

Studies on Mathematical Models for Characterizing Plume and Drift Behavior From Cooling Towers

Executive Summary

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From Cooling Towers
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**CS-1683-SY
Research Project 906-1**

Summary Report, April 1981
Work Completed, December 1979

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ABSTRACT

This report summarizes the contents of a five-volume work on new models for predicting plume rise and drift deposition from single and multiple natural-draft and mechanical-draft cooling towers.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Argonne National Laboratory is performing an effort to develop, improve, and validate mathematical models of cooling tower plumes. Emphasis is being placed on prediction of visible plume trajectory and deposition of saline droplet drift from the tower. Visible plumes and saline drift are environmental impacts of cooling towers that must be considered in power plant siting studies and licensing. A validated mathematical model of plume dispersion provides the industry with the tool required to make an assessment of environmental impact of the cooling tower.

This interim report, in five volumes plus an executive summary, describes results accomplished to date:

- Executive Summary--Overview
- Volume 1--Review of European Research
- Volume 2--Single-Source Model
- Volume 3--Drift Modeling of Single Sources
- Volume 4--Multiple-Source Model
- Volume 5--Drift Modeling of Multiple Sources

In a continuing effort, emphasis is being placed on developing a master model that is user-oriented and designed specifically for siting and licensing studies.

PROJECT OBJECTIVES

The goal of this effort is to develop, improve, and validate mathematical models of cooling tower plume dispersion for individual and clustered mechanical- and natural-draft cooling towers. The overall goal is to provide the utility planner with a tool for studies involving the environmental impact of cooling tower plumes.

PROJECT RESULTS

A model that has been developed and validated has prediction capabilities that are superior to other available mathematical models of cooling tower plume dispersion.

For example, in 77 percent of all cases of single sources that were studied, the model predicted a visible plume rise within a specified accuracy. This was the best performance among all available models (over a dozen) that were investigated.

This effort has also produced a useful review and summary of European research on cooling tower plume dispersion (Volume 1). Workshops in the fall of 1981 and in 1982 are being planned to disseminate to the industry the computer code that is being developed.

This series of volumes should be of value to utility planning engineers concerned with the impact of cooling tower plumes on plant siting.

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EXECUTIVE SUMMARY

This report, bound in five volumes, presents new models for predicting plume rise and drift deposition from single and multiple natural-draft and mechanical-draft cooling towers. These new models contain improved theory and compare better with field and laboratory data than do previous models largely because model improvement was based on an extensive analysis of available data as well as a detailed evaluation of earlier theories. At the present time, these models are being included in a systematic methodology for preparing seasonal and annual plume and drift environmental impact predictions. Our ultimate objective is to provide utilities with computer models which can accurately predict the impacts of cooling tower plumes and drift at reasonable cost and consistent with the reliability of existing data.

The model improvement work presented in these five volumes builds on our earlier evaluation of the theory and performance of over 30 plume and drift models available to utilities for preparation of their Environmental Reports. That earlier study, carried out for the U.S. Nuclear Regulatory Commission during the period of 1976 to 1978, was limited to the ad hoc evaluation of models to satisfy the immediate needs of the Commission staff and did not permit the modification of models to improve their predictive capability. The evaluation revealed that no single model predicted well over the full range of available data, although certain modeling approaches emerged as clearly superior to others. These results, coupled with a growing availability of field and laboratory data suitable for model development, made it possible to identify several key steps toward model improvement. We felt strongly that the gap which existed between the predictive capability of even the best of the available models and the body of observational data could be significantly reduced. Under EPRI sponsorship, we undertook a two-year program to develop, by identifying the best modeling hypotheses, new models which could be confidently used to predict the behavior of cooling tower plumes and drift.

We shall now summarize the contents of the report.

