AERMOD: Model Formulation and Evaluation Results

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ABSTRACT

AERMOD is an advanced plume model that incorporates updated treatments of the boundary layer theory, understanding of turbulence and dispersion, and includes handling of terrain

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interactions. This paper includes an overview of AERMOD's features relative to ISCST3, a dispersion model that is widely used for many applications.

AERMOD has been evaluated on 10 databases, which include flat and hilly terrain areas, urban and rural sites, and a mixture of tracer experiments as well as routine monitoring networks with a limited number of fixed monitoring sites. This paper presents a summary of the evaluation results of AERMOD with these diverse databases.

INTRODUCTION

In 1991, the United States Environmental Protection Agency (US EPA), in conjunction with the American Meteorological Society (AMS), formed the AMS/EPA Regulatory Model Improvement Committee (AERMIC). AERMIC's charter was to build upon earlier modeling developments to provide a state-of-the-art dispersion model. The resulting model, AERMOD[1], is the subject of this paper.

AERMOD represents an advance in the formulation of a steady-state, Gaussian plume model. It is apparent that AERMOD has an advantage over ISCST3 when the various scientific components are compared (see Table 1). Therefore, AERMOD would be expected to perform at least as well as or better than the existing modeling techniques.

The performance evaluation of AERMOD involved four short-term tracer studies and six conventional long-term SO_2 monitoring databases in a variety of settings. The purpose of these studies was to be sure that AERMOD had been tested in the various types of environments for which it will be used. Compared with other widely used models, AERMOD has been subjected to a large degree of testing with these evaluation databases.

AERMOD FORMULATION

The focus of the AERMIC group has been on applied models designed for estimating near-field impacts from industrial source types. The primary products of the ongoing AERMIC development work are the AERMOD (**AER**MIC **Mod**el) dispersion model, the AERMET meteorological preprocessor, and the AERMAP terrain preprocessor.

The development of a new model is generally dependent not only on published research in atmospheric diffusion, but also on model development work that has gone on before. This is certainly true with AERMOD. A "new generation plume model" is not simply a variation on the traditional Gaussian plume model, but, instead, takes advantage of more recent research on turbulence and diffusion in the atmosphere. Other models in this category include PPSP[2], HPDM[3], TUPOS[4], CTDMPLUS[5], and, more recently, ADMS[6] (developed in the United Kingdom) and OLM[7] (developed in Denmark). AERMIC members were involved in the development of three of these models, PPSP, CTDMPLUS and HPDM. As with most technological developments, AERMOD was built on the knowledge and experience gained from the development of these earlier models.

The AERMOD modeling system is composed of one main model (AERMOD) and two preprocessors—a meteorological preprocessor (AERMET) and a terrain preprocessor (AERMAP). AERMET calculates hourly boundary layer parameters for use by AERMOD, including friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale,

convective boundary layer (CBL) height, stable boundary layer (SBL) height, and surface heat flux. In addition, AERMET passes observed meteorological parameters to AERMOD including wind direction and speed (at multiple heights, if available), temperature, and, if available, measured turbulence. AERMOD uses this information to calculate concentrations in a manner that accounts for changes in dispersion rate with height, allows for a non-Gaussian plume in convective conditions, and accounts for a dispersion rate that is a continuous function of meteorology. In contrast, ISCST3 assumes that the dispersion rate is constant with height, that the plume is always Gaussian in form, and is based on discrete dispersion (stability) categories that were developed in the 1960's and can result in jumps in calculated concentrations with small changes in meteorology. AERMAP prepares terrain data for use by AERMOD. This allows AERMOD to account for terrain using a simplification of the procedure used in the CTDMPLUS model[5]. Table 1 summarizes the differences between AERMOD and ISCST3 (space limitations prevent the inclusion of contrasts between AERMOD and other models such as CTDMPLUS). Detailed descriptions of the formulations are presented by Cimorelli, et al[1].

MODEL EVALUATION DESIGN

The evaluation of AERMOD was accomplished in two phases. The first phase, the "developmental evaluation," was performed concurrently with the development of the model. As each feature of the model was added, a relevant portion of the developmental evaluation was repeated with five databases to identify any problems that might have been introduced at that stage of the model's development. Because of the possibility that the model may have been inadvertently biased to fit particular characteristics of the developmental databases used, a second phase, the "independent evaluation," was conducted using three additional data sets. This second evaluation was conducted with a minimum of model changes (only those required to fix run-time errors or to correctly implement the model formulation) prior to a peer review of AERMOD. In response to peer review comments, two independent complex terrain databases were added and some changes were made to the model algorithms involving stable plume dispersion.

