Screen Mesh Correction**

Using the corrected flow rates in ℓpm through the two modified Bowen ratio blowers (and, thus, through the wire mesh screens and glass fiber filters) the wire mesh screen PAEC results were corrected as outlined in Chapter 5.5.

**Side-by-Side Screen Ratio Adjustment**

As discussed in Chapters 6.3 and 6.4, the modified Bowen ratio up/down sampling run wire mesh screen PAEC results were adjusted to the average ratio of the screen PAEC results from the two side-by-side sampling runs conducted before and after. The side-by-side sampling run screen PAEC ratios were calculated as follows:

\[
\frac{\text{Side-by-Side Screen PAEC Ratio}}{=}
\frac{(\text{Screen-Mesh-Corrected Screen PAEC for Blower Placed at 8 m})}{(\text{Screen-Mesh-Corrected Screen PAEC for Blower Placed at 2 m})}
\]

Eq. 6.5.4.

Thus, the average ratio was determined by,

\[
\text{Average Side-by-Side Screen PAEC Ratio} = \frac{(\text{Side-by-Side Screen PAEC Ratio for Run A})}{2} + \frac{(\text{Side-by-Side Screen PAEC Ratio for Run C})}{2}
\]

Eq. 6.5.5.
This average side-by-side ratio was then applied to the screen mesh corrected PAEC result for the wire mesh screen of the blower placed upon the 2 m platform during the up/down sampling run (the “DOWN” blower in Run B) as,

\[
\text{Adjusted Screen PAEC for Blower Placed at 2 m for Run B} = \\
\left( \text{Screen - Mesh - Corrected Screen PAEC for Blower Placed at 2 m} \right) \times \\
\left( \text{Average Side - by - Side Screen PAEC Ratio} \right)
\]

\text{Eq. 6.5.6.}

Vertical Wind Velocity Correction

In Chapter 5.1, one of the key assumptions discussed with respect to the accuracy of the REA method, which is also applicable to the modified Bowen ratio method, is having a near-zero average vertical wind velocity \( \bar{w} = 0 \). Unfortunately, it is difficult to achieve this in an outdoor environment. Under the REA method, one of the screening criteria for selecting the final set of flux velocity measurements was whether or not the tilt angle of the SAM, calculated by the NSA2.EXE program, exceeded 2\(^\circ\). The reason for this criterion was to try to ensure that the average vertical wind velocity was close to zero with the SAM aligned with the vertical wind (see Chapter 5.5). In practice, this same criterion was applied to the flux velocity results from the modified Bowen ratio method. None of the modified Bowen ratio flux velocity measurements had a tilt angle in excess of 2\(^\circ\).
It is possible to correct the SAM wind velocity data for the tilt angle using a coordinate transformation. This correction, though, could not be applied to the REA method results since the SAM output was used directly to control the sampling of the air. In contrast, the modified Bowen ratio air sampling was performed independently of the SAM. Under the modified Bowen ratio method, the SAM data were used to calculate the covariance term, $\bar{w}'T'$, in Equation 6.1.5. $T'$ (calculated from the speed of sound) is unaffected by a coordinate transformation. But $\bar{w}$ can be adjusted to zero by a coordinate transformation based on the calculations performed by the NSA2.EXE program, resulting in a tilt angle and direction correction. Knowing the original coordinate system, the averaged velocities and the perturbation values of the three orthogonal wind components ($\bar{u}$, $\bar{v}$, $\bar{w}$, $u'$, $v'$, and $w'$), and the tilt angle and direction; the transformation for the perturbation values of the vertical wind velocity, $w'$, is

$$\text{new } w' = [\cos (\text{new } w, u)]u' + [\cos (\text{new } w, v)]v' + [\cos (\text{SAM tilt angle})]w' \quad \text{Eq. 6.5.7},$$

where “(new } w, u)”, “(new } w, v)”, and “(SAM tilt angle)” are the angles between the tilt-corrected (new) vertical wind velocity axis, new $w$, and the original orthogonal horizontal wind velocity axes, $u$, $v$, and $w$, respectively; and $u'$, $v'$, and $w'$ are the original perturbation values of the orthogonal wind velocities measured by the SAM and recorded in the up/down sampling run data file.

New perturbation values of the vertical wind velocity, new $w'$, were calculated for each modified Bowen ratio up/down sampling run using Equation

158
6.5.7; and new covariance terms, \( w'T' \), were generated for use in Equation 6.1.5. As a check, Equation 6.5.7 was used to calculate a new average vertical wind velocity, new \( \bar{w} \), to verify that the average vertical wind velocity did indeed equal zero after the transformation. A copy of the calculation sheet for the vertical wind velocity correction is included in Appendix A.

10 modified Bowen ratio flux velocity measurements were obtained in the year 2000 at the Socorro Airport.

**Error Analysis**

The error sources associate with the individual modified Bowen ratio measurements were evaluated. Many are the same as those associated with the REA measurements. Table 6.5.1 identifies the source and magnitude of each error while the notes below discuss how each error was corrected for or its impact on the measurement error depicted by the error bars on the subsequent plots.
### Table 6.5.1. Modified Bowen Ratio Flux Velocity Measurement Error Sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Method of Determination</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAEC Error*</td>
<td>Random</td>
<td>EXMAXDP.EXE Program</td>
<td>1 Sigma [8% (average)]</td>
</tr>
<tr>
<td>Flow Rate** Correction</td>
<td>Systematic</td>
<td>Laboratory Experiment</td>
<td>27% (average)</td>
</tr>
<tr>
<td>Screen Mesh* Correction</td>
<td>Systematic</td>
<td>ALLSCR.EXE Program</td>
<td>17% (average)</td>
</tr>
<tr>
<td>Side-by-Side** Screen Ratio Adjustment</td>
<td>Random</td>
<td>Field Site Testing</td>
<td>30% (average)</td>
</tr>
<tr>
<td>Vertical Wind† Velocity Correction (Tilt)</td>
<td>Random</td>
<td>NSA2.EXE Program</td>
<td>12% (average)</td>
</tr>
<tr>
<td>Temperature††</td>
<td>Random</td>
<td>Temperature Probe Intercalibration</td>
<td>1% (average)</td>
</tr>
</tbody>
</table>

* See Table 5.5.2 comments for same error source with the exception that the calculation form used was the Modified Bowen Ratio Method Calculation form (Appendix A).

** These errors were corrected for during the calculation of the flux velocity as shown on the sample Modified Bowen Ratio Method Calculation form (Appendix A) and did not contribute to the overall measurement error.

† An adjustment for this error was applied to the flux velocity error using standard error propagation when correcting the flux velocity for the tilt of the sonic anemometer, thus, contributing to the measurement error bars.

†† The error in the temperature difference between the probes located at 2 and 8 m was measured by intercomparison at the same height prior to usage at the Socorro Airport. No correction was applied to the individual modified Bowen ratio
measurements nor included in the measurement errors due to the small magnitude of the error.

All 10 modified Bowen ratio measurements (both uncorrected and corrected for the vertical wind velocity) are plotted versus the average horizontal wind speed in Figure 6.5.1. From Figure 6.5.1, it is apparent that correcting for the vertical wind velocity had only a minor effect on the data scatter.

Of the 10 modified Bowen ratio measurements, only 8 were included in the final data set. The following modified Bowen ratio measurements were excluded:

1. One modified Bowen ratio measurement was excluded because a second side-by-side sampling run was not conducted. Though it was possible to complete the flux velocity calculation of this modified Bowen Ratio sampling set with only one side-by-side sampling run, the accuracy of the result was considered suspect. Additionally, the atmospheric conditions had changed substantially during the course of the three sampling runs. Before the second side-by-side sampling run was commenced, it began to rain.

2. One modified Bowen ratio measurement was excluded because it was determined to be a statistical outlier. In conducting a statistical analysis of the remaining data after excluding the one measurement for not having a second side-by-side sampling run, one measurement was identified as an outlier. Therefore, this measurement was also excluded in the final set. It is assumed that some unidentified experimental error caused this one point to be so far outside the range of the remaining points.
Figure 6.5.1. Modified Bowen Ratio Flux Velocity Results vs Horizontal Wind Speed.
The final 8 modified Bowen ratio flux velocity measurements are plotted versus the average horizontal wind speed in Figure 6.5.2. Both the uncorrected and corrected (for vertical wind velocity) data points are shown to emphasize (on an expanded vertical scale) the minimal impact this correction had on the data scatter. The modified Bowen ratio results were then analyzed (see Chapter 6.6).
Figure 6.5.2. Final Modified Bowen Ratio Data Set vs Horizontal Wind Speed.
CHAPTER 6.6
MODIFIED BOWEN RATIO
RESULTS & DISCUSSION

Interpretation of the modified Bowen ratio method involves more assumptions and is not as direct a method for measuring flux velocity as the REA method. The modified Bowen ratio measurements were only attempted in an effort to obtain data with an independent above-the-vegetation-canopy method for comparison with the REA results. Due to the complexity of the technique and the length of time (7-8 hours) involved in making a single measurement, only a small number of measurements, covering a broad range of horizontal wind speeds, were obtained.

As discussed in Chapter 6.5, a total of 10 modified Bowen ratio flux/deposition velocity measurements were obtained. Figure 6.5.1 shows all 10 modified Bowen ratio flux velocity results (both uncorrected and corrected for vertical wind velocity) plotted versus the average horizontal wind speed. The error bars represent the cumulative error calculated (see Table 6.5.1). The primary error included is the PAEC counting error that is determined by the EXMAXDP.EXE program when processing the alpha counting system data file. Only 8 modified Bowen ratio measurements were selected for the final data analysis (see Chapter 6.5). Figure 6.5.2 shows the final 8 modified Bowen
ratio flux velocity measurements (again, both corrected and uncorrected for vertical wind velocity) plotted versus the average horizontal wind speed.

As plotted in Figure 6.5.2, the corrected data still appear to exhibit significant scatter. Analysis of the uncorrected data indicated that a significant correlating parameter with the data scatter was the vertical wind velocity, $w$, which ideally should have an average value of zero ($\bar{w} = 0$). The sensitivity of the modified Bowen ratio method to $\bar{w} \neq 0$, though, is clearly a more complex issue than with the REA method. Though the term $w'T'$ in Equation 6.1.5 is significantly affected by a non-zero average vertical wind velocity and, thus, was corrected for the vertical wind velocity; $\Delta c/\Delta T$ is less sensitive and the gradient may not change much because of an additional advective component. The uncorrected average vertical wind velocities, $\bar{w}$, for all 10 modified Bowen ratio measurements are plotted versus the average horizontal wind speed in Figure 6.6.1 while the uncorrected standard deviations of the vertical wind velocity, $\sigma_w$, are plotted versus the average horizontal wind speed in Figure 6.6.2.

Figures 6.6.1 and 6.6.2 are similar to Figures 5.6.1 and 5.6.2 for the REA method. The discussion in Chapter 5.6 of the effects of the vertical wind velocity on the data scatter applies here also. Unfortunately, correcting the data for the vertical wind velocity (i.e., making $\bar{w} = 0$) had minimal effect on the scatter.
Figure 6.6.1. Average Vertical Wind Velocity vs Horizontal Wind Speed.
Figure 6.6.2. Vertical Wind Velocity Standard Deviation vs Horizontal Wind Speed.
Other possible causes for the data scatter were investigated. Particularly, the average temperature gradient and the change in the temperature gradient (over the time period during which the modified Bowen ratio up/down sampling run was conducted) were investigated. The modified Bowen ratio measurements (corrected for vertical wind velocity) are plotted versus the average temperature gradient and the temperature gradient change in Figures 6.6.3 and 6.6.4, respectively. Unfortunately, the statistical scatter was too great to draw any conclusions regarding either the average temperature gradient or temperature gradient change. Figure 6.6.5 shows the same data as Figure 6.5.2, but sorted by data having a negative temperature gradient change (becoming less stable) and data having a positive/zero temperature gradient change (becoming more stable).

Figures 6.6.4 and 6.6.5 show no significant correlation between the flux velocity and the temperature gradient change and, thus, no apparent influence on the data scatter.
Figure 6.6.3. Vertical-Wind-Corrected Modified Bowen Ratio Flux Velocity vs Average Temperature Gradient.
Figure 6.6.4. Vertical-Wind-Corrected Modified Bowen Ratio Flux Velocity vs Temperature Gradient Change.
Figure 6.6.5. Vertical-Wind-Corrected Modified Bowen Ratio Data Sorted by Temperature Gradient Change.
The final 8 modified Bowen ratio measurements were analyzed for possible curve fits using the linear regression package found in Microsoft Excel and curve fitting package of NCSS. The following families of equations were evaluated:

- \( y = ax + b \) (linear)
- \( y = ax^2 + b \) (quadratic)
- \( y = ax^2 + bx + c \) (second order polynomial)
- \( y = ae^{bx} + c \) (exponential)
- \( y = ax^b + c \) (power)

None of the non-linear curves provided convincing evidence as to any superiority over a simple linear fit. Figure 6.6.6 shows the best-fit linear curve to the data, including error bars and 95% mean confidence level boundaries.
Figure 6.6.6. Best-Fit Linear Curve to Corrected Modified Bowen Ratio Data with 95% Mean Confidence Curves.
For the eight modified Bowen ratio data points the magnitude of the average flux velocity, \( v \), and its standard deviation of the mean were 6.6 ± 2.5 cm s\(^{-1}\) for an average horizontal wind speed of 5.8 m s\(^{-1}\) and an average vertical temperature gradient of -0.12 °C m\(^{-1}\) (unstable). The magnitude of the flux velocity appears to decrease slightly with increasing horizontal wind speed, but the trend is clearly not statistically significant. Data scatter does not significantly change with increasing horizontal wind speed, and the effect of correcting for the vertical wind velocity or eliminating those data points having a negative temperature gradient change were inconclusive. The fact that most of the modified Bowen ratio measurements had significantly non-zero average vertical wind velocities and considerable scatter makes the results of more limited use in comparison with the REA results. Additional measurements would likely improve the overall quality of results from the modified Bowen ratio method. However, based on the experience gained while performing the two above-canopy methods presented, it appears that the REA method is the superior approach for studying the flux densities and deposition velocities of nanometer-size particles if for no other reason than the substantially reduced time required to obtain a single measurement (approximately 2 hrs versus 7 hrs).
CHAPTER 7.1
SURFACE COLLECTION THEORY

The theory behind the surface collection method of measuring dry deposition velocity, \( v_d \), is very basic. For flat surfaces where vertical roughness elements are not a factor, the dry deposition velocity can be defined as the ratio of the amount of the constituent material of interest that collects on a unit area of surface per unit time to the amount of the same constituent material contained in a unit volume of air, at a specified reference height, to which the unit area of surface is exposed. Equation 7.1 shows this ratio (as applied to airborne and surface unattached radon progeny alpha activity and assuming a sticking probability of one) with appropriate units for the research presented here.

\[
v_d = \frac{\text{(amount per unit area)}}{\text{(amount per unit volume)} (\text{unit time})} = \left[ \frac{m^{-1}}{s} \right] = \left[ \frac{nJ m^{-2}}{nJ m^{-3}} \right] [s] \quad \text{Eq. 7.1.}
\]

Using this definition, a positive deposition velocity, \( v_d \), indicates a vertical aerosol flux density, \( F \), downward towards the ground as discussed in Chapter 2.1 (see pp. 7-8). For the moment, it will be assumed that the flux density at the surface is the same as that at a reference height of 4 m. The validity of this assumption will be discussed later. In order to allow comparison between the surface collection results and
those from the REA and modified Bowen ratio methods, negative deposition velocities (i.e., - $v_d$) were plotted for the surface collection method, matching the flux velocity, $v$.

For rough surfaces (such as vegetation) where the specified reference height is above the roughness elements, it may be necessary to define $v_d$ using the projected horizontal geometrical area below rather than the larger total surface area of the roughness elements that includes all top, side, and bottom surfaces regardless of orientation. This issue will be addressed later.

Similar to the procedure for determining the volumetric concentration of the unattached-to-aerosol radon progeny, the surface concentration was determined by counting the number of alpha decays after the surface was exposed, correcting appropriately back to the time that the exposure began. The alpha activity on the surface, assumed to be solely due to the dry deposition of unattached radon progeny [typically the dry deposition of attached radon progeny is of the order of $10^2$ smaller (Nazaroff and Nero, 1988; Porstendörfer, 1994)], was calculated with the EXMAXDP.EXE program by inputting a dummy flow rate of $1.00 \ell \text{pm}$ and a sample time equaling the actual exposure time into the SYS.EML file for the counter-scaler on which the collecting surface was counted. By using this procedure, the EXMAXDP.EXE program, which was designed for calculating volumetric concentrations, was adapted to calculate surface concentrations. Thus, a dummy potential alpha particle energy per unit volume concentration (dummy PAEC) was calculated for the collecting surface. Equation 7.2 was used to convert the EXMAXDP.EXE program’s dummy PAEC into the potential alpha particle energy per unit surface area concentration (PAESC),
where $7.89 \times 10^{-3} \text{ m}^2$ was the surface area of the 10 cm diameter collecting surfaces (matching the diameter of the scintillation detectors of the alpha counting system) used in collecting the unattached radon progeny, a fixed number regardless of their orientation.

The potential alpha energy activity in a unit volume of air (i.e., true PAEC) was taken directly from the EXMAXDP.EXE results for the wire mesh screens from either the REA, modified Bowen ratio, or gradient method sample taken concurrently to when the collecting surface was exposed. [Note that, although air samples were taken to perform a gradient method calculation, the other required data were unavailable to complete those calculations. But the airborne unattached radon progeny concentrations (PAEC) obtained allowed for deposition velocity calculations by the surface collection method.] The PAEC results of the two wire mesh screens were corrected for the collection efficiency, $\epsilon_{\text{Collection}}$, based on the blower flow rates, and averaged.

The PAESC (from Equation 7.2) and the average corrected wire mesh screen PAEC result were then inserted into Equation 7.1 and divided by the actual exposure time (in seconds) to determine the deposition velocity, $v_d$. The output of the EXMAXDP.EXE program included an error (1$\sigma$) value for both the PAESC and PAEC results. Using standard error propagation procedures, a cumulative error value was calculated for the results of Equation 7.1.
CHAPTER 7.2
REQUIRED DATA FOR
SURFACE COLLECTION METHOD

The following are the data requirements for computing the dry deposition velocity, $v_d$, by the surface collection method:

1. The background activity of the collecting surface prior to exposure (using the lowest of either the counter-scaler or alpha counting system data file) in total counts over a ten minute period;
2. The PAESC in nJ m$^{-2}$ on the collecting surface after exposure;
3. The average of the PAEC results in nJ m$^{-3}$ for the REA, modified Bowen ratio, or gradient method wire mesh screens [for the REA, modified Bowen ratio, or gradient sample taken concurrently with or closest in time to the time the collecting surface was exposed to the air];
4. The collection efficiencies ($\varepsilon_{collection}$) for the unattached radon progeny for the REA or modified Bowen ratio screens;
5. The surface area of the exposed side (i.e., $\pi \times $ diameter$^2$/4) of the collecting surface in m$^2$, excluding any corrections for roughness or orientation.
The horizontal wind speed and direction are required for additional analysis. They are obtained from either the SAM output file or an average of the measurements taken from the meteorological instruments at the site during the sampling run.
CHAPTER 7.3
SURFACE COLLECTION
SAMPLING TECHNIQUE

Sampling by the surface collection method simply involved placing collecting surfaces on the ground and, after exposure, counting the alpha activity, which had collected on them. Several different materials were used for collecting the unattached radon progeny. These materials were cut into 10 cm diameter circles (if not already so sized) to match the size of the scintillation detectors of the alpha counting system. The following materials were used as collecting surfaces:

1. Glass fiber filter (Gelman type A/E, the same type of filter used for sampling the air in both the REA and modified Bowen ratio methods);
2. Aluminum foil (standard commercial);
3. Sandpaper (standard commercial 60, 100, 150, and 220 Grit); and

Generally, two collecting surfaces were exposed at any given time. This coincided with the number of available counter-scalers of the alpha counting system not required for counting the wire mesh screens and glass fiber filters associated with either
the REA or modified Bowen ratio methods. The collecting surfaces were counted for background activity on the alpha counting system as in the REA method (see Chapter 5.3). The background count was used in calculating the PAESC on the collecting surface. All pertinent information was recorded on the same sampling run data sheet used for the concurrent REA, modified Bowen ratio, or gradient method.

The collecting surfaces were then taped to small rocks (to prevent their being blown away or turned upside down by the wind) and placed on the ground as shown in Figure 7.3.1 in an open area near to where the concurrent REA, modified Bowen ratio, or gradient sample was taken.

Figure 7.3.1. Sandpaper Collecting Surface Set Out For Exposure.
The collecting surfaces were set out and picked up such that the exposure time was equal to or greater than the sampling time of the concurrent REA, modified Bowen ratio, or gradient sample and such that the exposure time substantially (if not totally) overlapped the time during which the concurrent method sample was taken. Thus, the REA, modified Bowen ratio, or gradient sample screen PAEC results could be used in calculating the surface collection deposition velocity, $v_d$. Note, though, that the REA and modified Bowen ratio methods use the projected horizontal area above the roughness elements (i.e., vegetation) for calculating the flux density while the surface collection method uses the physical area ($\pi r^2$) of the collecting surface regardless of its orientation and any surrounding vegetation.