VOLUME 1

Volume 1 contains a critical review of pertinent European research related to cooling tower plume and drift prediction. These studies, which are not well known in the U.S. because of distance and language barriers, provided a great deal of useful information for our model development program. Our review was written to enable the U.S. utility engineer to obtain a brief overview of the relevant European research in an easy-to-use reference. Included among the work covered in Volume 1 are:

(a) laboratory data from Electricité de France (EDF) providing basic parametric studies on plume dispersion from one, two, and four towers of natural-draft type (The data on plume trajectory and dilution show the important influence of the wake of the tower structure in increasing plume bending and increasing dilution under larger winds);

(b) visible plume field data from Gardanne, Lünen and Neurath (supplemented by ambient profiles and tower-exit measurements) providing, in total, 24 new cases for use in model validation and improvement studies;

(c) an empirical formula for liquid water (recondensate) emission from natural- and mechanical-draft cooling towers. (We have used this formula to estimate liquid water emission for cases in which the rates were not measured.);

(d) European plume models. (These models provided some new insights on modeling hypotheses.);

(e) a two-year climatological study at a large power plant to determine the long-term physical and biological impacts of cooling towers;

(f) field measurements of the potential health risk due to bacterial emission from several German cooling towers using waste water; and

(g) in-plume measurements at the Neurath and Meppen sites.

VOLUMES 2 AND 4

Volume 2 discusses the theoretical development, calibration and verification of the ANL (EPRI) single-tower plume model. Our testing and evaluation of previous models revealed the following significant weaknesses in existing models:

(a) Proper Balance between Dilution and Bending

Plume air exiting the cooling tower mixes with ambient air and, as a result, gradually loses visibility as it moves upward under the influence of buoyancy and away from the tower under the influence of the wind. Both field and laboratory data show that the amount of dilution determined from a simple mixing analysis using the observed plume trajectory exceeds the amount of dilution obtained from a similar analysis based on the visible plume length. Thus, a viable plume model must include some mechanism to yield a rate of bending much greater than the rate of dilution.

(b) Treatment of Moisture Thermodynamics

Under most atmospheric conditions, the thermodynamic effects arising from condensation or evaporation of liquid water within the plume are insignificant. However, in about 20% of field cases, both the predicted visible plume length and visible plume rise can be appreciably affected by the treatment of thermodynamics. We found that those models which assume that condensation occurs whenever the bulk temperature and vapor content of the plume exceeds saturation will predict plumes which rise too rapidly due to excessive condensation heating. On the other hand, models which suppress condensation phenomena cannot predict the long, high and voluminous plumes that occur under certain atmospheric conditions. A correctly balanced treatment of moisture thermodynamic is essential to a good plume model.

(c) Tower Wake Effects

Our analysis of the field data revealed that significant downwash effects occur about 25% of the time. Visible plume outlines for the 39 single NDCT data sets in our data base showed that the visible plume dropped below tower-exit height whenever the ratio of wind speed to tower-exit velocity exceeds about 1.5. Evidence, especially clear in laboratory data, shows that in this region the tower wake plays an important role in increasing plume dilution. The effects of the tower wake must be properly handled for a model to predict well over the full range of wind speeds.

(d) Effects of Atmospheric Diffusion

The importance of treating atmospheric diffusion is underscored by the fact that for 10 of the 39 single NDCT plumes and virtually all plumes from the multiple NDCT's at the Amos site, plume length is determined by atmospheric diffusion after the plume has reached maximum rise.

Recognizing the above problem areas, we formulated a generic integral plume model to allow us to freely compare a variety of modeling hypotheses. As do all integral models, our model numerically solves a set of ordinary differential equations governing plume properties such as mass flow rate, temperature and vapor content as a function of distance along the plume trajectory. Modeling hypotheses were selected on the basis of providing the best qualitative agreement with systematic behaviors evident in the data. Specific values of the modeling coefficients were then chosen to provide the best overall agreement with the total data base, including both laboratory and field data from a wide variety of configurations. The model was also tested with new data not part of the calibration base and found to perform well.

To assess the relative performance of the ANL model, we have compared it with 5 other models which can handle both single and multiple tower configurations and which were also calibrated to all or part of our data base by their developers.

In predicting visible plume rise, the ANL model showed the best performance among the competing models in terms of all of our statistical measures of predictive capability. In roughly 77% of the cases, the ANL model predicts visible plume rise within a factor of 2. The model showed its greatest weakness for short plumes, cases for which errors in prediction are more acceptable. However, given the uncertainty in the data, the superiority of the ANL model over the second best performing model (KUMULUS) is not statistically significant. Both models do well and, with respect to the field data, may be considered on a par in predicting visible plume rise.