Developmental Evaluation

AERMOD is intended to handle a variety of pollutant source types (including surface and buoyant elevated sources) in a wide variety of modeling situations (including rural, urban, flat terrain and complex terrain). With this in mind, data from five diverse field studies were selected for the developmental evaluation. Due to space limitations, maps of the various sites are not provided in this report, but can be found in Paine et al[8].

The **Prairie Grass** study (Barad[9], Haugen[10]) used a near-surface, non-buoyant tracer release in a flat rural area. The Prairie Grass study involved a tracer of SO_2 released at 0.46 m above the surface. Surface sampling arrays (arcs) were positioned from 50 m to 800 m downwind. Meteorological data included wind, turbulence, and temperature data at five tower levels between 1 and 16 meters. Other surface parameters, including friction velocity, Monin-Obukhov length, and σ_y were estimated. A total of 44 10-minute sampling periods were used, including both convective and stable conditions.

The **Kincaid SF_6** study (Liu and Moore[11]; Bowne, et al.[12]) consisted of an elevated, buoyant tracer release in a flat rural area. An intensive study lasting six weeks was conducted during the

air quality dispersion models in the early 1980s[16]. There were six SO_2 monitors on the surrounding terrain that provided hourly averaged concentration data (one monitor was located in the river valley close to the plant). Meteorological data from the Clifty Creek field study covered the two year period from January 1, 1975 through December 31, 1976, although only the data from 1975 were used in this evaluation.

The **Martins Creek Steam Electric Station** (MCSES) is located on the Pennsylvania/New Jersey border, approximately 30 kilometers northeast of Allentown, PA and 95 kilometers north of Philadelphia, PA on the Delaware River. The area is characterized by complex terrain rising above the stacks toward the southeast. The seven SO_2 monitors providing hourly averages that were used in this evaluation[17] were located on Scotts Mountain, which is about 2.5 - 8 kilometers southeast of the Martins Creek facility. On-site meteorological data for the Martins Creek station covered the period from May 1, 1992 through May 19, 1993. Hourly temperature, wind speed, wind direction, and σ_A at 10 meters were recorded from an instrumented tower located in a flat area approximately 2.5 kilometers west of the Martins Creek power generation station. In addition, hourly multi-level wind measurements were taken by a SODAR located approximately three kilometers southwest of the Martins Creek station.

The **Westvaco** Corporation's pulp and paper mill in Luke, Maryland is located in a complex terrain setting in the Potomac River valley in western Maryland[18]. A single 190-m stack was modeled for this evaluation. There were 11 SO_2 monitors surrounding the facility, with eight monitors well above stack top on the high terrain east and south of the mill at a distance of 800 - 1500 meters. Hourly meteorological data were collected between December 1980 and November 1991 at three instrumented towers: the 100-meter Beryl tower in the river valley about 400 meters southwest of the facility; the 30-meter Luke Hill tower on a ridge 900 meters north-northwest of the facility; and the 100-meter Met tower 900 meters east-southeast of the facility on a ridge across the river.

The **Tracy Power Plant**[19] is located 27 kilometers east of Reno, Nevada in the Truckee River valley with mountainous terrain on all sides. A field tracer study was conducted at the power plant in August 1984 with SF_6 being released through the 91-m stack servicing unit 3. A total of 128 hours of data were collected over 14 experimental periods. Most of the hours were during stable atmospheric conditions. On-site meteorological data for Tracy were collected from an instrumented 150-m tower located 1.2 kilometers east of the power plant for the 128-hour period. The wind measurements from the tower were extended above 150 meters using a Doppler acoustic sounder and temperature measurements were extended with tethersonde data.

Evaluation Procedures

The model evaluation was designed to provide diagnostic as well as descriptive information about the model performance. Highlights of the evaluation results for the current model presented by Paine, et al.[8] used selected residual plots and quantile-quantile (Q-Q) plots. The residual plots feature box and whisker symbols that show the distribution of cases along the y-axis domain for various "bins" or domain segments along the x-axis. Q-Q plots are simple ranked pairings of predicted and observed concentrations, such that any given quantile of the predicted concentration is plotted against the same quantile of the observed concentration. The Q-Q plot is an effective method for comparing the frequency distributions of two data sets.

spring and summer of 1980 and 1981. Most of the tracer release hours occurred during convective conditions. During this study, approximately 200 monitors providing 1-hour averaged samples were placed in arcs from about 500 m to 50 km downwind of the single 187-m stack. Meteorological data included wind speed and direction, u-v-w winds, delta T from a 100-m instrumented tower, delta T from a 10-m instrumented tower, and nearby National Weather Service (NWS) data. Estimates of lateral plume spread (σ_y) are available from the sampling arcs.