The collecting surfaces were picked up and, then, within two minutes placed on the same counter-scaler used for determining the background activity. The counting procedure was, from this point on, the same as performed for the REA method (see Chapter 5.3).
CHAPTER 7.4
SURFACE COLLECTION
DATA PROCESSING

The following outlines the major points regarding the processing of the surface collection data and calculating the deposition velocity. The investigator:

1. Processed the alpha counting system data file using the COUNTER.EXE program, SYS.EML files, and EXMAXDP.EXE program to obtain the PAESC for the collecting surfaces;

2. Obtained the PAEC results and collection efficiencies, $\varepsilon_{Collection}$, from the concurrent REA, modified Bowen ratio, or gradient sampling run and entered the data onto the Surface Collection Deposition Velocity Calculation form (see sample copy in Appendix A);

3. Calculated the deposition velocity, $v_d$, using Equation 7.1;

4. Ran the NSA2.EXE program on the associated SAM file or averaged the wind speeds from the meteorological data to obtain the average horizontal wind velocity;

5. Plotted the negative of the surface collection method results, $-v_d$, versus the average horizontal wind speed.
CHAPTER 7.5
SURFACE COLLECTION
DATA CORRECTIONS/EVALUATION

Due to the simplicity of the surface collection method, i.e., the fact that only the PAESC and PAEC results were necessary to compute the deposition velocity, $v_d$, without any additional atmospheric parameter measurement; no corrections were applied to the calculated deposition velocities. The surface collection deposition velocity results were primarily evaluated versus the average horizontal wind speed, but were also evaluated against time of day, obstructed/unobstructed sectors, site location, and temperature gradient as were the REA and modified Bowen ratio results. The effect of the orientation of the collecting surface on deposition velocity was only evaluated in the experiment described in Chapter 7.7. Those results are not included as part of the data evaluated here. A total of 72 surface collection measurements were obtained, broken down by year, site location, and material as listed in Table 7.5.1. Some measurements were later excluded for various reasons as listed in the table.
Table 7.5.1. Breakdown of Surface Collection Deposition Velocity Measurements.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Measurements/Material (No. Excluded)</th>
<th>Site Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>32 Total, comprising</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11 Unused glass fiber filter (1*)</td>
<td>SS Ranch</td>
</tr>
<tr>
<td></td>
<td>16 Aluminum foil (1*)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 Sandpaper</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>28 Total, comprising all sandpaper</td>
<td>Socorro Airport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(REA Site)</td>
</tr>
<tr>
<td>2000</td>
<td>12 Total, comprising all sandpaper (1*)</td>
<td>Socorro Airport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(mod Bowen ratio site)</td>
</tr>
</tbody>
</table>

* No valid horizontal wind speed data for 4 m reference height

Error Analysis

The error sources associated with the individual surface collection measurements were evaluated. The only error source associated with the surface collection measurements was the **PAEC Error** addressed in Table 5.5.2. Refer to Table 5.5.2 for comments regarding this error source with the exception of the calculation form noted, which, in this case, was the Surface Collection Deposition Velocity Calculation form (see Appendix A).
All 72 surface collection measurements are plotted (using the negative of the deposition velocity, \(-v_d\), to allow comparison with the REA and modified Bowen ratio flux velocities, \(v\); indicating towards the ground) versus the average horizontal wind speed in Figure 7.5.1. The plot has the same year/material break down as Table 7.5.1.

Of the 72 surface collection measurements, only 69 were used in the final data set. 1 aluminum foil and 1 glass fiber filter measurement from 1996 were excluded because the only horizontal wind speed data available for these measurements was from the cup anemometer located at a height of 2 m on the meteorological tower. Thus, an average horizontal wind speed at the 4 m reference height could not be accurately determined. Additionally, 1 sandpaper measurement from 2000 was excluded because the last recorded wind speed data was taken over thirty minutes prior to the collecting surface being exposed.

The 69 final surface collection method results are plotted versus the average horizontal wind speed, sorted by site location, in Figure 7.5.2. The surface collection results were then analyzed (see Chapter 7.6).
Figure 7.5.1. Combined Surface Collection Deposition Velocity Measurements vs Average Horizontal Wind Speed.
Figure 7.5.2. Final Surface Collection Deposition Velocity Measurements Sorted by Site Location.
In addition to evaluating the data with respect to various atmospheric and other parameters, experiments were conducted in October of 1996 and December of 2000 to determine whether or not there was any difference in the deposition of unattached radon progeny onto different materials. Six different collecting surface materials, which had been checked for background activity, were placed together in an open area, exposed, and counted for collected alpha activity. The alpha counting system data files were processed to obtain the surface alpha activity (PAESC). The results of these experiments are presented in Chapter 7.7.
CHAPTER 7.6

SURFACE COLLECTION

RESULTS & DISCUSSION

The original intent of determining the deposition velocity, $v_d$, using the surface collection method, was to have results from an independent method to compare with the REA results. Since these more traditional surface collection measurements were taken below the vegetation canopy and do not reflect the larger surface area and roughness elements seen by the REA and modified Bowen ratio methods, the deposition velocities so obtained were expected to be smaller. The extent to which they were smaller may be a reflection of issues such as the leaf area index and the physical properties of the surfaces involved and is the subject of considerable research interest.

As discussed in Chapter 7.5, a total of 72 surface collection $v_d$ measurements were made. Figure 7.5.1 shows all 72 surface collection $v_d$ results plotted versus the average horizontal wind speed. Results are identified by the year in which they were taken, the sampling site location, and the material used. The error bars represent the cumulative error calculated. The errors include the PAESC and PAEC counting errors determined by the EXMAXDP.EXE program when processing the alpha counting system files for the collecting material and the wire mesh screens. Only 69 surface collection $v_d$ measurements were selected for the final data analysis (see Chapter 7.5). Figure 7.5.2
shows the final 69 surface collection $v_d$ results plotted versus the average horizontal wind speed. From Figure 7.5.2, a correlation between $v_d$ and horizontal wind speed appears to exist although there is a significant amount of scatter. Most of the data scatter in Figure 7.5.2, though, can be explained by statistical counting fluctuations in contrast with the REA and modified Bowen ratio methods.

The 69 final surface collection results were evaluated with respect to the average temperature gradients measured during the exposure times of the collecting surface. Figures 7.6.1 and 7.6.2 show the final surface collection method results plotted versus the average temperature gradient and average horizontal wind speed, sorted by average temperature gradient, respectively.

Figure 7.6.1 shows a very small, and unexpected, negative trend in the deposition velocity with increasing atmospheric stability; but, given the error bars, the slope, the lack of correlation ($R^2$), and the fact that most of the data points have near-neutral atmospheric stability, it is essentially a zero trend. Figure 7.6.2 shows no distinctive difference between those measurements having negative average temperature gradients and those having zero/positive gradients.
Figure 7.6.1. Surface Collection Deposition Velocity vs Average Temperature Gradient.
Figure 7.6.2. Surface Collection Deposition Velocity Measurements vs Horizontal Wind Speed, Sorted by Temperature Gradient.
The final 69 surface collection measurements were analyzed for possible curve fits using the linear regression package found in Microsoft Excel and curve fitting package of NCSS. The following families of equations were evaluated in order to identify any trends in the data such as a linear proportionality or a non-linear curvature:

- \( y = ax + b \) (linear)
- \( y = ax^2 + b \) (quadratic)
- \( y = ax^2 + bx + c \) (second order polynomial)
- \( y = ae^{bx} + c \) (exponential)
- \( y = ax^b + c \) (power)

Figure 7.6.3 shows the best-fit linear curve, including the error bars and showing the 95% mean confidence level boundaries. There were no non-linear curves that proved to be a better fit than a linear curve to the final surface collection deposition velocity data. Based on the analyses, the magnitude of the average deposition velocity, \( v_d \), and its standard deviation of the mean were 1.6 ± 0.1 cm s\(^{-1}\) for an average horizontal wind speed of 5.9 m s\(^{-1}\) and an average temperature gradient of \( -0.11 \) °C m\(^{-1}\) (unstable). This is higher than the results of Wyers and Veltkamp (1997) for \(^{214}\)Pb but expected for a below-the-vegetation-canopy method in comparison with above-canopy results. The surface collection deposition velocity average is approximately a factor of 7 smaller than the corresponding average REA and modified Bowen ratio flux velocity. A more detailed discussion comparing the surface collection and REA/modified Bowen ratio methods is presented in Chapter 8.
Figure 7.6.3. Best-Fit Linear Curve to Surface Collection Data with 95% Mean Confidence Curves.
CHAPTER 7.7
SURFACE COLLECTION
MATERIAL TESTING

In October of 1996 and again in December of 2000, supplemental experiments were conducted to evaluate the dry deposition of unattached-to-aerosol radon progeny onto different collecting materials. Since three different materials (unused glass fiber filters, commercial aluminum foil, and various grits of sandpaper) had been used as collecting surfaces in the surface collection method, there was some concern that the type of material might affect the deposition velocity, $v_d$, results. On 8 October 1996, an experiment was conducted in which six sample materials (matching the number of available counter-scalers and detectors of the alpha counting system) were counted for background activity and placed outdoors in the same area at ground level as shown in Figure 7.7.1. The six collecting surfaces were taped to a meter stick to prevent their being blown away or flipped over. The exposure time exceeded 40 minutes (the time at which the decay of the initially deposited unattached radon progeny begins to cause the collected alpha activity to level off). The sample materials were picked up after being exposed and immediately counted on the alpha counting system. From the alpha counting system data files, PAESC results were calculated for each sample material using the EXMAXDP.EXE program as done with the surface collection method. Since
atmospheric unattached radon progeny concentrations were not measured, deposition velocities were not calculated. Also, since the outdoor unattached radon progeny concentration varies diurnally and from one day to the next due to many factors, the six PAESC results were normalized to the PAESC of one collecting surface. The PAESC of the sandpaper collecting surface placed out horizontally (or one of the sandpaper collecting surfaces if more than one were placed out horizontally) was selected as the one against which the others would be normalized. Sandpaper was selected because it was considered to be the most representative of the surrounding surface roughness. The experiment was repeated in December 2000 on three different nights.

Figure 7.7.1. Exposure Arrangement of the Six Collecting Materials.
The collecting surface materials shown in Figure 7.7.1 are (from left to right) an unused glass fiber filter, a piece of aluminum foil (commercial grade), a piece of sandpaper (either 60, 100, 150, or 220 grit commercial grade), a wire mesh screen, another piece of sandpaper (note that it has been folded over and oriented vertically), and a piece of clear plastic. Figures 7.7.2 and 7.7.3 show the normalized PAESC ratios for the October 1996 and December 2000 experiments, respectively. The exact type of material and physical orientation with respect to the ground are identified. The PAESC ratios are plotted versus the number of the counter-scaler on which the collecting surface was checked for background and, ultimately, counted for collected alpha activity. The date and average horizontal wind speed, measured using a hand-held anemometer while the collecting surfaces were being exposed, are also indicated on the plots.

The 8 October 1996 experiment results shown in Figure 7.7.2 involved extremely low PAESC values. In comparison, the lowest PAESC value measured in December 2000 was approximately the same as the highest PAESC value measured in October 1996 and was for a clear plastic collecting surface that, in fact, had blown off in the wind and was found lodged in nearby grass. Because of the low PAESC values involved, the results of 8 October 1996 show much more scatter and are considered less reliable. The experiment conducted in December 2000 (results shown in Figure 7.7.3) was performed with greater attention to detail, leading to more consistent results.
Figure 7.7.2. Normalized PAESC Results of 8 October 1996.
Figure 7.7.3. Normalized PAESC Results of December 2000.
Figure 7.7.3 shows that the type of material and physical orientation with respect to the ground have little effect on the activity deposited with the exception of the wire mesh screens, which consistently had higher PAESC results. These higher PAESC values on the screens appear to indicate that small-scale airflows may have been passing through the wire mesh screens, resulting in higher amounts of collected alpha activity. The PAESC values of the unused glass fiber filters, though the filters are considered porous, do not indicate that similar airflows existed.

The fact that the physical orientation of the collecting material had no effect may be related to the unimportance of gravitational settling for nanometer-size particles (see Chapter 2.1). The available surface area, not orientation, appears to be the most important factor. It has sometimes been expected that above-canopy and below-canopy surface collection measurements will be similar in magnitude. This result helps shed light on some of the discrepancies between above-canopy and below-canopy methods where below-canopy methods, using surface collectors, often get lower deposition velocities. These results warrant further investigation.

One key issue not addressed in these experiments was that of the electrical conductivity/insulation properties of the materials, considering the usual electrical charge of the unattached-to-aerosol radon progeny and the Earth’s electric field (Schery and Whittlestone, 1995, and Nicholson and Garland, 1996). Other issues not addressed include the deposition of the larger accumulation mode attached-to-aerosol radon progeny and the effect of surface roughness. However, based on published indoor deposition velocities for attached-to-aerosol radon progeny, their deposition velocity should be small in comparison with that of the unattached radon progeny.
PART 8

COMBINED RESULTS
CHAPTER 8
COMBINED DATA RESULTS & DISCUSSION

After separately analyzing the results from the three methods used for measuring the flux/deposition velocity of the unattached-to-aerosol radon progeny, the results were combined and evaluated. A combined total of 140 measurements were evaluated, broken down as follows:

- 63 REA Measurements
- 8 Modified Bowen Ratio Measurements
- 69 Surface Collection Measurements

Figure 8.1 shows the flux velocities or negative of the deposition velocities for all 140 REA, modified Bowen ratio, and surface collection measurements plotted versus average horizontal wind speed, sorted by the method used.
Figure 8.1. Combined Flux/Deposition Velocity vs Horizontal Wind Speed Plot, Sorted by Method.
As Figure 8.1 shows, the magnitudes of the surface collection deposition velocities are significantly smaller (see later discussion) than the flux velocities measured using the REA and modified Bowen ratio methods. This was not unexpected since the surface collection method is a below-the-vegetation-canopy method while the REA and modified Bowen ratio methods are above-the-vegetation-canopy methods, responding to deposition over a greater total surface area (i.e., all the roughness elements of the surrounding vegetation and ground structures). This is discussed in detail later. As a consequence, the surface collection results were not evaluated in direct combination with the REA and modified Bowen ratio results.

From Figure 8.1, the REA and modified Bowen ratio flux velocity measurements appear to be generally consistent with each other. A statistical $t$-test comparing the means of both data sets yielded a two-sided $p$ value of 0.32, indicating no significant difference between them. Thus, the REA and modified Bowen ratio flux velocity measurements were combined for the final analysis. The combined 71 measurements are plotted in Figure 8.2 versus the average horizontal wind speed, sorted by both method and sampling site location. The best-fit linear curves for each sampling site location, regardless of the method used (i.e., the REA and modified Bowen ratio results for the Socorro Airport were evaluated together), are included to highlight possible differences in the results from the two sites although this was discounted as not statistically significant in Chapter 5.6.
Figure 8.2. Combined REA/Modified Bowen Ratio Flux Velocity Measurements vs Horizontal Wind Speed.
Figure 8.2 more clearly indicates a consistency between the REA and modified Bowen ratio flux velocity results. The combined data were analyzed similarly to those analyses performed separately with each method. Conclusions similar to those drawn for the REA method (as discussed in Chapter 5.6) were made. Some differences, though, did appear during the evaluation of the absolute values and standard deviations of the vertical wind velocities when comparing the results by both method and site location. For example, Figure 8.3 shows the standard deviations of the vertical wind velocity plotted versus the average horizontal wind speed for the SS Ranch and the two sampling sites at the Socorro Airport.

From Figure 8.3 it is apparent that the sampling site where the REA measurements were made at the Socorro Airport has a statistically significant different correlation (i.e., smaller) between the standard deviation of the vertical wind velocity and the average horizontal wind speed. Assuming no misalignment of the measuring equipment, this suggests some difference in the aerodynamic properties between the two Socorro Airport sampling site locations, which were physically separated by approximately 160 m. The vegetation surrounding the Socorro Airport REA sampling site location was much sparser than that surrounding the modified Bowen ratio sampling site location. From analyses of vertical wind gradients, the calculated terrain roughness heights were 30 cm at the SS Ranch and 7 cm at the Socorro Airport (based on wind data taken near the modified Bowen ratio sampling site location). But this does not adequately explain the observed differences. However, a systematic effect on the flux velocity data, if any, seems to have been overwhelmed by the previously noted random scatter.
Figure 8.3. Vertical Wind Velocity Standard Deviation vs Average Horizontal Wind Speed.
For completeness, the data of Figure 8.3 are noted here, but were not investigated further. Perhaps in future work, in a different context, further investigation would be of interest.

The combined REA and modified Bowen ratio data were analyzed using the linear regression packages found in Microsoft Excel and NCSS for a linear best-fit (of the type $y = ax + b$). Figure 8.4 shows the data, including error bars, with the best-fit linear curve and the 95% mean confidence level boundaries. The best-fit linear curve of Figure 8.4 is clearly an interpolation of those in Figures 5.6.9, 5.6.10, and 6.6.5 and shows the dominance of the REA measurements, which is expected since there were only 8 modified Bowen ratio measurements in the combined data set. The slope of the best-fit linear curve indicates an increase in the flux velocity of the order of 1 cm s$^{-1}$ per 1 m s$^{-1}$ increase in horizontal wind speed, although the 95% confidence intervals do not quite rule out a small probability (~ 5%) of no correlation.
Figure 8.4. Best-Fit Linear Curve to Combined REA and Modified Bowen Ratio Data with 95% Mean Confidence Curves.
In comparing atmospheric parameters associated with the REA and modified Bowen ratio method measurements and the SS Ranch and Socorro Airport sampling site locations, a significant difference was noted in the average temperature gradient associated with the results from the two methods. For the REA measurements, the average temperature gradient was essentially the same at both the SS Ranch and the Socorro Airport, measuring 0.03°C m⁻¹ and 0.02°C m⁻¹ (near neutral stability), respectively. In comparison, the average temperature gradient for the modified Bowen ratio measurements was −0.12°C m⁻¹ (unstable). Several factors are relevant to this comparison. A conscious decision was made to obtain REA measurements at various times of the day while sampling at the SS Ranch. This pattern was repeated when the REA sampling was moved to the Socorro Airport. But, due to the length of time involved in obtaining a single modified Bowen ratio measurement, this sampling pattern could not be repeated for the modified Bowen ratio method. It was decided that the up/down modified Bowen ratio sampling run should be performed in the mid to late afternoon when the negative temperature gradient would peak (a key parameter, as ∆T, in Equation 6.1.5) and the radon progeny concentrations, though normally at their lowest levels over a 24 hour period, would be relatively stable. Additionally, safety considerations dictated sampling during daylight hours since the airport aerobeacon had to be scaled in the performance of the up/down sampling run. From the analyses performed on the combined REA and modified Bowen ratio measurements, this difference in the average temperature gradient did not appear to influence the flux velocity results significantly.
Another difference in the atmospheric parameters was that the overall average horizontal wind speed was higher at the Socorro Airport for both the REA and modified Bowen ratio method measurements than at the SS Ranch. This was the result of an intentional decision to obtain flux velocity measurements having higher associated average horizontal wind speeds after shifting sampling to the Socorro Airport. It was considered necessary to take REA measurements over a broader range of horizontal wind speeds to evaluate more fully the efficacy of the REA method and the New Mexico Tech REA system. Likewise, the modified Bowen ratio method measurements needed to be obtained over a similar range of horizontal wind speeds in order to compare these results effectively with those from the REA method. Though data scatter increases with increasing horizontal wind speed, no differences in the flux velocity results from the different sampling site locations or methods appear to be directly attributable to the increased overall average horizontal wind speed. Of particular interest, though, was the observation that the delay correction factor (DCF) of the New Mexico Tech REA system leveled off at approximately 7 m s$^{-1}$ (see Figure 5.5.4). For this result alone, the decision to obtain measurements over a broader range of horizontal wind speeds at the airport was well justified.

The average flux velocity, $v$, for the combined REA and modified Bowen ratio measurements is towards the ground. Its magnitude and standard deviation of the mean were $9.4 \pm 1.5$ cm s$^{-1}$ for an average horizontal wind speed of 4.8 m s$^{-1}$, an average vertical temperature gradient of 0.009 ºC m$^{-1}$ (near neutral), and an average terrain roughness length of 19 cm. As noted, due to the limited number of modified Bowen ratio measurements and their significant scatter, the REA measurements clearly dominated the
combined results. But it is worthy of reiteration that the modified Bowen ratio measurements were consistent with the REA measurements (see discussion earlier in this chapter and in Chapter 5.6), increasing the confidence level in the REA results.

As discussed, the surface collection deposition velocity measurements could not be evaluated directly with the REA and modified Bowen ratio flux velocity measurements. But 42 of the 69 surface collection deposition velocity measurements were coincident with either an REA or modified Bowen ratio flux velocity measurement. Of those 42 coincident measurements, 38 were associated with the final REA and modified Bowen ratio data set. Two surface collection measurements were associated with an REA flux velocity measurement excluded due to excessive tilt angle (see discussion in Chapter 5.5) and two were associated with the two excluded modified Bowen ratio flux velocity measurements (see discussion in Chapter 6.5). The negative values of the surface collection deposition velocities are plotted versus their associated REA or modified Bowen ratio flux velocities, sorted by site location, in Figure 8.5. A best-fit linear curve is included. It is worth repeating that, although all three methods of calculating flux/deposition velocity use the PAEC results for a reference height of 4 m above ground level, for the surface collection method, the flux density comes from the unattached radon progeny deposited onto the collecting surfaces and their physical area ($\pi r^2$), whereas the flux density for the other methods is measured above the canopy (at 4 m reference height) for a unit area parallel to the ground.
Figure 8.5. Surface Collection vs Concurrent REA/Modified Bowen Ratio Measurements.
Figure 8.5 shows a weak correlation between the surface collection deposition velocities and the concurrently measured REA and modified Bowen ratio flux velocities. The individual ratios of the surface collection deposition velocities to their associated REA and modified Bowen ratio flux velocities were computed and are plotted in Figure 8.6 in chronological order with the sampling site locations identified. A representative ratio was calculated by taking the average of the surface collection deposition velocity measurements and dividing it by the average of the associated REA and modified Bowen ratio flux velocity measurements. This calculated ratio of the averages was \(0.14 \pm 0.04\), indicating that a significant portion (approximately 86%) of the unattached-to-aerosol radon progeny are “swept” from the air (i.e., removed by attachment to surfaces due to the horizontal air movement) within the vegetation canopy. The ratio is annotated on Figure 8.6. This small ratio may, in part, explain the significant differences reported in the literature between wind tunnel and field experiment results.