For visible plume length, the ANL model predicts within a factor of 2 (our value for an acceptable prediction within the limits of modeling and data uncertainties) approximately 60% of all field cases tested. Although this is only on par with the top models in terms of this single statistic, the ANL model is much less prone to gross over- or under-prediction (say, more than a factor of 5 in error) than the other models tested. A significant decrease in the number of very bad predictions comes at the price of a slight decrease in the number of very good predictions.

In comparisons with laboratory data, the ANL model is clearly superior to all tested models.

Volume 4 of the report describes the development and verification of the ANL multiple-source model, which is an extension of the single source model to include a physically sound merging scenario and a realistic analysis of tower downwash. The model has been calibrated with a limited amount of laboratory data and verified with field data and additional laboratory data.

Our merging methodology is a modification of the treatment developed by Wu and Koh. (1976). The Wu-Koh method is essentially a geometric treatment in which a merging plume is represented by a finite-length slot jet capped on each end by a half-round jet. Various criteria are presented to determine the exact location at which the two plumes have merged, the shape of the merged cross-section, and the fluxes of the merged plume in relation to the fluxes of the individual plumes prior to merging. The Wu-Koh treatment of merging satisfies two important physical constraints:

(i) for cases in which the wind is directed in line with a row of sources, the plume will rise higher after merging than for the identical case in which the wind is directed normal to a row of sources.

(ii) predicted plumes begin as round plumes, merge into more elliptical shapes, and finally evolve back into a round plume.

The downwash treatment in the multiple source model extends the methodology included in the single-source model to handle the more complex wakes produced by multiple NDCT structures and rows of MDCT cells.

Comparisons with the multiple NDCT data from Amos and Neurath show very good plume rise predictions with only a slight tendency to underpredict rise when observed plumes are high. Predictions of visible plume length are also good with, again, a slight tendency to underpredict the very longest plumes. Among all multiple tower models tested (5 in total), the ANL model shows the best predictive capability.

It must be emphasized that our goal is to achieve a model which not only can handle all situations of practical interest but which does so without the need to recalibrate the model parameters for each new situation. The success of the ANL model in comparisons with the broad base of observational data which we have assembled supports our belief that the ANL model can be confidently used over a wide range of applications and indeed, represents our best hope, for treating the large new plants with cooling towers.

VOLUMES 3 AND 5

Volumes 3 and 5 describe the development and performance of our improved drift deposition models for single and multiple sources, respectively.

A drift deposition model can be viewed as consisting of four basic submodels: plume, breakaway, evaporation and deposition. The development and validation of the plume models are discussed in detail in Volumes 2 and 4 of the report as outlined earlier. Therefore, Volumes 3 and 5 deal with our work in the remaining three areas and the testing of the drift model as a whole.

Our extensive analysis of droplet evaporation began with an examination of six formulations used in the available drift models. We found that the disparity among predictions was great and that many models involved simplifying assumptions that yielded errors in evaporation rates, distances to deposition, and final

particle characteristics of many fold. The treatments of dry particle formation from the drift drops were found to be grossly in error in terms of theory; in terms of performance, the models compared poorly with available laboratory data on particle drying rates.

Based upon the knowledge gained in the above-mentioned comparisons of existing evaporation submodels, we undertook the development of an improved analysis of drop dynamics and thermodynamics which was incorporated into our drift model. Starting from sound physical principles and calling upon previous experimental studies of drop evaporation, we have developed an analysis which avoids the arbitrary simplifications inherent in most of the earlier models. Important features of this model are: (a) it treats all the dynamic and thermodynamic phenomena characterizing an evaporating drop, (b) it uses proven correlations for heat and mass transfer coefficients, (c) all properties are considered to be temperature, and if appropriate, salt concentration or vapor concentration dependent, (d) it considers salt gradients internal to the drop and their effects on evaporation, precipitation, and desiccation, and (e) the drop model permits fully three-dimensional ambient conditions to be utilized. For drops reaching their final state, the present model predicts the point of deposition further from the tower than any of the other existing models tested. That result is due to the fact that the final state is actually a porous particle that is hollow inside instead of a commonly-assumed solid crystalline particle, a result consistent with observational data.

