AERMOD Modeling System Development and Update Plan

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AERMOD Modeling System Development and Update Plan

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1 Introduction

EPA's air quality modeling program within the Office of Air and Radiation (OAR) stems from the statutory requirements of Section 165 of the Clean Air Act (CAA), which states that "The Administrator… shall specify with reasonable particularity each air quality model or models to be used under specific sets of conditions for the purposes of this part…" To satisfy this congressional mandate, EPA established the *Guideline on Air Quality Models* (Appendix W to 40 CFR part 51, or *Guideline*) in 1978, which includes a list of EPA's promulgated preferred models and describes the review and approval approach that EPA must take in determining preferred models for use in regulatory air quality programs. Section 320 of the CAA also requires EPA to conduct a conference on air quality models at least once every 3 years to ensure ongoing formal public engagement, review, and comment on the existing preferred air quality models and future air quality model development needs necessary for various regulatory applications and compliance demonstrations.

Since the late 1970s, the Air Quality Modeling Group (AQMG) in OAR's Office of Air Quality Planning and Standards (OAQPS) has been responsible for the *Guideline* and its periodic revisions that include development and updates to air quality models. Based on this long-standing role and responsibility, the AQMG manager has served as the OAR representative on EPA's Council for Regulatory Environmental Modeling (CREM) and assisted in the development of the 2002 *Guidance for Quality Assurance Project Plans for Modeling* and the 2009 *Guidance on Development, Evaluation, and Application of Environmental Models*. Preferred models are defined as those models listed in appendix A of the *Guideline* as acceptable for specific regulatory applications without further requirements for approval or formal demonstration of applicability. EPA's process and criteria for establishing preferred models are provided in Section 3 of the *Guideline*, specifically Sections 3.1.1(c) and (d). When a model is being considered as a preferred model or when the formulation of an existing preferred model is updated, EPA ensures that the criteria required by the *Guideline* are met. Model formulation changes must be based on peer reviewed research and require a regulatory revision to the *Guideline*. A statistical evaluation of the model is performed against a suite of real-world measurement databases. Consequence analyses are performed when an existing model is updated to ensure any changes to the model do not adversely affect the performance of the model. The subsequent revision to the *Guideline* requires a notice of proposed rulemaking (NPRM) with a public comment period for evaluation and review of the proposed changes to the model.

Currently, EPA's preferred dispersion air quality model for many applications is the American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD) Modeling System, which was promulgated in 2005 after extensive peer-review and formal public review and comment. Consistent with the purpose of air quality models to inform CAA programs, as defined in the *Guideline*, EPA established the applicability and suitability of AERMOD through federal rulemaking under EPA's Action Development Process (ADP). This regulatory process

included full documentation of the model development and evaluation by EPA and clear demonstration to the public that the modeling system met the criteria as specified for preferred and alternative models in the *Guideline*. Aside from usability enhancements that make AERMOD more efficient for regulatory applications and "bug fixes" that address identified computer coding errors, the only model formulation update to AERMOD occurred in 2017. The 2017 update necessitated adoption through the federal rulemaking process including public review and comment and based upon peer-reviewed scientific research of those formulation changes.

This report details the development and update history of the AERMOD Modeling System and describes our current practice with this EPA preferred dispersion model. It also describes EPA's long-standing role in ensuring that EPA's air quality modeling program meets the needs under the CAA and adheres to appropriate and necessary quality assurance (QA) measures and standard operating procedures (SOPs).

2 Regulatory Use of Dispersion Models and Need for AERMOD

Dispersion models are commonly used to predict compliance with National Ambient Air Quality Standards (NAAQS), increment, and other regulatory requirements, such as New Source Review (NSR) and Prevention of Significant Deterioration (PSD) regulations. EPA addresses the regulatory application of these models in Appendix A of EPA's *Guideline on Air Quality Models* (published as Appendix W of 40 CFR Part 51), which was originally published in April 1978 to provide consistency and equity in the use of modeling within the U.S. air quality management system. These guidelines are periodically revised to ensure that new model developments or expanded regulatory requirements are incorporated.

The *Guideline* is used by EPA; state's, local, and tribal authorities; and industry to prepare and review new/modified source permits and SIP revisions. The *Guideline* is intended to ensure credible and consistent air quality analyses for use in a variety of CAA programs, specifically the activities regulated at 40 CFR 51.112, 51.117, 51.150, 51.160, 51.166, and 52.21. OAQPS originally published the *Guideline* in April 1978 and it was incorporated by reference in the regulations for the Prevention of Significant Deterioration (PSD) of Air Quality in June 1978. OAQPS revised the *Guideline* in 1986, and updated it with supplement A in 1987, supplement B in July 1993, and supplement C in August 1995. EPA published the *Guideline* as appendix W to 40 CFR part 51 when OAQPS issued supplement B in 1993.

It is necessary for EPA to periodically assess the appropriateness of its preferred models in response to external changes such as evolution of atmospheric modeling science or revisions to the CAA programs that may change requirements of air quality models to inform regulatory decisions. Such periodic assessments may indicate a need to change the underlying science of EPA's preferred model, i.e., a new model formulation or update to current model formulation. These formulation updates can only occur through the promulgation of an updated regulatory version of the model through the formal rulemaking process, which requires an update to the *Guideline*. Thus, such updates are based on scientific peer-review, but also subject to the regulatory public review process, ensuring that scientific updates are fully appropriate for

application in EPA's CAA programs.

To facilitate the improvement in EPA approved dispersion models, the Agency convenes a Conference on Air Quality Modeling every 3 years, as required by Section 320 of the Clean Air Act (CAA). The purpose of these conferences is to provide an overview of the latest features of the new air quality models and to provide for public review and comment on potential revisions to the way the Agency determines and applies the appropriate air quality models in the future. These comments on the *Guideline* and associated revisions assist the Agency in introducing improved modeling techniques into the regulatory process.

It was clear in the late 1980s that dispersion theory had made significant scientific improvements relative to the scientific basis of EPA's preferred model at that time. In response to the need for a state-of-the-science dispersion model, the AMS/EPA Regulatory Model Improvement Committee (AERMIC) was formed, comprised of AMS and EPA scientists, with the goal of developing a new regulatory dispersion model based on modern dispersion concepts.

This section describes the need for EPA to develop a new modeling system and establish it as the preferred model for near-field applications in support of CAA programs. The subsequent sections will discuss in more detail the developmental history of AERMOD including the activities and development process followed by AERMIC in the early 1990s through AERMOD's promulgation in 2005, updating and maintenance of AERMOD through 2015, and the revision to the *Guideline* with changes to the model's formulation in 2017.

2.1 The Need for a State-of-the-Science Dispersion Model

Prior to the promulgation of AERMOD in 2005, EPA's preferred dispersion model had remained fundamentally unchanged for 25 years and reflected first generation dispersion theory. First adopted into the *Guideline* in 1988, EPA's Industrial Source Complex (ISC) Model was the workhorse regulatory model, used in the construction of most State Implementation Plans (SIPs), new source permits, and risk assessments for criteria pollutants, specifically carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM), and lead (Pb). ISC was subsequently updated with versions ISC2 and ISC3, in 1995 and 1996, respectively. However, the ISC models did not incorporate the state-of-the-science of planetary boundary layer (PBL) dispersion based on similarity theory that had grown during the mid-1980s. Turbulence and dispersion in ISC are based on six Pasquill-Gifford (PG) stability classes (A-F), in which stability is defined by a combination of the wind speed and daytime solar insolation or nighttime cloudiness, ranging from extremely unstable to moderately stable. With the newer similarity theory methods, dispersion and turbulence could be calculated based on a more continuous categorization of stability in the PBL.

By the mid-to-late 1980s, a substantial scientific base on the PBL and new dispersion

approaches existed for revamping the scientific formulation of regulatory dispersion models. In a review of existing or proposed regulatory models developed prior to 1984 (Smith, 1984) reported that the techniques were many years behind the state-of-the-science and yielded predictions that did not agree well with observations. Similar findings were reported by Hayes and Moore (1986), who summarized 15 model evaluation studies. The need for a comprehensive overhaul of EPA's basic regulatory models was clearly recognized and was the focus of a "Workshop on Updating Applied Diffusion Models" sponsored by AMS and EPA that was held in January of 1984 (see (Weil, 1985)). This workshop was followed by the publication of review papers in the November 1985 issue of the *Journal of Climate and Applied Meteorology*.

In response to the need for comprehensive overhaul of EPA's regulatory models AERMIC was formed, comprised of AMS and EPA scientists, with the goal of developing a new regulatory dispersion model based on the state-of-the-science PBL dispersion concepts to replace ISC. To initiate project, AERMIC defined a set of model design criteria and a comprehensive six-step model development process. These criteria and the development process are discussed in detail in a later section.

3 Development of AERMOD

In April 2000, EPA proposed that the AERMOD Modeling System be adopted as a replacement to ISC3 in Appendix A of the Guideline. At the Seventh Modeling Conference, results of the performance evaluation and peer review were presented, and public comments were received. Based on these comments AERMOD was subsequently revised to incorporate the Plume Rise Model Enhancements (PRIME) algorithms for building downwash, to remove the dependency on modeling domain in AERMOD's complex terrain formulation, and a variety of other less significant issues. In November 2005, EPA finalized these revisions to AERMOD and adopted AERMOD as a preferred model, replacing ISC3 in the *Guideline.* Thus, AERMOD became the preferred model for both simple and complex terrain.

EPA's AERMOD Modeling System was promulgated through revisions to the *Guideline* on November 9, 2005. In accordance with the *Guideline*, after a one-year grace period, AERMOD was fully promulgated as of November 9, 2006 as the replacement to ISC3 for appropriate regulatory modeling applications. Figure 1 provides an overview of EPA's development process for the AERMOD Modeling System. The efforts of AERMIC in the AERMOD model development preceded the current EPA Quality System and associated guidance related to model development and updates. Despite that fact, as described in this report, EPA's AERMOD model development and update process adhered to EPA's required and recommended principals and processes for such activities. The models undergo extensive testing, evaluations, peer reviews, as well as extensive community vetting under section 320 CAA Modeling Conferences prior to becoming a "preferred" model under Appendix W all of

which are publicly available on EPA website https://www.epa.gov/scram. Given the CAA mandates for the *Guideline* and establishment of preferred air quality models, EPA has utilized the notice and comment rulemaking process that provides for the transparency and rigor necessary to provide public confidence in their use for regulatory decision making.

Regarding the scientific merits of AERMOD, substantial support was expressed in public comments that AERMOD represents sound and significant advances over ISC3. The scientific merits of AERMOD have been documented both through scientific peer review and performance evaluations. Its formulation has been subjected to an extensive, independent peer review. Findings of the peer review panel indicated that AERMOD's scientific basis is ''state-of-the-science.'' Additionally, the formulations used in AERMOD and the performance evaluations were published in two peer-reviewed journals. These evaluations demonstrated AERMOD's superiority to previous models in estimating impacts of greatest regulatory importance.

Based on the supporting information contained in the docket from the 7th Modeling Conference, and reflected in peer review and public comments, EPA concluded that: 1) AERMOD's accuracy is adequately documented; 2) AERMOD's accuracy is an improvement over ISC3's ability to predict measured concentrations; and 3) AERMOD is an acceptable regulatory air dispersion model replacement for ISC3.

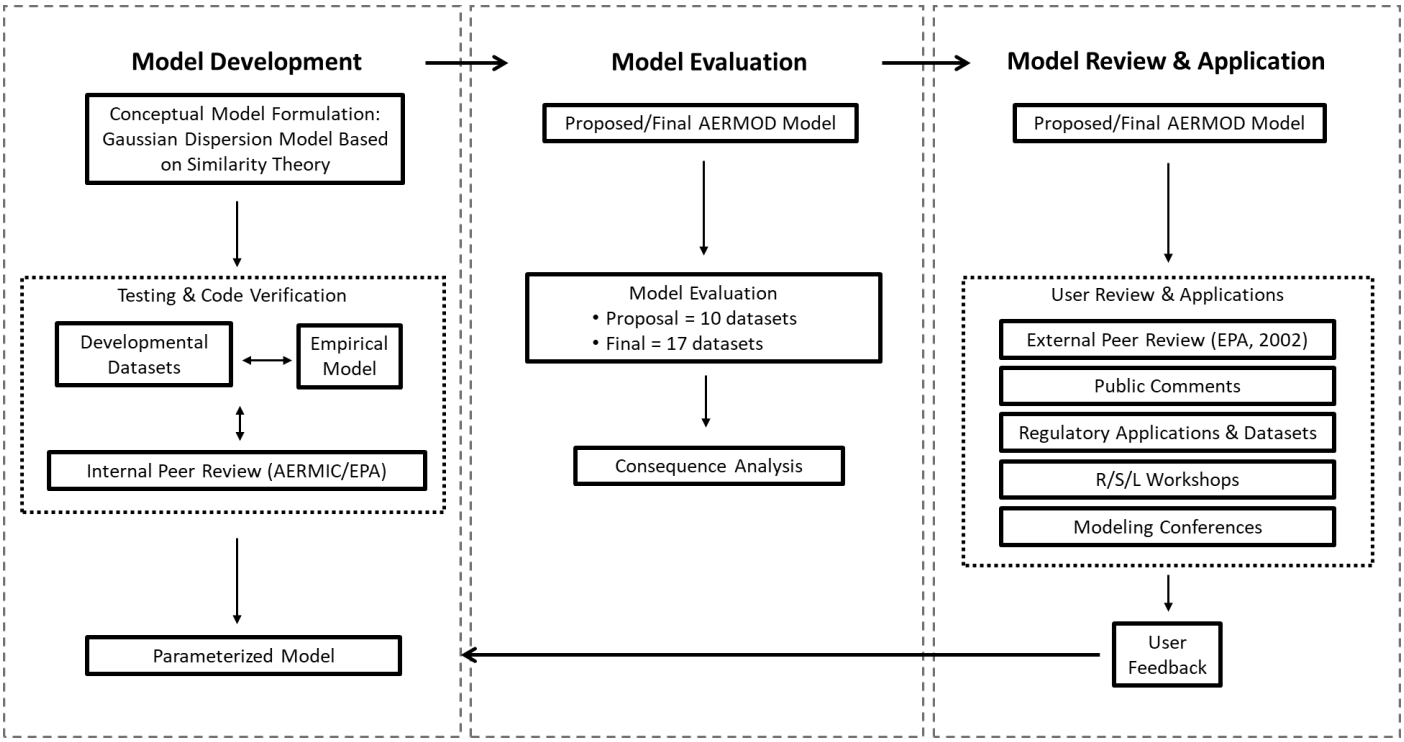

Figure 1. Development of AERMOD Modeling System

Figure 1 was adapted from, US Environmental Protection Agency, 2012, DRAFT FINAL Handbook for Developing Quality Assurance Project Plans. *http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OEI-2012-0774-0003*

3.1 AMS/EPA Regulatory Model Improvement Committee

In February 1991, EPA in conjunction with AMS held a workshop for state and EPA regional meteorologists on the parameterization of PBL turbulence and state-of-the-science dispersion modeling. It was here that AMS and EPA initiated a formal collaboration with the designed goal of introducing current PBL concepts into regulatory dispersion models. A working group (AERMIC) comprised of AMS and EPA scientists was formed for this collaborative effort. As noted above, the expressed purpose of the AERMIC activity was to build upon the earlier model developments and to provide a state-of-the-science dispersion model for regulatory applications. The early efforts of the AERMIC group are described by (Weil, 1992). In going through the design process and in considering the nature of present regulatory models, AERMIC's goal expanded from its early form. In addition to improved parameterization of PBL turbulence, other problems such as plume interaction with terrain, surface releases, building downwash, and urban dispersion were recognized as needing attention.

AERMIC focused its development efforts on short-range dispersion from stationary industrial sources, the same scenario handled by ISC3 (US EPA, 1995). This work clearly benefitted from the model development activities of the 1980s especially in the parameterization of mean winds and PBL turbulence, dispersion in the convective boundary layer (CBL), and the treatment of plume/terrain interactions. Techniques used in the newer dispersion models for PBL parameterizations and CBL dispersion are similar to those used in earlier models. Turbulence characterization in the CBL adopts "convective scaling" as suggested by Deardorff (1972). Algorithms used in these earlier models were considered along with variants and improvements to them. In addition, the developers of OML (acronym for the Danish term "*Operationelle Meteorologiske Luftkvalitetsmodeller*") met with AERMIC to discuss their experiences. Thus, much of the credit for the AERMIC model development is to be given to the pioneering efforts of the 1980s.

3.1.1 Summary of AERMIC Development Process

AERMIC's initial focus was on the regulatory models that are designed for estimating near-field impacts from a variety of industrial source types. EPA's regulatory platform for near-field modeling at this time, with few exceptions, remained fundamentally unchanged for decades. During this period, ISC3 was the workhorse regulatory model (used in the development of most SIPs, new source permits, risk assessments, and exposure analysis for toxic air pollutants). Therefore, AERMIC selected EPA's ISC3 model for a major overhaul. AERMIC's objective was to develop a complete replacement for ISC3 by: 1) adopting ISC3's input/output computer architecture; 2) updating, where practical, antiquated ISC3 model algorithms with newly developed or current state-of-the-science modeling techniques; and 3) ensuring that the source and atmospheric processes presently modeled by ISC3 will continue to be handled by AERMOD,,, albeit in an improved manner.

Further, EPA developed and codified in the *Guideline* a specific set of criteria that an air

quality model must meet to be considered for preferred status and listed in Appendix A of the *Guideline*. Each preferred model will have undergone the necessary peer scientific reviews (AMS, 1983); (U.S. EPA, 2002) and model performance evaluation exercises (Scire and Schulman, 1981); (U.S. EPA, 2003a) that include statistical measures of model performance in comparison with measured air quality data. EPA also established the Cox-Tikvart methodology as a specific evaluation protocol for preferred models that provides a statistical technique for evaluating model performance for predicting peak concentration values, as might be observed at individual monitoring locations (U.S. EPA, 1992).

In accordance with Section 3.1.1(c) and (d)[1] of the *Guideline*, the AERMOD was evaluated and met the following conditions prior to promulgation as a preferred model as listed in Appendix A:

i. The model must be written in a common programming language, and the executable(s) must run on a common computer platform.
ii. The model must be documented in a user's guide or model formulation report which identifies the mathematics of the model, data requirements and program operating characteristics at a level of detail comparable to that available for other recommended models in appendix A.
iii. The model must be accompanied by a complete test dataset including input parameters and output results. The test data must be packaged with the model in computer-readable form.
iv. The model must be useful to typical users, e.g., state air agencies, for specific air quality control problems. Such users should be able to operate the computer program(s) from available documentation.
v. The model documentation must include a robust comparison with air quality data (and/or tracer measurements) or with other well-established analytical techniques.
vi. The developer must be willing to make the model and source code available to users at reasonable cost or make them available for public access through the Internet or National Technical Information Service. The model and its code cannot be proprietary.

Based on the Guideline's criteria and EPA needs for modeling under CAA programs, AERMIC adopted design criteria to yield a model with desirable regulatory attributes. It was felt that the model should: 1) provide reasonable concentration estimates under a wide variety of conditions with minimal discontinuities; 2) be user friendly and require reasonable input data and computer resources as is the case with the ISC3 model; 3) capture the essential physical

[1] Of note, the 1996 version of the *Guideline*, Section 3.1.1(c) and (d) that was effective during the AERMIC development process is consistent with the current 2017 version of the *Guideline*, Section 3.1.1(c) and (d).

processes while remaining fundamentally simple; and 4) accommodate modifications with ease as the science evolves.

AERMIC designed and implemented a six-step model development process for AERMOD to inform EPA's promulgation of a regulatory replacement for the ISC3 model. The process followed included these steps:

1) initial model formulation;
2) developmental evaluation;
3) internal peer review and beta testing;
4) revised model formulation;
5) performance evaluation and sensitivity testing; and
6) external peer review.

Details regarding each step in the EPA/AERMIC development process are discussed below.