(Intentionally Blank)
Figure 8.6. Surface Collection to REA/Modified Bowen Measurement Ratio of Flux/Deposition Velocities.
Overall, the inferred REA deposition velocity results, supported by those from the modified Bowen ratio method, appear to be valid and are much larger than many of the predicted values (Sehmel and Hodgson, 1978; Slinn and Slinn, 1980; and Brutsaert, 1982) and experimental measurements (Slinn et al., 1978; McMahon and Denison, 1979; Sehmel, 1980; Chamberlain et al., 1984; Businger, 1986; Nicholson, 1988; Porstendörfer, 1994; Seinfeld and Pandis, 1998; and Wesely and Hicks, 2000) found in much of the traditional literature. But the results are consistent with some field measurements, particularly more recent ones (Wesely et al., 1977; McMahon and Denison, 1979; Hanson and Lindberg, 1991; Schery and Wasiolek, 1993; Porstendörfer, 1994; Schery and Whittlestone, 1995; Schery et al., 1998; Wesely and Hicks, 2000; and Horii et al., 2001), reported in the literature. Additionally, the REA methodology, including the accuracy issues addressed in Chapter 5.1, would appear to negate the concerns of Nicholson and Garland (1996) regarding previously reported high dry deposition velocities for nanometer-size particles (Schery and Whittlestone, 1995).

Unfortunately, direct comparison between the inferred deposition velocity results presented here and those in the literature is difficult for several reasons. First, most of the reported research has dealt primarily with gases and larger particulates (S, SO₂, NOₓ, O₃, HNO₃, etc.) but not small particles of the size of the unattached-to-aerosol radon progeny. Excluding previous research performed at New Mexico Tech by Schery et al. (1993, 1995, and 1998), only the research in the literature reviewed by Porstendörfer (1994) has directly involved radon progeny or other radionuclides. Of those reported measurements involving radon progeny or radionuclides, little information is generally provided (or, in some cases, known) regarding the size range of the particles investigated. In fact, much
of the early literature lacks adequate size information (note tables in Sehmel, 1980). More recent literature reports dry deposition velocity measurements for particles larger than nanometer-size. Again, Porstendörfer (1994) is one of the few sources for measurements involving nanometer-size particles. Second, much of the experimental work involving radon progeny has been done in the laboratory, using wind tunnels, vice field experiments (Porstendörfer, 1994). No above-canopy eddy correlation/accumulation measurements have been available prior to the recent work at the New Mexico Tech Atmospheric Radioactivity Laboratory. Of the other species investigated, only those results involving gas-phase HNO₃ (Hanson and Lindberg, 1991; Seinfeld and Pandis, 1998; Wesely and Hicks, 2000; and Horii et al., 2001) appear to be directly comparable to the results reported herein. Horii et al. (2001) reported average gas-phase HNO₃ dry deposition velocities of 4 cm s⁻¹ (ranging from 2 – 6 cm s⁻¹) using an eddy covariance method. This is not unexpected since HNO₃ is a highly reactive small molecule with a high probability of sticking to surfaces, properties making it similar to nanometer-size particles with regards to dry deposition.

By comparison, typical dry deposition velocities over land for atmospheric trace gases (excluding HNO₃) are less than 1 cm s⁻¹. Table 8.1 shows the dry deposition velocities for some of these gases.
Table 8.1. Typical Dry Deposition Velocities of Some Atmospheric Gases over Land
(adapted from Seinfeld and Pandis, 1998)

<table>
<thead>
<tr>
<th>Species</th>
<th>$v_d$ (cm s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.03</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0</td>
</tr>
<tr>
<td>NO</td>
<td>0.016</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>0.1</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.4</td>
</tr>
<tr>
<td>H$_2$O$_2$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Discrepancies in reported particle dry deposition velocities in the literature are numerous. Sehmel (1980) noted a three orders of magnitude range in reported dry deposition velocities. Slinn (1983) reported field measurements that were significantly larger than the predicted particle dry deposition velocities. Nicholson (1988) stated that the one to two orders of magnitude variance between the dry deposition velocities measured using micrometeorological techniques and theoretically predicted values made the suitability of all micrometeorological techniques uncertain. Butterweck (1991) reported field dry deposition velocity measurements that were 10 times larger than those of laboratory wind tunnel experiments. The various papers by Schery et al. (1993,1995, and 1998), reported significantly higher than predicted deposition velocities for nanometer-size particles. Finally, Wesely and Hicks (2000) noted continuing problems
between experimental and model results. The results presented here are consistent with the higher dry deposition velocities obtained in field experiments that have been reported in the literature. Most models are fundamentally based on the resistance model discussed in Chapter 2.1 and the discrepancies with historical model results are likely due to inaccurate modeling of the complex outdoor environment, especially with regards to the canopy surface area, surface roughness, and actual turbulence. Additionally, uncertainty as to the actual experimentally measured particle sizes may contribute to the noted discrepancies (Wesely and Hicks, 2000). The fact that the surface collection method deposition velocity measurements presented here (for a known particle size) were similar for both vertically and horizontally placed sandpaper collecting materials supports the importance of the vegetation canopy and removal involving horizontal motion within it. This aspect is in addition to any effect that the roughness of the vegetation canopy may have on increasing the aerodynamic transport (i.e., turbulence) above it. Many existing resistance models, including those for other chemical species, may not adequately reflect the effect of the vegetation surface area and aerodynamic turbulence. Hence, atmospheric transport models need improvement as suggested by Wesely and Hicks (2000).

The observed tendency for increasing inferred deposition velocity with increasing horizontal wind speed is consistent with the literature (Convair, 1960; Seinfeld and Pandis, 1998). Though the correlation values are not conclusive, they suggest that a relationship does exist. Similarly, the apparent, though lesser, correlation observed between the inferred deposition velocity and atmospheric stability is also consistent with the literature (Sehmel and Hodgson, 1978; Nicholson, 1988; Seinfeld and Pandis, 1998).
Sehmel and Hodgson (1978) predicted that the deposition velocity should be nearly independent of the atmospheric stability, which can be concluded from the results presented here.

The problem of positive (upward) fluxes is still not fully resolved. For the research presented, potential causes were discussed in Chapter 5.6. This problem, though, is not unique to the research reported here. Hicks et al. (1982) reported upward fluxes for atmospheric sulfur at night. These upward fluxes were attributed to resuspension by Wesely et al. (1983). This is unlikely for the unattached-to-aerosol radon progeny, but it does highlight the complexities and inherent difficulties in making field measurements.

The surface collection method deposition velocity results from the research presented here are generally higher than those reported in the literature. Unfortunately, direct comparisons are limited as there are few, if any, reported experimental results involving nanometer-size particles and/or using a similar methodology. For example, recently reported canopy-level surface collection measurements involving $^{214}\text{Pb}$ (Wyers and Veltkamp, 1997) (estimated particle activity median diameter (AMD) of 0.4 $\mu$m [accumulation mode] based on a cascade impactor) were slightly smaller than the surface collection results presented here. Based on their reported “correction” to exclude the unattached $^{214}\text{Pb}$, their average deposition velocity should have been significantly smaller (by a factor of 10 – 100). The similarity between the surface collection measurements from both vertically and horizontally placed collecting surfaces supports the conclusion that the sedimentation/dry deposition of larger accumulation mode attached radon progeny is not an issue here contrary to the discussion of Nicholson.
Actual surface area, regardless of orientation, appears to be the key factor for nanometer-size particles.

The relative humidity was not analyzed as a factor affecting the flux/deposition velocity in any of the three methods performed. In general, the relative humidity was less than 30% with the exception of those occasional early morning hours during the summer monsoon season when the relative humidity ranged above 60%. The relative humidity does not appear to have had an effect on the results, but a more detailed analysis is warranted.

Data scatter was a significant problem with all three methods used in the research presented here. Possible sources of scatter have been discussed in detail in Chapters 5.6, 6.6, and 7.6; only the overall impact and potential solutions will be addressed here. Unfortunately, because of scatter, it is extremely difficult to obtain measurements with near-zero vertical wind velocities (i.e., $w \leq 3 \text{ cm s}^{-1}$) with the REA or modified Bowen ratio methods, particularly at the higher average horizontal wind speeds (above 7 m s$^{-1}$). One possible solution is to increase the sampling time to greater than 40 minutes for the REA and modified Bowen ratio methods. Longer sampling times will not increase the amount of unattached-to-aerosol radon progeny alpha activity on the screens since collected alpha activity reaches equilibrium after about 40 minutes. But, a longer sampling time would result in a longer time averaging of the vertical wind velocity, hopefully resulting in near-zero average. This may be particularly necessary at the higher horizontal wind speeds. Additionally, a larger statistical database (i.e., more data) would definitely aid in averaging out the data scatter and identifying a more definitive
correlation between the inferred deposition velocity and the horizontal wind speed. Also, statistically, an increase in the number of samples will automatically decrease the error.

To eliminate the apparent data scatter caused by temperature gradient changes during sampling, sampling could be performed at times of the day during which the temperature gradient is expected to remain unchanged over a period of time. However, since radon progeny concentration and temperature gradients are known to have diurnal patterns, care must be taken so as not to bias the data set by limiting measurements to convenient times of the day.
PART 9

CONCLUSIONS
CHAPTER 9
CONCLUSIONS

Reliable above-the-vegetation-canopy field measurements of the surface flux/deposition velocity of nanometer-size particles were achieved using the REA system built by New Mexico Tech. Combined with some earlier preliminary results from New Mexico Tech (Schery et al., 1998), these are the first successful above-canopy measurements of this type. Given certain assumptions, these measurements can be used to infer the particle dry deposition velocity, $v_d$. On average, the atmospheric conditions generally assumed necessary for deducing the dry deposition velocity were met. Non-zero vertical wind velocity appears to be an important source of data scatter for the REA method. Notably, some of the flux velocities were positive (upward). These positive velocities were possibly caused by transient inhomogeneous airborne sinks/sources of radon gas and non-radioactive aerosol particles in the accumulation mode.

The inferred dry deposition velocities for the unattached-to-aerosol radon progeny from the REA method are greater than those predicted for nanometer-size aerosol particles by some commonly used models, but are consistent with a few, more recently reported, field experiment results found in the literature for both nanometer-size particles and HNO$_3$. Flux velocity measurements made using the modified Bowen ratio method, an independent above-the-vegetation-canopy technique, were consistent with those from
the REA method and support the overall results obtained using the REA method. The magnitude of the average flux velocity, \( v \) (also the magnitude of the inferred deposition velocity, \( v_d \)), and its standard deviation of the mean for the combined REA and modified Bowen ratio flux velocity measurements were 9.4 ± 1.5 cm s\(^{-1}\) for an average horizontal wind speed of 4.8 m s\(^{-1}\), an average vertical temperature gradient of 0.009 °C m\(^{-1}\) (near neutral), and an average terrain roughness length of 19 cm. This result compares with a value of 1 cm s\(^{-1}\) previously suggested by some authors (e.g., Nicholson and Garland, 1996) for somewhat comparable conditions. These new results have implications as to the need for developing/improving the dry deposition parameterization used in certain commonly used atmospheric climate and air pollution models.

Because of data scatter the exact quantitative relationship to the horizontal wind speed could not be established (i.e., linear, quadratic, exponential, etc.), but the dry deposition velocity appears to increase with increasing horizontal wind speed on the order of 1 cm s\(^{-1}\) per 1 m s\(^{-1}\) increase in wind speed, which is consistent with the literature. Terrain roughness appears to be a factor in this relationship, but the quantitative nature of its influence is less certain. Likewise, there appears to be a lesser correlation between the dry deposition velocity and atmospheric stability (i.e., the average temperature gradient) with larger deposition velocities occurring under unstable (negative gradient) atmospheric conditions. This is also consistent with the literature.

High precision is difficult to achieve with the REA method in the outdoor environment due to the varying atmospheric conditions, which cannot be controlled, resulting in significant data scatter. With careful analysis, though, some of the data scatter can be eliminated by excluding those measurements having high average vertical
wind velocities and, to a lesser extent, those measurements having negative trending temperature gradients (i.e., increasing atmospheric instability); but there remains a part of the scatter that cannot be explained by the variables so far measured. Additional measurements and longer sampling periods (approximately one hour) at the higher horizontal wind speeds (greater than 7 m s\(^{-1}\)) are potential solutions for further reducing the data scatter. Further research is recommended to identify fully and correct for the sources of data scatter.

The correction factor for the delay in the REA system response can be significant. The system delay correction was the single, largest correction applied to the REA flux velocity measurements at the higher horizontal wind speeds. Though a hardware modification to compensate physically for the system response delay is recommended, it may not be feasible with the current New Mexico Tech system. Regardless, the system response delay must be known for any REA system in order to correct the measurements properly.

The surface collection deposition velocity measurements were generally higher than previously reported results for below-the-vegetation-canopy methods. Physical orientation and the type of collecting material appear to have little effect on the unattached radon progeny deposited with the exception of the wire mesh screens, suggesting that small-scale airflows do exist at ground level. The fact that the physical orientation had no effect implies that the available surface area, not orientation, is the most important factor in the dry deposition of nanometer-size particles. The ratio of the above-canopy measurements (REA and modified Bowen ratio) to the surface collection measurements of the deposition velocity was of the order of 7. This large ratio may
perhaps explain some of the underestimation of dry deposition that is apparently common in the literature.

It is suggested that, with an expanded system having an additional alpha counting system, a second high-volume blower, additional sampling heads, and a modified tower, all three dry deposition measurement methods presented here could be performed simultaneously. This would allow direct intercomparison of all three methods, hopefully resulting in a clearer picture of the dry deposition process. Additionally, new field measurements over a much smoother surface, such as desert sand, would be of value to establish more clearly the dependence of dry deposition on surface roughness.

In reporting the results of field measurements, careful attention must be paid to also reporting the atmospheric conditions under which the dry deposition velocity measurements are made. This is important to ensuring that the assumptions associated with a given method are as closely met as possible. It is clear from the research presented here that atmospheric conditions, though largely uncontrollable, have a significant impact on the results. The measurement of additional atmospheric parameters (beyond those identified here) is probably required to reduce or correct for the data scatter observed. Also, because of the significant data scatter, statistical analysis is necessary for the proper interpretation of results. Apparent differences may, as noted here, not be statistically significant and the results of such analyses must be reported.


APPENDIX A

DATA FORMS
### ARREA LOG SHEET

**DATE:**                  **RUN:**             **MODE:**            **FASTCOM FILENAME:**

**WEATHER CONDITIONS:**

**TIME ZONE:**

### TEST INFORMATION

<table>
<thead>
<tr>
<th>BLOWER ON TIME</th>
<th>BLOWER OFF TIME</th>
<th>Temp. (°C)</th>
<th>RH (%)</th>
<th>Press. (mb)</th>
<th>SCREEN MESH</th>
<th>DEAD BAND (m/s)</th>
<th>OFFSET (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### COUNTER INFORMATION

<table>
<thead>
<tr>
<th>COUNTER</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>SCREEN#/FILTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACKGND ON</td>
</tr>
<tr>
<td>BACKGND OFF</td>
</tr>
<tr>
<td>10 Min BACKGND counts (scaler&amp;computer)</td>
</tr>
<tr>
<td>50 Min counts</td>
</tr>
<tr>
<td>FLOW RATE (SCFM)</td>
</tr>
<tr>
<td>CORRECTED FLOW RATE (SCFM &amp; ℓpm)</td>
</tr>
<tr>
<td>SCREEN EFFICIENCY (from _____ program)</td>
</tr>
<tr>
<td>particle size: nm</td>
</tr>
</tbody>
</table>

### WIND INFORMATION

<table>
<thead>
<tr>
<th>U</th>
<th>V</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>STD DEV</td>
<td>MEAN</td>
</tr>
<tr>
<td>UP% ON MINUTES</td>
<td>NEUT% ON MINUTES</td>
<td>DOWN% ON MINUTES</td>
</tr>
</tbody>
</table>

### VERTICAL ALIGNMENT: rotate from __ by ______ TILT: _____

### METEOROLOGICAL INFORMATION

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>2 m</th>
<th>8m</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIND SPD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIND DIR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

246
CORRECTED FLOW RATES FOR ______________ RUN _____

(Based on manufacturer’s instructions for blower)

\[ F = G \sqrt[3]{\frac{p_1}{p_0}} \frac{T_0}{T_1} \]

\[ p_0 = 1 \text{ atm} + 1 \text{ atm} = 2 \text{ atm} \]
\[ T_0 = 293 \text{ K} \]

\[ P_1 = ( \text{_________ mb})(1 \text{ bar} / 1 \times 10^3 \text{ mb})(1 \text{ atm} / 1.013 \text{ bar}) + 1 \text{ atm} = \text{________ atm} \]
(Local Pressure Reading)

\[ = ( \text{_________ mb})(0.7502 \text{ mmHg} / 1 \text{ mb}) = \text{__________ mmHg} \] [For screen efficiency calculation]

\[ T_1 = 273 \text{ K} + \text{_________ °C} = \text{__________ K} \]
(Local Temperature Reading)

\[ => F = G \sqrt{\frac{\text{atm}}{2 \text{ atm}}} \frac{293 \text{ K}}{K} = G \left( \text{_________} \right) \text{ SCFM} \]

[F is corrected flow rate; G is measured flow rate]

\[ \text{UP} = ( \text{_____ SCFM})( \text{______}) = ( \text{_____ SCFM})(28.32 \text{ ℓpm} / 1 \text{ SCFM}) = \text{_____ ℓpm} \]

\[ \text{NEUT} = ( \text{_____ SCFM})( \text{______}) = ( \text{_____ SCFM})(28.32 \text{ ℓpm} / 1 \text{ SCFM}) = \text{_____ ℓpm} \]

\[ \text{DOWN} = ( \text{_____ SCFM})( \text{______}) = ( \text{_____ SCFM})(28.32 \text{ ℓpm} / 1 \text{ SCFM}) = \text{_____ ℓpm} \]
DEPOSITION VELOCITY CALCULATION

SAMPLE DATE/TIME: ______________________ RUN NUMBER: ___________
SAMPLE LOCATION: ______________________ SCREEN MESH: ___________

UP SCREEN PAEC ($C_{UP}$): ___________ ± ___________ nJ/m³ (______ %)
*Screen Mesh Correction: $\times (\_\_\_\_\_) = ___________ nJ/m³

DOWN SCREEN PAEC ($C_{DOWN}$): ___________ ± ___________ nJ/m³ (______ %)
*Screen Mesh Correction: $\times (\_\_\_\_\_) = ___________ nJ/m³

Average Concentration ($C_{AVE}$) = ($C_{UP}$ + $C_{DOWN}$)/2 = ___________ nJ/m³
Error Analysis: $(\delta C_{UP}^2 + \delta C_{DOWN}^2)^{1/2} = ___________ nJ/m³

DEADBAND SETTING (inc. dial set): ________ m/s MEAN VERT WIND = ____ %
VERTICAL WIND DEVIATION ($\sigma_w$): ________ m/s $\sigma_w$
Normalized Deadband (DB/2 $\sigma_w$):
b₀ = ___________ [Identify source of value. Normally 0.57 or 0.6]
b = (b₀)(correction factor) = _______ [correction factor = _____ from _____]
[Identify correction factor source]

* $F_c$ (FLUX) = b $\sigma_w$ [$C_{UP}$ - $C_{DOWN}$] = ___________ ± ___________ nJ/m² s

* $v$ (DEPOSITION VELOCITY) = $F_c$/ $C_{AVE}$ = ___________ ± ___________ m/s

CORRECTIONS FOR DIFFERENCES IN FILTER PAECs:

UP FILTER PAEC: ___________ nJ/m³ DOWN FILTER PAEC: ___________ nJ/m³
* Screen Mesh Corrections:
[-(______) (______) ] = ___________ nJ/m³ [-(______) (______) ] = ___________ nJ/m³
CORRECTED $C_{UP}$ :
($C_{UP}$/2)(UP FILTER PAEC = DOWN FILTER PAEC)(1/UP FILTER PAEC)
Corrected $C_{UP}$ = ___________ ± ___________ nJ/m³
* Screen Mesh Corrected: ___________ nJ/m³

CORRECTED $C_{DOWN}$ :
($C_{DOWN}$/2)(UP FILTER PAEC = DOWN FILTER PAEC)(1/DOWN FILTER PAEC)
Corrected $C_{DOWN}$ = ___________ ± ___________ nJ/m³
* Screen Mesh Corrected: ___________ nJ/m³
CORRECTED $C_{AVE}$ = (CORRECTED $C_{UP}$ + CORRECTED $C_{DOWN}$)/2 = ___________ nJ/m³
* Screen Mesh Corrected: ___________ nJ/m³

*CORRECTED $F_c$ = ___________ ± ___________ nJ/m² s
* Screen Mesh Corrected: ___________ nJ/m² s

*CORRECTED $v$ = ___________ ± ___________ m/s
* Screen Mesh Corrected: ___________ m/s
**DEPOSITION VELOCITY**

**GRADIENT METHOD DATA/WORKSHEET**

<table>
<thead>
<tr>
<th>SAMPLE DATE/TIME:</th>
<th>RUN NUMBER:</th>
<th>RUN TIME:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SAMPLE LOCATION:</th>
<th>SCREEN MESH:</th>
<th>REL. HUM.(%):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BACKGROUND CHECKS:**

<table>
<thead>
<tr>
<th>Foil or Filter</th>
<th>Backgnd</th>
<th>Counter No.</th>
<th>50 Min Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCREEN #</th>
<th>COUNTER #</th>
<th>TIME ON</th>
<th>TIME OFF</th>
<th>BACKGND</th>
<th>50 Min Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-LARGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLOWER</td>
<td>FILTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-SMALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLOWER</td>
<td>FILTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**METEOROLOGICAL DATA:**

<table>
<thead>
<tr>
<th>2M</th>
<th>8M</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE (°C)</td>
<td></td>
</tr>
<tr>
<td>WIND SPEED (m s⁻¹)</td>
<td></td>
</tr>
<tr>
<td>WIND DIRECTION (°)</td>
<td></td>
</tr>
</tbody>
</table>