The **Indianapolis** study (Murray and Bowne[13]) consisted of an elevated, buoyant tracer (SF_6) released in an urban area. The site is a flat-terrain, urban to suburban area with a single 84-m stack. Data are available for approximately a four- to five-week period with 177 monitors providing 1-hour averaged samples in arcs from 250 m to 12 km downwind. Meteorological data included wind speed and direction, σ_θ on a 94-meter tower; and wind speed, ΔT (2m - 10m) and other supporting surface data at three other towers. Observed plume rise and estimates of plume σ_y are also available from the database.

The **Kincaid SO_2** study (Liu and Moore[11] Bowne, et al.[12]) consisted of a buoyant, continuous release of SO_2 from a 187-m stack. The site is in a rural area in flat terrain. The study includes about six months of data between April 1980 and June 1981. There were 30 SO_2 monitoring stations providing 1-hour averaged samples from about 2 km to 20 km downwind of the stack. The meteorological data are the same as in the Kincaid tracer study.

The **Lovett Power Plant** study (Paumier et al.[14]) consisted of a buoyant, continuous release of SO_2 from a 145-m tall stack. The site is located in complex terrain in a rural area. The data spans one year from December 1987 through December 1988. Data were collected from 12 monitoring sites (10 on terrain, 2 as background) providing 1-hour averaged samples that were located about 2 to 3 km from the plant. The important terrain features rise approximately 250 m to 330 m above stack base. Meteorological data include winds, turbulence, and delta T from a tower instrumented at 10 m, 50 m, and 100 m. NWS surface data were obtained from a station 45 km away.

Independent Evaluation

The independent evaluation of AERMOD initially employed the first three databases described below. Results for two additional databases were added to respond to comments by peer reviewers of AERMOD.

The **Baldwin Power Plant**[15] is located in a flat terrain setting of southwestern Illinois. Three 184-meter stacks aligned approximately north-south with a horizontal spacing of about 100 meters between each stack were modeled for this evaluation. There were 10 SO_2 monitors providing hourly averages that surrounded the facility, ranging in distance from two to ten kilometers. On-site meteorological data from the Baldwin field study covered the period from April 1, 1982 through March 31, 1983 and consisted of hourly wind speed, wind direction, and temperature measurements taken at 10 meters and hourly wind speed and wind direction at 100 meters.

The **Clifty Creek Power Plant** is located in southern Indiana on the north side of the Ohio River. The area immediately north of the facility is characterized by cliffs rising about 115 meters above the river and intersected by creek valleys. Three 208-meter stacks meters were modeled in this evaluation. This database was used in a major EPA-funded evaluation of rural

found in Paine et al[8]. In general, 1-hour average statistics are discussed below for the tracer databases, and 3-hour, 24-hour, and annual averages for the long-term databases.

Developmental Evaluation

Prairie Grass

The Q-Q plot for the Prairie Grass data set for AERMOD and ISCST3 (see Figure 1) indicates that both models predict well within a factor of 2. The 1-hour RHC results (see Table 2), consistent with the Q-Q plot, indicate a slight underprediction by AERMOD (0.87 ratio of predicted to observed RHCs), and an overprediction by ISCST3 (1.50).

Kincaid SF_6

Q-Q plots for all cases (see Figure 2) show that AERMOD's performance is clearly superior, with substantial underpredictions noted for ISCST3. A separate analysis[8] of convective conditions for AERMOD showed very good performance. The peak unstable concentrations are significantly higher than the peak stable concentrations. AERMOD's inability to match the comparatively lower observed stable concentrations may be partially due to a limited sample size in this database, and this behavior is not evident in the Kincaid SO_2 results discussed below.

The 1-hour RHC results (see Table 2) indicate a slight underprediction by AERMOD (0.76 ratio of predicted to observed RHCs), and an underprediction by ISCST3 (0.68).