3.1.1.1 Initial Model Formulation

In 1994, (Perry, et al., 1994) provided an initial presentation regarding the model formulation and foundational development of AERMOD to the modeling community at the 87th Annual Meeting of the Air and Waste Management Association. This introduction was followed by a second presentation and report out by (Cimorelli, et al., 1996) in 1996 at the 89th Annual Meeting of the Air and Waste Management Association that included the activities of AERMIC with respect to AERMOD model formulation development. It was clear from these early stakeholder community engagements by AERMIC that the AERMOD development focus was on incorporating scientific advances from the 1970s and 90s into a state-of-the-science dispersion model for regulatory applications. Relative to ISC3, the new and improved AERMOD formulation included: 1) dispersion in both the convective and stable boundary layers; 2) plume rise and buoyancy; 3) plume penetration into elevated inversions; 4) computation of vertical profiles of wind, turbulence, and temperature; 5) the urban nighttime boundary layer; 6) the treatment of receptors on all types of terrain from the surface up to and above the plume height; 7) the treatment of building wake effects; 8) an improved approach for characterizing the fundamental boundary layer parameters; and 9) the treatment of plume meander. From this initial work, AERMOD was then tested (developmental evaluation) against a variety of field measurements to identify areas needing further improvement. The developmental evaluation provided a basis for selecting formulation options.

3.1.1.2 Developmental Evaluation

This developmental evaluation was conducted using the following five data bases:

- <u>The Prairie Grass study</u> (Barad, M. L., 1958); (Haugen, D. A., 1959) 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 (see Figure A-18). Meteorological data included 2-m wind speed, standard deviation of horizontal wind direction (σ_θ or sigma-theta), and vertical change in temperature (ΔT or delta T) (2m - 16m). Other surface parameters, including friction velocity, Monin-Obukhov length, and lateral plume spread (σ_y or sigma-y) were estimated. A total of 44 sampling periods were used, including both convective and stable conditions.

- The Kincaid SF_6 study; (Liu and Moore, 1984); (Bowne, et. al., 1983) consisted of an elevated, buoyant tracer release in a flat rural area (see Figure A-11 for an area map). Six weeks of intensive study was conducted during the spring and summer of 1980 and 1981. During this study, approximately 200 monitors 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 (i.e., zonal, meridional, and vertical wind velocity), 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 σ_y are available from the sampling arcs.
- The Indianapolis study (Murray and Bowne, 1988) consisted of an elevated, buoyant tracer (SF6) released in an urban area (see Figures A-8 and A-9). 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 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, delta-T (2m - 10m) and other supporting surface data at three other towers. Observed plume rise and estimates of plume σy are also available from the database.
- The Kincaid SO2 study (Liu and Moore, 1984); (Bowne, et. al., 1983) 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 from about 2 km to 20 km downwind of the stack (see Figure A-11). The meteorological data are the same as in the Kincaid tracer study.
- The Lovett Power Plant study (Paumier, et. al., 1992) 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 (see Figure A-3). The data spans one year from December 1987 through December 1988. Data were collected from 12 monitoring sites (10 on terrain, two as background) located about 2 to 3 km from the plant. The important terrain features rise approximately 250 m to 330 m above stack base. The monitors on terrain are generally about 2 to 3 km downwind from the stack. 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.

Each of these developmental datasets are detailed in Appendix A, Table A-1. Three consisted of event-based tracer releases, while the other two each contain up to a full year of

continuous SO_2 measurements. These databases cover elevated and surface releases, complex and simple terrain, and rural and urban boundary layers. A description of the early developmental evaluation is reported by (Lee, et al., 1998) and (Paine, et. al., 1998).

An external peer review of a pre-proposal version of AERMOD was conducted in 1998 as detailed later (U.S. EPA, 2002). As a result of this peer review, AERMIC performed the following testing, evaluation, and documentation (U.S. EPA, 2002):

- Revised and expanded the AERMOD Model Formulation Description,
- Modified AERMOD code accordingly,
- Evaluated the complex terrain portion of the model with additional databases (Tracy and Westvaco), and
- Revised and clarified the model evaluation documentation.

AERMOD also underwent a comprehensive performance evaluation (U.S. EPA, 2003) designed to assess how well AERMOD's concentration estimates compare against the developmental databases and to assess the adequacy of the model for use in regulatory decision making. That is, how well does the model predict concentrations at the high end of the concentration distribution? AERMOD was evaluated against five independent data bases (two in simple terrain and three in complex terrain), each containing one full year of continuous SO_2 measurements. Additionally, a consequence analysis was conducted that compared AERMOD's performance against the performance of four other applied, regulatory models: ISC3 (U.S. EPA, 1995), CTDMPLUS (Perry, 1992), RTDM ((Paine and Egan, 1987)), and HPDM ((Hanna and Paine, 1989), (Hanna and Chang, 1993)). The performance of these models against AERMOD has been compared using the procedures in EPA's "Protocol for Determining the Best Performing Model" (U.S. EPA, 1992).

AERMIC made many revisions to the original formulation based on these evaluations, analyses, and comments received during the peer review, beta testing, as well as the public comments from EPA's Sixth Conference on Air Quality Modeling (in 1995). (Lee, et al., 1998) describe the developmental evaluation repeated with the current model (i.e., revisions based on the developmental evaluation and peer review).

3.1.1.3 Internal Peer Review and Beta Testing

As described above, to inform the 2000 proposal, EPA and AERMIC conducted multiple performance evaluations, consequence analyses, and internal beta testing of developmental versions of AERMOD (versions 95272, 96113, 97363, 98314, 99020) and the publicly released proposed version (99351). Two reports listed below were a result of public comments to the 2000 proposal and further and beta testing:

- "AERMOD Latest Features and Evaluation Results" (U.S. EPA, 2003a)
- "Comparison of Regulatory Design Concentrations" (US EPA, 2003b).

The results of the internal beta testing led to a revised model formulation (version

02222) described below which was similarly subject to model performance evaluation and sensitivity testing.

3.1.1.4 Revised Model Formulation

Based on public comments to the April 2000 proposal to replace ISC3 with AERMOD, and internal beta test, AERMOD (99351) was revised to include the formulation changes to an updated version (02222). The changes were listed as part of a Notice of Data Availability (NODA) in September 2003 (FR 529934-529935), with the addition of the PRIME downwash algorithm in AERMOD being the main reason for regulatory review and public comment for the NODA. In addition to the PRIME downwash inclusion into AERMOD, other changes were:

- Modification of the complex terrain algorithms to make AERMOD less sensitive to the selection of the domain of the study area;
- Modification of (a) urban dispersion for low-level emission sources, such as area sources, to produce more realistic urban dispersion and (b) minimum mixing layer depths used to calculate the effective dispersion parameters for all dispersion settings;
- Addition of plume meander to all stable and unstable conditions; and
- Upgrades to AERMOD to include all the newest features that existed in the latest version of ISC3, such as FORTRAN 90 compliance, allocatable arrays, EVENTS processing, and the TOXICS option.

Performance evaluations and consequence analyses resulting from the model changes are described below.

3.1.1.5 Performance Evaluation and Sensitivity Testing

Based on the model updates as described in the 2003 NODA to AERMOD version 99351, two reports were published as discussed above. The first report (US EPA, 2003a) documented the model evaluation of AERMOD version 02222 against the original development databases and several other evaluation databases listed in Appendix A of this document. The model evaluations results (US EPA, 2003a) indicated that the revised version of AERMOD (02222) was slightly better than the proposed April 2000 version (99351). Both versions of AERMOD significantly outperformed ISCST3 and AERMOD with PRIME performed better than ISC-PRIME for downwash cases.

The second report (US EPA, 2003b) was a consequence analysis that documented EPA's inter-model comparisons of AERMOD results to those from ISC3, CTDMPLUS, and ISC-PRIME. The consequence analyses presented in the report covered three environments of regulatory model applications: 1) the flat and simple terrain component; 2) building downwash component; and 3) the complex terrain component. The consequence analysis found that:

- For non-downwash settings, the revised version of AERMOD (02222), on average, tended to predict concentrations closer to ISCST3 with somewhat smaller variations than the April 2000 proposed version of AERMOD (99351).

- When downwash was a significant factor in the air dispersion analysis, the 02222 version of AERMOD predicted maximum concentrations that are very similar to ISC-PRIME.
- For those scenarios where maximum 1-hour cavity concentrations were calculated, the average AERMOD predicted cavity concentrations tended to be about the same as the average ISC-PRIME cavity concentrations.
- In general, the consequences of using the 02222 version of AERMOD, instead of the older model ISCST3, in complex terrain remained essentially unchanged, although they varied in individual circumstances.

Based on the performance evaluation and sensitivity testing, EPA concluded that AERMOD (02222) was ready to be incorporated into the *Guideline* and EPA moved forward to promulgate the modified version 02222 of AERMOD, ultimately as version 04300, in the 2005 rulemaking.

3.1.1.6 External Peer Review

Results of the external peer review (U.S. EPA, 2002) were presented at the Seventh Conference on Air Quality Modeling on June 28-29, 2000. The external peer review consisted of a panel of three members, Dr. Steven Hanna, Mr. Mark Garrison, and Mr. Bruce Turner. The role of the panel was to provide specific technical comments on a pre-proposal version of the AERMOD model as well as provide answers to 12 questions ranging over four topic areas to determine if AERMOD was ready for use as a regulatory model. Overall, the panel was supportive of the replacement of ISC3 with AERMOD. The topic areas with EPA charge questions and the panel's responses (in bold) were:

1. Model formulation
    a. Does AERMOD represent the state of the science in its handling of boundary layer turbulence and dispersion?

    AERMOD embodies state-of-the-science approaches to boundary layer turbulence and dispersion.

    b. Within the context of regulatory dispersion models in the US, does AERMOD represent significant scientific advances over ISC3?

    AERMOD represents significant scientific advances over ISC3. However, AERMOD is similar to other available state-of-the-art models such as SCIPUFF, OML, ADMS, CTDM, and HPDM.

    c. What do you think are the most scientific advancements in AERMOD?

    AERMOD incorporates several scientific advancements, including the use of convective scaling and non-Gaussian pdfs of vertical velocity in convective conditions. Also, dividing streamlines are used for complex terrain. The vertical profiles of meteorological variables are developed based on state-of-the-art methods. However, the peer review committee mentions that such advancements are available in other models as well, such as SCIPUFF, CTDM, and HPDM.

d. Are there areas or features of AERMOD in which an improved formulation or treatment would be desired? If so, please discuss whether you think the revised treatment would lead to better performance and how much.

The urban dispersion algorithms need more development and justification. An updated downwash algorithm is desired. It would be useful to remove the tendency towards underpredictions. The specification of meteorological inputs should be clarified.

2. Documentation

a. Is the current organization of the model formulation document and User's Guide appropriate or would an alternative be desired?

The separation of technical details into a model formulation document (particularly the much-improved, current version of the MFD) is fine. The User's Guide is well-organized and useful.

b. Is the presentation of the model clear and explanatory? Please note any specific sections of the documentation that were unclear or confusing.

The peer review panel had numerous concerns regarding the original March 1998 documentation, mostly regarding the MFD. The current version of the MFD is an improvement over the last version and will provide users with a good description of the model. Further justification of algorithms is needed.

c. Is the documentation sufficient for a typical ISC-type user to guide them in the use of the model and its preprocessors? Do you think training sessions would be particularly useful?

The documentation is sufficient. Because the model is not simple, training sessions would be helpful for most users.

3. Evaluation and performance

a. How do you rate the performance of AERMOD relative to ISC3 and the other models included in the evaluation exercises?

Overall, the performance of AERMOD is good over a wide range of scenarios. Some of the evaluations of AERMOD show a slight tendency for AERMOD to underpredict near the upper end of the frequency distribution. The model needs more evaluation for downwash scenarios.

b. From a model design, scientific, and performance perspective, what comments do you have on the replacement of ISC3 with AERMOD for regulatory applications?

The replacement of ISC3 with AERMOD for regulatory applications is appropriate. We recommend that this be done in a stage process so as to allow for testing of the new algorithms and the development of guidance for optimum meteorological inputs. All of the AERMOD evaluation data bases (except for Prairie Grass) involved tall stacks with buoyant plumes (the shortest stack in the group was 84 meters in Indianapolis), with little probability of downwash occurring. The vast majority

of ISC3 applications involve modest stacks with modest buoyancy flux values, most of which are subject to some degree of aerodynamic downwash, as well as area and volume source configurations which were not evaluated or tested (at least not in the documentation provided) to determine how AERMOD predictions compare to predictions using ISC3.

c. When considering the eight data bases used to evaluate the model, would additional evaluation of AERMOD be desirable?

The number of data bases is actually ten, with the addition of Tracy and Westvaco. Additional evaluations of AERMOD in urban settings, for surface release, and for downwash impacts would be desirable, as would further diagnostic evaluation of model performance in complex terrain. But use of the model should not be delayed pending the completion of these evaluations. A "interim" approval status might be appropriate for AERMOD while further evaluations are conducted, in particular while the downwash and deposition algorithms are being subjected to further testing and modification.

4. Other questions

a. Is the AERMOD approach to modeling urban sources scientifically sound and state of the art?

The urban formulation of AERMOD embodies many parts of a state-of-the-science approach. There are still issues remaining concerning the method of estimating stability in urban areas.

b. Do the building downwash algorithms with AERMOD represent current state of science and are these algorithms appropriate to regulatory applications?

The building downwash algorithms in AERMOD are essentially the same as those currently in ISC3. Consequently, they should be suitable for regulatory applications. However, there is no information in the documentation provided as to how these algorithms work within AERMOD, and none of the evaluation data sets concerned downwash.

As described above, this external peer review was critically important to inform further internal testing, evaluation, and beta testing of AERMOD code and confirmed the scientific appropriateness of AERMOD as a replacement to the ISC3 model.

3.2 Establishing AERMOD Modeling System as EPA's Preferred Near-Field Dispersion Model

As discussed earlier, the promulgation of the AERMOD Modeling System as a replacement to ISC3 in Appendix A of the *Guideline* was initiated well before the final promulgation in 2005. The formal promulgation was initiated with the proposal in April 2000. Based on the internal and external peer review, the model was updated, resulting in a September 8, 2003 Notice of Data Availability (NDA).

- Proposed rulemaking to adopt AERMOD as an EPA preferred model (April 21, 2000)

  In April 2000, EPA proposed that the AERMOD Modeling System (version 99351) be adopted as a replacement to ISC3 in Appendix A of the Guideline. To prepare for the April 2000 proposal, the EPA and AERMIC members presented interim developmental and evaluation results of AERMOD at the Sixth Conference on Air Quality Modeling. This Sixth conference was held in Washington, D.C. on August 9-10, 1995. The Sixth conference featured presentations in several key modeling areas. One presentation by AERMIC covered developing AERMOD, an enhanced Gaussian dispersion model with boundary layer parameterization. AERMIC stated that AERMOD is a state-of-the-practice Gaussian plume dispersion model whose formulation is based on planetary boundary layer principles, and that AERMOD provides better characterization of plume dispersion than does the ISC3 model.

  Comprehensive comments were submitted on the AERMOD code and formulation document and on the AERMET draft User's Guide (AERMET is the meteorological preprocessor for AERMOD) in response to the presentation at the Sixth Conference. Comments on AERMOD identified inconsistencies in the AERMOD code including variables and recommended specific default values. Comments were also provided expressing concern that databases historically used by EPA to initially develop AERMOD lacked the variables required by AERMET and AERMOD, potentially weakening AERMOD's evaluation. In the 2000 proposal, EPA responded that the databases used for the AERMOD evaluations are felt to contain the critical variables needed by AERMOD, concluding that AERMOD has been adequately tested and represents, through its formulations, a technical advancement over its predecessors.
- Seventh Conference on Air Quality Modeling (June 28 - 29, 2000)

The Seventh Conference on Air Quality Modeling was held in Washington, DC on June 28-29, 2000. The purpose of this conference was to receive comments on the April 2000 proposal. At the Seventh Conference, results of the performance evaluation and peer review were presented, and public comments were received.

Commenters indicated that AERMOD: brings sound scientific advancement into regulatory modeling; provides significant improvement over the currently approved models; is an improvement (over ISC3) based on evaluation studies; enhances atmospheric simulations, including the elimination of the stability class discontinuities; has demonstrated scientific merit; has a better theoretical basis than ISC3;reflects the state-of-the-science; and represents an important advance in the prediction of pollutant concentrations in both flat and elevated terrain. In addition, most commenters asked for the new downwash algorithm, PRIME (Plume Rise Model Enhancements) to be incorporated into AERMOD. AERMOD was subsequently revised to incorporate the PRIME algorithms for building downwash.

- Notice of Data Availability (September 2003)

As discussed in Section 3.1.1.4, a NODA was released based on model changes as an outgrowth of public comment for the 2000 proposal. Specifically, the incorporation of the PRIME downwash algorithm in the model formulation of AERMOD necessitated an additional regulatory action to allow for public review and comment on the revisions to the originally proposed version of AERMOD. The NODA furnished pertinent technical details related to model changes since the April 2000 NPRM, including new performance data and evaluation of design concentrations (see 3.1.1.5 above) based upon the revised AERMOD version. The NODA also formally solicited another round of public comments on the revised model.

- Eighth Conference on Air Quality Modeling (September 22-23, 2005)

The Eighth Conference on Air Quality Modeling was held on September 22-23, 2005, in Research Triangle Park, NC. The conference contained several presentations regarding the complete AERMOD Modeling System as well as the individual components. The Eighth Conference took place approximately 1.5 months before the final rulemaking that adopted AERMOD and removed ISC3 as the preferred near field dispersion model. The Eighth Conference also contained numerous presentations including model updates and evaluations, an approach to updating regulatory dispersion models, model development, procedures for evaluating new dispersion models, and EPA's protocol for determining best performing model.

- Final rulemaking to adopt AERMOD and remove ISC3 and associated revisions to *Guideline* (November 9, 2005)

The culmination of nearly a decade of development, evaluation, review, and public comment occurred on November 9, 2005 with the final rulemaking of the Guideline that adopted AERMOD (version 04300) and removed ISC3 as EPA's preferred near-field dispersion model. Version 04300 was based on version 02222 with some fixes to minor code issues and non-regulatory draft options. The updates listed in version 04300 included:

  - Correction to the area source algorithm in simple and complex terrain for dividing streamline height calculation,
  - Correct turbulence parameters passed to PRIME,
  - Add limit on plume cooling within PRIME to avoid supercooling, which had led to runtime instability,
  - Correction to avoid AERMOD termination under certain situations with capped stacks
  - Addition of dry and wet deposition for particles and gases,
  - Ozone Limiting Method (OLM) and Plume Volume Molar Ratio Method (PVMRM) added for NO_2 modeling, and
  - Correction of Bulk Richardson number approach for near-surface temperature differences.

Figure 2 provides a timeline of the major events in EPA's development of and updates to the AERMOD Modeling System. Since its promulgation as a preferred model in 2005, AERMOD has been maintained and regularly updated to address bug fixes and add new options to ensure the model meets user needs under the CAA, most notably after the revisions to the 2010 SO_2 and NO_2 NAAQS which resulted in new 1-hour standards. Updates to AERMOD have largely been based on feedback received during Modeling Conferences, annual Regional, State, and Local (RSL) Modelers' Workshops; and the use of the model for regulatory applications (i.e., the feedback mechanisms discussed previously).

Figure 2. The Timeline for the AERMOD Model

Source: U.S. Environmental Protection Agency, Office of Inspector General. EPA Can Strengthen Its Process for Revising Air Quality Dispersion Models that Predict Impact of Pollutant Emissions. Report No. 18-P0241. September 5, 2018.

3.2.1 The AERMOD Modeling System: EPA's Preferred Near-Field Dispersion Model

As shown in Figure 3, EPA's AERMOD Modeling System includes the following regulatory components:

- AERMOD: the dispersion model https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod
- AERMAP: the terrain processor for AERMOD https://www.epa.gov/scram/air-quality-dispersion-modeling-related-model-support-programs#aermap
- AERMET: the meteorological data processor for AERMOD https://www.epa.gov/scram/meteorological-processors-and-accessory-programs#aermet

Other components that may be used, depending on the application, are:

- BPIPPRIME: the building input processor https://www.epa.gov/scram/air-quality-dispersion-modeling-related-model-support-programs#bpipprm

Figure 3 indicates the relationship among the inputs and outputs of the AERMOD modeling system.

