Final Report — September 2004

Big Bend Regional Aerosol and Visibility Observational Study

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Note to Readers

This report relies extensively on color its charts and figures. Although the charts in the report are designed so that their meanings can generally be discerned from a black-and-white copy, full understanding of the information in some complex figures can only be achieved when they are viewed in color. Adobe Acrobat files containing the report and appendix are available on compact disc (CD) at the back of the original printed versions of the report and from the IMPROVE web site at http://vista.cira.colostate.edu/improve/.

Preface

The following is a report about the results of a study concerning the causes of visibility impairment at Big Bend National Park (NP) in west Texas. The study was prompted by observations in the early 1990s that visibility at the Park was frequently degraded and was apparently getting worse.

A preliminary study was sponsored by the U.S. Environmental Protection Agency (EPA), the National Park Service (NPS), and governmental agencies from Mexico. This preliminary study was conducted in 1996 and a report of its findings released in January 1999. The findings indicated that fine particulate sulfur compounds played a large role in observed impairment and that there was apparent transport of particulate sulfur compounds from sources in Mexico and the U.S. The preliminary report concluded that, in order to get a better understanding of the contributors to impairment at Big Bend NP, an enhanced study would be necessary that expanded the scope of the field measurement activities and expanded the spatial domain of the preliminary study, particularly to the northeast, south, and into the Gulf of Mexico.

The EPA, the NPS, and the Texas Commission on Environmental Quality (TCEQ) comprised the Steering Committee for the enhanced study, the Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study. In April 1999, Mexico elected not to participate in the Study, which resulted in the Study being unable to gather ambient monitoring and atmospheric tracer release data in Mexico. Although this was a disappointing development, the monitoring and atmospheric tracer protocols were altered to maximize data collection in the U.S. border area nearest Mexico. The BRAVO Technical Sub-committee designed and directed the field-measurement portion of this study that ran from July through October 1999, and interpretation and analyses of these field data were completed in early 2004.

The BRAVO Study was designed as an investigation of the causes of haze at Big Bend National Park, but not as an assessment of regulatory options. The Study constituted one of the largest and most comprehensive visibility field studies and air quality modeling evaluation efforts conducted in the U.S. It used state-of-the-science monitoring, air quality modeling, and laboratory and statistical analyses and involved over 30 researchers from research and academic institutions throughout the U.S. It used inert atmospheric tracers over a huge geographic scale and made use of the best available air emissions input data. Evaluation of the collected data continued for over three years after the end of the 1999 field study.

While the Steering Committee was responsible for the ultimate publication of the BRAVO final report, the Steering Committee relied upon the BRAVO Technical Sub-committee to conduct or sponsor detailed analyses of the field data and source-region attribution analyses and to prepare the final report. Findings presented in the final report were thoroughly discussed by the Steering Committee, the Technical Sub-committee, and a

Non-governmental Sub-committee consisting of industry and environmental advocacy groups.

The final report provides estimates of the contributions of broad geographic regions to visibility impairment at the Park during the study period. Contributions from the eastern U.S., eastern Texas, and Mexico were noted. Because of the relative proximity of the *Carbón* I and II power plants to the Park, contributions specific to those facilities were estimated in this analysis. Such source-specific calculations were not made for other sources in the study domain. Of particular significance was the indication that sources over a broad geographic region play roles in the observed visibility impairment in the Park, suggesting too that the solution should be based on international and regional, multi-State strategies.

The confidence in these results notwithstanding, it must be emphasized that the endorsement of these findings by the BRAVO Steering Committee is made with the understanding that uncertainties exist and that analysis tools, no matter how sophisticated, only approximate atmospheric transport and chemical reactions. However, the Steering Committee is confident that the results of the study have been fairly presented with the concomitant caveats.

The BRAVO Steering Committee wishes to acknowledge the commitment and contribution of all that participated in this study and the preparation of this report. Our understanding of the science of the effects of atmospheric aerosol on visibility has been greatly expanded, as has our understanding of the causes of visibility impairment at Big Bend NP.

As the Steering Committee for the BRAVO Study:

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The BRAVO Study could not have been accomplished without the enthusiastic support of participant organizations and individuals. From the initial planning in 1997, through the four-month ambient monitoring program in 1999, to the assessment process, and culminating in 2004 with the preparation of the final report, this study has been fortunate to include many talented and dedicated individuals from a number of organizations functioning together as a team. We are indebted to both the individuals for their thoughtful and energetic participation, and to their parent organizations that permitted and encouraged involvement by their staff.