Indianapolis

The Indianapolis data set provides a database on which to test the behavior of the models in an urban setting. The Q-Q plots that include the entire database (see Figure 3) show a nearly unbiased trend for AERMOD over the entire range of concentrations, while ISCST3 exhibits an overprediction tendency over the whole range. In convective conditions, AERMOD shows a very slight underprediction tendency, with only a small trend with distance. The Q-Q plot[8] for stable conditions (not shown) indicates a nearly unbiased performance for AERMOD for a large portion of the concentration domain. Residual plots[8] for AERMOD indicate a notable trend with distance, with underpredictions especially evident in the near field (within 1 km). However, these distances are generally associated with low observed concentrations (near the observation threshold), so an underprediction ratio involving two small values is not of significant concern.

The 1-hour RHC results (see Table 2) indicate a slight overprediction by AERMOD (1.20 ratio of predicted to observed RHCs), and a higher overprediction by ISCST3 (1.30).

Kincaid SO_2

The Kincaid SO_2 database provides data from the same stack source as the Kincaid SF_6. There are, however, three main differences in that study: 1) The database contains several months of continuous observations, 2) the sampler network is less dense, and 3) the pollutant being measured is the SO_2 that is emitted due to the sulfur contained in the fuel instead of the SF_6 tracer. Because the samplers are not arranged in arcs, residual plots by distance are not meaningful, and therefore have not been included. However, the database does allow for computation of 1-hour , 3-hour, 24-hour, and "annual" average concentration statistics. For this data set, the single highest concentration for each evaluation period was used. In each case for the Q-Q plots (see Figure 4), AERMOD's curve parallels the 1-1 line more closely than ISCST3,

Cox and Tikvart[20] proposed a robust test statistic that represents a smoothed estimate of the highest concentrations, based on a tail exponential fit to the upper end of the distribution. With this procedure, the effect of extreme values on model comparison is reduced. This statistic is the robust highest concentration (RHC) and evaluation results using the RHC are reported elsewhere in this paper.

Comparisons between AERMOD and ISCST3[21] are included in the evaluation results. Comparisons were also made with the CTDMPLUS model[22] and RTDM[23] for complex terrain and with the HPDM model[3,15] for selected data sets[8].

For the tracer databases, observations and predictions used in statistics such as the Q-Q plots and RHC calculations corresponded to maximum concentrations on each arc of samplers, rather than at each individual sampler, to eliminate the effect of wind direction uncertainties in the evaluation results. The exception to this practice occurred for Tracy, for which arcs could not be defined due to the irregular terrain features. For Tracy, the highest concentration over all samplers for each hour was used in the evaluation statistics. For Prairie Grass, Kincaid, and Indianapolis, the use of arc maxima was possible due to the dense coverage of samplers along each arc.

This treatment is in contrast to the long-term (annual) databases with much sparser spatial coverage, for which statistics for observed and predicted concentrations at each individual monitor were used in the RHC evaluation statistics. An RHC was calculated for each separate monitor, and the highest RHC was reported in accordance with the Cox and Tikvart procedures. However, the Q-Q plots used only the single highest observation and prediction for each hour over all monitors, so that a given hour did not unduly dominate the results.

For the tracer databases, results for 1-hour averages are reported (with the Prairie Grass 10-minute averages taken as 1-hour averages). For the 1-year SO_2 data sets, 3-hour, 24-hour, and annual results are reported. All of the observed concentrations for the long-term databases are subject to uncertainty because a background concentration is subtracted from the actual monitored observations to obtain a "source-caused" impact. In addition, it should be realized that SO_2 monitors typically have a 6 ppb (16 $\mu g/m^3$) detection limit, and baseline (zero) drifts of up to 10 ppb (26 $\mu g/m^3$) are not corrected[24]. Concentrations below the detection limit are typically set to half of the limit (8 $\mu g/m^3$), even though they may actually be zero. Another factor that could result in overestimates of "observed" concentrations is the acceptance without correction of nonzero concentrations caused by baseline drift that should actually be reported as zero. Therefore, the combined potential errors in SO_2 measurements from the detection limit treatment, ignored baseline drifts, and background concentration estimates can result in significant uncertainties in "observed" annual averages. Peak short-term averages are not affected significantly because the uncertainty is typically a small percentage of the reported value. However, the reader should interpret evaluation results for annual averages with considerable caution.

EVALUATION RESULTS

Due to space limitations, a limited number of figures showing Q-Q plots for the various databases provided in this report, while more extensive results (including residual plots) can be

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2) indicate a modest overprediction tendency for AERMOD for the 3-hour average (ratio of 1.31) and a nearly unbiased 24-hour and annual average set of ratios (1.02 for the 24-hour average and 0.97 for the annual average). ISCST3 results indicate higher overpredictions for the 3-hour and 24-hour averages (ratios of 1.48 and 1.13, respectively), and underpredictions for the annual average (a predicted to observed ratio of 0.63).