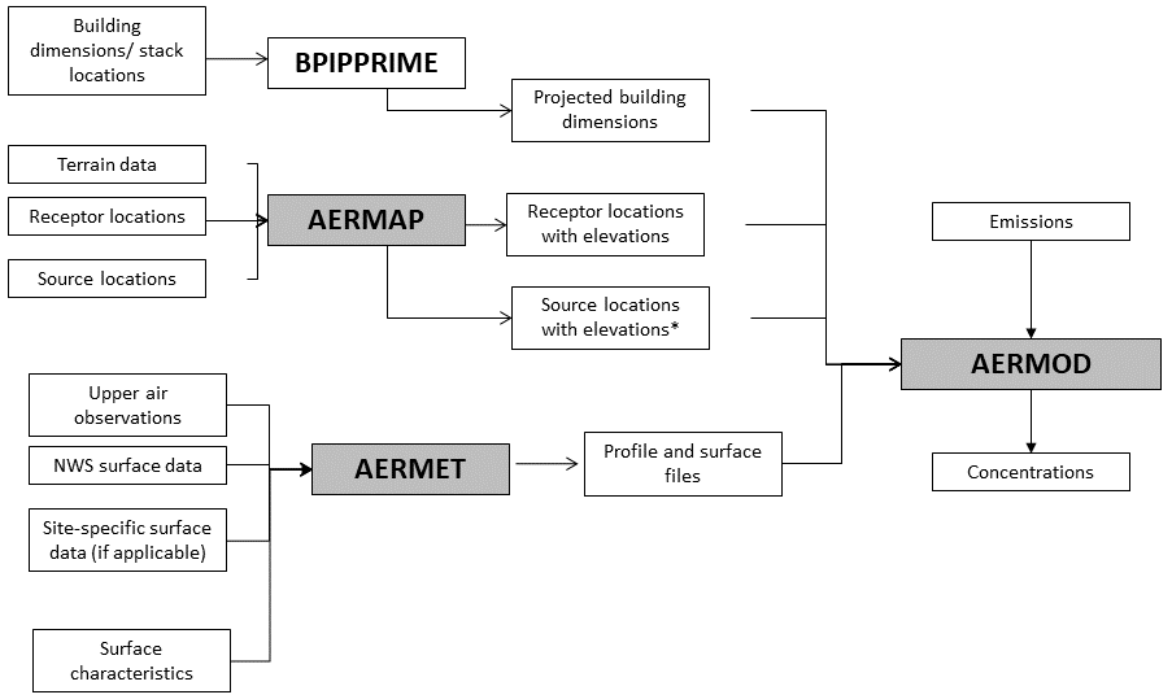

Figure 3. Data inputs and outputs of the AERMOD Modeling System

4 EPA Maintenance and Updates to AERMOD Modeling System: 2005 to 2015

Since the promulgation of AERMOD in 2005, EPA has released periodic updates to AERMOD and related programs (i.e., AERMET and AERMAP) that address:

1) corrections to coding errors commonly referred to as bug fixes, and
2) Incorporation of new post-processing and output options into the model. For example, various options have been added to accommodate revisions to the form of the 2010 SO_2 and NO_2 NAAQS to hourly standards.

In addition, as research is ongoing, and the science of dispersion modeling is continually advanced, beta options have been added for consideration of their potential to improve the performance of the promulgated formulation of the model. However, a revision to the *Guideline* is required for these beta options to become part of the scientific formulation of the regulatory version of the model. As beta options, they are provided to the user community for testing and evaluation with opportunity to provide feedback to EPA through mechanisms such

as published journal articles, annual modeling workshops and scientific conferences, and EPA's triennial modeling conference. The first beta options, POINTHOR and POINTCAP, were introduced into AERMOD with version 06341, the first update to AERMOD after promulgation in 2005. The POINTHOR and POINTCAP beta options were added to address the need for special treatment in the dispersion from horizontal and capped stacks, respectively. Figure 5 is a timeline of the released versions of AERMOD, AERMET, and AERMAP from the initial promulgation of AERMOD in 2005 through 2015 and including the update to the *Guideline* in 2017.

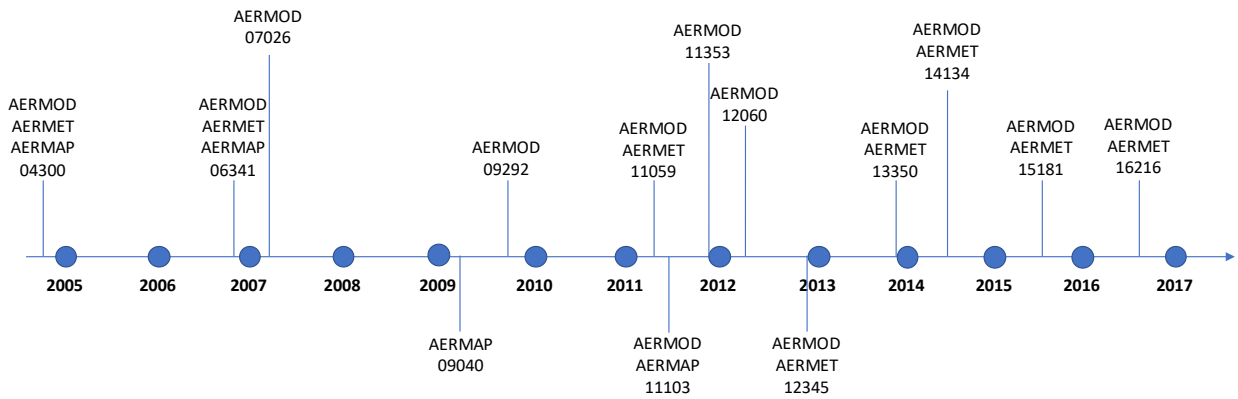

Figure 4. Timeline of AERMOD, AERMET, and AERMAP Versions

There are two broad categories of updates to program source code that were applied during the 2005 to 2015 timeframe that resulted in the release of updated versions of the model. These categories are defined by the following:

- **Bug fixes** – these are changes to the model source code that correct coding errors. These errors could include formulation bug fixes (i.e., when the programming logic or an algorithm does not reflect the intended underlying science), processing and output bug fixes (e.g., correct error messages), or a variety of changes to the source code that correct existing features of the model that may have been coded improperly.

- **Model enhancements**[2] – these are changes to the model source code that improve the usability for the community. These types of changes could include additional internal post-processing and output options (e.g., the post-processing added to accommodate the short-term NO_2, SO_2, and $PM_{2.5}$ NAAQS), additional informational messages (e.g., error and warning messages that clarify conflicting model options), or additional modeling options (e.g., the ability to provide background as a function of the wind

[2] Note that the Model Change Bulletins for previous model version releases have included category referenced as "miscellaneous" updates, which should be included in the "model enhancements" category outlined here.

direction). Model enhancements have also included beta options that represent a change in the scientific formulation but have not yet been promulgated by an update to the *Guideline*, and therefore, cannot be used for regulatory purposes without approval to be used as an alternative model per the requirements of the *Guideline*.

Between promulgation in 2005 and 2015 prior to the model version released concurrent with the regulatory update to the *Guideline* in 2017 (i.e., version 16216), AERMOD dispersion model was updated 11 times. During that period, AERMET was updated six times and AERMAP was updated three times. Each update release by EPA included full documentation through Model Change Bulletins (MCBs) that identify in detail all updates applied to the source code and an assessment of the consequences of the changes to the source code. All updates to AERMOD, AERMET, and AERMAP during this time were either bug fixes or enhancements. Some of the enhancements added during this time were beta options and their use for regulatory purposes required approval as an alternative model per Section 3 of the *Guideline.*

Figure 6 is a diagram of the AERMOD update process followed by EPA to apply user enhancements and bug fixes since promulgation in 2005 through 2015. Table 1 through Table 3 include listings of each updated release of AERMOD, AERMET, and AERMAP, respectively, after promulgation in 2005 through 2015, i.e., prior to the update to the *Guideline* in 2017. A brief summary of the types of enhancements and bug fixes is also provided. The MCBs on EPA's Support Center for Regulatory Atmospheric Modeling (SCRAM) website provide more detailed descriptions of the code updates for each version release.

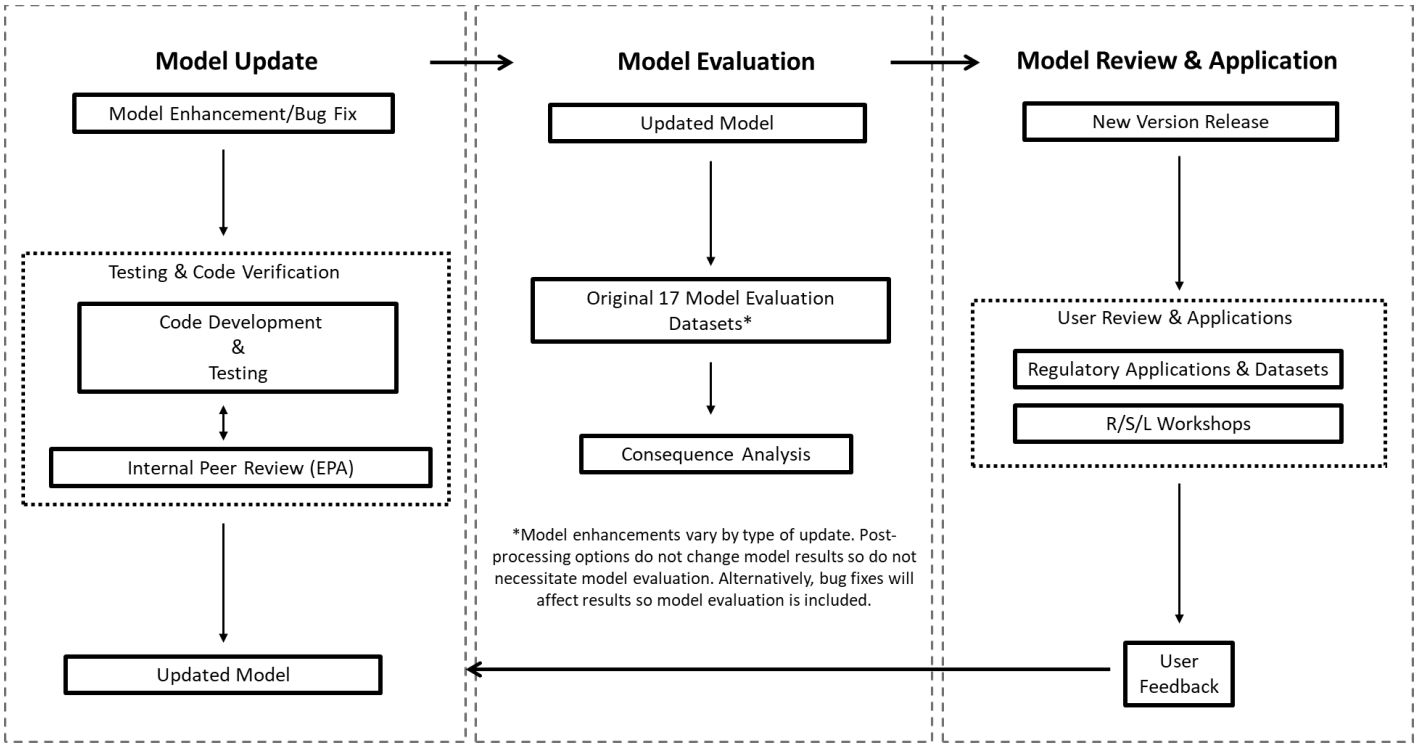

Figure 5. Model Enhancements and Bug Fixes to the AERMOD Modeling System

Table 1. Model User Enhancements and Bug Fixes to AERMOD Modeling System from 2005 to 2015

Version	Date	Enhancements	Bug Fixes
06341	12/7/2006	• Add BETA keyword and the following non-default draft options: POINTCAP source, POINTHOR source, and PSDCREDIT for PVMRM NO_2 conversion option. • Add options to vary emissions by month, hour-of-day, and day-of-week. • Extend urban option to allow multiple urban areas. • Add processing to calculate $PM_{2.5}$ design values. • Add option for initial in-stack NO_2 ratio for PVMRM and OLM options. • Refinements to error checking, range checks, and array storage.	• Bug fixes for area source concentrations, undefined and uninitialized variables, multiyear processing, variable type declarations, and treatment of point sources under stable conditions.
07026	1/26/2007	• Additional support for PSDCREDIT option.	• Bug fixes for array allocation and processing, error checking, mixed precision calculations, deposition applications, HOUREMIS option, potential division by zero, and output format.

Version	Date	Enhancements	Bug Fixes
09292	10/19/2009	• The following options were added: specify emissions by hour-of-day and day-of-week, hourly varying release height and initial dispersion coefficients for VOLUME and AREA sources, non-default Method 2 for particulate and non-particulate (gaseous) emissions for OPENPIT sources, specify flat and elevated terrain by source, FASTALL, non-default user-defined dry deposition velocity for gaseous emissions, SUMMFILE output, support to output modeled concentrations in exponential notation in output concentrations, file sharing across multiple model runs, WARNDCHKD. • Enforce urban roughness length of 1.0m for regulatory DFAULT applications. • Miscellaneous code upgrades and clean-up. • Additional support for calm and missing hours when using STARTEND and/or DAYRANGE keywords.	• Miscellaneous bug fixes for array allocation and processing, SCREEN option, data read/write statements, treatment of stable and missing hours in solar irradiance calculation, MAXIFILE and POSTFILE, and data range checks. • Updates to checks on meteorological data start/end hours, end-of-file condition for hourly input filed, handling of INCLUDED files, deposition depletion, flow vector assignments, adjusted emission rates for OPENPIT and FASTAREA options.

Version	Date	Enhancements	Bug Fixes
11059	2/28/2011	• Add support for 1-hour NO_2 and SO_2 and 24-hour $PM_{2.5}$ NAAQS including updates to RECTABLE and new output options such as MAXDAILY, MXDYBYYR, and MAXDCONT, among other support features. • Enhanced support for NO conversion options. • Refinement to urban option for transition from nighttime urban boundary layer to daytime convective layer. • Update WAKFLG to no longer ignore potential downwash effects for stack heights that equal or exceed the EPA formula height. Criterion implemented within PRIME downwash algorithm is applied.	• Bug fixes for variable initialization, emission factors, date sequence checks, calm and missing ours processing, and user-defined file units for input/output files.
11103	4/13/2011		• Bug fixes for RECTABLE output and Fortran format statements.

Version	Date	Enhancements	Bug Fixes
11353	12/19/2011		• Bug fixes for MAXDCONT and PLOTFILE output, ANNUAL average option in 03VALS subroutine, temporally varying background concentrations, and processing meteorological data files that extend beyond the maximum number of years specified by the user.
12060	2/29/2012	• Updates to URBANSRC option and improvements to memory requirements for MAXDCONT processing.	• Bug fixes to MAXDCONT processing, OLM and PVMRM with 03READ keyword, estimate of PG class from Monin-Obukhov length and surface roughness, and range checks.
12345	12/10/2012	• Following options were added: LOWWIND1 and LOWWIND2 BETA options and LINE source type. • Add support for AERMET ADJ_U* BETA option.	• Bug fixes to wind speed adjustments, missing hourly ozone data, multiyear processing with DAYRANGE keyword, range checks, control file processing.

Version	Date	Enhancements	Bug Fixes
13350	12/16/2013	• Add default Ambient Ratio Method (ARM) and non-default ARM2 BETA option. • Add option to vary ozone background data by wind sector. • Debug support for OLM, ARM, and ARM2 options.	• Bug fixes for range checks, conversion to Julian day with DAYRANGE keyword, double-counting of non-hourly background emissions, calculation of center of effective area source for OPENPIT sources, plume rise for penetrated source for wet deposition and depletion, substitution of missing ozone data, EVENT processing, and error/warning messages.

Version	Date	Enhancements	Bug Fixes
14134	5/14/2014	• Enhanced support for special processing associated with 1-hour NO_2, SO_2, and 24-hour $PM_{2.5}$, MMIF-generated meteorological inputs, and debug for AREA/LINE sources.	• Miscellaneous bug fixes for PVMRM, OLM, ARM, and ARM2 options, calculation of annual averages for ARM and ARM2 options, skipped concentration calculations (e.g., receptor located less than 1m from POINT source), variable allocation and storage, LINE aspect ratio, calculation of vertical dispersion coefficients based on distance-dependent effective parameters for LINE source, debug output, source groupings, range checks and error/warning messages. • Updates to met file error handling for 1-hour SO_2 and NO_2 and 24-hour $PM_{2.5}$.

Version	Date	Enhancements	Bug Fixes
15181	6/30/2015	• The following non-default BETA options were added: PVMRM2, LOWWIND3, and BUOYLINE source (from BLP model). • Enhanced debug support for PVMRM/PVMRM2, ANNUAL POSTFILE, and page headers to include additional information about RURAL/URBAN source categorization.	• Bug fixes for POINTCAP and POINTHOR sources with NOSTD option, distance-dependent centroid height, limits on plume rise for tall sources in urban areas, MAXDCONT output option, FASTAREA and FASTALL options, penetrated plume contribution for PVMRM and PVMRM2 options, and PVMRM source contribution to NO-to-NO_2 conversion. • Updates to define elevation of receptor above source elevation based on dominant source rather than vary for each source, total NOx emissions of major contributing sources, array indexing for ozone concentrations, processing leap years and non-leap years, tolerance parameter for winds blowing nearly perpendicular to AREA/LINE sources, and clarify ambient temperature included in METEOR debug file is at stack height.

Table 2. AERMET Updates Since 2005 Promulgation and Prior to Guideline Update in 2017

Version	Date	Enhancements	Bug Fixes
06341	12/7/2006	• Combined three stage processing into a single program executable (original release included two separate executable files). • Enhanced support for surface pressure estimation from sea-level pressure, and enhanced support for processing Integrated Surface Hourly Data (ISHD).	• Various bug fixes to the extraction and processing of ISHD formatted surface data, upper and lower bounds checks, missing data codes, calculation of critical solar angle, and Fortran format statements.
11059	2/28/2011	• Enhanced support for handling missing station pressure, increased flexibility in selection of most appropriate upper air sounding, addition of 1-minute ASOS-based winds, enhanced error handling for processing onsite data, addition of secondary surface characteristics when substituting missing onsite wind data with NWS wind data, and the utilization of on-site precipitation and humidity data.	• Various bug fixes for data extraction and processing onsite data, data substitution, time zone adjustments, range checks, error handling, and processing ISHD formatted data.

Version	Date	Enhancements	Bug Fixes
12345	12/10/2012	• Improvements for processing 1-minute ASOS wind data, addition of adjust surface friction velocity, or u*, (ADJ_U*) BETA option, enhanced support for storing upper air sounding data, and improved error/warning messaging.	• Bug fixes for processing Hourly US Weather Observations (HUSWO) data, convective mixing height calculation, and checks for onsite mixing heights.
13350	12/16/2013	• Incorporate a modified Bulk Richardson Number approach under ADJ_U* BETA option, enhanced support for data filling/substitution of missing cloud cover and ambient temperatures, and improved error/warning messaging.	• Bug fixes to ADJ_U* BETA option, time zone adjustment when both upper air and onsite mixing-heights are available, mechanical mixing height coefficient, cloud cover data processing, error handling, Fortran format statements, and upper air sounding window for extraction.
14134	5/14/2014	• Add option to disable substitution of missing cloud cover and ambient temperature, improved utilization of onsite data when available, enhancements to Bulk Richardson Number method and the use of onsite solar radiation and delta-temperature in lieu of cloud cover, and enhanced support to track use of MMIF-generated inputs as pseudo-onsite data.	• Bug fixes for missing cloud cover and ambient temperature substitution, onsite station pressure and relative humidity calculations, bounds checks, upper air sounding selection, temporary file storage, mixed precision, Bulk Richardson method for ADJ_U* BETA option, error handling and messaging.

Version	Date	Enhancements	Bug Fixes
15181	6/30/2015	• Refinements to the ADJ_U* BETA option in conjunction with the Bulk Richardson Number (BULKRN) option, enhanced output statistics, improved error/warning messaging.	• Bug fixes to ADJ_U* BETA option and Bulk Richardson method.

Table 3. AERMAP Updates Since 2005 Promulgation and Prior to Guideline Update in 2017.

Version	Date	Enhancements	Bug Fixes
06341	12/7/2006	• Enhanced support for debug output, improved data file checks/validation prior to processing, optimizations in data file processing, enhanced summary output, and improved documentation of source code.	• Bug fixes for coordinate conversions, data gaps, elevation and hill height scale calculations and optimization, reading 7.5-minute DEM files, and array processing (out-of-bounds runtime error).
09040	2/9/2009	• Add support for AERMOD POINTCAP, POINTHOR, OPENPIT source types and processing of USGS National Elevation Dataset (NED) files and processing multiple DEM files having different data resolutions. • Remove requirement for user-defined domain, update code with allocatable arrays, add support for INCLUDED keyword to allow source and receptor data from external files, enhanced debug and summary output, improve portability for applications outside of Northern/Western hemispheres, improved error/warnings and messaging, and miscellaneous code clean-up/documentation.	• Corrections with processing DEM data for Alaska. • Bug fixes to datum conversions, processing non-standard (non-USGS) DEM files converted from other formats, errors related to processing control file, error handling of receptors outside of range of DEM data, missing elevation data, and variable initialization.
11103	4/13/2011	• Extend length of source IDs.	• Correction to message format.