The list of organizations that participated in the BRAVO Study includes

- **Sponsors:** U.S. Environmental Protection Agency, National Park Service, and the Texas Commission on Environmental Quality;
- **Contributors:** EPRI, and the National Oceanic and Atmospheric Administration - Air Resources Laboratory;
- **Research Institutions and Universities:** University of California - Davis, Desert Research Institute and the Cooperative Institute for Atmospheric Science and Terrestrial Applications at the University of Nevada, Cooperative Institute for Research in the Atmosphere at Colorado State University, Pennsylvania State University, Carolina Environmental Program at the University of North Carolina, and Brookhaven National Laboratory;
- **Consulting Firms:** Atmospheric and Environmental Research, Inc, Air Resource Specialists, Inc, and Aerosol Dynamics; and
- **Stakeholders:** the Environmental Defense, the Sierra Club, American Electric Power, TXU, and Reliant Energy.

The list below includes the individual participants that are not already acknowledged on the cover page as authors. It takes a lot of good people to accomplish a program of this magnitude and we were lucky to have a great team.

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List of Abbreviations and Acronyms

ACARS ....Aircraft Communications Addressing and Reporting System
AGL ....above ground level
AIM.................................Aerosol Inorganics Model
AP ....accumulation potential
ARL.................................NOAA Air Resource Laboratory
ATAD ....NOAA ARL's Atmospheric Transport and Dispersion model
b_{abs} ....coefficient of optical absorption (a measure of light absorption)
BBNP ....Big Bend National Park
BC ....black carbon
BEIS................................Biogenic Emissions Inventory System
BELD ....Biogenic Emissions Landcover Database
b_{ext} ....coefficient of optical extinction (a measure of light extinction)
BNL.................................Brookhaven National Laboratory
b_{sp} ....coefficient of optical scattering (a measure of light scattering by particles)
CAPITA ....Center for Air Pollution Impact and Trend Analysis (Washington University, St. Louis, MO)
CASTNET........................USEPA Clean Air Status and Trends Network
CEM................................continuous emissions monitors
CENEPRED.....................Centro Nacional de Prevención de Desastres (Mexico's National Center for Disaster Prevention)
CJ ....Ciudad Juarez
CM ....coarse-particle mass
CMAQ.............................Models-3/Community Multiscale Air Quality model (simulates various chemical and physical processes that are thought to be important for understanding atmospheric trace gas transformations and distributions over urban and regional scales)
CMB................................Chemical Mass Balance (a receptor model)
CMC................................CAPITA Monte Carlo
COSPEC ....correlation spectrometer
CPI ....carbon preference index

List of Abbreviations and Acronyms (continued)

CSU................................Colorado State University
D....................................normalized directional frequency
EC ....elemental carbon
EDAS ....Eta Data Assimilation System (collects data for input to the Eta weather forecast model)
EDGAR...........................Emission Database for Global Atmospheric Research
EI....................................emissions inventory
EOF ....Empirical Orthogonal Function
EPS.................................Emissions Preprocessor System
ERG................................Eastern Research Group
f(RH) ....relative humidity adjustment factor (adjusts the light scattering effect of sulfates and nitrates to account for particle growth caused by water vapor in the atmosphere)
FA ....factor analysis
fL....................................femtoliter
FMBR ....Forward Mass Balance Regression
GC/MS ....gas chromatography with mass spectrometry
GDAS.............................Global Data Assimilation System
GEIA ....Global Emissions Inventory Activity
GOCART ....Global Ozone Chemistry Aerosol Radiation Transport global climate model
GOES ....NOAA Geostationary Operational Environmental Satellites system
HCP................................high conditional probability
HIP ....high incremental probability
HRT................................high condition residence time (residence time for transport during high concentration or haze level conditions, typically the top 10% to 20% of conditions)
HSC................................high condition source contribution
HYSPLIT ....Hybrid Single-Particle Lagrangian Integrated Trajectory model
IF ....influence function
IMPROVE.......................Interagency Monitoring of Protected Visual Environments

List of Abbreviations and Acronyms (continued)

INE..................................Instituto Nacional de Ecología
(Mexico's National Institute of Ecology)

INEGI..............................Instituto Nacional de Estadística Geografía e Informática

IPCC................................Intergovernmental Panel on Climate Change

i-PPCH ....perfluoro-iso-propylcyclo-hexane
(a perfluorocarbon used as an artificial tracer)

LAC.................................light-absorbing carbon

LCP ....low conditional probability

LIP...................................low incremental probability

LRT ....low condition residence time (residence time for transport during low concentration or haze level conditions, typically the lowest 10% to 20% of conditions)

LSC ....low condition source contribution

MADRID ....Model for Aerosol Dynamics, Reaction, Ionization, and Dissolution (simulates atmospheric particulate matter)