**SCREEN ACTIVITY:**

<table>
<thead>
<tr>
<th>2M SCREEN PAEC:</th>
<th>+/−</th>
<th>nJ/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Mesh Corrected (x ____):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8M SCREEN PAEC:</td>
<td>+/−</td>
<td>nJ/m³</td>
</tr>
<tr>
<td>Screen Mesh Corrected (x ____):</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Unattached/Ultrafine Average Concentration \([C_U = \frac{C_{U2m} + C_{U8m}}{2}]\):** | nJ/m³ |

**Error Analysis (δC_{U2m}² + δC_{U8m}²):** | nJ/m³ |

**ΔC_U = C_{U8m} - C_{U2m}:** | nJ/m³ |

**ΔC_U/C_U:** | |

**FILTER ACTIVITY:**

<table>
<thead>
<tr>
<th>2M FILTER PAEC:</th>
<th>+/−</th>
<th>nJ/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Mesh Corrected (x ____):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8M FILTER PAEC:</td>
<td>+/−</td>
<td>nJ/m³</td>
</tr>
<tr>
<td>Screen Mesh Corrected (x ____):</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Attached Average Concentration \([C_A = \frac{C_{A2m} + C_{A8m}}{2}]\):** | nJ/m³ |

**Error Analysis (δC_{A2m}² + δC_{A8m}²):** | nJ/m³ |

**ΔC_A = C_{A8m} - C_{A2m}:** | nJ/m³ |

**ΔC_A/C_A:** | |

**GEOMETRIC MEAN HEIGHT \([z_m = \sqrt[2]{z_{2m}z_{8m}}}]\):** | |

**RICHARDSON'S NUMBER FOR GEOMETRIC MEAN HEIGHT:** | |

**FLUX (F_c):** | +/− | nJ/m³ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Mesh Corrected:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DEPOSITION VELOCITY (v):** | +/− | m/s |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Mesh Corrected:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FLUX/DEPOSITION VELOCITY CALCULATIONS:**

249
MODIFIED BOWEN RATIO METHOD
CALCULATION FORM

SAMPLE DATE: ______________________________
SAMPLE LOCATION: _________________________

RUN A (Side-by-Side) SCREEN MESH CORRECTED AND FILTER ADJUSTED PAEC VALUES:

BLOWER ___ (PLACED @ 8M FOR RUN B):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

BLOWER ___ (PLACED @ 2M FOR RUN B):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

RUN C (Side-by-Side) SCREEN MESH CORRECTED AND FILTER ADJUSTED PAEC VALUES:

BLOWER ___ (PLACED @ 8M FOR RUN B):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

BLOWER ___ (PLACED @ 2M FOR RUN B):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

SIDE-BY-SIDE SCREEN PAEC RATIOS:

RUN A (8M ___ / 2M ___ ) = ( _______ nJ/m³ / _______ nJ/m³) = _______

RUN C (8M ___ / 2M ___ ) = ( _______ nJ/m³ / _______ nJ/m³) = _______

AVERAGE SCREEN PAEC RATIO = (RUN A RATIO + RUN B RATIO)/2 = _______

V_{DEP} CALCULATION FOR RUN B (Up/Down):

SCREEN MESH AND FILTER ADJUSTED PAEC VALUES:

BLOWER ___ (PLACED @ 8M):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

BLOWER ___ (PLACED @ 2M):
SCREEN _______ +/- _______ nJ/m³
FILTER _______ +/- _______ nJ/m³

C_{Ave. Screen} = (C_{8M Corrected/Adjusted Screen} + C_{2M Corrected/Adjusted Screen}) / 2

\frac{w'\Delta T}{T'} = \frac{\text{m s}^{-1}}{\text{°C}} \text{ Covariance from Excel File}

\Delta C = \frac{\text{PAEC}_{8M \text{ Screen}} - \text{PAEC}_{2M \text{ Screen}}}{-} +/- \sqrt{(\frac{\text{RUN A RATIO}}{2})^2 + (\frac{\text{RUN B RATIO}}{2})^2} \text{ nJ/m}^3

\Delta T = \frac{\Sigma(\Delta T_i)}{n} \text{ (i.e. average T}_{8M} - T_{2M}) = \text{_______ °C}

* \text{PARTICLE FLUX} = w'\Delta T / \Delta C = \text{_______ +/- _______ nJ m}^{-2} s^{-1}

* \text{V}_{DEP} = \frac{F_{Part}}{C_{Ave. Screen}} = \text{_______ +/- _______ m/s}
SAMPLE DATE/TIME (inc. Zone): _________________________ RUN: _____
SAMPLE LOCATION: __________________________________________________________

RUN A (Side-by-Side) CORRECTED (Collection Efficiency) SCREEN PAEC RESULTS:

BLOWER ___ (PLACED @ 8M FOR RUN B) SCREEN PAEC: _______ ± _______ nJ/m³
BLOWER ___ (PLACED @ 2M FOR RUN B) SCREEN PAEC: _______ ± _______ nJ/m³

RUN C (Side-by-Side) CORRECTED (Collection Efficiency) SCREEN PAEC RESULTS:

BLOWER ___ (PLACED @ 8M FOR RUN B) SCREEN PAEC: _______ ± _______ nJ/m³
BLOWER ___ (PLACED @ 2M FOR RUN B) SCREEN PAEC: _______ ± _______ nJ/m³

SIDE-BY-SIDE CORRECTED SCREEN PAEC RATIOS:

RUN A (8M ___ / 2M ___) = ( _______ nJ/m³ / _______ nJ/m³) = __________
RUN A (8M ___ / 2M ___) = ( _______ nJ/m³ / _______ nJ/m³) = __________

AVERAGE CORRECTED SCREEN PAEC RATIO = (RUN A RATIO + RUN B RATIO)/2 = __
(BLOWER ___ TO ___)

FLUX VELOCITY CALCULATION FOR RUN B (Up/Down):

CORRECTED (Collection Efficiency) SCREEN PAEC RESULTS:

ADJUSTED-FOR-SIDE-BY-SIDE-RATIO PAEC

BLOWER ___ (PLACED @ 8M): _______ ± _______ nJ/m³ _______ nJ/m³
BLOWER ___ (PLACED @ 2M): _______ ± _______ nJ/m³ _______ nJ/m³

\[
\overline{C_{\text{Average Screen}}} = \frac{(C_{8M \text{ Corrected Screen}} + C_{2M \text{ Corrected Screen}})}{2} = \text{______________ nJ/m}^3
\]

\[
\overline{w'T'} = \text{______________ m s}^{-1} {^\circ C} \text{ (Covariance)}
\]

\[
\Delta C = \text{______________ ± ______________ nJ/m}^3 \quad \Delta T = \text{___________} {^\circ C}
\]

\[
*\text{FLUX} \ (F) = \overline{w'T'} \left( \frac{\Delta C}{\Delta T} \right) = \text{______________ ± ______________ nJ m}^{-2} \text{ s}^{-1}
\]

\[
*\text{FLUX VELOCITY} \ (V_{\text{DEP}}) = F / \overline{C_{\text{Average Screen}}} = \text{______________ ± ______________ m/s}
\]
MODIFIED BOWEN RATIO VERTICAL WIND CORRECTION
& REVISED FLUX/DEPOSITION VELOCITY CALCULATION

Sample Date: _____________________   Sample Time (inc. Time Zone): _________

Sample Location: ________________________________

NSA2.EXE Program Tilt Correction: ______ º  From ____; Tilt ______ by ______º

Averages from NSA2.EXE:

\[
\begin{align*}
+ & u \\
- & v \\
+ & v \\
- & u \\
\end{align*}
\]

\[
\begin{align*}
u &= \text{______ m/s} \\
v &= \text{______ m/s} \\
w &= \text{______ m/s} \\
\end{align*}
\]

Projection \( u = w \left( \sin \left( \text{______ [tilt angle]} \right) \right) \times \left( \sin \left( \text{______ [rotation]} \right) \right) = \text{___________} \)

Projection \( v = w \left( \sin \left( \text{______ [tilt angle]} \right) \right) \times \left( \cos \left( \text{______ [rotation]} \right) \right) = \text{___________} \)

New angle rotated \( w \) to old \( u \) \( \theta_{wu} \) = \( \arccos \left( \text{Proj } u \right) / w \) = \( \text{___________} \º \left( w', u \right) \)

New angle rotated \( w \) to old \( v \) \( \theta_{wu} \) = \( \arccos \left( \text{Proj } v \right) / w \) = \( \text{___________} \º \left( w', v \right) \)

\[
\Rightarrow \quad w' = \left[ \cos(\text{w}', \text{u}) \right] u + \left[ \cos(\text{w}', \text{v}) \right] v + \left[ \cos(\text{tilt}) \right] w
\]

Average \( w' = \left[ \cos(\text{______}) \right](\text{______}) + \left[ \cos(\text{______}) \right](\text{______}) + \left[ \cos(\text{______}) \right](\text{______}) \)

\[
= \left( \text{___________} \right) + \left( \text{___________} \right) + \left( \text{___________} \right) = \text{___________} \text{ m/s}
\]

Multiply all readings in SAM file by above coefficients to get new \( w' \) values
Then compute new covariance of \( w' \) and \( T \)

New Covariance = \text{___________} \text{ m/s ºC} \quad \Delta c = \text{______} \pm \text{______} \text{ nJ/m}^3 \quad \Delta T = \text{______} \ºC

Flux = Covariance \times (\Delta c / \Delta T) = \text{___________} \pm \text{______} \text{ nJ m}^{-2} \text{ s}^{-1} \text{ Ave} = \text{______} \text{ nJ m}^{-3}

Flux/Deposition Velocity = \( F / c (\text{ave}) = \text{___________} \pm \text{______} \text{ m/s} \)
DIRECT DRY DEPOSITION VELOCITY CALCULATION

SAMPLE LOCATION: ______________ SAMPLE DATE/TIME (inc. Time Zone): ________
ASSOCIATED ARREA or BOWEN METHOD RUN: ________ EXPOSURE TIME: _______

MATERIAL: _____________________________
ALPHA COUNTER NUMBER: _____________
BACKGROUND COUNTS: (Counter Scaler) _______ (Alpha Counting System File) _____
50 MINUTE TOTAL COUNTS: __________
PAEC (from EXMAXDP): ________________

TOTAL ACTIVITY ON MATERIAL:

\[(1 \times 10^{-4} \text{ m}^3)(\text{PAEC}) = (1 \times 10^{-4} \text{ m}^3)(\_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{nJ/m}^3) = \_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{nJ}\]

*TOTAL ACTIVITY PER UNIT AREA OF MATERIAL:

\[(\text{Above})/(7.885429 \times 10^{-3} \text{ m}^2) = (\_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{nJ})/(7.885429 \times 10^{-3} \text{ m}^2) = \_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{nJ/m}^2\]

AVE. ACTIVITY ON BLOWER SCREENS: (Taken w/ associated ARREA or Bowen)
[Provides air activity]

Po218: \[\left(\frac{C_{\text{Po218 Screen A Bq/m}^3} + C_{\text{Po218 Screen B Bq/m}^3}}{2} \pm \sqrt{\left(1\sigma_{\text{Po218 Screen A Bq/m}^3}\right)^2 + \left(1\sigma_{\text{Po218 Screen B Bq/m}^3}\right)^2}/2\right)\]

\[= (\_\_\_\_\_\_ \text{Bq/m}^3 + \_\_\_\_\_\_ \text{Bq/m}^3)/2 \pm (\_\_\_\_\_\_ \text{Bq/m}^3)^2 + (\_\_\_\_\_\_ \text{Bq/m}^3)^2)/2\]

\[= (\_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{Bq/m}^3)\]

Pb214: \[\left(\frac{C_{\text{Pb214 Screen A Bq/m}^3} + C_{\text{Pb214 Screen B Bq/m}^3}}{2} \pm \sqrt{\left(1\sigma_{\text{Pb214 Screen A Bq/m}^3}\right)^2 + \left(1\sigma_{\text{Pb214 Screen B Bq/m}^3}\right)^2}/2\right)\]

\[= (\_\_\_\_\_\_ \text{Bq/m}^3 + \_\_\_\_\_\_ \text{Bq/m}^3)/2 \pm (\_\_\_\_\_\_ \text{Bq/m}^3)^2 + (\_\_\_\_\_\_ \text{Bq/m}^3)^2)/2\]

\[= (\_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{Bq/m}^3)\]

Bi214: \[\left(\frac{C_{\text{Bi214 Screen A Bq/m}^3} + C_{\text{Bi214 Screen B Bq/m}^3}}{2} \pm \sqrt{\left(1\sigma_{\text{Bi214 Screen A Bq/m}^3}\right)^2 + \left(1\sigma_{\text{Bi214 Screen B Bq/m}^3}\right)^2}/2\right)\]

\[= (\_\_\_\_\_\_ \text{Bq/m}^3 + \_\_\_\_\_\_ \text{Bq/m}^3)/2 \pm (\_\_\_\_\_\_ \text{Bq/m}^3)^2 + (\_\_\_\_\_\_ \text{Bq/m}^3)^2)/2\]

\[= (\_\_\_\_\_\_ \pm \_\_\_\_\_\_ \text{Bq/m}^3)\]

CORRECTION FACTOR: $\varepsilon$ (Efficiency)

$\varepsilon_{\text{Total}} = (\text{Average } \varepsilon_{\text{Collection}})(\text{Average } \varepsilon_{\text{Counter}}) = ((\_\_\_\_ \pm \_\_\_\_)/2)((\_\_\_\_ \pm \_\_\_\_)/2) = (\_\_\_\_)(\_\_\_\_) = \_\_\_\_
CORRECTED AVE. SCREEN ACTIVITIES:

\[ N_1 = \frac{(Po218 \text{ Activity Bq/m}^3)}{\varepsilon_{\text{Total}}} = \pm \text{Bq/m}^3 \]
\[ N_2 = \frac{(Pb214 \text{ Activity Bq/m}^3)}{\varepsilon_{\text{Total}}} = \pm \text{Bq/m}^3 \]
\[ N_3 = \frac{(Bi214 \text{ Activity Bq/m}^3)}{\varepsilon_{\text{Total}}} = \pm \text{Bq/m}^3 \]

*TOTAL ACTIVITY CONCENTRATION IN AIR:

\[ C_{\text{Total}} \text{nJ s m}^{-3} = 1462 \text{nJ s Bq}^{-1} N_1 + 11504 \text{nJ s Bq}^{-1} N_2 + 3580 \text{nJ s Bq}^{-1} N_3 \]
\[ = (1462)(\pm \text{Bq/m}^3) + (11540)(\pm \text{Bq/m}^3) + (3580)(\pm \text{Bq/m}^3) \]
\[ = (\pm \text{nJ s m}^{-3}) + (\pm \text{nJ s m}^{-3}) + (\pm \text{nJ s m}^{-3}) \]
\[ = \pm \text{nJ s m}^{-3} \text{[Compute error as square root of sum of squares]} \]

DEPOSITION VELOCITY (\( \upsilon \)):

\[ \upsilon = \frac{(\text{nJ m}^{-2})}{(\text{nJ m}^{-2} \text{s})} = \frac{(\text{Total Activity per Unit Area})}{(C_{\text{Total}})} \]
\[ = (\pm \text{nJ m}^{-2})/(\pm \text{nJ m}^{-3} \text{s}) \]

Error:

\[ \delta \upsilon/\upsilon = \sqrt{\left(\frac{\delta\text{Activity per Unit Area}/\text{Activity per Unit Area}}{\delta C_{\text{Total}}/C_{\text{Total}}}\right)^2} \]
\[ = \sqrt{\left(\frac{\pm \text{nJ m}^{-2}}{\pm \text{nJ m}^{-3} \text{s}}\right)^2} \]
\[ = \sqrt{\left(\frac{\pm \text{nJ m}^{-2}}{\pm \text{nJ m}^{-3} \text{s}}\right)^2} \]
\[ = \pm \text{nJ m}^{-2}/\pm \text{nJ m}^{-3} \text{s} \]
\[ \delta \upsilon = (\delta \upsilon/\upsilon)(\upsilon) = (\pm \text{nJ m}^{-2}/\pm \text{nJ m}^{-3} \text{s}) = \pm \text{nJ m}^{-2}/\pm \text{nJ m}^{-3} \text{s} \]

\[ \Rightarrow \upsilon = \pm \text{nJ m}^{-2}/\pm \text{nJ m}^{-3} \text{s} \text{ (DOWNWARD)} \]

@ \pm \text{nJ m}^{-2}/\pm \text{nJ m}^{-3} \text{s} \text{ Horizontal Wind Velocity from } \pm \text{°}
SURFACE COLLECTION DEPOSITION VELOCITY CALCULATION

SAMPLE LOCATION: ____________ SAMPLE DATE/TIME (inc. Time Zone): __________
ASSOCIATED REA or MOD BOWEN RATIO RUN: ___ EXPOSURE TIME: __ min ( __ s)

MATERIAL:
ALPHA COUNTER NUMBER: __________
BACKGROUND COUNTS: (Counter Scaler) _____ (Alpha Counting System File) _____
50 MINUTE TOTAL COUNTS: ____________
PSEUDO-PAEC (from EXMAXDP): ______________ ± ______________ nJ/m³

TOTAL ACTIVITY ON MATERIAL:

(Pseudo-PAEC)(1 × 10³ m³/l)(1 lpm)(Exposure Time)
= ( __________ ± __________ nJ/m³)(1 × 10³ m³/l)(1 lpm)(___ min)
= __________ ± __________ nJ

*TOTAL ACTIVITY PER UNIT AREA OF MATERIAL:

(Total Activity on Material)/(7.885429 × 10⁻³ m²) = ( _____ ± _____ nJ)/(7.885429 × 10⁻³ m²)
= __________ ± __________ nJ/ m² ****

*TOTAL ACTIVITY CONCENTRATION IN AIR (from REA or Modified Bowen Data):

Corrected for Collection Efficiency Up Screen PAEC: ______ ± ________ nJ/m³
Corrected for Collection Efficiency Down Screen PAEC: ______ ± ________ nJ/m³

Average Corrected Screen PAEC = (Corrected Up Screen PAEC +
Corrected Down Screen PAEC)/2
= __________ ± __________ nJ/m³ ****

[error computed as square root of sum of squares]

*DEPOSITION VELOCITY (vd):

*vd = (nJ/ m²)/( nJ/m³ s)
= (Total Activity per Unit Area)/(Total Activity Concentration in Air)(Exposure Time)
= ( __________ ± __________ nJ/ m²)/[( __________ ± __________ nJ/m³)( _____ s)]

Error:
δv/v = √{[δ(Activity per Unit Area)/Activity per Unit Area)² + (δC_Total/C_Total)²}
= √{[____________ / ____________]² + [____________/ ____________]²}
= __________

δv = (δv/v)(v) = (____________)(____________) = __________

**** vd = ______________ ± ______________ m/s (DOWNWARD)
@ ______ m/s Horizontal Wind Speed
from ______ °
APPENDIX B

COMPUTER SOFTWARE
The AC.EXE (AC for automatic counter) program outlined below is a Quick Basic program that controlled all functions of the automatic alpha counting system employed in the research presented herein, including recording and storing the minute-by-minute alpha counts detected by each of the six scintillation detectors and controlling power to instruments plugged into the system interface box. The system interface box was built by Stewart Whittlestone, Ph.D., Australian Science and Technology Organization (ANSTO), PMB 1, Menai, NSW 2234, Australia, e-mail swh@atom.ansto.gov.au.

'********* AC ***** for POWER BASIC *********** 7 March 1993 ***********
'       HEX alpha counter for NMIMT
'***** Data are stored on disc each TC minutes.
'***** Data is stored on a random access file in 54 byte records with format:
'*** 0,8 9,14 15,20 21,26 27,32 33,38 39,44 45,50 51,52
53,54
'*** YY MM DD HH MM
'DATE TIME CH1 CH2 CH3 CH4 CH5 CH6 status cr
lf
',

'***** All I/O is via the parallel printer port which controls an 8255
'***** configured with port C as output for digital operations, B as output
'***** when configuring the counters, but usually input,
'***** and A as output for addressing A/D and counter
'***** data are read via the pp status input register as two 4 bit
nibbles
'***** This program reads 2 boards with device numbers allocated at
link A:
'***** 1) device 2 for transfer to computer
'***** 3 (link A default) for transfer from computer
'***** 2) device 1 (link A next to default)
'***** 0 for transfer from computer.
'***** Counter ID is 1,2,3 for device 1 and 4,5,6 for device 3.