5 EPA Rulemaking to Update AERMOD Modeling System: 2015 to 2017

As highlighted in the previous section, some of the updates to AERMOD, since it was promulgated as a preferred model in 2005, included beta options to address needed scientific improvements, which required approval as an alternative model under section 3 of the *Guideline* prior to being incorporated as regulatory options in AERMOD. Adoption of these beta options into the regulatory version of the model requires a regulatory update to the *Guideline*, which must follow federal rulemaking under the ADP. That process includes a Notice of Proposed Rulemaking (NPRM), a public comment period, then a Final Rulemaking (FRM) action. A revision to the *Guideline* was proposed an NPRM published in the Federal Register in 2015 with the release of AERMOD version 15181, followed by a public comment period, and an FRM published in the Federal Register in 2017 with the release of AERMOD version 16216. Similar to the initial model development process, EPA followed the process outlined in Figure 6 and relied upon published peer reviewed literature to identify and implement the scientific improvements that were necessary to improve model performance to meet the purposes under the CAA.

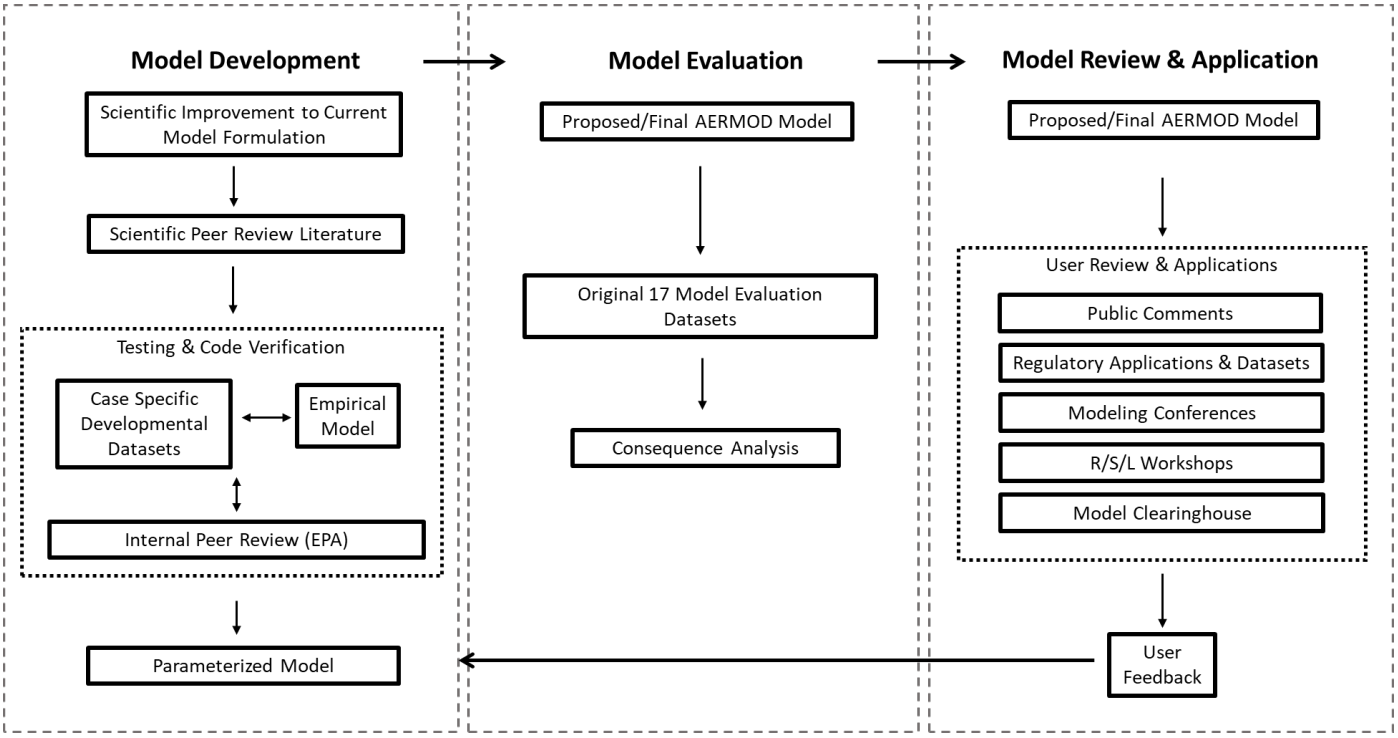

Figure 6. Model Formulation Updates to the AERMOD Modeling System.

Figure 6 was adapted from, US Environmental Protection Agency, 2012, DRAFT FINAL Handbook for Developing Quality Assurance Project Plans. *http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OEI-2012-0774-0003*

5.1 Need for Updates to AERMOD Model Formulation

In 2010, EPA promulgated new 1-hour standards for NO_2 and SO_2. Although the evaluations that formed the basis of AERMOD's promulgation demonstrated that AERMOD provides generally unbiased estimates of concentrations, the increased stringency of the new standards resulted in increased scrutiny of AERMOD by the modeling community. In response, EPA issued several guidance memoranda to clarify the applicability of the *Guideline* and address initial issues with the use of current models and procedures under PSD permitting (U.S. EPA, 2010a; U.S EPA, 2010b; U.S. EPA, 2010c; U.S. EPA, 2010d). However, to address performance issues for PSD permitting under the new standards, the situation also necessitated EPA and the modeling community more closely evaluate the science and AERMOD's formulation. As part of this effort, EPA reconvened the AERMOD Implementation Workgroup (AIWG) with an emphasis on the new 1-hour NO_2 and SO_2 NAAQS. AIWG was compromised of members from EPA and state/local agencies. AIWG modeled a variety of hypothetical sources and results of the assessment were presented at the Tenth Modeling Conference in 2012 to inform the modeling community potential implications and areas for improvement in the model and guidance for their use.[3]

Several presentations at the Tenth Modeling Conference addressed issues and challenges associated with the 1-hour NO_2 and SO_2 NAAQS. The American Petroleum Institute (API) presented an evaluation of AERMOD performance under low wind speed conditions using National Oceanic and Atmospheric Administration (NOAA) field studies at Oak Ridge, TN and Idaho Falls, ID.[4] These studies were not part of the original 17 databases used to evaluate AERMOD in its 2005 promulgation. The API study showed significant model overprediction of concentrations, especially for the Oak Ridge study where observed wind speeds were below 0.5 m/s for 10 of the 11 tracer tests and included wind speeds as low as 0.15 m/s. The study also included proposed modifications to the AERMET pre-processor and AERMOD model to address the bias toward overprediction under stable/light wind conditions.

Prior to the promulgation of the 1-hour NO_2 NAAQS, compliance with the previous annual NO_2 NAAQS was routinely demonstrated based on the Tier 1 assumption of full conversion or a Tier 2 option based on an ambient ratio of 75 percent conversion of nitrogen oxides (NO_X) to NO_2, referred to as ARM. However, compliance with the new 1-hour NAAQS has typically required a more refined treatment of NO_X conversion to NO_2. Therefore, several presentations at the Tenth Modeling Conference focused on issues associated with

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[3] https://www3.epa.gov/ttn/scram/10thmodconf/presentations/2-9-aiwg_3-14-12_v2.pdf

[4] AECOM, 2010. AERMOD low wind speed evaluation study results, http://mycommittees.api.org/rasa/amp/Modeling%20Documents/AECOM%202009%20Low%20Wind%20Speed%20Evaluation%20Study%20Report.pdf.

demonstrating compliance with the new 1-hour NO2 NAAQS. These presentations included an overview of an API-funded study to develop a Tier 2 ambient ratio method for the 1-hour NO_2 NAAQS, referred to as ARM2. The ARM2 approach was developed based on an extensive analysis of ambient ratios of NO_2/NO_X that were analyzed by land use (urban vs. rural) and geographical areas. Based on these analyses of the ambient NO_2/NO_X ratios, an empirical relationship between ambient concentrations of NO_2 and NO_X was developed. EPA subsequently reviewed and evaluated this ARM2 approach and then incorporated this screening technique as a non-Default/Beta option in version 13350 of AERMOD in December 2013. Another issue associated with NO_2 NAAQS compliance presented at the Tenth conference focused on the use of relative (instantaneous) dispersion coefficients to define the plume volume which determines the amount of ozone available to convert nitric oxide (NO) to NO_2 using the PVMRM option in AERMOD. The relative dispersion coefficients originally incorporated in AERMOD for PVMRM are best representative of daytime convective conditions and may tend to overestimate plume volumes during stable conditions. Such overestimation of the plume volume will tend to result in PVMRM overestimating concentrations of NO_2.

5.2 EPA's 2015 Proposed Model Formulation Updates to AERMOD Modeling System

In July 2015, EPA proposed updates to the *Guideline*, which included enhancements to the formulation and application of the AERMOD Modeling System and the incorporation of a tiered demonstration approach to address the secondary chemical formation of ozone and $PM_{2.5}$ associated with precursor emissions from single sources. The proposal also included allowing the use of prognostic meteorological data for regulatory modeling applications in situations where representative NWS data is not available and where it is cost prohibitive or infeasible to collect adequately representative site-specific data. Additionally, EPA proposed various editorial changes to update and reorganize information throughout the *Guideline* to streamline the compliance assessment process. Proposed changes to the model formulation in the included:

- The ability to adjust u* (Luhar, A.K., and K. N. Rayner, 2009; Qian & Venkatram, 2011), i.e., ADJ_U*, in the AERMET pre-processor to address issues with model tendency to overpredict concentrations under stable low wind speed conditions;;;
- A related option in AERMOD, LOWWIND3, to similarly address issues of model overprediction under low wind conditions;
- Modifications to the AERMOD formulation to address the model tendency to overpredict for relatively tall stacks located near relatively small urban areas;
- Proposed regulatory options in AERMOD to address plume rise for horizontal and capped stacks based on the July 9, 1993 Model Clearinghouse memorandum with adjustments to account for the PRIME algorithm for sources subject to building downwash; and
- A buoyant line source option in AERMOD, based on the Buoyant Line and Point Source

(BLP) model to eliminate the need to use two models for sources using BLP.

Proposed changes, such as the adjusted u* option, were based on peer-reviewed literature as cited above. Therefore, such proposed changes have already been evaluated and documented. After inclusion in the model by EPA, the changes listed above went through extensive evaluation procedures using the Cox-Tikvart Protocol, (Cox and Tikvart, 1990), which is the basis for EPA's Protocol for Determining Best Performing Model (U.S. EPA, 1992) to the 17 field study databases used in the original evaluation and promulgation of AERMOD (Perry, et al, 2005).

5.3 EPA's 2017 Model Formulation Updates to AERMOD Modeling System

After receiving and reviewing public comments on the proposed Guideline, EPA finalized the update to the *Guideline* in January 2017. With the exception of the LOWWIND3 option, the proposed changes to the model formulations were finalized in the 2017 version of the *Guideline*.

As described above, as part of the proposed updates to AERMOD, especially for the adjusted u* option, LOWWIND3, and acceptance of prognostic data, AERMOD performed extensive evaluations of the proposed updates, including the use of the original 17 AERMOD evaluation databases and the Cox-Tikvart Protocol. The same was done for the final updates after receiving public comment on the proposed changes. As a result of the numerous evaluations using the Cox-Tikvart Protocol, EPA determined in the final action, that the adjusted u* option should not be used when the site-specific meteorological data used in AERMOD contained turbulence measurements but could be used when the meteorological data did not contain turbulence measurements. As discussed in the preamble to the FRM for the 2017 *Guideline*, use of the adjusted u* option with turbulence data tended to show underprediction for the Tracy field study and the 1972 Idaho Falls field study thus leading to EPA's final decision on the use of adjusted u* when turbulence data are present.

Numerous evaluations of LOWWIND3, with and without adjusted u* and with and without turbulence measurements, led EPA to not promulgate LOWWIND3 as part of the final revision to the *Guideline*. The evaluations showed that LOWWIND3 tended to bias toward model underpredictions. The evaluations found that when adjusted u* and LOWWIND3 were applied together, the model tended toward underprediction due to both options influencing the value of σ_v, the lateral plume meander, either by adjusting u* (from the adjusted u* option) or direct influence by LOWWIND3 in AERMOD. Several commenters recommended that EPA's proposed revisions to AERMOD be further evaluated given the lack or paucity of peer-reviewed literature upon which they were based. EPA agreed with the commenters that further study was warranted for LOWWIND3 before its promulgation, and therefore, it was not promulgated in the 2017 revision to the *Guideline*, pending further investigation. More details about the rationale for EPA's decision can be found in the preamble to the 2017 *Guideline*.

Table X. AERMOD Version 16216 Enhancements and Bug Fixes

Version	Date	• Enhancements	• Bug Fixes
AERMOD 16216	12/21/2016	• Replaced PVMRM with PVMRM2, removed the BETA requirement for PVMRM, OLM, ARM2, POINTCAP, and the POINTHOR options, removed the BETA requirement for using MMIF data	• Allow more complex AERAPOLY sources, added several processing options for BLP
AERMET 16216	12/21/2016		• Fixes to the ADJ_U* and BULKRI options, made RANDOM the default for WIND_DIR in Stage 3 processing for National Weather Service

6 EPA's 2018 & 2019 Model Update

In April 2018, EPA released an update to the AERMOD model, version 18081, and in August 2019, EPA released AERMOD version 19191. As described in Section 3.3, EPA has a model maintenance cycle that results in roughly an annual update to the model consisting of model user enhancements and bug fixes. Following the regulatory update to in 2017, EPA continued its maintenance cycle, releasing updated versions 18081 of the model in 2018 and 19191 in 2019 that contained, bug fixes and user enhancements, and formulation updates. In addition, to enhance community feedback on scientific development, in 2018 EPA initiated a new approach for model updates that allows EPA to provide formulation updates to the community during any model release and gain feedback on such scientific improvements and facilitate their regulatory use, if appropriate, through the alternative model approval process. This new approach adopted in version 18081 formally incorporates "ALPHA" options (i.e., options that are experimental and not intended for regulatory usage) and "BETA" options (i.e., options that meet the *Guideline*'s criteria as an alternative model), as fully described below. These options promote timely and more routine interactions between EPA and the stakeholder community (e.g., through the annual RSL Modelers' Workshop) on planned science updates well before any regulatory update to the model is formally proposed through rulemaking. By doing so, this allows for a more informed and streamlined regulatory update process.

6.1 AERMOD Version 18081

To improve upon the staging of potential new formulation updates to the model (i.e., model options that EPA believes are appropriate for an alternative model and may eventually be promulgated as a regulatory default) and to differentiate model updates that are intended for research and evaluation and not ready for regulatory application, EPA decided to refine the "BETA" label for model options. Thus, in addition to the normal bug fixes and enhancements that accompany a model release (listed in Table 4), AERMOD version 18081, released on April 24, 2018, EPA added a new "ALPHA" option to accompany the current "BETA" option to address these model development needs.

Table 4. AERMOD Version 18081 Enhancements and Bug Fixes

Version	Date	• Enhancements	• Bug Fixes
AERMOD 18081	3/22/2018	• ARM2 enabled with buoyant line source. • Add ALPHA option flag and LOW_WIND ALPHA options which include	• Bug fixes for downwash receptor bug, SO_2 urban half-life for non-default applications, ANNUAL POSTFILES,

		user-defined minimum wind speed, sigma-v, and maximum meander factor. • Removal of LOWWIND1, LOWWIND2, LOWWIND3 and ARM options. • Add support for command-line arguments.	summary of buoyant line source information in output files, seasonal assignment for calculation of cuticle resistance for ozone for winter and snow precipitation, ARM2 range checks, background sector output, application of minimum wind speed, empty meteorological file, and variable initializations.
AERMET 18081	3/22/2018	• Add support for command-line arguments.	• Correction to precipitation code when amount greater than zero for NWS data. • Bug fix to avoid attempt to write past end-of-file and modifications to BULKRI subroutine to set variables to missing to avoid NaNs in output surface file.
AERMAP	3/22/2018	• Add support for command-line	• Add allocatable array for RMIN to

18081		arguments.	avoid errors on Linux systems.

6.2 ALPHA and BETA options

EPA has augmented the AERMOD model development process to change the prior "beta" options to include two classes of model options, "ALPHA" and "BETA." We are now defining BETA options as those that include scientific updates to the formulation of the model that have met the criteria in Section 3.2.2e of the *Guideline* as follows:

- The update has undergone scientific peer review,
- The update has been demonstrated to be applicable to the problem on a theoretical basis,
- There exists available and adequate databases to perform the analysis, and
- Performance evaluations have shown that the model or technique is not inappropriately biased the application

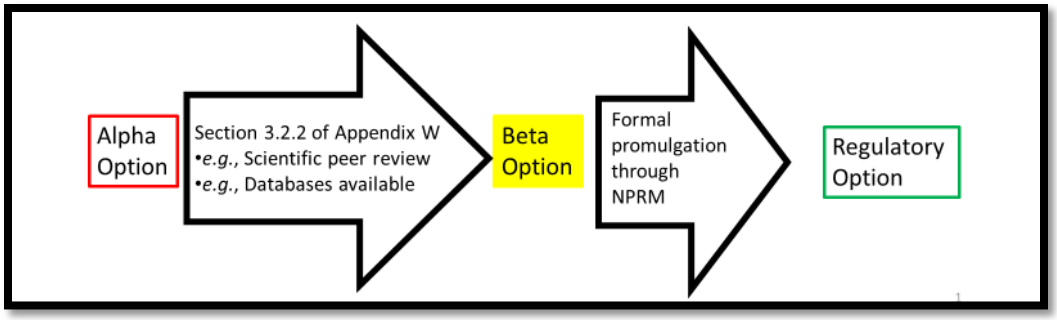
In short, BETA options are options that EPA considers largely appropriate to consider for regulatory use when theoretically appropriate, though still require alternative model approval. Generally, BETA options are those that are being considered for adoption into the regulatory default version of the AERMOD modeling system through a regulatory update to the *Guideline*. Figure 7 illustrates the path of progression of an ALPHA option to BETA option to an approved regulatory option.

ALPHA options can include scientific updates to the model formulation that are experimental or research grade and are generally not meant to be used for regulatory applications. ALPHA options that represent a scientific update have not yet met the theoretical, peer review, database, and evaluative criteria in Section 3.2.2e of the *Guideline.* Typically, they will be based upon a white paper outlining the need for the new option and summarizing the current state of the science around the option. This approach allows EPA to implement new ALPHA options into the model for evaluation and feedback from the user community, while maintaining clarity that the BETA model options have received sufficient scientific peer review and evaluation to be considered for regulatory purposes. In general, new model options that represent a science update will be introduced as ALPHA options and when the criteria for an alternative model have been met per Section 3 of the *Guideline*, the ALPHA options will be reclassified to BETA options. However, the process may also result in ALPHA options being deemed inappropriate and ultimately removed from the model system. It should be noted that classification of scientific updates as ALPHA options in the AERMOD Modeling System does not preclude approval of their use in site-specific applications if all the appropriate alternative model provisions in Section 3.2.2.b.2 of the *Guideline* are satisfied for that specific application of the model.

ALPHA options can also include model enhancements (i.e., updates other than scientific updates) that are still undergoing testing and evaluation for functionality. Model enhancements, once fully evaluated and implemented, would generally be integrated directly into the regulatory version of the model, rather than being migrated to a BETA option, as these changes to the model would not require formal promulgation. Although, many of these types of model enhancements will skip the ALPHA stage entirely and be integrated directly into the regulatory version of the model.

In terms of future scientific updates, the ALPHA options, in particular, allow for more open evaluation and potential collaboration of model improvements by the community as they are being developed. As new or updated model formulations are defined through white papers or other scientific literature, EPA can pursue incorporating those formulations available to the modeling community for hands-on evaluation. This allows for a much wider evaluation of the model formulation updates and a greater understanding of the evaluation and consequences of these changes likely across more source types than EPA can evaluate on its own.