MAE................................mean absolute error

MCIP...............................Meteorology Chemistry Interface Processor, Meteorology-Chemistry Interface Processor

MDL................................minimum detection limit

Mm^{-1} ....inverse megameter (1/1,000,000 meter; a light extinction measurement unit)

MM5 ....Pennsylvania State University/National Center for Atmospheric Research mesoscale model (a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation)

MMS ....Minerals Management Service

MOAD ....Outer Continental Activity Database

MOHAVE........................Measurement of Haze and Visibility Effects

MOUDI ....Micro-Orifice Uniform Deposit Impactor
(a cascade impactor that collects size-fractionated aerosol particle samples for gravimetric and chemical analysis)

MRF ....Medium Range Forecast model

N MX NEI.......................Mexico's national emissions inventory

NCEP ....National Centers for Environmental Prediction

List of Abbreviations and Acronyms (continued)

NEI ....National Emissions Inventory
ng.....................................nanogram
NGO ....non-governmental organization
NO ....nitrogen oxide
NOAA ....National Oceanic and Atmospheric Administration
NO_X ....oxides of nitrogen
NO_Y ....sum of NO_X + HNO_3 + HONO + PAN
NPS ....National Park Service (part of the U.S. Department of the Interior)
OC ....organic carbon
OCM ....organic carbon mass concentration
OLS ....ordinary least squares
OMC ....organic carbon compounds
oPDCH ....perfluoro-1,2-dimethylcyclohexane (a perfluorocarbon used as an artificial tracer)
ocPDCH ....an isomer of oPDCH accounting for 45% (a perfluorocarbon used as an artificial tracer)
ORT.................................overall residence time
OSC.................................overall source contribution
PAVE ....Package for Analysis and Visualization for Environmental data (a software application to visualize multivariate gridded environmental datasets)
PDCB ....1,1,2,2,3,4-hexafluoro-3,4-bis(trifluoro-methyl) cyclobutane (a perfluorocarbon used as an artificial tracer)
PDF ....probability density function
pg.....................................picogram (10^{-12} g)
PM_{10} ....particulate matter with aerodynamic diameters smaller than 10 µm
$PM_{2.5}$ ....particulate matter with aerodynamic diameters smaller than 2.5 µm
ppq...................................parts per quadrillion
PROFEPA ....La Procuraduría Federal de Protección al Ambiente (Mexico’s Program of Environmental Justice Procuration)
PTCH ....perfluoro-1,3,5-trimethylcyclohexane (a perfluorocarbon used as an artificial tracer)

List of Abbreviations and Acronyms (continued)

r or R ....correlation coefficient
r^2 or R^2..............................correlation coefficient squared, also coefficient of determination
RADM..............................Regional Acid Deposition Model
RASS................................radio acoustic sounding system
READY............................NOAA ARL's Real-Time Environmental Applications and Display System
REMSAD.........................Regional Modeling System for Aerosols and Deposition
RH...................................relative humidity
RMSE..............................root mean square error
RT ....residence time
RWP................................radar wind profiler
SC....................................source contribution
SEM ....scanning electron microscopy
SEMARNAT....................Secretaría de Medio Ambiente y Recursos Naturales (Mexico's Ministry of the Environment)
SMOKE...........................Sparse Matrix Operator Kernel Emissions model
SO_2 ....sulfur dioxide
SO_4 or $SO_4^{=}$ or SO_4^{2-} ....sulfate
SSI...................................Spectral Statistical Interpolation
TAGIT..............................Tracer-Aerosol Gradient Interpretive Technique (uses tracer data from a monitoring network to distinguish sites impacted by a source tagged with artificial tracer from nonimpacted sites)
TCEQ ....Texas Commission on Environmental Quality (formerly Texas Natural Resource Conservation Commission)
TJ.....................................Tijuana
TOR.................................thermal/optical reflectance
TrMB...............................Tracer Mass Balance
TS....................................total sulfur (contributed by both SO_2 and $SO_4^{=}$)
UCD ....University of California at Davis
URG ....University Research Glassware
USEPA.............................U.S. Environmental Protection Agency

List of Abbreviations and Acronyms (continued)

UTC.................................Coordinated Universal Time (the international time standard; UTC is the current term for what was commonly referred to as Greenwich Meridian Time [GMT]; zero [0] hours UTC is midnight in Greenwich, England)

VIF ....variance inflation factor (indicates the collinearity of a source area with all other source areas in TrMB analysis)

Vis5d ....an OpenGL-based volumetric visualization program for scientific datasets in 3+ dimensions

WRAP ....Western Regional Air Partnership

σ_z ....standard deviation of the vertical dispersion of a Gaussian plume for stable conditions