'***** DIGITAL I/O for each device - 8255
'*****
'***** PA 0-2 adc, counter addresses
'***** PA 3 enable adc read
'***** PA 4 select adc low byte
'***** PA 5 select adc high byte
'***** PA 6 counter select
'***** PA 7 ADC run/hold. +ve pulse starts conversion
'**** PC 3     Test to input bit 7
'**** PC 5     Pump 1
'**** PC 6     Bell
'**** PC 7     Pump 2

'**** DIGITAL INPUT
'**** CLK0    X10/2,3 Counters 1,4
'**** CLK1    X11/2,3 Counters 2,5
'**** CLK2    X12/2,3 Counters 3,6

'**** ANALOG CHANNELS
'**** none selected

'**** The time is polled by all time consuming routines and "RTIMER" called
'**** when there is less than 2 s before an automatic operation is due,

$STACK 3072
DEFSTR C : DEFINT I,J,K,M,N : DEFLNG l
DEF FNNOWOFF  '***** Toggle automatic most recent data display

*********
LOCATE 23,1 : COLOR 7,0 : PRINT STRING$(55," ");
CKEY(0,3)="NOW on" : KEY 4,CKEY(0,3)
FNNOWOFF=0
END DEF
DEF FNITTG(II)   '***** TIME TO GO IN SECONDS before next minute

***** SHARED t0,tend,ttg,ihtg,imintg,istg,igo   '***** shared times for rtimer
t0=TIMER
IF igo=2 THEN ttg1
t0=tend-ttg : FNittg=99
EXIT DEF

ttg1:
  ttg=tend-t0 : IF ttg<0 THEN ttg=ttg+86400
  ihtg=INT(ttg/3600)
  imintg=INT(ttg/60.0)-60.0*ihtg
  istg=ttg-ihtg*3600.0-imintg*60.0
  FNittg=60
  IF ttg<60 THEN FNittg=istg
END DEF
DEF FNi$(j,k) '*** form string of k characters - blanks then value of j**
c=STR$(j) : FNi$=c : il=LEN(c) : IF il>k THEN FNi$=RIGHT$(c,k)
  IF il<k THEN FNi$=STRING$(k-il," ")+c
END DEF
DEF FNl$(l,k) '*** form string of k characters - blanks then value of l**
c=STR$(l) : FNl$=c : il=LEN(c) : IF il>k THEN FNl$=RIGHT$(c,k)
  IF il<k THEN FNl$=STRING$(k-il," ")+c
END DEF
'*** fill HEX$(j) with spaces to obtain field width k characters
DEF FNH$(J,K)=STRING$(K-LEN(HEX$(J))," ")+HEX$(J)
DEF FNb$(J,K)=STRING$(K-LEN(BIN$(J))," ")+BIN$(J)
ON ERROR GOTO ERRTRAP
DIM NKEY(4,10) '*** STATUS OF FUNCTION KEYS, NKSET SETS GROUP OF 10 KEYS
DIM CKEY(4,10) '*** KEY DISPLAY (only two used)
DIM IDT(8),DNT(8),DOT(8),ID(8),DC(8),DN(8) '*** COUNTERS NEW AND OLD
DIM dcold(8),jppdat(4,4),ipio(5)
DIM dr(8),iadjtab(16),er(16),p(2),rp(2)
DIM cnow(21),cparm(20),cpump(5)
DIM prset(20),cpset(20),istep(3) '*** presets read from SETTINGS

'**************** READ IN PRESETS AND CAL FACTORS
'****************
'*** The SETTINGS file contains 20 sets of label, ascii number
'*** the first two characters of the first label are used as a data file
'*** identification or tag.
'*** cp prset(0) = count period, minutes
'*** nc (1) = number of counters
'*** pp1 (2) = pump1 ON period after start, minutes
'*** pp2 (3) = pump2 ON period after start, minutes
'*** 4-19 spare

'*** Parallel Port allocations, setup
'****************
ippdat=&H378 : ippc=ippdat+2 '*** parallel port data and control
ippin=ippdat+1
ipio(3)=4 : ipio(0)=8 : ipio(1)=12 : ipio(2)=0 '*** PIO A,B,C addresses
jppdat(1,2)=4 : jppdat(3,2)=4 : CALL ppset(1)
CALL ppset(3) '*** set up pp board and reset counters
ip1on=32 : ip1off=-32: CALL ppc(1,ip1off,cp1stat,"OFF") '** pump1=SV1
ip2on=128 : ip2off=-128 : CALL ppc(1,ip2off,cp2stat,"OFF") '*pump2=SV3
ipson=64 : ipsoff=-64: CALL ppc(1,ipson,csstat,"OFF") '*** bell=SV2
itest0=-8 : itest1=8                     '*** test bit to port bit 7
CALL inc(-1) '*** zero counters
c22=STRING$(22,196) : DN(4)=0 : dt(4)=0
cv=CHR$(179) : cvh=CHR$(195)                  '**** line drawing characters
OPEN "settings" FOR INPUT AS #1 '*** read settings for analog channels
FOR i=0 to 19 : IF iskip=1 THEN 115
INPUT #1,cpset(i),prset(i)
NEXT i
115 iskip=0 : CLOSE 1
ncount=prset(1) '*** number of counters used
cntag=LEFT$(cpset(0),2)
DATA cp,nc,pp1,pp2,a4,a5,a6,a7,a8,a9,a10
DATA a11,a12,a13,a14,a15,a16,a17,a18,adel
FOR i=0 TO 19 : READ cparm(i) : NEXT i
cparms="cp nc pp1 pp2 "
DATA """"""Pump 1 ","Pump 2 ","Pump1&2" FOR i=0 TO 3 : READ cpump(i) : NEXT i
DATA 1,1,01,1.02,1.04,1.1,1.2,1.4,2,4,10,10,20,30,40 '*** er
DATA 0,0, 1, 1, 2, 4, 10,20,30,40 '*** iadjtab
FOR i=0 TO 9 : READ er(i) : NEXT i
FOR i=0 TO 9 : READ iadjtab(i) : NEXT i

cfmt1="###.#" : cfmt2="##.##"

cfmt1="###.#" : cf5="###" : cf6="####" : cf7="#######" :

cf8="########"
cf10="##########" : ci0=CHR$(0)+CHR$(0)

'**** setup initial operating parameters ****
NKSET=0 : INOW=1 : INOWT=1             '*** FIRST MENU, DISPLAY

"NOW"

istep(1)=0 : istep(2)=0 : istat=0 : CLS

tend=60*(INT(TIMER/60)+prset(0)) : IF tend>86399 THEN tend=tend-

FOR I=0 TO 9 : READ CKEY(0,I) : NEXT I

FOR I=0 TO 9 : READ CKEY(1,I) : NEXT I

CALL SELKEY(NKSET)                          '*** MENU 0 FOR FUNCTION


crlf=CHR$(10)+CHR$(13)

CDT = DATE$  : COLOR 7,0                       '*** READ IN LAST 20

RECORDS

CFILE = ctag+MID$(CDT,1,2)+MID$(CDT,4,2)+MID$(CDT,9,2)+".DAT"
OPEN "R",#1,CFILE,54 : IF iskip=1 THEN 151

FIELD #1,54 AS CREC : IRECT=LOF(1)/54

IR= IRECT-19 : IF IR<1 THEN IR=1   '*** END OF DATA FILE

FOR i=0 TO 19 : ii=irect-19+i :

 FOR i=0 TO 9 : READ CKEY(1,I) : NEXT I

CALL SELKEY(NKSET)

"*** MENU 0 FOR FUNCTION

KEYS

CRLF=CHR$(10)+CHR$(13)

CDT = DATE$  : COLOR 7,0

RECORDS

CFILE = ctag+MID$(CDT,1,2)+MID$(CDT,4,2)+MID$(CDT,9,2)+".DAT"
OPEN "R",#1,CFILE,54 : IF iskip=1 THEN 151

FIELD #1,54 AS CREC : IRECT=LOF(1)/54

151 IR= IRECT-19 : IF IR<1 THEN IR=1   '*** END OF DATA FILE

FOR i=0 TO 19 : ii=irect-19+i :

CNOW(i)="......."+STRING$(45,CHR$(32))+crlf

IF ii<1 OR iskip=1 THEN 150      '**INITIALISE cnow()

GET #1,ii : cnow(i)=crec

150 NEXT i

iskip=0 : CLOSE 1

IGO=2: newdisp=1 : CGO="timer ON    

200 '**** START TIMER LOOP : this is supposed to take less than 1 sec

'*** key entry operations are aborted if data transfer pending

'*** Current data are displayed - counts, status

'*** "newdisp" indicates that the headings are required as well as

numbers

i=FNittg(ii) : IF istg<2 AND IGO=2 THEN CALL RTIMER '*** DATA TRANSFER

KEY ON : IF newdisp=0 THEN 210           '*** update minimum
display

*** Update current data display ***

LOCATE 1,58 : COLOR 7,0 : PRINT cv;"

COLOR (IGO-2)*8,7 : PRINT CGO : COLOR 7,0

LOCATE 2,58 : PRINT cv;DATE$;" 

LOCATE 3,58 : PRINT cv;" TIME TO GO  : 

LOCATE 4,58 : PRINT cv;

LOCATE 5,58 : PRINT cv;

LOCATE 6,58 : PRINT cvh;c22;

LOCATE 7,58 : PRINT cv;"COUNTER count";

LOCATE 8,58 : PRINT cv;" 1 

LOCATE 9,58 : PRINT cv;" 2 

LOCATE 10,58 : PRINT cv;" 3 

LOCATE 11,58 : PRINT cv;" 4 

260
LOCATE 12,58 : PRINT cv;"  5                  ";
LOCATE 13,58 : PRINT cv;"  6                  ";
LOCATE 14,58 : PRINT cvh;c22 /*underline
LOCATE 15,58 : PRINT cv;"PUMP 1 ";
LOCATE 16,58 : PRINT cv;"PUMP 2 ";
LOCATE 17,58 : PRINT cv;"BELL ";
LOCATE 18,58 : PRINT CHR$(192);c22;
newdisp=0 : COLOR 7,0 : LOCATE 24,1 : PRINT cerr1;
210 LOCATE 2,71 : PRINT TIMES$ ; : i=FNITTG(ii) : IF IGO=2 THEN i=istg
LOCATE 3,71 : PRINT USING "##";ihtg;
LOCATE 3,74 : PRINT USING "##";imintg; : LOCATE 3,77 : PRINT
USING"##";i;
    CALL inc(0)                                      '**** read COUNTERS
FOR i=0 TO ncount-1
    LOCATE 8+i,75 : PRINT USING cf5;dc(i); : NEXT i
LOCATE 15,67 : IF istep(1)=-1 THEN COLOR 16,7
    PRINT cp1stat; : COLOR 7,0 : PRINT USING cf4;istep(1);
LOCATE 16,67 : IF istep(2)=-1 THEN COLOR 16,7
    PRINT cp2stat; : COLOR 7,0 : PRINT USING cf4;istep(2);
LOCATE 17,67 : PRINT csstat;
    CALL pptest
    IF INOW=1 AND INOWT=1 THEN GOSUB 3250
290 C=INKEY$ : IF C="" THEN GOTO 200
292 CC=INKEY$ : C=C+CC : IF CC<>"" THEN GOTO 292
    ON NKSET+1 GOTO 600,700                              '***** MENU
    SELECTION
GOTO 200
600 FOR IK=0 TO 9 : IF C=CKEY(NKSET,IK) THEN GOTO 602
    NEXT IK : GOTO 200
602 ON IK+1 GOTO DATD,UP,DOWN,NOW,LIMIT,bell,dira,pumpon,pumpof,NEXT0
    GOTO 200
'**** FUNCTION KEYS with NKSET=0
DATD:
    i=FNITTG(II) : IF istg>5 THEN GOSUB 3000
    GOTO 200
UP:
    i=FNITTG(II) : IF istg>3 THEN GOSUB 3100
    GOTO 200
DOWN:
    i=FNITTG(II) : IF istg>3 THEN GOSUB 3200
    GOTO 200
NOW:
    IF INOW=1 THEN 610
    INOW=1 : INOWT=1 : CKEY(0,3)="NOWoff" : KEY 4,CKEY(0,3) : GOTO 794
610 INOW=0 : INOWT=0 : CKEY(0,3)="NOW on" : KEY 4,CKEY(0,3) : GOTO 794
LIMIT:
    i=FNITTG(II) : IF istg>5 THEN GOSUB 3500
    newdisp=1 : GOTO 200
bell:
    IF csstat=" ON" THEN 662
    CALL ppc(1,ison,csstat," ON")                  '*** bell ON
    CKEY(0,5)="belOFF" : KEY 6,CKEY(0,5) : KEY ON : GOTO 200
662 CALL ppc(1,isoff,csstat,"OFF")                 '*** bell OFF
    CKEY(0,5)="bel ON" : KEY 6,CKEY(0,5) : KEY ON : GOTO 200
dira:
    i=FNittg(ii) : IF istg<6 THEN CALL RTIMER
    CLS
LOCATE 1,1: SHELL "DIR A:" : KEY ON : GOTO 200

pumpon: "*** start pump at the start of the next count period"
LOCATE 24,1 : cc="START pump (1) (2) (B)oth or CR "
c="": CALL keyread(c,cc) : newdisp=1
IF c="1" OR c="b" OR c="B" THEN istep(1)=-1
IF c="2" OR c="b" OR c="B" THEN istep(2)=-1
IF (c<"2") AND (c<"1") AND (c<"b") AND (c<"B") THEN 200
IGO=2 : CGO=" Timer ON ": CKEY(1,8)="HALT ": GOTO 200

pumpof: "*** pumps are stopped immediately this instruction is issued"
LOCATE 24,1 : cc="STOP pump (1) (2) (B)oth or CR "
c="": CALL keyread(c,cc) : newdisp=1
IF c="1" OR c="b" OR c="B" THEN
  CALL ppc(1,ip1off,cp1stat,"OFF") : istat=istat AND 2 : istep(1)=0
END IF
IF c="2" OR c="b" OR c="B" THEN
  CALL ppc(1,ip2off,cp2stat,"OFF") : istat=istat AND 1 : istep(2)=0
END IF
GOTO 200

NEXTO:
  NKSET=1 : CALL SELKEY(NKSET) : ifflag=ifflag OR 7 : GOTO 200

  "**** KEYS WITH NKSET=1 ***"
700 FOR IK=0 TO 9 : IF C=CKEY(1,IK) THEN GOTO 702
  NEXT IK : GOTO 200
702 ON IK+1 GOTO QUIT,TIMIN,DATIN,XSHELL,FILE,dirb,iostest,200,HALT,NEXT1
  GOTO 200
QUIT:
  CC="enter Q to quit, CR to resume ": c="": color 7,0
LOCATE 24,1 : CALL KEYREAD(C,CC)
if c="Q" or c="q" THEN STOP
GOTO 200

TIMIN:
i=FNITTG(II) : IF istg<10 THEN GOTO 200
COLOR 7,0
720 CC="set time of day - FORMAT hh:mm[:ss] - CR if OK ": c=time$
  CCC=C : LOCATE 24,1 : CALL KEYREAD(C,CC)
  IF MID$(c,3,1)=":" AND LEN(C)=5 THEN 722
  IF MID$(c,6,1)=":" AND LEN(c)=8 THEN 722
  COLOR 7,0 : GOTO 720
722 IF CCC=C THEN GOTO 200
TIME$=C : GOTO 200

DATIN:
i=FNITTG(II) : IF istg<10 THEN GOTO 200
COLOR 0,7
732 CC="set date - note MONTH/DAY/YEAR format - CR if OK ": c=date$
  LOCATE 24,1 : CALL KEYREAD(C,CC)
  IF MID$(c,3,1)="/" AND MID$(c,6,1)="/" AND LEN(c)<11 THEN GOTO 734
  IF MID$(c,3,1)="-" AND MID$(c,6,1)="-" AND LEN(C)<11 THEN GOTO 734
  COLOR 0,7 : GOTO 732
734 DATE$=c : GOTO 200

XSHELL:
i=FNITTG(II)
CC="Minutes before data transfer "+STR$(imint)+"SHELL to DOS  -Y(CR aborts) ? ":
  C="": COLOR 0,7 : LOCATE 24,1 : CALL KEYREAD(C,CC)
IF C<>"y" AND C<>"Y" THEN GOTO 200
LOCATE 24,1 : PRINT "Use EXIT to leave DOS after SHELL is executed " ;

SHELL
ifflag=ifflag OR 7 : INOWT=1 : KEY ON : newdisp=1 : GOTO 200

FILE:  "******** CHANGE DISK FILE NAME ***
i=FNIT(TG(i)) : IF istg<6 THEN GOTO 200
CC=" Disk File is (CR if OK) " : COLOR 0,7
760 LOCATE 24,1 : C=CFILE
CALL KEYREAD(C,CC) : IF C=CFILE THEN GOTO 765
CFILE=C
765 LOCATE 24,1 : COLOR 7,0 : PRINT SPACE$(80); : GOTO 200

dirb:
i=FNittg(ii) : IF istg<6 THEN CALL RTIMER
CLS
LOCATE 1,1 : SHELL "DIR B:" : KEY ON : GOTO 200
iost:  '***** display count channels 0-1 or port B, A\D 0-4

0.

CLS : KEY OFF : newdisp=1 : inowt=1 : idev=1
PRINT"Q,q to quit                   x ppdata  X ppctrl1"
PRINT"2  (not z) initialise PP   Aa,B ,Cc  8255 port set";
PRINT"p,p pump ON, OFF (devl for
PRINT"#1, dev3 for #2)            y,Y  8255 control word"
PRINT"R,r to reset count rates,   D,d  toggle idev"
PRINT
PRINT"Testing Parallel Port DEVICE ";idev
PRINT cp=" Holding data, any key to continue "
776 t1=TIMER
LOCATE 8,11
FOR i=1 TO ncount : PRINT USING"##";i; : PRINT SPACE$(8); : NEXT i
PRINT"TIME"
PRINT"COUNT  " : PRINT" c/s ";
LOCATE 12,1 : PRINT "PUMP 1"
LOCATE 13,1 : PRINT "PUMP 2"
LOCATE 17,1
PRINT " A   B   C   BUS   PORT  AD
STAT"; CALL inc(1);  "**** uses dr(i) for old reading
FOR I=0 TO ncount-1 : dr(I)=dn(i) : NEXT i
770 ii=FNittg(i) : IF istg<2 THEN CALL rtimer
771 t=TIMER -t1 : IF t<0.2 THEN 771
LOCATE 9,7  : CALL inc(1)
772 FOR ii=0 TO ncount-1
   IF dc(ii)>55000.0 THEN 776
   PRINT USING cf10;dc(ii); : NEXT ii
776 FOR ii=0 TO ncount-1
   PRINT USING"#####.#";t; : LOCATE 10,7
   FOR ii=0 TO ncount-1
      PRINT USING" #.#.#.#";dc(ii)/t; : NEXT ii
   LOCATE 12,8 : PRINT cp1stat;";
   LOCATE 13,8 : PRINT cp2stat;"
789 LOCATE 18,1
FOR i=0 TO 2 : PRINT FNh$(jppdat(idev,i),10); : NEXT i
CALL ppin(idev,0,i) : PRINT FNh$(i,10);
CALL ppin(idev,2,i) : PRINT FNh$(i,10);
j=INP(ippin) AND 8 : PRINT USING cf8; j
C=INKEY$: IF C="" AND ia=0 THEN GOTO 770
IF C="" THEN PRINT cp: : GOTO 789

263
ia=0 : PRINT SPACE$(40);  
ida=ASC(c)-48
IF c="" THEN 770
IF c="Q" OR c="q" THEN 200
IF idev=1 THEN
  IF c="P" THEN CALL ppc(1,ip1on,cp1stat," ON") : istat=istat OR 1
  IF c="p" THEN CALL ppc(1,ip1off,cp1stat,"OFF") : istat=istat AND 2
END IF
IF idev=3 THEN
  IF c="P" THEN CALL ppc(1,ip2on,cp2stat," ON") : istat=istat OR 2
  IF c="p" THEN CALL ppc(1,ip2off,cp2stat,"OFF") : istat=istat AND 1
END IF
IF c="Z" THEN CALL ppset(idev) : irimerr=0 : GOTO 770
IF c="R" OR c="r" THEN 776
IF c="D" OR c="d" THEN idev=idev XOR 2 : LOCATE 7,30 : PRINT idev;
  i=0 : cc="enter DATA for CHANNEL "+c+" 
  IF c="A" OR c="a" THEN
    i=1 : IF c="B" THEN
      ib=1 : CALL ppout(idev,3,&H80) : CALL ppout(idev,0,jppdat(idev,0))
      CALL ppout(idev,2,jppdat(idev,2)) : GOTO 782
      END IF
      i=2 : IF c="C" OR c="c" THEN 782
      i=3 : cc="8255 CONTROL WORD ? ": IF c="Y" OR c="y" THEN 782
      i=4 : cc="pp data or ctrl port ? ": IF c="X" OR c="x" THEN 782
      GOTO 770
    PRINT : c1="" : CALL keyread(c1,cc) : ii=VAL(c1) : IF ii>255 THEN
      IA=1
      IF (i=4) AND (c="x") THEN OUT ippdat,ii : PRINT ippdat,ii;cp;
      IF (i=4) AND (c="X") THEN OUT ippc,ii : PRINT ippc,ii;cp;
      IF i<=3 THEN CALL ppout(idev,i,ii)
      IF i=1 THEN CALL ppin(idev,0,j) : PRINT " ***BUS*** ";FNh$(j,6);
      INPUT c
      GOTO 770
    HALT:
      LOCATE 24,1 : cc="STOP counting (Y) or CR ")
      IF igo=4 THEN cc="START counting (Y) or CR "
      c="" : CALL keyread(c,cc) : IF c<"Y" AND c<"y" THEN 200
      IF IGO=4 THEN 792
      IGO=4 : CGO=" Timer HALTED": CKEY(1,8)="START ": KEY 9,CKEY(1,8)
      KEY ON
      newdisp=1 : istep(1)=0 : istep(2)=0 : istat=0
      CALL ppc(1,ip1off,cp1stat,"OFF")
      CALL ppc(1,ip2off,cp2stat,"OFF")
      GOTO 200
    792 IGO=2 : CGO=" Timer ON ": CKEY(1,8)="HALT ": KEY 9,CKEY(1,8)
    tend=60*(INT(TIMER/60)+1) : IF tend>86399 THEN tend=tend-86400
    794 LOCATE 1,68 : COLOR (IGO-2)*8,7 : PRINT CGO : COLOR 7,0
    KEY ON : GOTO 200
NEXT1:
  NKSET=0 : CALL SELKEY(NKSEL) : INOWT=1 : GOTO 200
' *** ERROR TRAP ***
ERRTRAP: '*** Check for EOF and resume after corrective action ***
  x=POS(xx) : y=CSRLIN : COLOR 0,7 : nerr=nerr+1
  cerrl="error "+FNi$(nerr,6)+" "+TIME$"  DEV "+ERDEV$+STR$(ERDEV)
  i=ERR : ii=ERL : li=ERADR
  cerrl=cerrl+" CODE "+FNi$(i,3)+" LINE "+FNi$(ii,5)+" ADDR "+FNi$(li,8)
  ifflag=ifflag OR 7 : iskip=0 : newdisp=1 : IF i>24 AND i<77 THEN
    iskip=1
    LOCATE 24,1 : PRINT cerrl1 : COLOR 7,0
    LOCATE 23,1 : PRINT"ANY KEY, otherwise AUTO next after 10 sec";
  ertime=TIMER : LOCATE y,x
ERR1: '*** poll keyboard and wait 10 sec ***
  c=INKEY$ : ertime=TIMER-ertime1 : IF ertime>10 THEN err3
  IF c="" THEN err1
  waitime=TIMER : LOCATE 23,1 : COLOR 16,7 : PRINT"****** WAIT ";
ERR2: '*** poll keyboard and wait 2 sec for no key ***
  c=INKEY$ : IF c<>"" THEN waitime=TIMER
  waitime=TIMER-waitime1 : IF waitime<2 THEN err2
  COLOR 7,0 : LOCATE 23,1: PRINT"CR retry N(ext) Q(uit)";
  INPUT c : IF c="N" OR c="n" THEN err3
  STOP
err3:
  LOCATE 23,1 : PRINT SPACE$(57) : RESUME NEXT
1050 RESUME