Figure 7. Normal Progression of ALPHA and BETA Options to a Regulatory Option in AERMOD Modeling System.



Notes: ALPHA options are experimental and are not generally available for regulatory use, while BETA options are peer-reviewed options potentially ready for consideration as an alternative model. Also, in some situations BETA options could be introduced into AERMOD without first being included as an ALPHA option.

6.3 AERMOD Version 19191

To continue the staging of potential new formulation updates to the model initiated with the ALPHA and BETA options established in AERMOD version 18081, the 19191 version of the model added a BETA option and several ALPHA options, in addition to the normal bug fixes and enhancements that accompany a model release (listed in)

Version	Date	• Formulation updates	• Enhancements	• Bug Fixes
AERMOD 19191	8/21/2019	• Added the BETA RLINE source type • Added ALPHA RLINEXT source type • Added several ALPHA downwash options • Modified the METHOD_2 deposition, such that is now ALPHA	• Add the URBAN option to the RLINE, RLINEXT, and BOUYLINE sources • Added the EVENT processing for the RLINE and RLINEXT sources	• Bug fixes for background concentrations and deposition, several fixes to error messages and summary information
AERMET 19191	8/21/2019			• Properly skip days when there is not an available

				sounding and there are onsite mixing heights • Not replace a duplicate observation's precipitation for a given hour if the newest precipitation is missing or zero

Table 5. AERMOD Version 19191 Enhancements and Bug Fixes

7 EPA Path Forward for AERMOD Model Formulation Updates

The underlying approach to AERMOD development is embodied in Figure 6, shown earlier in Section 5.3. This figure shows that for future model updates, specifically formulation updates, the model continually undergoes development, evaluation, and application, a cycle that closely follows the cycle established by the initial model development and the 2017 formulation updates. The formulation updates are motivated primarily by the multiple and varied regulatory uses of AERMOD by the modeling community. These regulatory applications identify areas where the model and the modeling community still have challenges in unique situations (e.g., model performance during low wind conditions). As part of this process, EPA has acknowledged and is actively embracing the need for input on model updates by not only identifying where there are issues, but to also continue the historical practice of co-operatively working with the stakeholder community to develop and evaluate potential model updates. However, given the limited available internal and external resources, EPA needs to prioritize the needs for model updates for the most important science improvements. To accomplish this, EPA developed a series of white papers that cover EPA's current model update topics, which was released on September 19, 2017. The expectation is that the white papers will establish the next round of model updates, which will result in the development of ALPHA and BETA options and will ultimately be adopted into the model in a future rulemaking.

7.1 EPA White Papers

As noted above, EPA recently provided a series of white papers that outline the scientific model enhancements that EPA is currently working on or plans to work on in the near future. These white papers are intended to clearly articulate the state of the science, discuss the current implementation of AERMOD with respect to the scientific update being addressed, and provide considerations for the path forward on adopting a model change to address the issue presented in each white paper. The papers have a standard format to ensure these items are addressed to lay the appropriate groundwork for further research and development, as follows:

- Overview of issue – This section provides a description of the known issue in AERMOD that needs to be addressed. The emphasis is that there is a clearly demonstrable deficiency in the model related to specific features or formulations of the model (e.g., a statement that the model overpredicts is too general to serve as the basis for further model development).

- Current implementation in AERMOD – This section is meant to provide a summary of the model formulation in AERMOD (or other preferred model if AERMOD is not the preferred model).

- Summary of current literature or research – In general, the modeling issues addressed in the model development plan white papers have some sort of path forward, i.e., that there is already research or development for EPA and stakeholder to consider. Thus, this section should provide a summary of known literature on the topic or provide other pertinent information, such as field study data available to inform the development process.

- Considerations for updates to the model system – This section is meant to summarize how the available information could be applied in the modeling system, with an emphasis on the practical application and implementation.

The current iteration of the model development plan consists of a body of white papers that have been developed solely by EPA. However, many of the white paper topics are based on work initiated or completed and provided by the modeling community (e.g., downwash and overwater dispersion). By providing this template for white paper development, EPA is actively seeking input from the stakeholder community on potential model improvements by requesting similar white papers. EPA can evaluate community-supplied white papers, and if appropriate, incorporate them into EPA's set of AERMOD development white papers and distribute them to the wider stakeholder community.

7.2 Priority Science Improvements for AERMOD Modeling System

EPA has identified six areas where there is active research and development related to dispersion models by EPA, federal partners, or the modeling community. White papers summarize the state of the development area and provide context for EPA's considerations for the pathway forward to provide updates to the AERMOD on each development area. EPA's current white papers on AERMOD development are available at EPA's AERMOD Modeling System Development website (and future updates to the white papers will also be posted to this website):

https://www.epa.gov/scram/aermod-modeling-system-development

The following list briefly summarizes the current development topics, along with a classification of the time ranges expected before potential model improvements are available to the community for usage.

- **Treatment of Low Wind Conditions**: This white paper addresses the continued efforts by EPA and the community to improve model predictions in low wind conditions for some source types. The current version of AERMOD provides a LOW_WIND ALPHA option that will provide the basis for further research; however, there is no imminent BETA option for low wind conditions. This is expected to be a medium-term development.

- **Saturated Plumes**: This white paper addresses the efforts to enhance AERMOD's' treatment of moist plumes due to enhanced thermodynamics not currently accounted for by the model. There has been significant effort by the modeling community to develop improvements on this issue, but there is a need for a field database to evaluate these improvements before these updates would be available as a BETA option. This is expected to be a medium to long-term development.

- **Downwash Algorithms**: This white paper addresses the efforts to improve AERMOD predictions for downwash situations involving near-term updates and long-term incorporation of new research. There is significant active research on this topic, including wind tunnel and computational fluid dynamics modeling and existing field databases available to evaluate these improvements. EPA is currently working to integrate proposed algorithms into AERMOD as ALPHA options and it is reasonable to expect that some of these improvements will progress to BETA options in the near future. This is expected to be a short to medium-term development.

- **NO_2 Modeling Techniques:** This white paper currently addresses the continued efforts intended to improve performance of AERMOD's Tier 3 methods for modeling the conversion of NO to NO_2. There is significant active research on this topic which includes the development of new field databases to evaluate these improvements. EPA is

currently expecting to integrate proposed new algorithms into AERMOD as ALPHA or BETA options in the next version of the model, and it is reasonable to expect that some of these improvements will progress to BETA options in the near future. This is expected to be a short to medium-term development.

- **Mobile Source Modeling:** This white paper addresses the efforts intended to integrate the R-LINE line source dispersion model into the AERMOD dispersion model for future consideration as an EPA preferred model.

- **Overwater Modeling:** This white paper addresses development efforts required to replace the OCD model with AERMOD as an EPA preferred model for offshore applications.

7.2.1 Other Areas for Consideration

EPA has also identified other areas below that have been considered for additional research and development; however, these areas need additional research, review and further development for consideration in the creation of White Papers on these topics and for future versions of the AERMOD Development Plan:

- AERMOD Modeling System: Formulation Science Issues
    - Theta* calculation method and pass through from AERMET
    - Penetrated plumes
    - Tall stacks in urban areas (boundary layer characterization)
    - Underprediction for tall stacks in flat terrain during stable hours (assess HPDM approach)
    - Complex terrain characteristics and influences
- Industrial Heat Island Effects
    - Heat islands that are not captured by populations (effective population/use of satellite data)
- Buoyant Line Sources
    - Scientific update to buoyant line source reflecting AERMOD's scientific model formulation
- Deposition
    - Particle deposition/depletion
    - Gas deposition/depletion
    - SO_2 half-life

To get feedback on the first release of AERMOD update white papers, EPA has participated in several conferences since their release to present these topics and receive directed feedback from the stakeholder community. Specifically, these conferences were the Air and Waste Management Association (AWMA) specialty modeling conferences in 2018 and 2019 hosted in Raleigh, NC and the 2019 RSL Modelers' Workshop hosted in Seattle, WA.

Ultimately, the feedback from these conferences and other stakeholder engagements will help further inform the sessions for the Twelfth Modeling Conference, to be held in Research Triangle Park, NC in October 2019 so that EPA can consider adopting these and other needed scientific formulation updates to the AERMOD modeling system. The feedback from the Twelfth Modeling Conference will be used to inform the next proposed rulemaking to update AERMOD, as has been done in the initial promulgation of AERMOD and was completed with the updates in 2017 (see Figure 1 and Sections 2 through 5).

7.3 Improvements to EPA's Model Development and Update Process

As described above, the ALPHA and BETA options provide a new route for the evaluation of improvements to the modeling system. In terms of future scientific updates, the ALPHA options allow for more open evaluation of model improvements by the community as they are being developed. As alternative model formulations are proposed via white papers or other scientific literature, EPA can make those formulations available to the modeling community for hands-on evaluation. This allows for a much wider evaluation of the model changes and a greater understanding of how these changes impact sources from more source types than EPA can evaluate on its own. In addition to this improved model update approach, EPA learned valuable lessons from the 2017 regulatory update regarding the process it has used to update the model. In particular, EPA has identified several areas where additional documentation, a more comprehensive application of standard operating procedures (SOPs), and additional quality assurance and control activities can help improve the model update process. Additionally, these activities can help assure that consistent and appropriate quality control and assurance activities are conducted when revising preferred models by helping assure that the predicted results are of sufficient quality for the extensive regulatory applications of the model.

7.3.1 Updates to AERMOD Modeling System

As described in the AERMOD Model Formulation and Evaluation document (US EPA, 2017), the AERMOD development process consists of the following six-step process:

1. Initial model formulation
2. Developmental evaluation
3. Internal peer review
4. Revised model formulation
5. Performance evaluation and sensitivity testing
6. External peer review

The current model update process has been improved from the previous model development and update processes. These improvements are applicable for both model formulations updates as well as bug fixes and enhancements. In general, these improvements include more comprehensive SOPs for handling planned model updates, the use of a GitHub repository for code tracking, and more detailed review of model code by staff and management (see Figure 8. Snapshot of the GitHub repository used by EPA to track and manage code

modifications and collaboration).

In general, a particular model revision (formulation update, bug fix, or enhancement) is handled in the following manner:

1. Model revision is identified by EPA and logged in an internal tracker. The tracker is updated throughout the revision process, logging details on the code modification, personnel involved in the modification and review, and the completion status.
2. Code developers manage revisions in an internal GitHub repository, with individual code branches used for specific model revision. Code revisions are verified by a second code developer and each revision is tested against case-specific model scenarios and against a suite designed to test the various model options.
3. Once enough model revisions have been accumulated, the model documentation is updated, model code goes through additional internal testing, the model is evaluated against the 17 evaluation databases. (Even when code modifications are made that are not expected to change model performance, this evaluation serves as additional testing and verification of the composite code update.) The new model package is reviewed and approved by management.

This model revision process respects the spirit of the formulation update process:

7.3.1.1 Developmental evaluation, internal peer review, and testing

Each model change (i.e., an incremental and internal modification to address a specific issue, rather than an official release of the model to the community comprising of multiple model changes) is tracked in a GitHub repository, so that code changes are clearly identifiable and can be reviewed by multiple members of the model development team. Each model change is tested using case-specific model runs by multiple members of the development team to confirm the model change addresses the specific need.

Figure 8. Snapshot of the GitHub repository used by EPA to track and manage code modifications and collaboration

7.3.1.2 Performance evaluation and sensitivity testing

When an updated version of the model is ready for release, the updated model is used for a large number of standard test cases (currently 71 cases) to benchmark model concentrations between model versions and various options in the model. These consequence analyses are documented in a spreadsheet that has been released with each model version since AERMOD version 12345. Furthermore, the model performance is evaluated using the 17 field databases used in the original model performance evaluation (Perry, et al, 2005). Several of the performance evaluations leverage the Cox-Tikvart protocol to perform a robust comparison of model versions and to delineate the best performing model and model options. In the recent update to the *Guideline*, the demonstration of the improved model performance

across these 17 databases using the Cox-Tikvart protocol served as the basis for the acceptance of the updated model promulgated through the update to the *Guideline* (US EPA, 2017). Descriptions of the databases can be found in Appendix A.

7.3.1.3 External peer review

EPA relies heavily on scientific peer review. The *Guideline* states that peer review is an essential piece of the model development process and that it ensures that the model development meets quality assurance standards and is applicable to the use in EPA's programs. The importance of scientific peer review for a preferred model is explicit in the *Guideline,* which states in Section 3.1.1a:

Refined models that are preferred and required by EPA for particular applications have undergone the necessary peer scientific reviews and model performance evaluation exercises that include statistical measures of model performance in comparison with measured air quality data as described in section 2.1.1.

Any formulation changes that are incorporated into the regulatory version of the model need to have sufficient scientific peer review. EPA relies on scientific development from the community (e.g., the adjusted u* option adopted in the recent revision to the *Guideline*), ORD (e.g., the replacement of CALINE3 with AERMOD was based on an ORD/OAQPS scientific journal article), and internal OAQPS input. When considering a formulation update to the model, EPA looks first at the state of scientific development on any aspect of the model formulation (as outlined in more detail in the section above).

7.3.1.4 Submission for consideration as a regulatory model.

Whenever there is a need to formally incorporate scientific formulation enhancements, the modeling system must be formally approved through the regulatory process, i.e., an update to Appendix A of the *Guideline*, as was proposed in 2015 and finalized in 2017. The public review and comment process accompanying the formal promulgation of the model further ensures that the model update appropriately improves model performance and meets the needs for application in EPA's CAA programs. This process will be initiated at the Twelfth Modeling Conference, where the next round of formulation updates to the AERMOD modeling system will be discussed. Based on those discussions, EPA will revise or create additional white papers on the potential formulation updates and continue to develop ALPHA and BETA options for evaluation by the community. From this feedback cycle, EPA can prepare the next rulemaking to update the *Guideline* and regulatory version of the model.

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Appendix A Description of AERMOD Evaluation Databases

The 17 databases used in AERMOD evaluations are briefly described in this section and summarized in Table 6. The stack heights, terrain complexity, urban/rural status, importance of downwash, inclusion of turbulence parameters, and meteorological data included for the database are listed for each area. The databases are arranged by the following hierarchy:

- Field studies that with and without site-specific turbulence measurements
- Within each of those categories, databases were ordered by complexity of terrain (complex or flat)
- Within those two categories, databases were ordered by increasing release height.

Table 6. AERMOD evaluation databases. Databases in gray are also subject to EPA's protocol for determining best performing model

Location	Stack heights	Urban/ rural	Terrain	Downwash	Turbulence parameters	Site specific AERMET inputs
Martins Creek	59, 76, 183 m	Rural	Complex	Yes	10 m σ_v, σ_w	10m wind, temperature; 90-420 m wind (every 30 m).
Tracy	91 m	Rural	Complex	No	σ_v, σ_w	10 and 50-400 m (every 25 m) wind, temperature
Lovett	145 m	Rural	Complex	No	σ_v, σ_w	10, 50, and 100 m wind, temperature
Westvaco	190 m	Rural	Complex	No	σ_v, σ_w	30, 210, 326, 366, and 416 m wind, temperature
DAEC	1 m, 24 m, 46 m	Rural	Flat	Yes	σ_v	Insolation, 10, 23.5 and 50 m wind, temperature
EOCR	1, 25, 30 m	Rural	Flat	Yes	σ_v	4, 10, and 30 m wind, temperature
Alaska	39.2 m	Rural	Flat	Yes	σ_v, σ_w	33 m wind, temperature
Indianapolis	84 m	Urban	Flat	No	σ_v, σ_w	Station pressure, net radiation, 10 m wind, temperature
Kincaid	187 m	Rural	Flat	No	σ_v, σ_w	Net radiation, insolation, 10 , 30, and 50 m wind, temperature
AGA	9.8, 14.5, 24.4 m	Rural	Flat	Yes	None	10 m wind and temperature
Millston	3 stacks 29 m (freon) 48 m (SF6)	Rural	Flat	Yes	None	10 m wind speed ; 43.3 m wind and temperature
Bowline	2 stacks 86.87 m	Rural	Flat	Yes	None	100 m winds and temperature
Baldwin	3 stacks 184.4 m	Rural	Flat	Yes	None[2]	10 and 100 m wind, temperature
Clifty Creek	3 stacks 207.9 m	Rural	Flat/Elev	No	None	10 m temperature; 60 m wind
Lee wind tunnel	64.8 m	Rural	Flat	Yes	None	10 m temperature; 64.8 m winds
Prairie Grass	0.46 m	Rural	Flat	No	σ_v, σ_w	U*, 1, 2, 4, 8, and 16 m winds and temperature

Appendix A.1 Martin's Creek

The Martins Creek Steam Electric Station is located in a rural area along the Delaware River on the Pennsylvania/New Jersey border, approximately 30 km northeast of Allentown, PA and 95 km north of Philadelphia, PA (Figure 9). The area is characterized by complex terrain rising above the stacks. Sources included multiple tall stacks ranging from 59 to 183 m in height, including Martins Creek and three background sources located between 5 and 10 km from Martins Creek. The seven SO_2 monitors were located on Scotts Mountain, which is about 2.5 - 8 km southeast of the Martins Creek facility. On-site meteorological data covered the period from May 1, 1992 through May 19, 1993. Hourly temperature, wind speed, wind direction, and sigma-theta (standard deviation of the horizontal wind direction) at 10 m were recorded from an instrumented tower located in a flat area approximately 2.5 km west of the plant. In addition, hourly multi-level wind measurements were taken by a sodar located approximately three km southwest of the Martins Creek station.

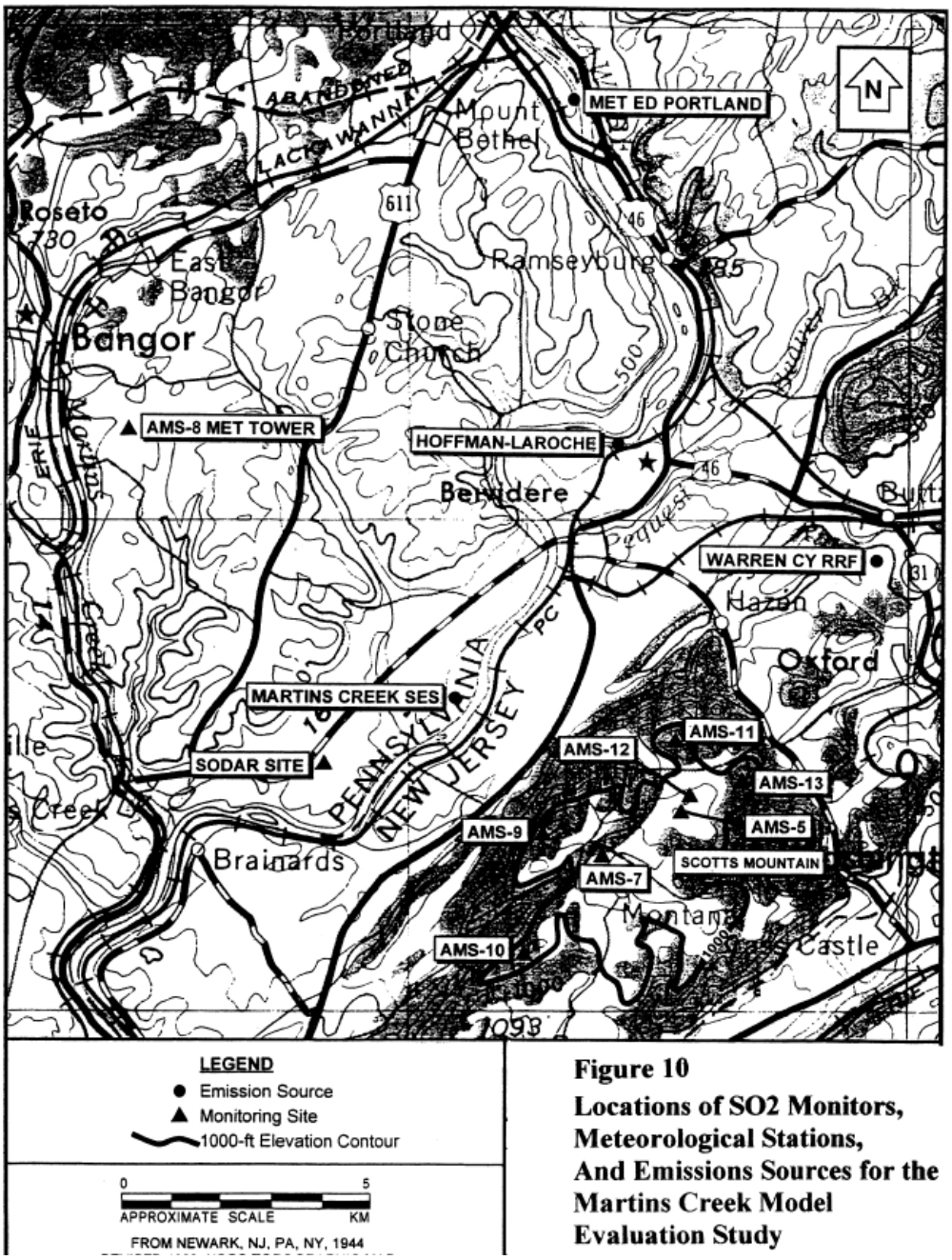


Figure 9. Martin's Creek study area

Appendix A.2 Tracy

The Tracy Power Plant is located 27 km east of Reno, Nevada in the rural Truckee River valley completely surrounded by mountainous terrain (Figure 9). A field tracer study was conducted at the power plant in August 1984 with SF_6 being released with the moderately buoyant plume from a 91-m stack. A total of 128 hours of data were collected over 14 experimental periods. Stable atmospheric conditions were dominant for this study. Site-specific meteorological data (wind, temperature, and turbulence) for Tracy were collected from an instrumented 150-m tower located 1.2 km east of the power plant. The wind measurements from the tower were extended above 150 meters using a Doppler acoustic sounder and temperature measurements were extended with a tethersonde.