Clifty Creek

This case features a tall stack with terrain extending at least halfway to stack top. Q-Q plots of AERMOD results (see Figure 7) show nearly unbiased results for the 1-hour and 3-hour averages, and a modest underprediction for 24-hour averages. For the 1-hour, 3-hour, and 24-hour averages, ISCST3 shows nearly unbiased concentrations for the top end of the concentration domain, but AERMOD's performance is better for a much larger range of the concentration domain.

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2) indicate a modest overprediction tendency for AERMOD for the 3-hour average (ratio of 1.25) and a modest underprediction for the 24-hour average (0.72). ISCST3 results for the same averaging times are 0.98 and 0.67 for the 3-hour and 24-hour averages, respectively. Both models show underpredictions for the annual peaks (ratios of 0.54 for AERMOD and 0.31 for ISCST3).

Martins Creek

This site represents a test of the complex terrain algorithms of AERMOD, ISCST3, and CTDMPLUS. Q-Q plots of AERMOD results (see Figure 8) show a similar trend in each case, featuring overpredictions over most of the concentration domain, but showing that the curve approaches the 1-1 line at the top, or has two peak points below the line. On the other hand, predictions of ISCST3 and CTDMPLUS show significant overpredictions (with turbulence data for CTDMPLUS coming from AERMOD internally-generated profiles).

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2)indicate a nearly unbiased result for AERMOD for the 3-hour average (ratio of 1.06) and an overprediction for the 24-hour average (1.74). AERMOD shows a modest underprediction ratio for the annual average (0.74). In contrast, the 3-hour and 24-hour ratios for ISCST3 are 7.25 and 8.88, showing significant overprediction. The CTDMPLUS resulting ratios are 4.80 and 5.56 for the same averaging times. For annual averages, ISCST3 and CTDMPLUS are still overpredicting, with predicted to observed ratios of 3.37 and 2.19, respectively.

Westvaco

Westvaco is another complex terrain database. It was one of the independent evaluation data sets for CTDMPLUS. Q-Q plots of AERMOD results (see Figure 9) show a nearly unbiased trend for the upper part of the concentration domain for each averaging time. For the short-term averages, CTDMPLUS shows a factor-of-2 overprediction trend, with less overprediction for the annual average.

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2) indicate a nearly unbiased result for AERMOD for the 3-hour and 24-hour averages (ratios of 1.08 and 1.14, respectively), and an overprediction for the annual average (1.64). For the short-term averages,

which is shown to consistently underpredict. Analyses[8] of the convective AERMOD predictions show good results that are consistent with those of the Kincaid SF_6 results. The Q-Q plot of the stable hours (not shown) indicates reasonably good AERMOD performance, in contrast with the poorer showing of AERMOD in the sample size-limited Kincaid SF_6 database.

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2) indicate a nearly unbiased predicted to observed ratio for AERMOD for the 3-hour and 24-hour averages (1.01 and 0.97, respectively) as opposed to underpredictions by ISCST3 (ratios of 0.45 and 0.45 for the 3-hour and 24-hour averages). Both models underpredict for the annual RHC statistic (0.30 for AERMOD and 0.14 for ISCST3). However, the low annual concentrations (near the instrument threshold) and the uncertainties in subtracting background concentrations make the "observed" average concentrations subject to considerable uncertainty.

Lovett

The Lovett data set provides a test on the AERMOD treatment of complex terrain. In terms of the complexity of its theoretical formulation, AERMOD lies between the current screening models and the CTDMPLUS refined model (Perry, 1992). Q-Q plots of AERMOD results (see Figure 5) show a curve very close to the 1-1 line for the upper portion of the concentration domain for each averaging time. ISCST3, on the other hand, substantially overpredicts these concentrations for all three averaging times. (ISCST3 uses the COMPLEX-I screening model and the EPA Intermediate Terrain Procedures in these calculations, which is inherently "conservative," that is, it tends to overpredict.) The CTDMPLUS results show a consistent overprediction tendency, by about a factor of 2.

In convective conditions, the AERMOD Q-Q plot curve (not shown) parallels the 1-1 line with very little bias for most of the concentration domain. In stable conditions, the AERMOD curve overstates concentrations except for the top few, which indicate a modest underprediction tendency.