'******* DISK DATA DISPLAY
*************************************************************************************************************************
3000 INOW=FNNOWOFF
3010 COLOR 0,7 : LOCATE 24,1 : CC="Display Data. RECORD NUMBER ? ": C=""
  CALL KEYREAD(C,CC) : IF C="" THEN GOTO 3450
  RECU=VAL(C) : IF RECU<1 OR RECU>32000 THEN GOTO 3010
  IRU=RECU : GOTO 3300
3100 '*** DISPLAY NEXT PAGE ********
  INOW=FNNOWOFF : IRU=IRU-20 : IF IRU<1 THEN IRU=1
  GOTO 3300
  '*** DISPLAY PREVIOUS PAGE *****
3200 INOW=FNNOWOFF : IRU=IRU+20 : IF IRU>32000 THEN IRU=32000
  GOTO 3300
  '*** DISPLAY CURRENT DATA, this mode persists until a different
  ****
  '*** display key is used
3250 INOW=1 : INOWT=0    '*** USED BY MONITOR (200+. ) FOR UPDATE
3300 CLS : KEY ON : LOCATE 2,1 : COLOR 7,0
  i=FNITTG(II) : IF istg<2 THEN GOTO 3450
  PRINT" DATE TIME CH1 CH2 CH3 CH4 CH5 CH6 status";
  IF INOW=1 THEN GOTO 3330
  OPEN "R",#1,CFILE,54 : IF iskip=1 THEN 3440
  FIELD #1,54 AS CRec : IRECT=LOF(1)/54
3330 IF (INOW=1) OR (iru>irect-19) THEN IRU=IRECT-19 '*** SET TO END OF FILE-19
  LOCATE 1,1 : cru=cnow(0) : IF INOW=1 THEN 3340
  IF iru<1 THEN IRU=1
GET #1, iru : cru=crc : IF iskip=1 THEN 3440
IF iru=LOF(1)/54 THEN GOTO 3430
3340 COLOR 0,7 : PRINT"BLOCK "; : PRINT USING"#####";iru;
COLOR 7,0 : LOCATE 3,1
FOR IIU=0 TO 19 : IU=IIU+IRU
CRU=CNOW(IIU) : IF INOW=1 THEN 3345
GET #1, IU : cru=crc : IF iskip=1 THEN 3440
IF IU=LOF(1)/54 THEN GOTO 3430
3345 PRINT LEFT$(cru,50);cpump(VAL(MID$(CRU,52,1)))
NEXT IIU
GOTO 3440
3430 COLOR 0,7 : PRINT : PRINT"END OF FILE";STRING$(15," "); : COLOR 7,0
3440 iskip=0 : COLOR 0,7 : IF INOW<>1 THEN CLOSE 1
IF INOW=1 THEN PRINT"MOST RECENT DATA";STRING$(10," "); : CDT=DATE$
IF INOW=1 THEN
CFILE=ctag+MID$(CDT,1,2)+MID$(CDT,4,2)+MID$(CDT,9,2)+".DAT"
PRINT"Disk file is ";cfile;"
RETURN
'****** Analog cal, set and error set
**********************************************************************
3500 KEY OFF : COLOR 0,7 : LOCATE 24,1
FOR i=0 TO 3 : PRINT" ";cparm(i); : PRINT USING cf4;prset(i); :
NEXT i
COLOR 7,0
CEND=SPACES(79) : cc="WHICH PARAMETER - " : c=""
LOCATE 23,1 : CALL keyread(c,cc)
FOR i=0 TO 19 : IF c=cparm(i) THEN 3510
NEXT i
GOTO 3515
3510 c=STR$(prset(i)) : CALL keyread(c,cparm(i))
IF c="" THEN prset(i)=VAL(c)
IF (prset(1)>6 OR prset(1)<1) THEN prset(1)=6
ncount=prset(1)
3515 c="" : cc="SAVE SETTINGS - Y or CR "
CALL keyread(c,cc) : IF c>"Y" AND c<"y" THEN 3520
OPEN"settings" FOR OUTPUT AS #1
FOR i=0 to 19 : IF iskip=1 THEN 3519
WRITE #1,cpset(i),prset(i)
NEXT i
3519 iskip=0 : CLOSE 1
3520 LOCATE 24,1 : COLOR 7,0 : PRINT SPACE$(78); : KEY ON : RETURN

'************ TIMER
*************************************************
'*** DISK DATA RECORD IS 54 BYTES in ASCII form.
'**** Entry is after FNTTG gives <2 sec before a 1 min time boundary.
SUB RTIMER
SHARED ICADDR, ICCTRL, CFILE, IDT(), DNT(), dc(), CNOW(), INOWT, IRECT
SHARED dn(), dt(), dot(), IGO, ttg, ihtg, imintg, istg, t0, tend, prset()
SHARED newdisp, ctag, iskip, istep(), cpset(), crlf
SHARED ip1on, ip1off, cp1stat, ip2on, ip2off, cp2stat, ncount, istat, ips
SHARED ison, csstat, ckey()
newisp=1
IF iigo=4 THEN rtend

266
rt0:
i=FNittg(ii) : IF istg>0 THEN rt0 '*** wait for isttg=0

rt1:
IF (istat AND 1)>0 THEN
    istep(1)=istep(1)+1                     '*** update pump1 run time
    IF istep(1)>prset(2) THEN
        istep(1)=0 : istat=istat AND 2
        CALL ppc(1,iploff,cp1stat,"OFF")
        CALL ppc(1,ison,csstat," ON")       '*** bell ON
        CKEY(0,5)="belOFF" : KEY 6,CKEY(0,5)
    END IF
END IF
IF istat>1 THEN
    istep(2)=istep(2)+1
    IF istep(2)>prset(3) THEN
        istep(2)=0 : istat=istat AND 1
        CALL ppc(1,ip2off,cp2stat,"OFF")
        CALL ppc(1,ison,csstat," ON")       '*** bell ON
        CKEY(0,5)="belOFF" : KEY 6,CKEY(0,5)
    END IF
END IF
IF ttg>0.5 THEN rtend
' **** DATA TRANSFER ****
tend=60*(INT((TIMER+2)/60)+prset(0)) : IF tend>86399 THEN
tend=tend-86400
LOCATE 1,68 : COLOR 16,7 : PRINT"DATA TRANSFER"
CALL inc(-1)                  '*** reset counters, counts to dc(i)
FOR IT=0 TO ncount-1
    d=dc(it)
    IF D<0 THEN D=65536!+D
    IF d>32767 THEN d=d-65535
    IDT(IT)=d : NEXT IT
END IF
LOCATE 1,64 : COLOR 7,0 : PRINT STRING$(17," ")
**C** with "BS" editing

*** Calls from analog set function print extra data

**SUB** KEYREAD(c,ccc)

```
SHARED pval(),pcol(),poff(),istg
it=0 : IYY=CSRLIN : cc=ccc
IF iyy>24 THEN iyy=24
LOCATE iyy,1 : ILEN=LEN(CC)+1
```

4020 COLOR 7,0 : PRINT cc;
COLOR 0,7 : PRINT C ; COLOR 7,0 : PRINT SPACE$(78-LEN(C)-LEN(CC));
```
cp=STR$(pval(iad)) : l=LEN(cp) : cb=cp : IF l<9 THEN 4025
```
**test for
```
cb=LEFT$(cp,7) : IF MID$(cp,1-4,1)="E" THEN cb=cb+MID$(cp,1-4,5)
```
** silly
4025 PRINT cb;
```
"** million digit formats
```
4030 i=FNITTG(II) : IF istg<2 THEN CALL RTIMER **** DATA TRANSFER DUE
```
CK=INKEY$ : IF CK$<>""" THEN 4040
GOTO 4030
```
4040 IF CK=CHR$(13) THEN 4990 *** CR ends data entry
IF CK=CHR$(8) THEN 4100 *** BS key
IF ASC(CK)<32 THEN 4030 *** ignore control characters
```
IF LEN(C)+ILEN=80 THEN C=LEFT$(C,LEN(C)-1)
```
IF it=0 THEN c=""
C=C+CK : it=1
```
4080 LOCATE iyy,1
GOTO 4020
```
4100 it=1 : IF LEN(C)=0 THEN 4080 **** NO BACKSPACE PAST ZERO
```
C=MID$(C,1,LEN(C)-1) : GOTO 4080
```
4990 COLOR 7,0 : LOCATE IYY,1 : PRINT SPACE$(79); : LOCATE iyy,1
4999 END SUB

**** FUNCTION KEY ALLOCATION ********************************************

**SUB** SELKEY(NKSET)

```
SHARED CKEY()
FOR I=0 TO 9 : KEY I+1,CKEY(NKSET,I) : NEXT I : KEY ON
```

END SUB

**SUB** ppc(idév,i,cs,css) *** send data to digital output. Only the bit with
```
SHARED jppdat() *** value ABS(i) is changed. Update 8255 port C status
```
i=ABS(i)
```
jppdat(idév,2)=jppdat(idév,2) OR ii
```
IF i<0 THEN jppdat(idév,2)=jppdat(idév,2) XOR ii """ if i<0, reset bit
```
i=jppdat(idév,2)
CALL ppout(idév,2,ii) ; cs=css
```
SUB inc(iold) '****** read in counters. iold=1 uses dr() as zero values
SHARED dn(),dc(),dnt(),dr(),ncount '*** iold=-1 resets run zero
SHARED jppdat(),ipio(),ttg,ibgt,bgc(),istep
SHARED prset(),imintg,told,dcold()
FOR i=0 TO ncount-1
   CALL devin(i,il)
   CALL devin(i,ih)
   DN(I)=-il-ih*256.0 '*** counters count down
dc(i)=dn(i)-dnt(i) '*** SUBTRACT OLD READING
   IF dc(i)<0 THEN dc(i)=65536!+dc(i) '*** polarity test
   IF iold=-1 THEN inc1
   IF iold=1 THEN dc(i)=dn(i)-dr(i) : GOTO inc1
   dctest=dc(i)-dcold(i)
   IF dctest>200 THEN
      dctest=(dc(i)-dcold(i)) MOD 256 '*** test for 256 increments
   END IF
   inc1:
      dcold(i)=dc(i)
   IF (iold=-1) THEN dnt(i)=dn(i) : dcold(i)=0 : told=t0
   NEXT i
END SUB

SUB inadc(i,a,b) '**** READ ADC(i) *********
SHARED prset() '**** b = raw adc reading
SHARED ippin,ipio(),iadc() '**** a = (b-prset(i+11))*prset(i+15)
idev=1 '**** ADC's from pp device 1 only
CALL ppout(idev,0,&H78+i) '** start adc read - select mux
CALL ppout(idev,0,&H78+i) : CALL ppout(idev,0,&H78+i) '** start conversion pulse
   DELAY prset(19)/100
   t=TIMER
   ad2: '*** wait for conversion sensed by ADC status on bit 3 of pp input reg.
      j=INP(ippin) AND &B1000 : tt=TIMER-t
      IF (j>0) AND (tt<0.5) THEN ad2
      CALL ppout(idev,0,&H50+i) : CALL ppin(idev,0,il)
      CALL ppout(idev,0,&H60+i) : CALL ppin(idev,0,ih)
      CALL ppout(idev,0,&H78+i) '*** disable adc
      IF ih>31 THEN b=9999 : a=999.9 : GOTO ad1:
      IF ih>15 THEN b=(ih-16)*256+il : GOTO ad1
      b=-ih*256-il
      IF i=3 THEN '*** flow sensor
         a=999: bz=b-prset(7)
         IF (bz>(-10)) AND (bz<500) THEN '**** flow cal works only in this range
            a=prset(8)*bz+prset(9)*bz*bz+prset(10)*bz*bz*bz
         END IF
         IF (a>999) OR (a<-99) THEN a=999
         ELSE
            a=(b-prset(i+10))*prset(i+14)
         END IF
      END IF
   ad1:
SUB ppout(idev,ic,idat) STATIC
  '* Send ipio(ic) to control port, idat to data
  *** idat is put into jppdat(idev,ic) as a record of the current state
  *** For output to B the bus devices are disabled first and B set as output
  *** the board should be reset after output to B, to take B off the bus
  SHARED jppdat(),ipio(),ippc,ippdat
  jp=jppdat(idev,ic) : jppdat(idev,ic)=idat : OUT ippdat,idat
  OUT ippc,ipio(ic)
  OUT ippc,ipio(ic)+idev
  OUT ippc,ipio(ic)
END SUB

SUB ppin(idev,ip,i)   STATIC
  '* Read 2 nibbles from pp input register
  SHARED ipio(),ippin,ippc,jppdat(),ippdat  *** ip=0 for bus, 2 for digital input
  OUT ippc,ipio(ip)+idev-1 : j=INP(ippin) XOR 128 : j=INP(ippin) XOR 128
  OUT ippc,ipio(ip+1)+idev-1 : k=INP(ippin) XOR 128 : k=INP(ippin)
  i=INT(j/16)+(k AND &Hf0)
END SUB

SUB ppset(idev)   '*** reset pp board.
  SHARED dnt(),jppdat()
  SHARED dn(),dc(),dr(),ncount
  SHARED ipio(),ttg,ibgt,bgc(),istep
  CALL ppout(idev,3,&H80)                       '*** ports A,B and C outputs
  FOR I=0 TO 2 : CALL devout(idev,3,64*i+&H30)'**enable counter
  CALL devout(idev,i,0) : CALL devout(idev,i,0)    '** load counter
  NEXT I
  CALL ppout(idev,3,&H82)                '** port A,C output, port B input
  CALL inc(-1)                           '** zero counters
  CALL ppout(idev,0,&H78)  '** disable A/D, counter read, adc conversion
  jppdat(idev,2)=0 : CALL ppout(idev,2,jppdat(idev,2))  *** pump off
END SUB

SUB devout(idev,iaddr,idat) '*** data to counter iaddr (0 to 2), board idev
  SHARED jppdat()       '*** 0-2 are device 1, 3-5 device 2
  CALL ppout(idev,1,idat) '*** 8255 must be all outputs, data to bus iad=iaddr+&H38  '*** port B address lines are bits 0&1, 5=-WR, 4=-RD
  CALL ppout(idev,0,iad) '*** enable counter, set address
  CALL ppout(idev,0,iad AND &HDF) : CALL ppout(idev,0,iad)  *** strobe -WR
  CALL ppout(idev,0,&H78)
END SUB
SUB devin(icount,idat) '*** data from counter icount (0 to 5)
SHARED jppdat()       '*** 0-2 are device 1, 3-5 device 2
         iaddr=icount MOD 3
         idev=1+2*(INT(icount/3))
iad=iaddr+&H38   '*** port B address lines are bits 0&1, 5=-WR, 4=-RD
         CALL ppout(idev,0,iad)                       '** address to device
         CALL ppout(idev,0,iad AND &HEF)              '** strobe -RD
         CALL ppin(idev,0,idat)                       '** data from bus via pp status
         CALL ppout(idev,0,iad)                       '** -RD high
         CALL ppout(idev,0,&H78)                      '** disable devices
END SUB

SUB pptest   '*** toggle 8255 bit PC3 and read from PORT bit 7
(X7/15)
SHARED itest0,itest1
         idev=1
         CALL ppc(idev,itest1,c,cc) : CALL ppin(idev,2,it1) : it1=it1 AND 128
         CALL ppc(idev,itest0,c,cc) : CALL ppin(idev,2,it0) : it0=it0 AND 128
         ctest=SPACE$(20) : ctest1="
         IF (it0>0) OR (it1=0) THEN
         ctest1="1,"
         CALL ppset(idev)                        '*** reset 8255 and counters
         END IF
         idev=3
         CALL ppc(idev,itest1,c,cc) : CALL ppin(idev,2,it1) : it1=it1 AND 128
         CALL ppc(idev,itest0,c,cc) : CALL ppin(idev,2,it0) : it0=it0 AND 128
         ctest2="
         IF (it0>0) OR (it1=0) THEN
         ctest2="3"
         CALL ppset(idev)                        '*** reset 8255 and counters
         END IF
         IF ctest1="1," OR ctest2="3" THEN
         ctest=" PP Device "+ctest1+ctest2+" Error" : COLOR 16,7
         END IF
         LOCATE 19,60 : PRINT ctest; ; COLOR 7,0
END SUB
The COUNTER.EXE program outlined below is a Quick Basic 4.5 program written by Jeremy Broestl, a New Mexico Tech undergraduate student working for the Atmospheric Radioactivity Laboratory in 1992. Its function was to take the stored alpha count data recorded by the AC.EXE program and separate it into individual counter files for specified time periods that could be further processed to obtain the PAEC/PAESC values for the wire mesh screen, glass fiber filter, or collecting surface counted.

```
1 INPUT "enter the name of the input file"; n$
3 INPUT "enter the length of the sampling time (min)"; l
4 INPUT "enter the flow rate (Lpm)"; f
5 INPUT "enter the time when the sampling started (HH, MM)"; h, m
7 INPUT "enter the number of the valid data points"; d
10 h1 = h
15 m1 = m + l + 2
20 OPEN n$ FOR INPUT AS #7
25 INPUT "enter file name for counter1"; n1$
30 OPEN n1$ FOR OUTPUT AS #1
35 INPUT "enter file name for counter2"; n2$
40 OPEN n2$ FOR OUTPUT AS #2
45 INPUT "enter file name for counter3"; n3$
50 OPEN n3$ FOR OUTPUT AS #3
55 INPUT "enter file name for counter4"; n4$
60 OPEN n4$ FOR OUTPUT AS #4
65 INPUT "enter file name for counter5"; n5$
70 OPEN n5$ FOR OUTPUT AS #5
80 INPUT "enter file name for counter6"; n6$
85 OPEN n6$ FOR OUTPUT AS #6
140 IF m1 >= 60 THEN
145 m1 = m1 - 60
150 h1 = h + 1
155 END IF
157 INPUT #7, y, mo, dy, hr, min, c1, c2, c3, c4, c5, c6, dummy2, dummy1
160 IF hr = h1 AND min = m1 THEN
190 FOR i = 1 TO 6
195 PRINT "enter comments for counter"; i; "(filter(or screen)-?.?m)"
200 INPUT comt$
205 PRINT #i, "start time:"; y; mo; dy; ","; h; ","; m; ",";
210 PRINT #i, "sample length:"; l; "min, "; "flow rate:"; f; "Lpm, ";
212 IF i = 1 THEN PRINT #i, "sys1.eml"
214 IF i = 2 THEN PRINT #i, "sys2.eml"
216 IF i = 3 THEN PRINT #i, "sys3.eml"
218 IF i = 4 THEN PRINT #i, "sys4.eml"
219 IF i = 5 THEN PRINT #i, "sys5.eml"
```
220 IF i = 6 THEN PRINT #i, "sys6.eml"
230 NEXT i
310 FOR i = 1 TO d
320 INPUT #7, y, mo, dy, hr, min, c1, c2, c3, c4, c5, c6, dummy1, dummy2
330 WRITE #1, c1
340 WRITE #2, c2
350 WRITE #3, c3
360 WRITE #4, c4
370 WRITE #5, c5
380 WRITE #6, c6
390 NEXT i
395 ELSE
398 GOTO 157
400 END IF
420 CLOSE (1)
430 CLOSE (2)
440 CLOSE (3)
450 CLOSE (4)
460 CLOSE (5)
470 CLOSE (6)
480 CLOSE (7)
490 END
The EXMAXDP.EXE program outlined below along with the SYS.EML files were written in Borland’s Turbo Pascal by Earl O. Knutson, Ph.D., of the Environmental Measurements Laboratory (EML) (Knutson, 1989) utilizing the Expectation-Maximization (EM) algorithm (Maher and Laird, 1985). The SYS.EML files are short supplementary calibration data files utilized in the EXMAXDP.EXE program. The EXMAXDP.EXE program takes the gross alpha counts in the files resulting from running the COUNTER.EXE program and finds a combination of radon progeny concentrations that maximizes the probability of having the observed counts.

PROGRAM ExMaxDecayProd;
(*======================================================================

This is a program that had to be written because the problem is tailor-made for the EM algorithm. The input data are raw radioactivity counts, widely accepted as conforming to Poisson statistics, as required for EM.

This program is designed to accept the same input files as RWRENNGW.BAS. Handling the three-fold option for input of parameters was more difficult in Pascal than in BASIC, as can be seen from the PROCEDURE initialize.

The concise equations given by Nazaroff (Health Phys. 46, 395) are used in building the kernel matrix for the algorithm. In fact, the set has been expanded to include three equations for thoron progeny; these were written down by analogy with the radon progeny equations.

Although the input data are in terms of counts in equal time intervals, we have chosen to collect the counts into 5, 6 or 7 time brackets (depending on the number of input data points) for this calculation. Analysis for thoron progeny is attempted if and only if the total count interval spans at least 300 minutes.