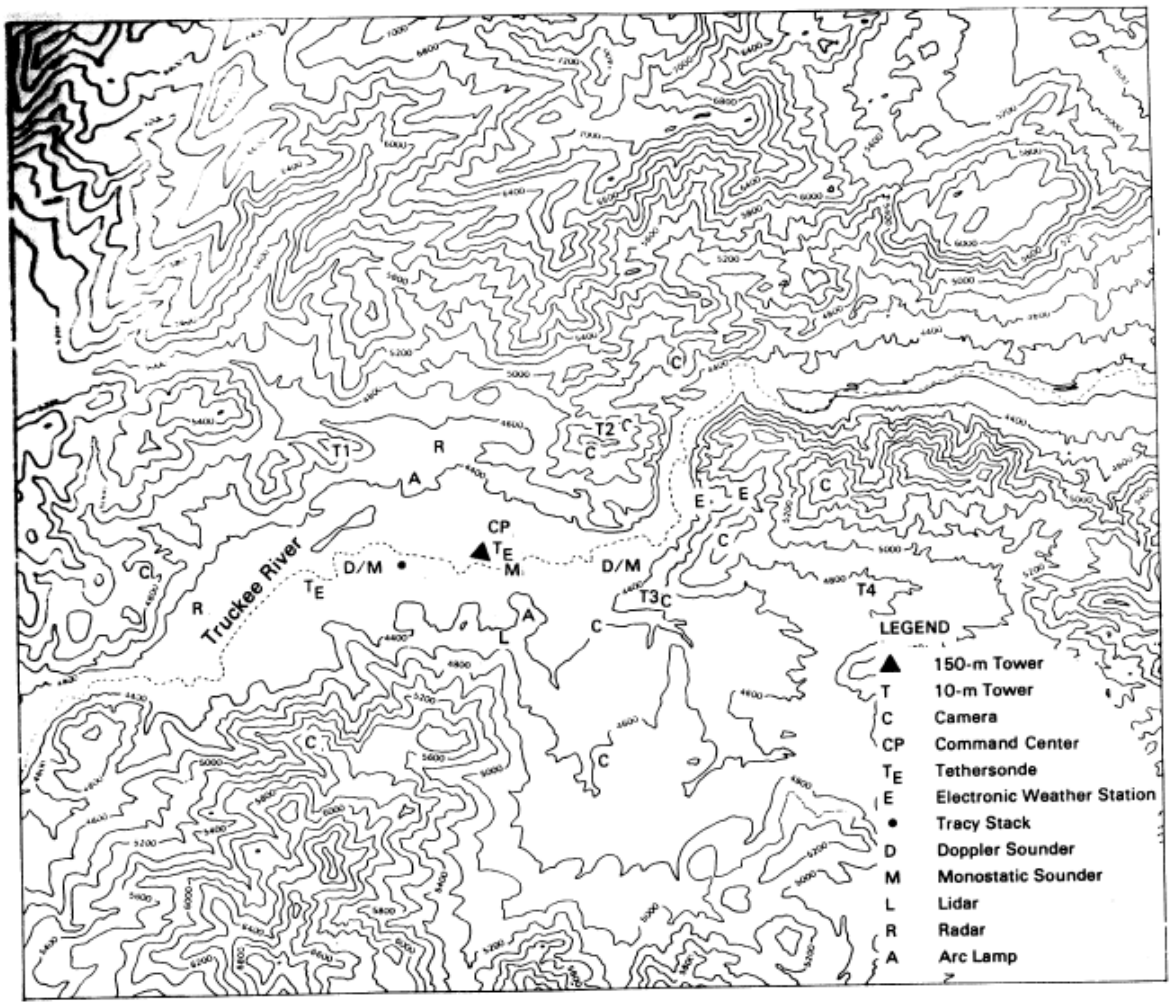


Figure 10. Tracy power plant study area

Appendix A.3 Lovett

The Lovett Power Plant study consisted of a buoyant, continuous release of SO_2 from a 145-m tall stack located in a complex terrain, rural area in New York State (Figure 11). The data spanned one year from December 1987 through December 1988. Data were collected from 12 monitoring sites (ten on elevated terrain and two near stack-base elevation) that were located about 2 to 3 km from the plant. The monitors provided hourly-averaged concentrations. The important terrain features rise approximately 250 m to 330 m above stack base at about 2 to 3 km downwind from the stack. Meteorological data include winds, turbulence, and ΔT from a towe instrumented at 10 m, 50 m, and 100 m. National Weather Service surface data were available from a station 45 km away.

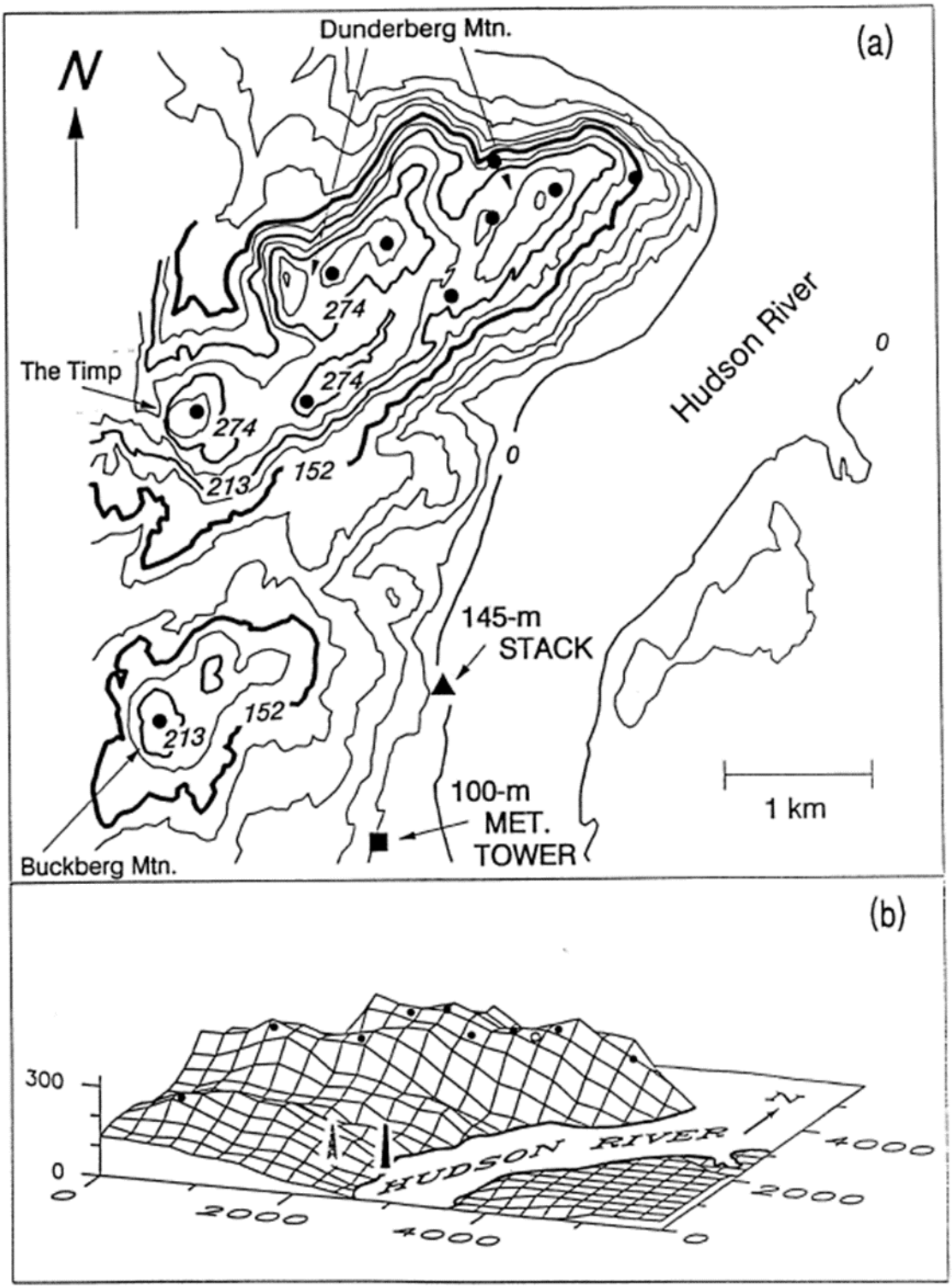


Figure 11. Lovett study area

Appendix A.4 Westvaco

The Westvaco Corporation's pulp and paper mill in rural Luke, MD is in a complex terrain setting in the Potomac River valley (Figure 12). A single 183-m buoyant source 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 m. Hourly meteorological data (wind, temperature, and turbulence) were collected between December 1980 and November 1991 at three instrumented towers: the 100-m Beryl tower in the river valley about 400 m southwest of the facility; the 30-m Luke Hill tower on a ridge 900 m north-northwest of the facility; and the 100-m Met tower located 900 m east-southeast of the facility on a ridge across the river.

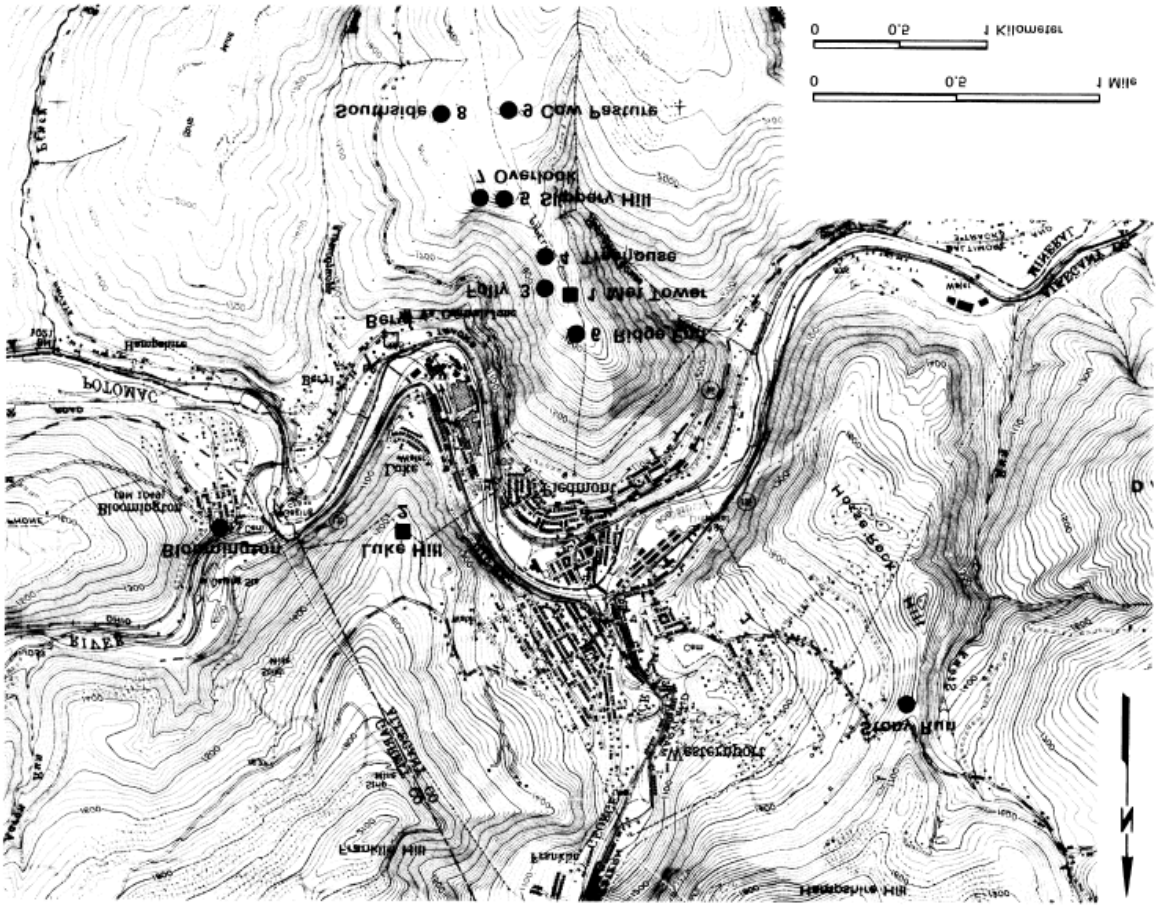


Figure 12. Westvaco study area

Appendix A.5 Duane Arnold Energy Center

The Duane Arnold Energy Center (DAEC) is located in rural Iowa, located about 16 km northwest of Cedar Rapids. It is located in a river valley with some bluffs on the east side. Terrain varies by about 30 m across the receptor network with the eastern half of the semicircular receptor arcs being flat and the western half elevated. The tracer study involved SF_6 releases from two rooftops (46-m and 24-m levels) and the ground (1-m level). Building tiers for the rooftop releases were 43 and 24 m high, respectively. The 1-m and 24-m releases were non-buoyant, non-momentum, while the 46-m release was close to ambient but had about a 10 m/s exit velocity. The number of tracer release hours was 12, 16 and 11 from the release heights of 46 m, 24 m, and 1 m, respectively. There were two arcs of monitors at downwind distances of 300 and 1000 m (see Figure 13). Meteorological data consisted of winds at 10, 24, and 50 m. The meteorological conditions were mostly convective (30 out of 39 hours), with fairly light wind speeds. Only one hour had a wind speed above 4 m/s (4.6), and almost half of the hours were less than 2 m/s.

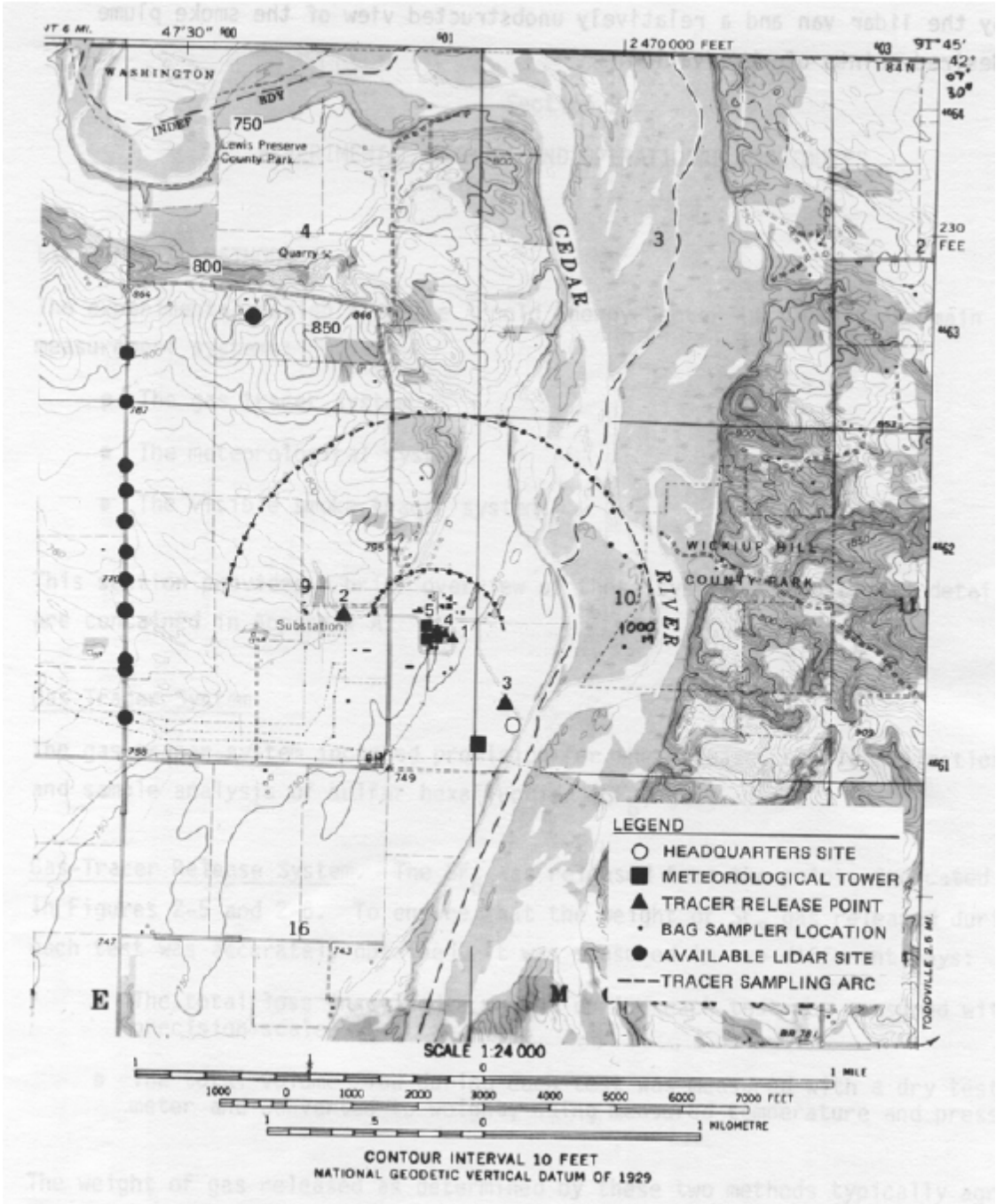


Figure 13. DAEC study area (SF6 releases)

Appendix A.6 Experimental Organically Cooled Reactor

The Experimental Organically Cooled Reactor (EOCR) study involved the simultaneous release of three tracer gases (SF_6, F_{12}, and Freon-12B2) at three levels around the EOCR test reactor building at the Idaho National Engineering Laboratory in Southeast Idaho. The terrain was flat with low-lying shrubs. The main building was 25 m high with an effective width of 25 m. The tracer releases typically occurred simultaneously and were conducted during 22 separate time periods. Tracer sampler coverage was provided at eight concentric rings at distances of about 50, 100, 200, 400, 800, 1200, and 1600 m from the release points (see Figure 14). The stability classes ranged from stable to unstable. The 10-m wind speeds for the cases selected ranged from 3 to 8 m/s.