A third area of detailed evaluation and improvement is the treatment of droplet deposition. A number of drift models employ the Ballistic-Gaussian approach to handle droplet dispersion in a field of ambient turbulence. Our study of those deposition formulations shows that most are unvalidated, do not conserve mass, and do not give the correct qualitative behavior when parameters such as wind speed are changed. Considering these deficiencies in the available deposition formulations, the following advancements and improvements have been made: (a) a basic nondimensionalization of the deposition problem has been developed which reduces the number of parameters that must be considered and has allowed clearer insight into the effects of different variables, (b) a Monte Carlo simulation has been developed which will serve as a standard of comparison, and (c) a sensitivity study has been carried out with the Monte Carlo model in order to gain insight into the effect of nondimensional parameters on deposition patterns. Our drift model will continue to employ the Ballistic approach until work on a cost-effective and accurate methodology can be completed.

Droplet breakaway refers to the point at which the drop is visualized to be just free of the plume influence and moving within the ambient, although it is doubtful whether such an idealized point exists. The test used to determine if the drop experiences a "plume" or an "ambient" environment is known as the breakaway criterion. Four common breakaway criteria along with a new method of continuously varying the drop environment were studied using the plume, evaporation and deposition submodels as described above. Significantly different predictions of breakaway points and distances to deposition were found for drops in the diameter range of 100-850 microns. Below 100 μm , evaporation occurs so rapidly that the breakaway criterion does not materially influence drop behavior. Similarly, above 850 μm , evaporation proceeds so slowly and is so rapid that the effects of the breakaway criterion are small. Lacking data by which to test the breakaway criterion separately, the choice of breakaway method for use in the improved drift model was made based on comparisons which field data as will now be briefly outlined.

The improved drift model with five possible breakaway criteria (user selectable) was tested with data from the 1977 Chalk Point Dye Tracer Study. This study, which provided the best data on cooling tower drift deposition presently available, involved the use of a fluorescent dye in the cooling tower/condenser water flow so as to be able to distinguish cooling tower drift deposition from other sources such as the stack at the plant. Model predictions of sodium deposition flux, liquid mass deposition flux, number drop deposition flux, and drop diameter at deposition were compared with measured values at 500 and 1000 m from the tower. The study showed that the ANL model performed best with (a) the method of breakaway which provided a continuous variation of drop environment and (b) the simpler "radius" criterion, in which the drop adjusts suddenly from plume to ambient conditions at the point where the drop has settled below the centerline a distance equal to the local plume radius. The "radius" criterion was thus selected for its simplicity although both methods performed equally well; the user may choose a continuous variation of drop environments as an option.

The improved drift model performed well with the Chalk Point data. Performance of the ANL single source drift model may be given in terms of a rough statistic: a model succeeds in its prediction of drift at a given sampler if that prediction is within a factor of three of the measured data. If we do not distinguish between successes and failures among different deposition indicators (sodium deposition flux, number drop deposition flux, average diameter, and liquid mass deposition flux), we find that the ANL model with either of the two breakaway criteria noted above had 24 successes of 26 individual sampler comparisons. This

good performance was with field data taken at downwind distances of 0.5 and 1.0 km. The single source model is untested for distances greater than 1.0 km due to the lack of good-quality field data at those distances.

The multiple-source drift model was tested using data on ground-level sodium deposition flux taken at Pittsburg, California, a site with two mechanical-draft cooling towers of 13 cells each. Although these data are the best available for multiple sources, they do suffer in that: (a) the droplet spectrum and tower liquid emission rate were not measured in detail sufficient for definite model validation, (b) ambient profiles of wind speed, humidity, and temperature were periodically taken for some dates; on other dates, only ground-level measurements are provided, and (c) large wind speeds led to smearing of drops on sensitive papers at ground level raising questions as to the accuracy of the drop size measurements.

Model/data comparisons revealed that except for one date (of five), our model predicted sodium deposition within a factor of 3, or 50% of all samplers over the four survey dates. Future improvement work on our multiple source plume and drift model will involve an attempt to determine under which multiple-tower conditions, simplifications in the model (and computer code) are warranted.