Earl O. Knutson
USDOE Environmental Measurements Laboratory
May, 1988

A very important correction was made on 2 Feb 1989. Prior to that time, we had wrongly included a function G44, pertaining to the "alpha" from Pb-212. The potential alpha energy table was also wrong prior to that time.

274
USES Crt, Dos, Globals, mtrx, algorithm;

VAR decayconst, alphaenergy,
    dpconc, stderr, eweight : rsltvector;
kernel : kernelmatrix;
rawdata, fitdata : datavector;
i, j, k, maxiter, lastiter, halfpage : integer;

infilename, outfilename, titleoftest : string;
indata, results, parameters : text;
bkgdcount, numdatapts, numcounts : integer;
inthebag, nextblock, numnuclides : integer;
counts : ARRAY [1..2000] OF integer;
cntsperblk : ARRAY [1..12] OF integer;
cnteffic : ARRAY [1..5] OF real;

bkgdtime, deadtime, flowrate, sum : real;
initguess, sampletime, temp,
    transfertime : real;
timepercount, timebtwncnts : real;
ta, tb, t0, concriterion, chisqr : real;
ok, dothoron : boolean;

year, month, day, dayofweek : word;

FUNCTION f(i, j : integer) : real;
BEGIN
  f := decayconst[i]/(decayconst[i] - decayconst[j]);
END;

FUNCTION r(i : integer; t : real) : real;
BEGIN
  IF decayconst[i]*t > 80 THEN r := 1.0
  ELSE r := 1.0 - exp(-decayconst[i]*t);
END;

FUNCTION s(i : integer; t : real) : real;
BEGIN
  IF decayconst[i]*t > 80 THEN s := 0.0
  ELSE s := exp(-decayconst[i]*t);
END;

(*
As explained by Nazaroff, Gij is the accumulated number
of alphas emitted from nuclide i on the filter, due to
collecting the j-th nuclide at a rate of 1 Bq per min.
The factor 60, which is dpm per Bq, replaces Nazaroff's
2.22, which is dpm per pCi. The units of Gij are min per Bq.
*)

FUNCTION G11(t, t0 : real) : real;
VAR G : real;
BEGIN
  IF t < t0 THEN

G := t - r(1,t)/decayconst[1] 
ELSE 
  G := t0 - r(1,t0)*s(1,(t - t0))/decayconst[1]; 
G11 := 60*G/decayconst[1]; 
END;

FUNCTION G31(t, t0 : real) : real; 
VAR G : real; 
BEGIN 
  IF t < t0 THEN 
    G := t 
    - f(2,1)*f(3,1)*r(1,t)/decayconst[1] 
    - f(1,2)*f(3,2)*r(2,t)/decayconst[2] 
    - f(1,3)*f(2,3)*r(3,t)/decayconst[3] 
  ELSE 
    G := t0 
    - f(2,1)*f(3,1)*r(1,t0)*s(1,(t - t0))/decayconst[1] 
    - f(1,2)*f(3,2)*r(2,t0)*s(2,(t - t0))/decayconst[2] 
    - f(1,3)*f(2,3)*r(3,t0)*s(3,(t - t0))/decayconst[3]; 
  G31 := 60*G/decayconst[1]; 
END;

FUNCTION G32(t, t0 : real) : real; 
VAR G : real; 
BEGIN 
  IF t < t0 THEN 
    G := t 
    - f(3,2)*r(2,t)/decayconst[2] 
    - f(2,3)*r(3,t)/decayconst[3] 
  ELSE 
    G := t0 
    - f(3,2)*r(2,t0)*s(2,(t - t0))/decayconst[2] 
    - f(2,3)*r(3,t0)*s(3,(t - t0))/decayconst[3]; 
  G32 := 60*G/decayconst[2]; 
END;

FUNCTION G33(t, t0 : real) : real; 
VAR G : real; 
BEGIN 
  IF t < t0 THEN 
    G := t - r(3,t)/decayconst[3] 
  ELSE 
    G := t0 - r(3,t0)*s(3,(t - t0))/decayconst[3]; 
  G33 := 60*G/decayconst[3]; 
END;

(*
To permit including thoron progeny in the analysis, the functions G54 and G55 - shown below - have been added to Nazaroff's list. They were written down by analogy: G54 from G32; G55 from G33. (This was changed on 2 Feb 1989. Prior to that time, we had wrongly included a function G44, pertaining to the "alpha" from Pb-212. The alpha energy table was also wrong prior to that time.)*)
FUNCTION G54(t, t0 : real) : real;
VAR G : real;
BEGIN
   IF t < t0 THEN
      G := t
      - f(5,4)*r(4,t)/decayconst[4]
      - f(4,5)*r(5,t)/decayconst[5]
   ELSE
      G := t0
      - f(5,4)*r(4,t0)*s(4,(t - t0))/decayconst[4]
      - f(4,5)*r(5,t0)*s(5,(t - t0))/decayconst[5];
   G54 := 60*G/decayconst[4];
END;

FUNCTION G55(t, t0 : real) : real;
VAR G : real;
BEGIN
   IF t < t0 THEN
      G := t - r(5,t)/decayconst[5]
   ELSE
      G := t0 - r(5,t0)*s(5,(t - t0))/decayconst[5];
   G55 := 60*G/decayconst[5];
END;

FUNCTION kbquery(msg : string) : boolean;
VAR query : char;
BEGIN
   REPEAT
      WRITE(msg,' Enter Y or N ');
      READLN(query)
   UNTIL query IN ['y','Y','n','N'];
   kbquery := (query IN ['y','Y']);
END;

PROCEDURE ScanForTitle (VAR inputfile : text);
VAR validtitle : boolean;
BEGIN
   WINDOW(1,1,80,24);
   REPEAT
      READLN(inputfile, titleoftest);
      validtitle := (length(titleoftest) > 0) AND (titleoftest[1] <> '*')
      AND (titleoftest[1] <> ' ');
      IF NOT validtitle THEN WRITELN(results,titleoftest);
      GoToXY(1,23); WRITELN(' ':72);
      GoToXY(1,23); WRITELN (titleoftest);
   UNTIL validtitle OR EOF(inputfile);
END;

PROCEDURE transcribe(msg : string; nmbr : integer);
(* Take a number from a file or kybd, write into a new file *)
VAR x : real;
BEGIN
   GoToXY (1,24);
   WRITE(msg, nmbr,' :');
   READ(parameters,x);
   IF EOLN(parameters) THEN READLN(parameters);
WRITE(results,x:8:3);
END;

PROCEDURE FixTheString(VAR scratch : string);
VAR i : integer;
BEGIN
  IF Pos('.',scratch) = 1 THEN Insert('0',scratch,1);
i := Pos(' .',scratch);
  WHILE i > 0 DO
    BEGIN
      Insert('0',scratch,i+1);
i := Pos(' .',scratch);
    END;
i := Pos('. ',scratch);
  WHILE i > 0 DO
    BEGIN
      insert('0',scratch,i+1);
i := Pos('. ',scratch);
    END;
  i := length(scratch);
  IF copy(scratch,i,1) = '.' THEN scratch := scratch + '0';
END;

PROCEDURE initialize;
VAR i : integer;
  scratch : string;
  thisfile, otherfile, fromkbd : boolean;
BEGIN
(* decay constants in inverse minutes *)
decayconst[1] := LN(2)/3.11;
decayconst[2] := LN(2)/26.8;
decayconst[3] := LN(2)/19.9;
decayconst[4] := LN(2)/638.4;
decayconst[5] := LN(2)/60.5;

(* alphaenergies in nano joules *)
alphaenergy[1] := 13.69*1.6021E-4;

halfpage := 0;
FOR j := 1 to 5 DO eweight[j] := alphaenergy[j]*60.0/decayconst[j];

(*
This code rewrites files prepared for RWRENNGW.BAS into a
standard form 'tempfile.dat' for use by the present Pascal
program.
*)
ClrScr;
WRITE('Name of RWRENNGW-compatible data file ');
READLN(infilename);
ASSIGN(indata, infilename);  RESET(indata);
ASSIGN(results,'tempfile.dat');  REWRITE(results);

ScanForTitle(indata);

WHILE NOT EOF (indata) DO
BEGIN

  WRI

  (*  Find source of parameters - thisfile, otherfile, fromkbd *)
  READLN(indata,scratch);
  thisfile := (Pos('.',scratch) > 0) AND (scratch[1] < 'A') ;
  otherfile  := (scratch[1] >= 'A');
  fromkbd := NOT (thisfile OR otherfile);

  IF otherfile THEN
    BEGIN
      ASSIGN(parameters,scratch);
      RESET(parameters);
      READLN(parameters,scratch);
      CLOSE(parameters);
    END;

  IF thisfile OR otherfile THEN
    BEGIN
      (*  fix the 'naked decimal points' that TURBO doesn't like *)
      FixTheString(scratch);
      WRITELN(results, scratch);
    END;

  IF fromkbd THEN
    BEGIN
      (*  construct and insert the parameters line. *)
      ASSIGN(parameters,'CON');
      RESET(parameters);
      FOR i := 1 TO 5 DO transcribe('count effic',i);
      WRITE(results, 1,1,1,0,0,0);
      transcribe('bkgd count time         ',0);
      transcribe('bkgd count              ',0);
      transcribe('dead time each pulse, us',0);
      transcribe('flowrate, Lpm            ',0);
      transcribe('sampling time, min        ',0);
      transcribe('transfer time, s          ',0);
      transcribe('time per count           ',0);
      transcribe('time between counts      ',0);
      WRITELN(results);
      CLOSE(parameters);
    END;

  REPEAT
    READLN(indata,scratch);
    WRITELN(results,scratch);
  UNTIL scratch[0] = CHR(0);

END;
CLOSE(indata); CLOSE(results);
ClrScr;
WRITE('Enter limit on number of EM iterations ');
READLN(maxiter);
WRITE('Enter EM convergence criterion ( << 1) ');
READLN(concriterion);
WRITELN;
WRITELN('Data was taken from file      ',infilename);
WRITE('Enter name of file for output ');
READLN(outfilename);
ASSIGN(indata,'tempfile.dat');  RESET(indata);
ASSIGN(results, outfilename);  REWRITE(results);
END;

PROCEDURE GetNextData;
(* Reads the next block of data from 'tempfile.dat'. *)
VAR i : integer;
   x : real;
BEGIN
ScanForTitle(indata);
IF NOT EOF(indata) THEN
BEGIN
  GoToXY (1,23);
  i := 0;
  WHILE i < 19 DO
  BEGIN
    i := i + 1;
    IF EOLN(indata) THEN READLN(indata);
    READ (indata, x);
    CASE i OF
     1,2,3,4,5      : cnteffic[i]  := x;
    (*
      discard the next 6 numbers
    *)
     12     : bkgdtime     := x;
     13     : bkgdcount    := TRUNC(x);
     14     : deadtime     := x*1.0E-6/60.0;
     15     : flowrate     := x;
     16     : sampletime   := x;
     17     : transfertime := x/60.0;
     18     : timepercount := x/60.0;
     19     : timebtwncnts := x/60.0
    END;
  END;
  i := 0;
  REPEAT
    WHILE NOT EOLN (indata) DO
    BEGIN
      i := i + 1;
      IF i <= 2000 THEN READ (indata, counts[i]);
      END;
  END;
END;
READLN(indata);
UNTIL EOLN(indata);
IF i <= 2000 THEN numcounts := i ELSE i := 2000;

IF (counts[1] < 0) THEN
BEGIN
FOR i := 2 TO numcounts DO counts[i-1] := counts[i];
numcounts := numcounts - 1;
transfertime := transfertime + timepercount + timebtwncnts;
END;
END;

PROCEDURE buildthekernel;
BEGIN
i := 1;
t0 := sampletime;
ta := t0 + transfertime;
inthebag := 0;
dothoron := (timepercount*numcounts > 300.0);
IF dothoron THEN numnuclides := 5
ELSE numnuclides := 3;
REPEAT
nextblock := numcounts - inthebag;
IF nextblock > inthebag THEN nextblock := inthebag;
IF nextblock = 0 THEN nextblock := 1;
cntsperblk[i] := 0;
FOR j := 1 TO nextblock DO
  cntsperblk[i] := cntsperblk[i] + counts[inthebag + j];

rawdata[i] := (cntsperblk[i] - nextblock*timepercount*bkgdcount/bkgdtime)*
  (1.0 + (nextblock -1)*timebtwncnts/(nextblock*timepercount));
tb := ta + nextblock*timepercount
  + (nextblock -1)*timebtwncnts;

kernel[i,1] := G11(tb,t0) - G11(ta,t0)
  + G31(tb,t0) - G31(ta,t0);
kernel[i,2] := G32(tb,t0) - G32(ta,t0);
kerneld[i,3] := G33(tb,t0) - G33(ta,t0);
IF dothoron THEN
BEGIN
  kernel[i,4] := G54(tb,t0) - G54(ta,t0);
  kernel[i,5] := G55(tb,t0) - G55(ta,t0);
END;
FOR j := 1 to numnuclides DO
  kernel[i,j] := kernel[i,j]*cnteffic[j]*flowrate/1000.0;
GoToXY (1,24);
WRITE('rawdata[',i:2,'] = ',rawdata[i]:12:3);
umdatapts := i;
i := i + 1;
ta := tb + timebtwncnts;
inthebag := inthebag + nextblock;
UNTIL (inthebag = numcounts) OR (i = 12);
END;

PROCEDURE printresults (VAR outpath : text);
BEGIN
  WRITELN(outpath,'*EX-MAX CALCULATION of DECAY PRODUCT CONCENTRATION ...
for data set:');
  WRITELN(outpath,titleoftest);
  WRITELN(outpath,'----------------------------------------------------
----------------
   Nuclide   Concent.  1-sigma');
  WRITELN(outpath,'Flowrate, Lpm   ', flowrate:14:2,'   ',
            'Po-218 ',dpconc[1]:9:3,stderr[1]:9:3,' Bq/m3');
  WRITELN(outpath,'Sample time, min', sampletime:14:2,'   ',
            'Pb-214 ',dpconc[2]:9:3,stderr[2]:9:3,' Bq/m3');
  WRITELN(outpath,'Transfer time, s',ROUND(60*transfertime):14,'   ',
            'Bi-214 ',dpconc[3]:9:3,stderr[3]:9:3,' Bq/m3');
  IF dothoron THEN
  BEGIN
    WRITELN(outpath,' ':33,
             'Pb-212 ',dpconc[4]:9:3,stderr[4]:9:3,' Bq/m3');
    WRITELN(outpath,' ':33,
             'Bi-212 ',dpconc[5]:9:3,stderr[5]:9:3,' Bq/m3');
  END;
  WRITELN(outpath,' ':33,
            'WtdAve ',dpconc[6]:9:3,stderr[6]:9:3,' Bq/m3');
  WRITELN(outpath);
  WRITELN(outpath,' ':33,
            'PAEC ',dpconc[7]:9:3,stderr[7]:9:3,' nJ/m3');
  WRITELN(outpath,' ':33,
            'PAEC ',dpconc[8]:9:3,stderr[8]:9:3,' mWL');
  WRITELN(outpath);
  WRITELN(outpath,' ':33,' Block Counts RawData  FitData');
  FOR i := 1 TO numdatapts DO
  BEGIN
    CASE i OF
      1 : WRITE(outpath,'Number of count intervals',numcounts:5,'   ');
      2 : WRITE(outpath,'Calculation done (Yr,Mo,Dy)',')');
      3 : WRITE(outpath,'  :17,year:5,month:4,day:4,'   ');
      4 : WRITE(outpath,'Convergence criterion',concriterion:9:5,'   ');
      5 : WRITE(outpath,'Iterations (max',maxiter:6,')',lastiter:8,' ');
      ELSE
    WRITE(outpath,' ':33);
  END;
  END;

282
BEGIN (* MAIN PROGRAM *)

ClrScr;
Window(14,10,80,25);
GetDate(year, month, day, dayofweek);
WRITELN('EM Calculation of Rn-Th Decay Product Concentration');
WRITELN;
WRITELN('Pascal Program by E.O. Knutson, 1988');
WRITELN;
WRITELN('Patterned after Maher and Laird''s 1985 paper on');
WRITELN('unfolding data from diffusion batteries.');
WRITELN;
IF NOT kbquery('Ready to start?') THEN EXIT;
Window(1,1,80,25);
initialize;
GetNextData;
REPEAT
buildthekernel;

initguess := counts[1]*(1000.0/flowrate/sampletime) /
(cnteffic[1]*timepercount*60.0);
FOR j := 1 TO 8 DO
BEGIN
dpconc[j] := initguess;
IF j > numnuclides THEN dpconc[j] := 0.0;
stderr[j] := -1.0;
END;

IF dothoron THEN (* do 20 iterations to get better start on Bi-212 *)
BEGIN
ExpectMax (rawdata, numdatapts, numnuclides, 20, 0.00001, kernel, dpconc, lastiter, fitdata, ok);
dpconc[5] := dpconc[4];
END;

ExpectMax (rawdata, numdatapts, numnuclides, maxiter, concriterion*initguess, kernel, dpconc, lastiter, fitdata, ok);
(*
In this case, for sure, the data itself is a good estimate of the variance; hence 'fitdata' in the PROC call below.*)

StandardErr(fitdata, numdatapts, numnuclides, kernel, stderr, ok);

sum := 0.0;
dpconc[7] := 0.0;
FOR j := 1 TO numnuclides DO
  BEGIN
    sum := sum + eweight[j];
  END;
dpconc[8] := dpconc[7]/20.8;

temp := 0.0;
FOR j := 1 TO numnuclides DO
  FOR k := 1 TO numnuclides DO
    temp := temp + eweight[j]*eweight[k]*matrix2[j,k];
  stderr[7] := SQRT(temp);
  stderr[8] := stderr[7]/20.8;

ClrScr;
printresults(output);
halfpage := halfpage + 1;
IF (halfpage MOD 2) = 1 THEN WRITELN(results, '*n*');
printresults(results);

getnextdata;

UNTIL EOF(indata);
CLOSE(results);

END.
The CONVERT.EXE program outlined below was supplied with the Gill Instruments Solent Model 1012 R2 sonic anemometer (SAM). It converted the raw SAM ASCI data into a standard text file used for calculating the covariance of the perturbation values of the vertical wind speed and temperature for the modified Bowen ratio method.

```c
#include <stdio.h>

main()
{
    int ch;
    FILE *in, *out;

    in  = fopen("prac.dat", "rb");
    out = fopen("out.dat", "w");

    while ((ch = fgetc(in)) != EOF)
    {
        fprintf(out, "%d\n", ch);
    }
```
The NSA2.CPP program outlined below was written using Borland C++ Version 4.5 by Bruce Nemetz (1997) of the Atmospheric Radioactivity Laboratory of New Mexico Tech to calculate the mean values and standard deviations of the wind in the three orthogonal axes, \( u \), \( v \), and \( w \), the time that each solenoid (Up, Down, and Neutral) was open based on the vertical wind velocity, and the direction and amount of tilt required to align the SAM to the vertical wind (i.e., to get \( \bar{w} = 0 \)). The results of this program were used to calculate the flux velocities in the REA method.

```c
/* nsa2.cpp
This is the program that creates information about a wind data set stored by the program FASTCOM supplied with a 3-D sonic anemometer. It calculates average wind speed in the three coordinates \( u, v \), and \( w \) and it also calculates the average speed of sound. The program will calculate how long each intake that corresponds to a vertical wind of up, down, or neutral is on based on information entered for the width of the dead band and wind speed offset. The program will calculate the direction the horizontal wind is coming from and the amount the sonic anemometer needs to be tilted up or down to give an average vertical wind speed of zero.
*/

#include <stdio.h>
#include <math.h>
#include <ctype.h>
#include <stdlib.h>
#include <string.h>
#include "sa_wind.h"
#include "getnumb.h"

#define MS_TO_MV .08333

double get_theta(double x[4]);
void error(int x, char *str1, char *str2);

void error(int status, char *str1, char *str2)
{
    printf("\n\n!!!Error %d -- %s %s\n", status, str1, str2);
    exit(status);
}

// Function that calculates the angle of horizontal wind
```
float get_theta(float wind[4])
{
    float angle;
    if (wind[1] <= 0)
        angle = 57.3*atan(fabs(wind[0]/wind[1])) -180;
    else
        if (wind[0] <= 0)
            angle = -57.3*atan(fabs(wind[0]/wind[1]));
        else
            angle = 57.3*atan(fabs(wind[0]/wind[1]));
    return(angle);
}

int main(void)
{
    Sa_Wind wd; // Declaration of a Sa_Wind class
    int sign, new_sign;
    long cnt1, i, up_cnt, dn_cnt, eddy;
    float mean[4], total[4], up_thrsh, dn_thrsh, dd_bnd, ff_st,
    a_in[5],
    wind[4], std_dev[4], ttl_sqr[4], theta, psi;
    char in_file[13], out_file[13], *direct, buffer[81];
    FILE *in, *out; // Declaration of two file pointers

    direct = "UVWS"; // Wind coordinate string

    // Initialization of some variables to zero
    for(i = 0; i < 4; i++)
        mean[i] = total[i] = std_dev[i] = ttl_sqr[i] = 0.0;

    // Get input file name
    printf("Enter Input File: ");
    gets(in_file);

    // Open input file if possible
    if ((in=fopen(in_file,"rb")) == NULL)
        error(1, "Couldn't Open Input File", in_file);

    // Get output file name
    printf("Enter Output File: ");
    gets(out_file);

    // Open output file if possible
    if (out_file[0] == '\0')
        out = stdout;
    else
        if ((out=fopen(out_file,"w")) == NULL)
            error(1, "Couldn't Open Output File", out_file);

    // Get dead band size
    printf("Enter Size of Deadband in M/S: ");
    dd_bnd = Numbers.get_double();