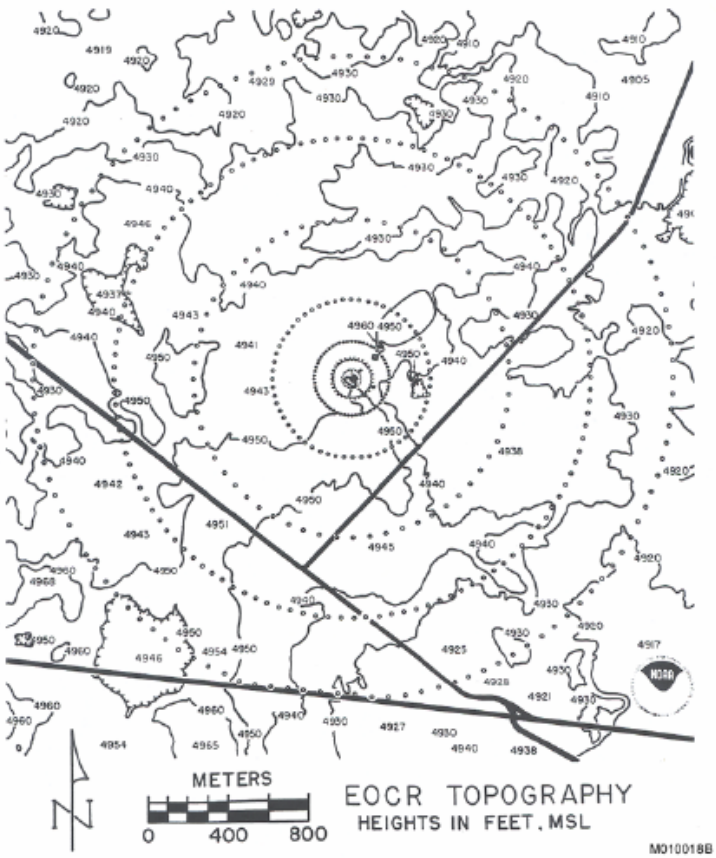


Figure 14. Terrain map featuring the entire EOCR grid with the source at the grid center (SF6 releases). Arcs are at distances of about 40, 80, 200, 400, 800, 1200, and 1600 m.

Appendix A.7 Alaska North Slope

The Alaska North Slope tracer study (see Figure 15) involved 44 hours of buoyant SF_6 releases from a 39-m high turbine stack. Tracer sampler coverage ranged over seven arcs from 50 to 3,000 m downwind. Meteorological data, including wind speed, wind direction, temperature, sigma-theta, and sigma-w, were available from an on-site tower at the 33-m level. Atmospheric stability and wind speed profiles were influenced by the smooth snow-covered tundra surface with negligible levels of solar radiation in the autumn months. All experiments (44 usable hours) were conducted during the abbreviated day light hours (0900 – 1600). Wind speeds taken at the 33-m level during the tests were less than 6 m/s during one and part of another test, between 6 and 15 m/s during four tests, and in excess of 15 m/s during three tests. Stability conditions were generally neutral or slightly stable.

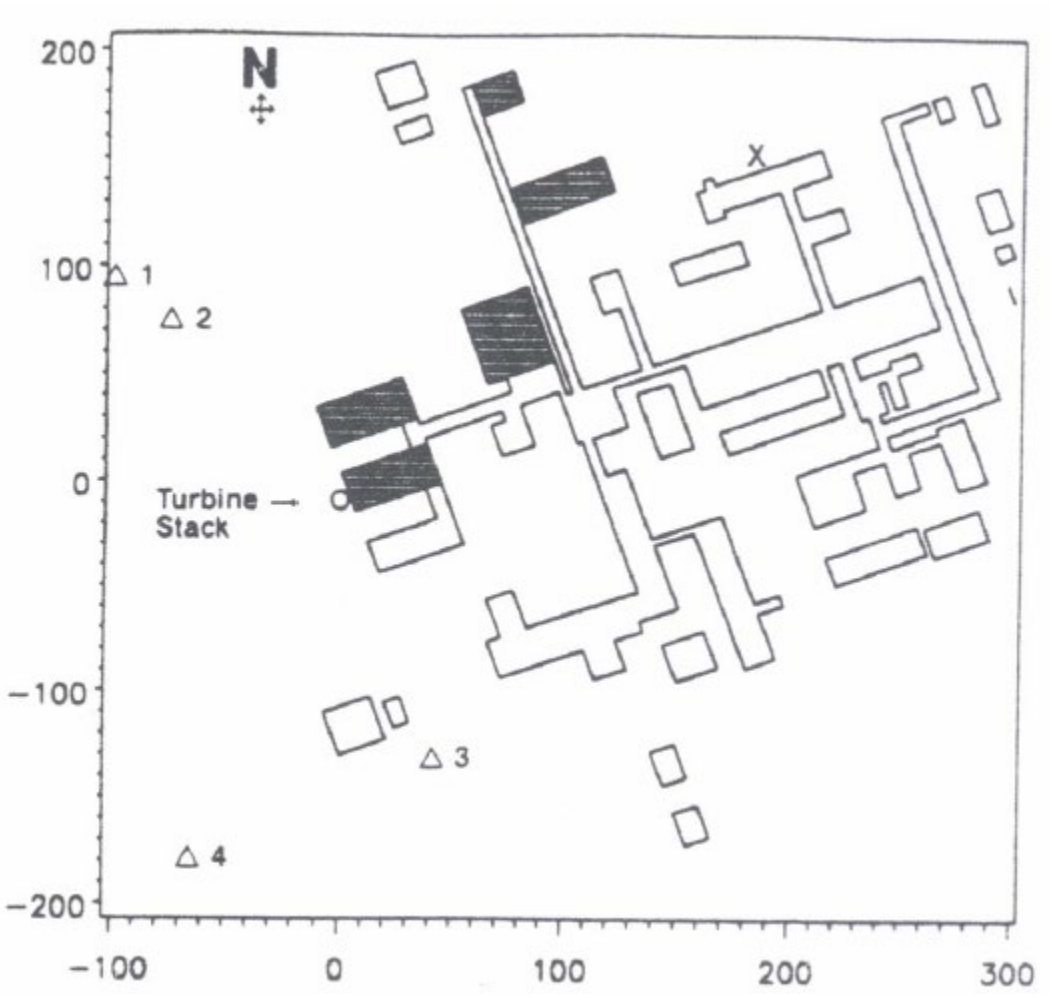


Figure 15. Depiction of Alaska North Slope Oil Gathering Center turbine stack, meteorological tower (X), and camera locations used to visualize plume rise.

Appendix A.8 Indianapolis

The Indianapolis study consisted of an elevated, buoyant tracer (SF6) released in a flat-terrain urban to suburban area from a single 84-m stack (Figure 16). Data are available for approximately a four- to five-week period with 177 monitors providing 1-hour averaged samples along arcs from 250 m to 12 km downwind for a total of 1,297 arc-hours. Meteorological data included wind speed and direction, sigma-theta on a 94-meter tower; and wind speed, ΔT (2m - 10m) and other supporting surface data at three other 10-m towers (Figure 17). Observed plume rise and estimates of plume sigma-y are also available from the database.

Figure 16. Map showing the location of the Perry-K Station (A), the Hoosier Dome (B), and the central Indianapolis business district (C). The downtown surface meteorological site is located at (D) and the "bank tower" site was on top of the building at (E).

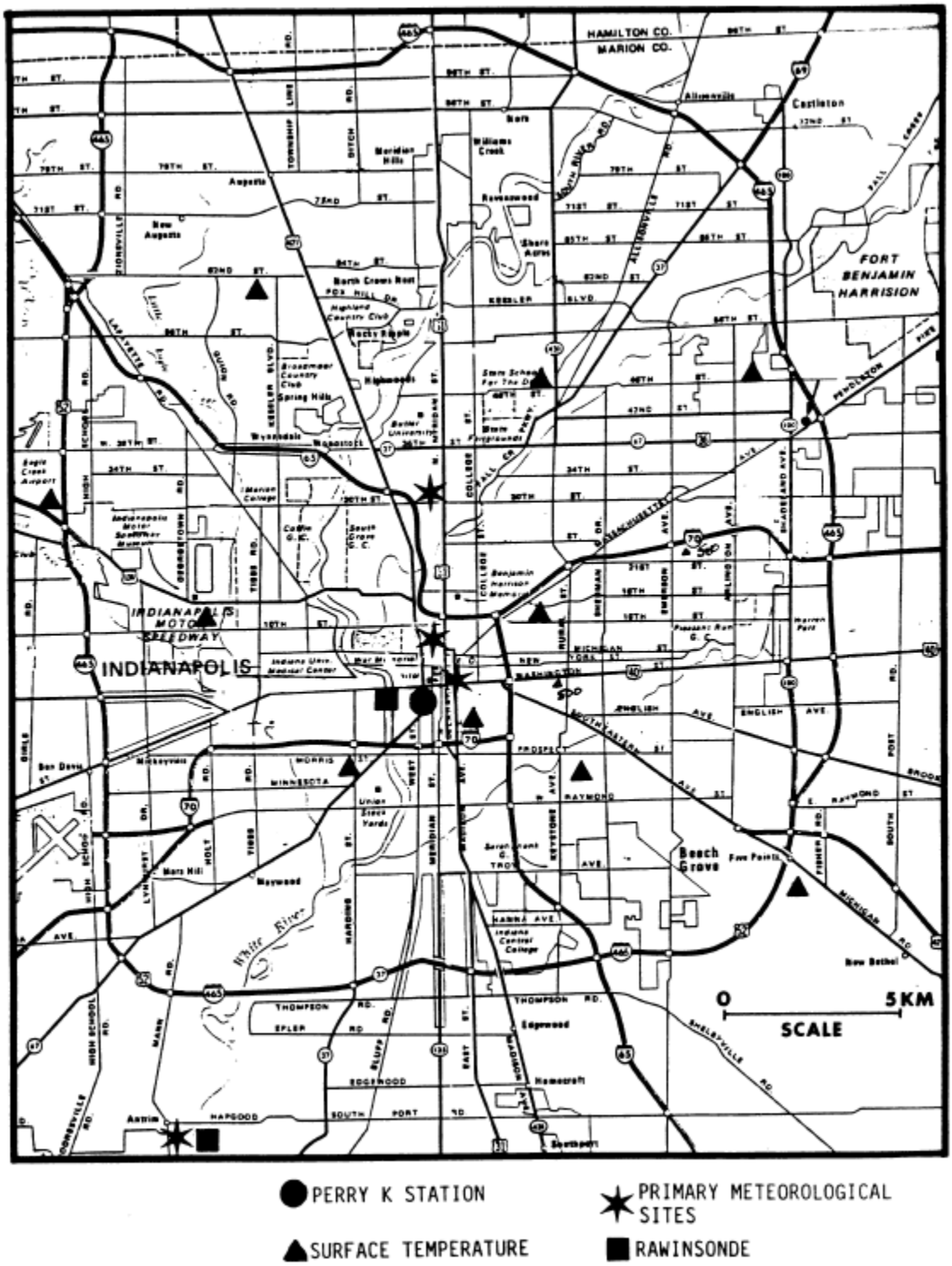


Figure 17. Indianapolis meteorological sites and emissions site (Perry K Station).

Appendix A.9 Kincaid

The Kincaid SO_2 study was conducted in a flat rural area of Illinois (Figure 18). It involved a buoyant, continuous release of SO_2 from a 187-m stack in rural flat terrain. The study included about six months of data between April 1980 and June 1981 (a total of 4,614 hours of samples). There were 30 SO_2 monitoring stations providing 1-hour averaged samples from about 2 km to 20 km downwind of the stack. Meteorological data included wind speed, direction, and temperature from a tower instrumented at 2, 10, 50, and 100 m levels, and nearby National Weather Service data. The SF_6 study (Figure 19) was episodic and covered the same time period as the SO_2 study. Note that while occurring in the same location and same time period, these are counted as two different studies in regard to the 17 evaluation databases.

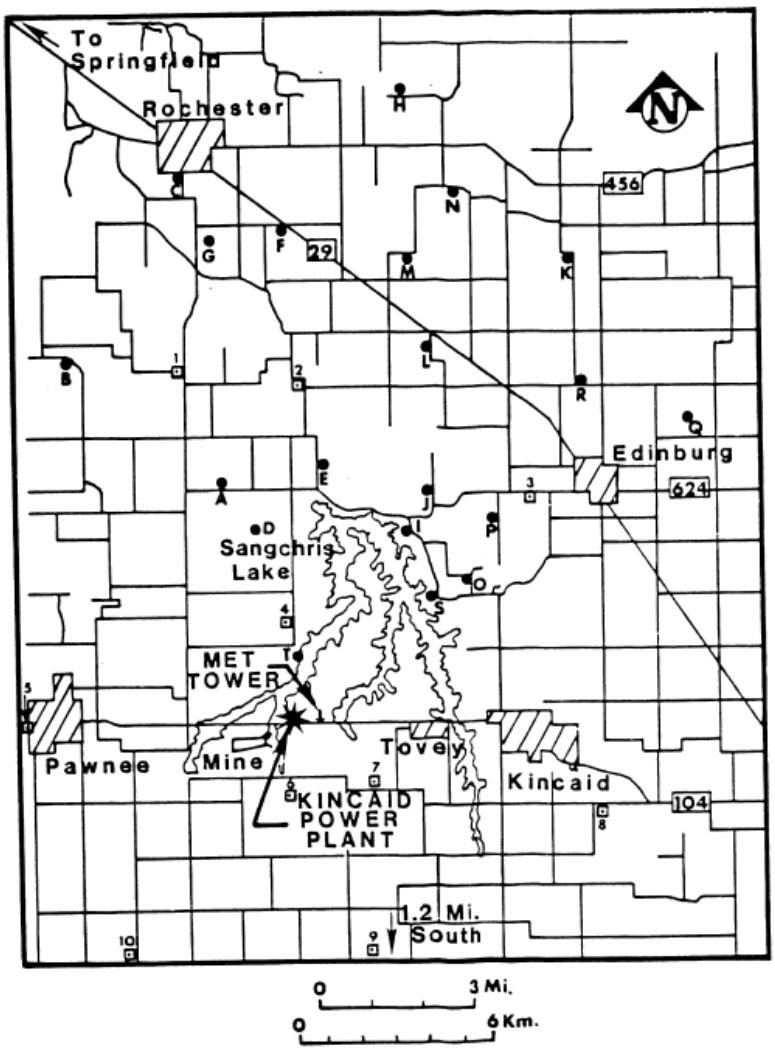


Figure 18. Kincaid study area.

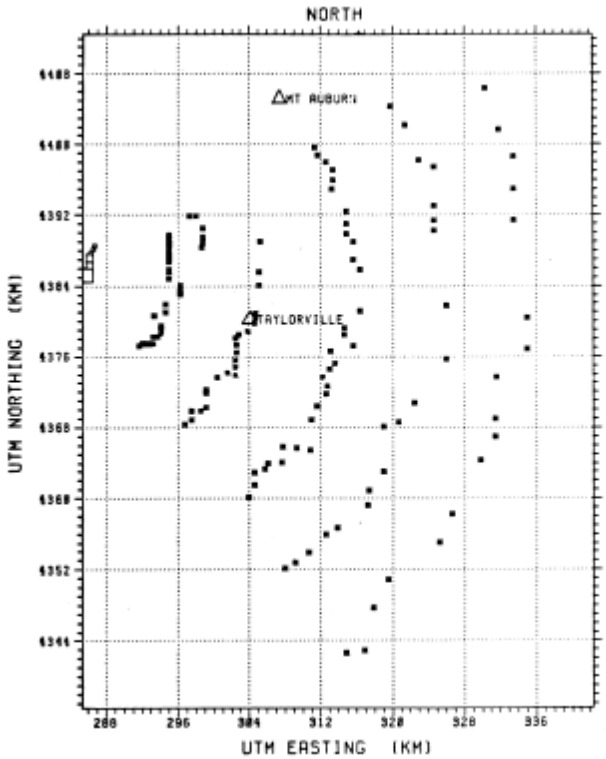


Figure 19. Kincaid SF6 monitoring locations.

Figure B-1.

Appendix A.10 American Gas Association

The American Gas Association (AGA) experiments occurred during spring and summer 1980 at gas compressor stations in Texas and Kansas. At each test facility, one of the gas compressor stacks was retrofitted to accommodate SF_6 tracer gas emissions. In addition, stack height extensions were provided for some of the experiments (with the normal stack height close to 10 m). The stack height to building height ratios for the tests ranged from 0.95 to 2.52. There was a total of 63 tracer releases over the course of the tests, and the tracer samplers were located between 50 and 200 m away from the release point (see Figure 20). An instrumented 10-m tower was operated at both experimental sites. The tracer releases were generally restricted to daytime hours. Stability classes range from neutral to extremely unstable, except for three hours that were slightly stable. Wind speeds range from 2 to 11 m/s over the 63 hours.

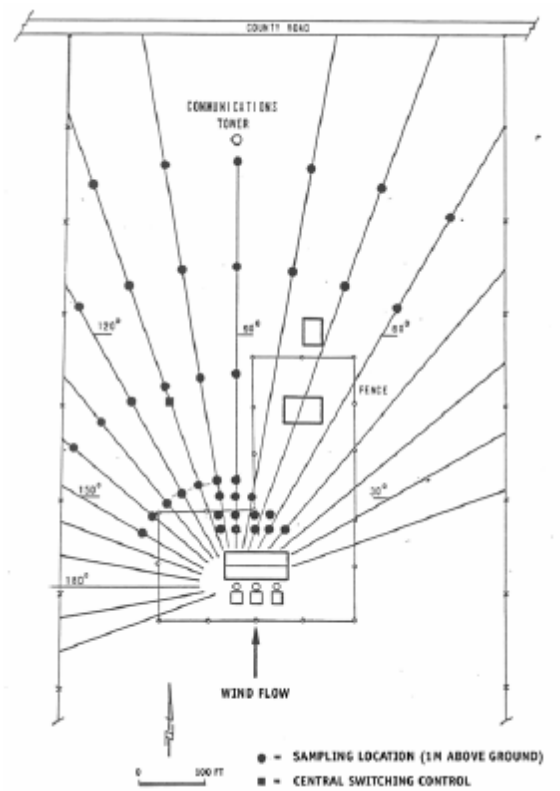


Figure 20. Plan view of the locations of tracer samplers at Site 1, AGA field study (SF6 releases).

Appendix A.11 Millstone

The Millstone nuclear power plant is located on the Connecticut coast, near Niantic. The model evaluation database features 36 hours of SF_6 emissions from a 48-m reactor stack and 26 hours of Freon emissions from a 29-m turbine stack. Exit temperatures were close to ambient (about 295K) with exit velocities of about 10 m/s for both the reactor stack (48.3 m) and the three turbine stacks (29.1 m). These stacks were associated with 45-m and 28-m building tiers, respectively. The monitoring data consisted of three arcs at 350, 800 and 1,500 m. Meteorological data were available from an on-site tower at the 10-m and 43-m levels. There was about an even split between stable and unstable hours, with mostly on-shore winds and fairly high wind speeds. There were only 3 stable hours with wind speed less than 4 m/s, and the majority was above about 7 m/s and several above 10 m/s. Figure 21 shows the layout of the study area.

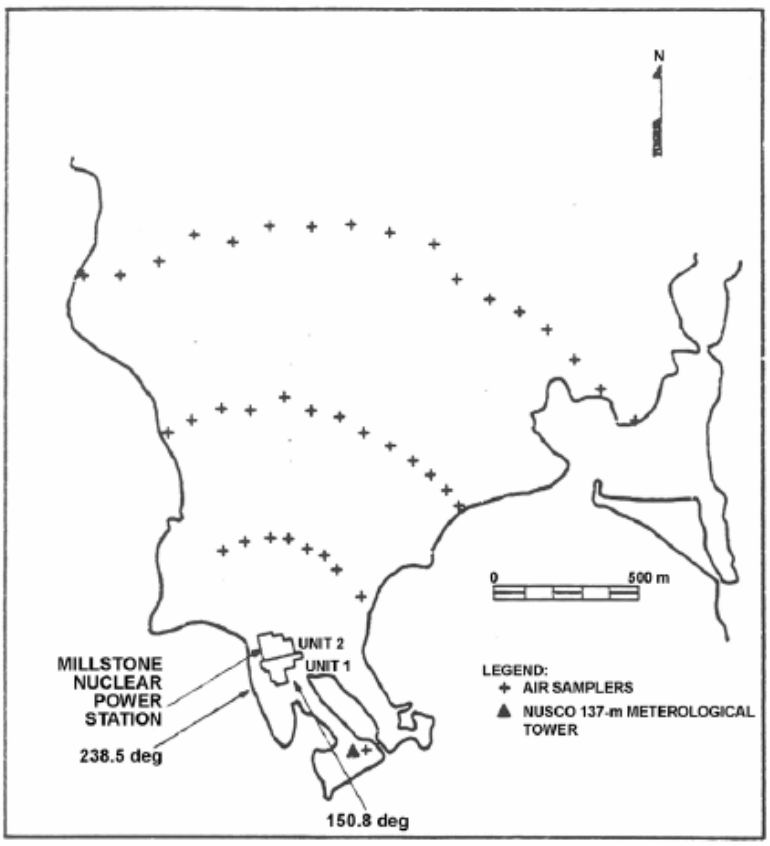


Figure 21. Millstone study area (SF6 and freon releases).