The 3-hour and 24-hour RHC results and the annual peak results (see Table 2) indicate an unbiased predicted to observed ratio for AERMOD for the 3-hour and 24-hour averages (1.00 for both averaging times) as opposed to overpredictions by ISCST3 (ratios of 8.20 and 9.11 for the 3-hour and 24-hour averages) and overpredictions by CTDMPLUS (ratios of 2.36 and 2.02 for the 3-hour and 24-hour averages). AERMOD shows a slight underprediction for the annual average (ratio of 0.78), while ISCST3 continues to show a large overprediction (ratio of 7.49), as well as CTDMPLUS (ratio of 1.71).

Independent Evaluation

Baldwin

The Baldwin site is a test of the model performance for tall stacks in flat terrain. Q-Q plots of AERMOD results (see Figure 6) show nearly unbiased results at the upper portion of the concentration domain for all three averaging times. In each case, ISCST3 shows nearly unbiased concentrations for the top end of the concentration domain, but AERMOD's performance is much better for a much larger range of the concentration domain in each case. ISCST3 underpredicts at the lower concentration values in each case.

2. Weil, J.C. and R.P. Brower, 1984. An Updated Gaussian Plume Model for Tall Stacks. *J. Air Pollut. Control Assoc.*, **34**, 818-827.

3. Hanna, S.R. and R.J. Paine, 1989: Hybrid Plume Dispersion Model (HPDM) Development and Evaluation. *J. Appl. Meteor.*, 28, 206-224.

4. Turner, D.B., T. Chico and J. Catalano, 1986. TUPOS—A Multiple Source Gaussian Dispersion Algorithm Using On-site Turbulence Data. EPA/600/8-86/010. US EPA, Research Triangle Park, NC, 39 pp.

5. Perry, S.G., D.J. Burns, L.H. Adams, R.J. Paine, M.G. Dennis, M.T. Mills, D.J. Strimaitis, R.J. Yamartino, and E.M. Insley, 1989. User's Guide to the Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS) Volume I: Model Description and User Instructions. EPA-600/8-89-041. U.S. Environmental Protection Agency, Research Triangle Park, NC (NTIS PB89-181424).

6. Carruthers, D.J., R.J. Holroyd, J.C.R. Hunt, W.S. Weng, A.G. Robins, D.D. Apsley, D.J. Thomson, and F.B. Smith, 1992. UK-ADMS – a New Approach to Modelling Dispersion in the Earth's Atmospheric Boundary Layer. In Proceedings of the Workshop: Objectives for Next Generation of Practical Short-Range Atmospheric Dispersion Models, May 6-8, 192, Riso, Denmark, pp. 143-146.

7. Olesen, H.R., P. Lofstrom, R. Berkowicz, and A.B. Jensen, 1991. An Improved Dispersion Model for Regulatory Use – the OML Model. In Proceedings of the 19th International Technical Meeting on Air Pollution Modeling and its Applications, Ierapetra, Crete, Greece. 29 September – 4 October 1991.

8. Paine, R.J, R.F. Lee, R. Brode, R.B. Wilson, A.J. Cimorelli, S.G. Perry, J.C. Weil, A. Venkatram, and W. Peters, 1998. Model Evaluation Results for AERMOD. http://www.epa.gov/scram001/

9. Barad, M. L., (Ed.), 1958: *Project Prairie Grass, A Field Program in Diffusion.* Geophysical Research Papers, No. 59, Vols. I and II, Report AFCRC-TR-58-235, Air Force Cambridge Research Center, 439 pp.

10. Haugen, D. A. (Editor), 1959: Project Prairie Grass, A field program in diffusion. Geophysical Research Paper, No. 59, Vol. III. Report AFCRC-TR-58-235, Air Force Cambridge Research Center, 439 pp.

11. Liu, M. K., and G. E. Moore, 1984: Diagnostic validation of plume models at a plains site. EPRI Report No. EA-3077, Research Project 1616-9, Electric Power Research Institute, Palo Alto, CA.

12. Bowne, N. E., R. J. Londergan, D. R. Murray, and H. S. Borenstein, 1983: *Overview, Results, and Conclusions for the EPRI Plume Model Validation and Development Project: Plains Site.* EPRI Report EA-3074, Project 1616-1, Electric Power Research Institute, Palo Alto, CA, 234 pp.

13. Murray, D. R., and N. E. Bowne, 1988: Urban power plant plume studies. EPRI Report No. EA-5468, Research Project 2736-1, Electric Power Research Institute, Palo Alto, CA.