    // Get vertical wind offset
    printf("Enter Wind Speed Offset in M/S: ");
    ff_st = Numbers.get_double();
}
// Define threshold values for up and down wind
up_thrsh = dd_bnd/2.0+ff_st;
dn_thrsh = -dd_bnd/2.0+ff_st;

cnt1 = dn_cnt = up_cnt = eddy = sign = 0;

wd.get_header(in); // Get the wind data file header

// Go though vertical wind speed data and check to see if wind is
up,down
// or neutral
while (wd.get_wind(wind, a_in, in) != 0) {
    for(i = 0; i < 4; i++) {
        total[i] = total[i] + wind[i];
ttl_sqr[i] = ttl_sqr[i] + pow(wind[i],2);
    }

    // Checks to see if the wind has changed direction
    if (wind[2] >= 0)
        new_sign = 1;
    else
        new_sign = 0;
    if (new_sign != sign) {
        sign = new_sign;
eddy++;
    }

cnt1++;

    // Check to see if wind is up
    if (wind[2] > up_thrsh)
        up_cnt++;
    else
        // Check to see if wind is down
        if (wind[2] < dn_thrsh)
            dn_cnt++;
}

// Print out information for input file
fprintf(out, "Input File: %s\n", in_file);
fprintf(out, "%s%s%s\n", wd.get_mode(), wd.get_ana(),
wd.get_time());
fprintf(out, "Based upon %ld wind readings\n", cnt1);
fprintf(out, "Up Threshold Wind Speed = %3.3f\n", up_thrsh);
fprintf(out, "Down Threshold Wind Speed = %3.3f\n\n", dn_thrsh);

// Print out calculated information for the vertical wind
for(i = 0; i < 4; i++) {
    mean[i] = total[i]/cnt1;
    std_dev[i] = sqrt(fabs((ttl_sqr[i] -
cnt1*pow(mean[i],2))/(cnt1-1)));
    fprintf(out, "The Mean %c-Wind Is %3.3f m/s\n", direct[i],
mean[i]);
    fprintf(out, "With A Standard Deviation of %3.3f m/s\n\n", std_dev[i]);
}
// Print out information on how long the up, down, and neutral wind are on
    fprintf(out, "Percent Up Valve on = %3.2f\n", (float)up_cnt/cnt1*100.0);
    fprintf(out, "Approximate time that Up Valve was on = %3.2f minutes\n\n", up_cnt*.048/60);
    fprintf(out, "Percent Neutral Valve on = %3.2f\n", (float)(cnt1-(up_cnt+dn_cnt))/cnt1*100.0);
    fprintf(out, "Approximate time that Neutral Valve was on = %3.2f minutes\n\n", (cnt1-(up_cnt+dn_cnt))*.048/60);
    fprintf(out, "Percent Down Valve on = %3.2f\n", (float)dn_cnt/cnt1*100.0);
    fprintf(out, "Approximate time that Down Valve was on = %3.2f minutes\n\n", dn_cnt*.048/60);

// Print out the eddy reversal frequency and vertical alignment parameters
    fprintf(out, "Eddy reversal frequency = %3.2f Hz\n", eddy/(cnt1*.048));
    theta = get_theta(mean);
    fprintf(out, "Rotate indicator from v direction %3.1f Degrees (u is at +90 Degrees)\n\n", theta);
    psi = 57.3*atan(mean[2]/(sqrt(mean[0]*mean[0] +mean[1]*mean[1])));
    if (psi > 0)
        fprintf(out, "Tilt indicator up by %3.1f Degrees\n", psi);
    else
        fprintf(out, "Tilt indicator down by %3.1f Degrees\n", -psi);

    fclose(out);
    return(0);
The DELAY.CPP program outlined below was written using Borland C++ Version 4.5 by Bruce Nemitz (1997) of the Atmospheric Radioactivity Laboratory of New Mexico Tech to calculate the percent difference in flux between a delayed vertical wind speed set of measurements and one that is not delayed. This information was used to correct the flux velocities calculated in the REA method.

/* delay.cpp
The function of this program is to calculate the difference in flux density between shifted by delay and unshifted sonic anemometer wind data. It reads in the sonic anemometer wind data and does a mathematical shift of these data and calculates the flux density for both the unshifted and shifted data. The results of the calculations are output to a file.
*/

// General header files that need to be included
#include <stdio.h>

// Specific header files that need to be included
#include "l_list.h"
#include "sa_wind.h"
#include "getnumb.h"

main()
{
    LList<float> li; // Pointer to a float type link list
    LLPPosition P[3]; // Three pointers to a link list
    Sa_Wind wd; // Declaring a Sa_Wind class
    FILE *in, *f_out; // Two file pointers

    // Declaration of variables that are necessary
    long up_cnt, dn_cnt, n_cnt;
    int i, j, dly_cnt, delay[10], off[10];
    char buffer[81];
    float wind[4], up_thrsh, dn_thrsh, dd_bnd, ff_st, a_in[5],
         mod[10],
         flux[2], wnd[3], up_flux[2], dn_flux[2], w_dn, w_up, w_ne, up_con,
         dn_con,
         ne_con, slope, b, min, max;

    // Initialization of some of the variables to zero
    up_cnt = dn_cnt = n_cnt = w_dn = w_up = w_ne = min = max = 0;

    // Get input file name
    printf("Enter input file name: ");
    gets(buffer);

    // Open input file if possible
    if ((in = fopen(buffer, "rb")) == NULL) 
    {
printf("Couldn't open input file %s !!!\n");
exit(255);
}

// Get the number of delays (max=10) that will be calculated
printf("\nEnter the number of delays [maximum of 10]: ");
dly_cnt = Numbers.get_int();
if (dly_cnt > 10)
dly_cnt = 10;

// Get the length of each delay in milliseconds
for (i = 0; i < dly_cnt; i++) {
    printf("\nEnter length of delay %d in milliseconds: ", i+1);
delay[i] = Numbers.get_int();
    if (delay[i] == 0) {
        off[i] = 0;
        mod[i] = 0;
    }
    else {
        // Setting of the offset
        off[i] = delay[i]/TIME + 1;
        mod[i] = ((float)(delay[i]))/((float)(TIME)) -
        (float)(off[i]) + 1;
    }
}

// Get the size of the dead band
printf("\nEnter Size of Dead band in M/S: ");
dd_bnd = Numbers.get_double();

// Get wind speed offset
printf("\nEnter Wind Speed Offset in M/S: ");
ff_st = Numbers.get_double();

// Define up and down threshold values
up_thrsh = dd_bnd/2.0+ff_st;
dn_thrsh = -dd_bnd/2.0+ff_st;

// Get output file name
printf("\nWhat file would you like the output to go to: ");
gets(buffer);

// Open output file if possible
if (buffer[0] == '\0') {
    f_out = stdout;
}
else {
    f_out = fopen(buffer, "w");
}

// Read sonic anemometer file and put vertical wind speed into link list
printf("\nLoading List\n");
wd.get_header(in);
while (wd.get_wind(wind, a_in, in) != 0) {
    li.AddTail(wind[2]);
// Going through link list of sonic anemometer vertical wind speeds
P[0] = li.GetHeadPosition();
while (P[0] != NULL) {
    wnd[0] = li.GetNext(P[0]);
    // Determine maximum vertical wind speed
    if (wnd[0] > max) {
        max = wnd[0];
    }
    else
        // Determine minimum vertical wind speed
        if (wnd[0] < min) {
            min = wnd[0];
        }
    // Check to see if vertical wind speed is an up wind
    if (wnd[0] > up_thrsh) {
        up_cnt++;
        w_up = w_up + wnd[0];
    }
    else
        // Check to see if vertical wind speed is a down wind
        if (wnd[0] < dn_thrsh) {
            dn_cnt++;
            w_dn = w_dn + wnd[0];
        }
        else
            // If vertical wind is neither up or down it must be neutral
            n_cnt++;
            w_ne = w_ne + wnd[0];
    }
// Calculate average wind speed for up, down, and neutral
    w_up = w_up/up_cnt;
    w_dn = w_dn/dn_cnt;
    w_ne = w_ne/n_cnt;

// Get up concentration
printf("\nEnter up concentration: ");
    up_con = Numbers.get_double();
// Get down concentration
printf("\nEnter down concentration: ");
    dn_con = Numbers.get_double();
// Get neutral concentration
printf("\nEnter neutral concentration: ");
    ne_con = Numbers.get_double();

// Print some wind values and concentrations to the output file
fprintf(f_out, "Mean W-dn = %2.4e m/s\nMean W-ne = %2.4e m/s\nMean W-up = %2.4e m/s\n\n", w_dn, w_ne, w_up);
fprintf(f_out, "Down-con = %2.4e nJ/m^3\nNeutral-con = %2.4e nJ/m^3\nUp-con = %2.4e nJ/m^3\n\n", dn_con, ne_con, up_con);
fprintf(f_out, "Minimum = %2.4e m/s, Maximum = %2.4e m/s\n\n", min, max);
// Calculate linear fit, based on concentrations and average vertical wind speeds
slope = (up_con - dn_con) / (w_up - w_dn);
b = up_con - w_up * slope;

// Print linear fit equation to the output file
fprintf(f_out, "Concentration = a(Wind Speed) + b, where a = %2.4e nJ/s/m^4 and b = %2.4e nJ/m^3\n\n", slope, b);

// Go through each delay
for (i = 0; i < dly_cnt; i++)  {
    fprintf(f_out, "For delay = %dms\n", delay[i]);  // Print which delay

    // Shift the wind data by the offset amount
    for (j = 0, up_cnt = dn_cnt = 0; j < off[i] && P[0] != NULL; j++) {
        wind[0] = li.GetNext(P[0]);
    }
    P[2] = P[0];
    if (off[i] != 0) {
    }

    // Get new flux density values based on shifted wind data
    while(P[0] != NULL) {
        wind[0] = li.GetNext(P[0]);
        if (off[i] != 0) {
            wind[0] = wind[2] + (wind[0] - wind[2]) * mod[i];
        }
        if (wind[1] > up_thrsh) {
            up_cnt++;
            up_flux[0] = up_flux[0] + wind[1] * slope + b;
        } else if (wind[1] < dn_thrsh) {
            dn_cnt++;
            dn_flux[0] = dn_flux[0] + wind[1] * slope + b;
        }
    }

    // Calculate shifted flux density values
    flux[0] = up_flux[0] / up_cnt - dn_flux[0] / dn_cnt;

    // Print concentration values and differences for shifted and unshifted data
293
fprintf(f_out, "Linear: Up conc. = %2.4e nJ/m^3, Down conc. = %2.4e nJ/m^3\n", up_flux[0]/up_cnt, dn_flux[1]/dn_cnt);
fprintf(f_out, "Linear Conc. difference = %2.4e nJ/m^3\n\n", flux[0]);
fprintf(f_out, "Delayed Linear: Up conc. = %2.4e nJ/m^3, Down conc. =%2.4e nJ/m^3\n", up_flux[1]/up_cnt, dn_flux[1]/dn_cnt);
fprintf(f_out, "Delayed Linear Conc. difference = %2.4e nJ/m^3\n\n", flux[1]);
fprintf(f_out, "The percent difference in linear flux is %2.2f percent\n\n", 100*(flux[1]/flux[0]-1));
}
fclose(f_out);
return 0;
The VDEP.CPP program outlined below was written using Borland C++ Version 4.5 by Bruce Nemetz of the Atmospheric Radioactivity Laboratory of New Mexico Tech to calculate the flux velocity for the REA method.

/* vdep.cpp
This program calculates the deposition velocity of the radon progeny based upon parameters entered by the program user.
*/

// Inclusion of necessary generic header files
#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#include <ctype.h>

// Function that gets a string and converts it to a double
double get_value(char *str)
{
    char buff[81];
    double x;

    printf("%s", str);
    gets(buff);
    x = atof(buff);
    return x;
}

// Beginning of main program
main(void)
{
    FILE *out;
    int i;
    double scr_con[3], scr_err[3], fil_con[3], fil_err[3], scr_eff[3], db, std_w,
    mean_w, b0, cave, cave_err, mesh_scr_con[3],
    mesh_scr_err[3], mesh_fil_con[3],
    cor_scr_con[3], cor_scr_err[3], mesh_cor_scr_con[3],
    mesh_cor_scr_err[3],
    cor_cave, cor_cave_err, mesh_cave, mesh_cave_err,
    mesh_cor_cave,
    mesh_cor_cave_err, beta_cor, beta, flux, flux_err, vdep,
    vdep_err, cor_flux,
    cor_flux_err, cor_vdep, cor_vdep_err, mesh_cor_flux,
    mesh_cor_flux_err,
    mesh_cor_vdep, mesh_cor_vdep_err;

    char buff[81], date[20], time[20], run[3], mesh[3], local[81];
    // Get all user inputted data
printf("Enter date of sample: ");
gets(date);
printf("Enter time of sample: ");
gets(time);
printf("Enter run number of sample: ");
gets(run);
printf("Enter screen mesh: ");
gets(mesh);
printf("Enter location of sample: ");
gets(local);
scr_con[0] = get_value("Enter up screen PAEC: ");
scr_err[0] = get_value("Enter up screen error PAEC: ");
scr_con[1] = get_value("Enter down screen PAEC: ");
scr_err[1] = get_value("Enter down screen error PAEC: ");
scr_con[2] = get_value("Enter neutral screen PAEC: ");
scr_err[2] = get_value("Enter neutral screen error PAEC: ");
fil_con[0] = get_value("Enter up filter PAEC: ");
fil_err[0] = get_value("Enter up filter error PAEC: ");
fil_con[1] = get_value("Enter down filter PAEC: ");
fil_err[1] = get_value("Enter down filter error PAEC: ");
fil_con[2] = get_value("Enter neutral filter PAEC: ");
fil_err[2] = get_value("Enter neutral filter error PAEC: ");
scr_eff[0] = get_value("Enter up screen efficiency: ");
scr_eff[1] = get_value("Enter down screen efficiency: ");
scr_eff[2] = get_value("Enter neutral screen efficiency: ");
db = get_value("Enter the width of the dead band: ");
std_w = get_value("Enter the standard deviation of vertical wind: ");
mean_w = get_value("Enter the mean vertical wind: ");
b0 = get_value("Enter value for b0 for Beta calculation: ");

// Give option to print information to a file
printf("Would you like to print this to a file? ");
gets(buff);

// Check to see if information needs to be printed to a file
if (toupper(buff[0]) == 'Y') {
    printf("Enter output file name: ");
    gets(buff);
    // Open output file if possible
    if ((out = fopen(buff, "w")) == NULL) {
        printf("Couldn't open output file %s !!!\n", buff);
        exit(1);
    }
} else {
    out = stdout;
}

// Calculate average concentration and error
cave = (scr_con[0] + scr_con[1])/2;
cave_err = sqrt(pow(scr_err[0],2) + pow(scr_err[1], 2));

// Calculate efficiency values and filter corrected screen concentrations
for (i=0; i < 3; i++) {
    mesh_scr_con[i] = 100*scr_con[i]/scr_eff[i];
}
mesh_scr_err[i] = 100*scr_err[i]/scr_eff[i];
mesh_fil_con[i] = fil_con[i] - ((100/scr_eff[i])-1)*scr_con[i];
cor_scr_con[i] = scr_con[i]/2*(fil_con[0] +
fil_con[1])/fil_con[i];
cor_scr_err[i] = scr_err[i]/2*(fil_con[0] +
fil_con[1])/fil_con[i];
}

// Calculate screen mesh corrected values of screen concentrations
for (i=0; i<3; i++) {
    mesh_cor_scr_con[i] = mesh_scr_con[i]/2*(mesh_fil_con[0] +
mesh_fil_con[1])/mesh_fil_con[i];
    mesh_cor_scr_err[i] = mesh_scr_err[i]/2*(mesh_fil_con[0] +
mesh_fil_con[1])/mesh_fil_con[i];
}

// Calculate average values for filter and mesh corrected
concentrations
    cor_cave = (cor_scr_con[0] + cor_scr_con[1])/2;
    cor_cave_err = sqrt(pow(cor_scr_err[0],2) + pow(cor_scr_err[1],2));
    mesh_cave = (mesh_scr_con[0] + mesh_scr_con[1])/2;
    mesh_cave_err = sqrt(pow(mesh_scr_err[0],2) + pow(mesh_scr_err[1],2));
    mesh_cor_cave = (mesh_cor_scr_con[0] + mesh_cor_scr_con[1])/2;
    mesh_cor_cave_err = sqrt(pow(mesh_cor_scr_err[0],2) +
pow(mesh_cor_scr_err[1],2));

// Calculate beta value based on what b0 is
    beta_cor = 1-.427*(1-exp(-2.01*db/(2*std_w)));
    beta = b0*beta_cor;

// Calculate flux values and deposition values with errors
    flux = beta*std_w*(scr_con[0] - scr_con[1]);
    flux_err = beta*std_w*cave_err;
    vdep = flux/cave;
    vdep_err = flux_err/cave;
    cor_flux = beta*std_w*(cor_scr_con[0] - cor_scr_con[1]);
    cor_flux_err = beta*std_w*cor_cave_err;
    cor_vdep = cor_flux/cor_cave;
    cor_vdep_err = cor_flux_err/cor_cave;
    mesh_cor_flux = beta*std_w*(mesh_cor_scr_con[0] -
mesh_cor_scr_con[1]);
    mesh_cor_flux_err = beta*std_w*mesh_cor_cave_err;
    mesh_cor_vdep = mesh_cor_flux/mesh_cor_cave;
    mesh_cor_vdep_err = mesh_cor_flux_err/mesh_cor_cave;

// Print out all information
    fprintf(out, "SAMPLE DATE/TIME:  %s %s  RUN NUMBER:  %s
", date,
time, run);
    fprintf(out, "SAMPLE LOCATION:  %s  SCREEN MESH:  %s

", local,
mesh);
    fprintf(out, "UP SCREEN PAEC (C-UP):   %3.3f +/- %1.3f nJ/m^3
(%.2f\%%)
", scr_con[0], scr_err[0], 100*scr_err[0]/scr_con[0];
    fprintf(out, "Up screen efficiency:  %2.2f\%%
", scr_eff[0]);
    fprintf(out, "*Screen mesh correction:X(%.1f\%%) = %3.3f +/- %1.3f
nJ/m^3
(%.2f\%%)
", 100/scr_eff[0], mesh_scr_con[0], mesh_scr_err[0];
    fprintf(out, "DOWN SCREEN PAEC (C-DOWN):  %3.3f +/- %1.3f nJ/m^3
(%.2f\%%)
", scr_con[1], scr_err[1], 100*scr_err[1]/scr_con[1];
fprintf(out, "Down screen efficiency:  \%2.2f/\n", scr_eff[1]);
fprintf(out, "*Screen mesh correction:*X(\%1.3f) = \%3.3f +/- \%1.3f
nJ/m^3/\n\n", 100/scr_eff[1], mesh_scr_con[1], mesh_scr_err[1]);
fprintf(out, "Average Concentration (CAVE) = \%3.3f nJ/m^3/\n\n", cave);
fprintf(out, "Average Concentration error = \%3.3f nJ/m^3/\n\n", cave_err);
fprintf(out, "DEADBAND SETTING:  \%1.2f m/s  Mean-W/std-W = \%2.1f/\n", db, 100*mean_w/std_w);
fprintf(out, "VERTICAL WIND DEVIATION:  \%1.3f m/s^2/\n\n", std_w);
fprintf(out, " Normalized Deadband DB/2*std_w:  \%1.3f/\n\n", db/(2*std_w));
fprintf(out, "b0 = \%1.3f  b = (b0)*(correction factor) = \%1.3f/\n\n", b0, beta);
fprintf(out, " correction factor = 1-a0*[1-exp(-a1*db/2*std_w)] =\n\n", from E. Pattey, etal. paper, a0 = .427, a1 = 2.01/\n\n");
fprintf(out, "Flux:  \%1.3f +/- \%1.3f nJ/m^3/\n\n", flux, flux_err);
fprintf(out, "Deposition velocity:  \%1.3f +/- \%1.3f m/s/\n\n", vdep, vdep_err);
fprintf(out, "UP FILTER PAEC:  \%3.3f +/- \%3.3f nJ/m^3/\n\n", fil_con[0], fil_err[0]);
fprintf(out, "*Screen mesh correction:[-(%1.3f)(%2.3f)] = \%3.3f
nJ/m^3/\n\n", 100/scr_eff[0]-1, scr_con[0], mesh_fil_con[0]);
fprintf(out, "DOWN FILTER PAEC:  \%3.3f +/- \%3.3f nJ/m^3/\n\n", fil_con[1], fil_err[1]);
fprintf(out, "*Screen mesh correction:[-(%1.3f)(%2.3f)] = \%3.3f
nJ/m^3/\n\n", 100/scr_eff[1]-1, scr_con[1], mesh_fil_con[1]);
fprintf(out, "Filter corrected C-UP:  \%3.3f +/- \%1.3f nJ/m^3/\n\n", cor_scr_con[0], cor_scr_err[0]);
fprintf(out, "Filter corrected C-DOWN:  \%3.3f +/- \%1.3f nJ/m^3/\n\n", cor_scr_con[1], cor_scr_err[1]);
fprintf(out, "Filter Corrected Flux:  \%1.3f +/- \%1.3f nJ/m^2/s/\n\n", cor_flux, cor_flux_err);
fprintf(out, "Filter Corrected Deposition Velocity:  \%1.3f +/- \%1.3f
m/s/\n\n", cor_vdep, cor_vdep_err);
fprintf(out, "Mesh & filter corrected C-UP:  \%3.3f +/- \%1.3f
nJ/m^3/\n\n", mesh_cor_scr_con[0], mesh_cor_scr_err[0]);
fprintf(out, "Mesh & filter corrected C-DOWN:  \%3.3f +/- \%1.3f
nJ/m^3/\n\n", mesh_cor_scr_con[1], mesh_cor_scr_err[1]);
fprintf(out, "Mesh & filter corrected C-UP:  \%3.3f +/- \%1.3f
nJ/m^2/s/\n\n", mesh_cor_flux, mesh_cor_flux_err);
fprintf(out, "Mesh & filter corrected C-DOWN:  \%3.3f +/- \%1.3f
nJ/m^2/s/\n\n", mesh_cor_vdep, mesh_cor_vdep_err);