Appendix A.12 Bowline

The Bowline Point site, located in the Hudson River valley in New York State, is shown in Figure A-14 (topographic map). The electric utility site included two 600-MW units, each with an 86.9-m stack and a dominant roof tier with a height of 65.2 m high in a rural area. There were four monitoring sites as shown in Figure 22 that ranged from about 250 to 850 m from the stacks. Hourly emissions data was determined from load data, coal analyses, and site-specific relationships between loads and fuel consumption. Meteorological data was obtained from a 100-m tower at the site. This site was also used as an independent evaluation database with the entire year included.

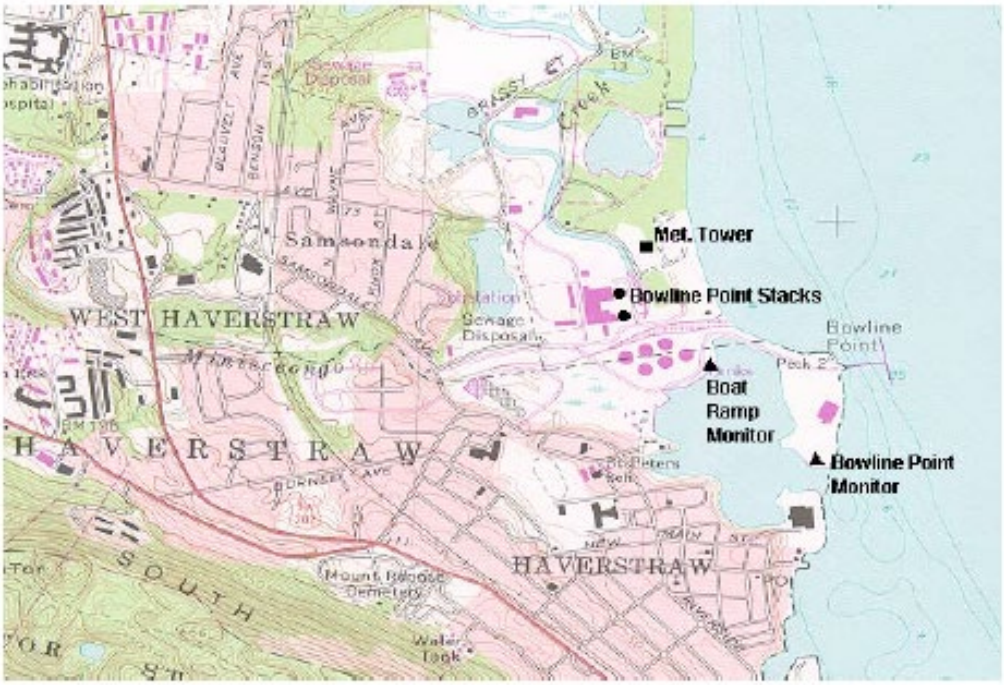


Figure 22. Bowline Point study area (SO2 releases).

Appendix A.13 Baldwin

The Baldwin Power Plant is located in a rural, flat terrain setting of southwestern IL and has three identical 184-m stacks aligned approximately north-south with a horizontal spacing of about 100 m (Figure 23). There were 10 SO_2 monitors that surrounded the facility, ranging in distance from two to ten km. On-site meteorological data was available during the study period of April 1, 1982 through March 31, 1983 and consisted of hourly averaged wind speed, wind direction, and temperature measurements taken at 10 m, and wind speed and wind direction at 100 m.

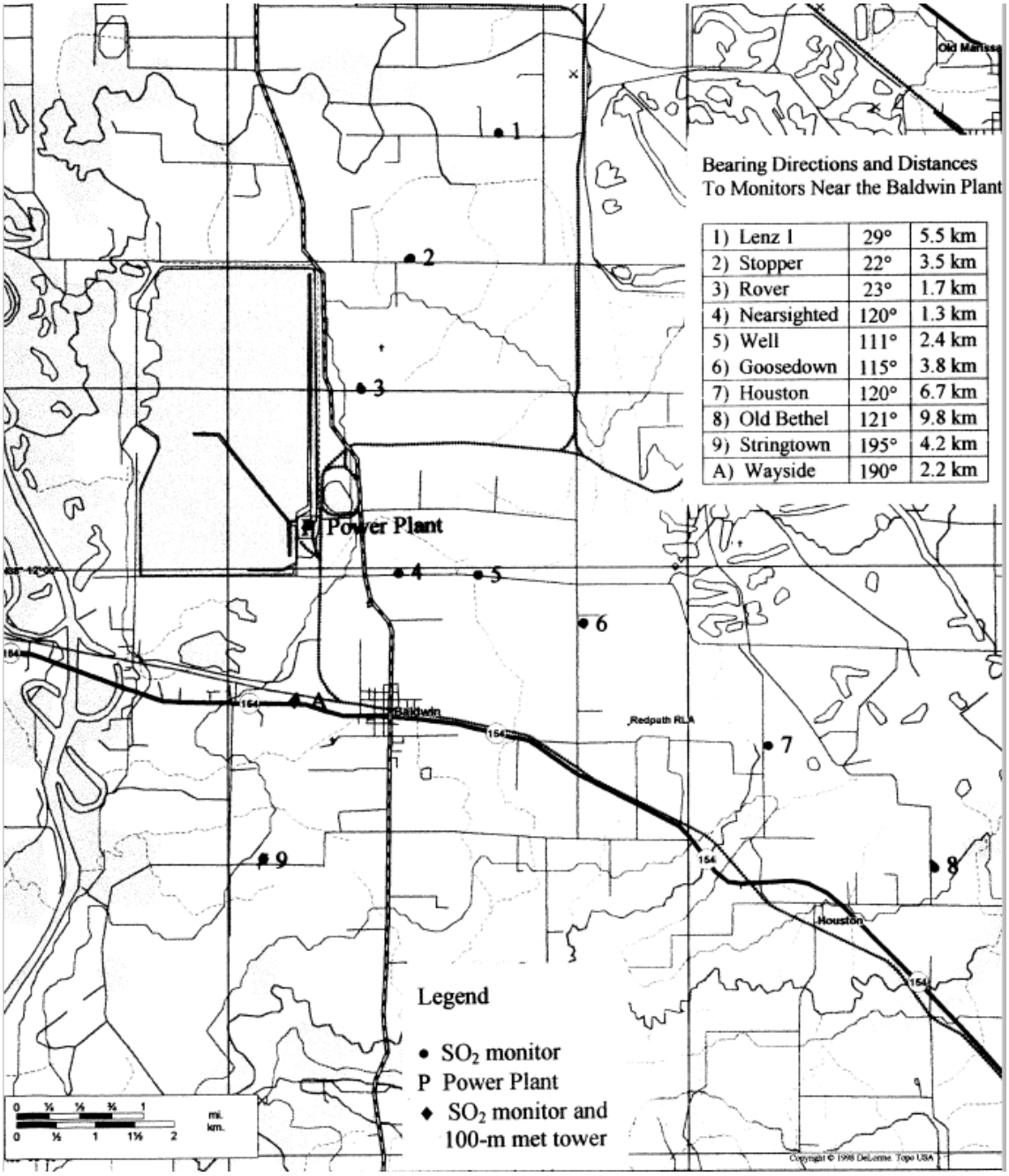
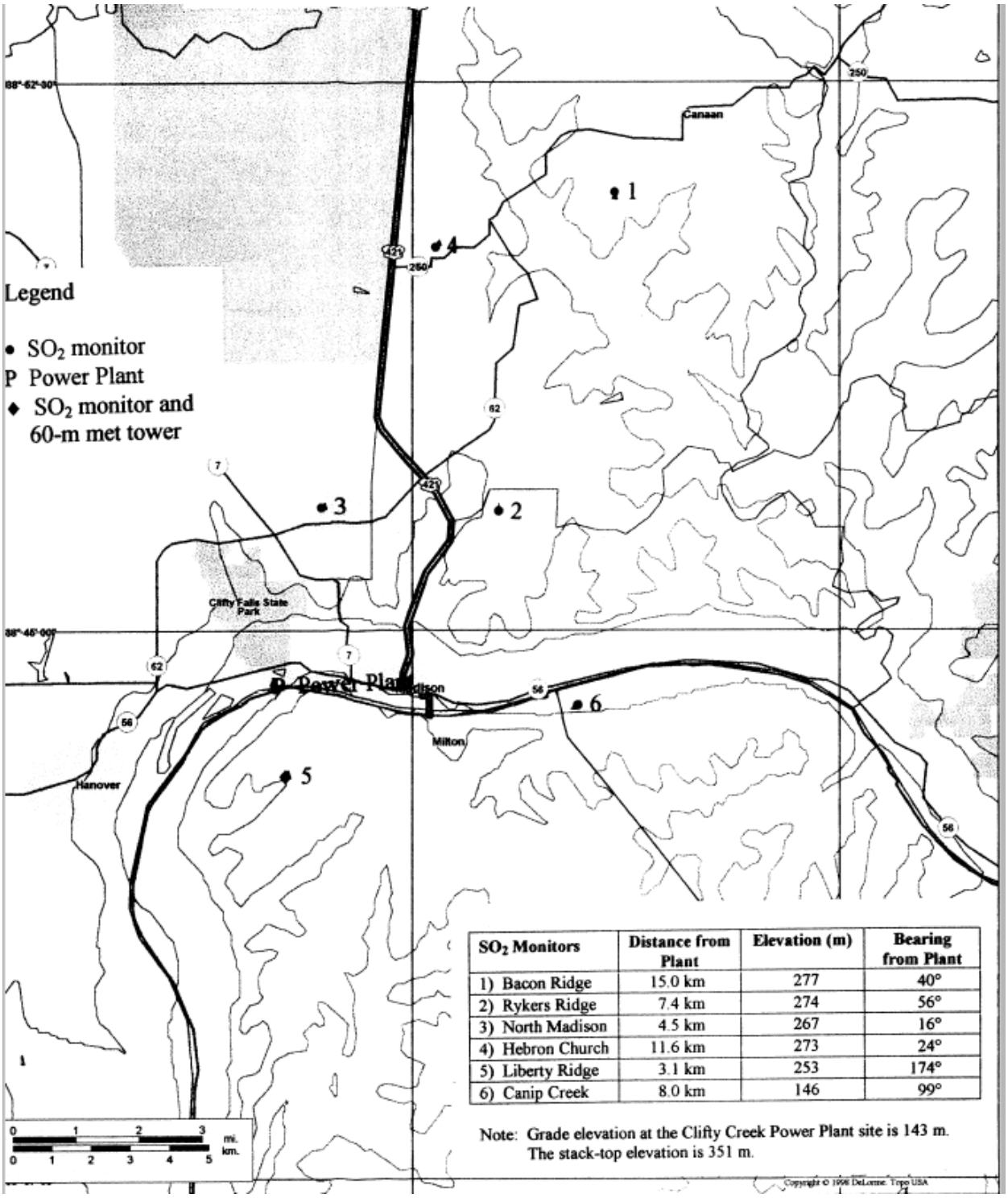


Figure 23. Baldwin study area.

Appendix A.14 Clifty Creek

The Clifty Creek Power Plant is located in rural southern IN along the Ohio River with emissions from three 208-m stacks during this study (Figure 24). The area immediately north of the facility is characterized by cliffs rising about 115 m above the river and intersected by creek valleys. Six nearby SO_2 monitors (out to 16 km from the stacks) provided hourly averaged concentration data. Meteorological data from a nearby 60-m tower covered the two-year period from January 1, 1975 through December 31, 1976, although only the data from 1975 were used in this evaluation. This database was also used in a major EPA-funded evaluation of rural air quality dispersion models in the early 1980s.



SO_2 Monitors	Distance from Plant	Elevation (m)	Bearing from Plant
1) Bacon Ridge	15.0 km	277	40°
2) Rykers Ridge	7.4 km	274	56°
3) North Madison	4.5 km	267	16°
4) Hebron Church	11.6 km	273	24°
5) Liberty Ridge	3.1 km	253	174°
6) Canip Creek	8.0 km	146	99°

Note: Grade elevation at the Clifty Creek Power Plant site is 143 m. The stack-top elevation is 351 m.

Figure 24. Clifty Creek study area.

Appendix A.15 Lee

The Lee Power Plant wind tunnel study featured releases from steam boiler stacks with a common height of 64.8 m, affected by a building tier with a height of 42.6 m. The world's largest fluid modeling study chamber at Monash University in Australia was used for these experiments (see plan view in Figure 25). Stable conditions were simulated by using an inverted model of the facility that was suspended from the ceiling of the tunnel. A stably stratified layer was developed along the tunnel by heating the inflowing air, and a buoyant plume was simulated by using a negatively buoyant gas mixture. A stable potential temperature lapse rate of 0.035 K/m was modeled with a stack-top real-world equivalent wind speed of 7 m/s with several wind directions being tested. In neutral conditions, stack-top speeds (at the 64.8-m level) ranged in real-world equivalents from 5 to 40 m/s. There were 78 combinations of wind direction, wind speed, and plume buoyancy tested for the neutral cases, and 14 combinations for the stable cases. The tracer sampler coverage included ground-level concentrations at six distances ranging from the cavity zone to beyond the wake (150-900 m). Since the actual Lee Power Plant area is rural, the models were run with a rural source characterization. The EPRI model evaluation considered both urban and rural source representations because of the enhanced turbulence levels present in the wind tunnel. Consistent with the EPRI model evaluation, the wind tunnel observations were adjusted from an assumed 5-minute duration to a full hour using a time-dependent 1/5 power law.

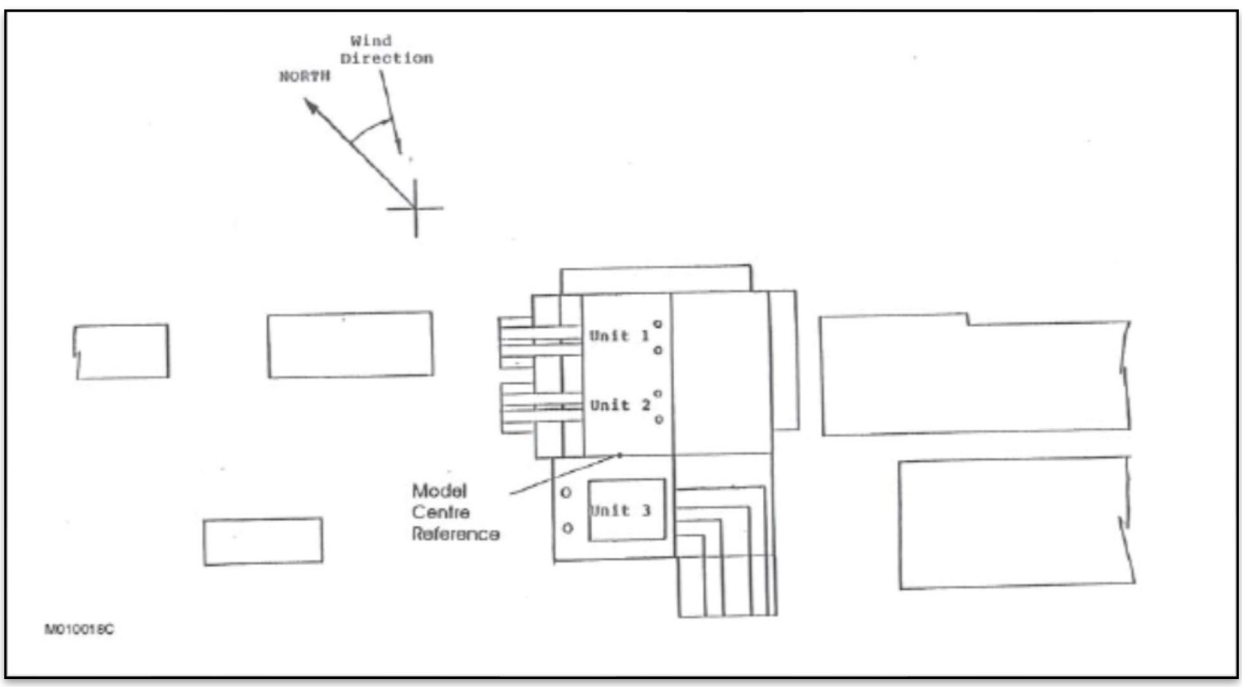


Figure 25. Plan view of the Lee Power Plant model.

Appendix A.16 Prairie Grass

The Prairie Grass study (Figure 26) used a near-surface, non-buoyant tracer release in a flat rural area in NE. This 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 the 2-m level wind direction and speed, the root-mean-square wind direction fluctuation, and the temperature difference (ΔT) between 2 m and 16 m. Other surface parameters, including friction velocity, Monin-Obukhov length, and lateral plume spread were estimated. Wind, turbulence, and temperature were obtained from a multi-leveled instrumented 16-m meteorological tower. A total of 44 ten-minute sampling periods were used, including both convective and stable conditions.

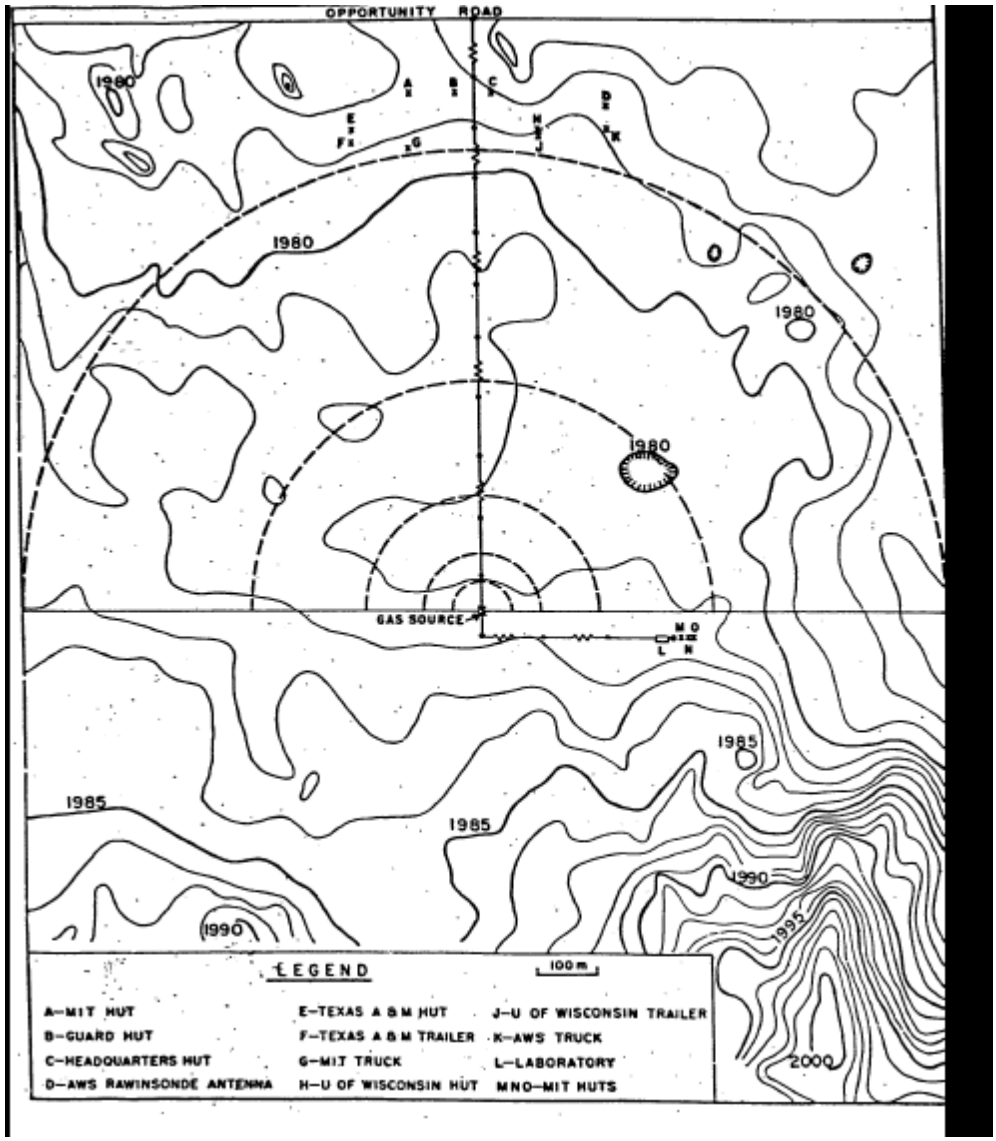


Figure 26. Prairie Grass study area.

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