Distribution Category:
Heat Rejection and Utilization (UC-12)

ANL/ES-53

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

ATMOSPHERIC IMPACTS OF EVAPORATIVE COOLING SYSTEMS

by

James E. Carson

Division of Environmental Impact Studies

October 1976

PREFACE

This document was prepared as a result of work conducted at Argonne National Laboratory during an ongoing research program on the environmental effects of power-plant cooling systems, under the auspices of the U. S. Nuclear Regulatory Commission (NRC). It is a "generic" report in that it deals with the atmospheric effects of cooling system in general rather than those associated with a specific plant. The author has endeavored to summarize the results of the known atmospheric effects of cooling systems, basing his conclusions on five years of experience in the preparation of environmental impact statements for the NRC, together with extensive literature surveys, personal observations at operating power plants, participation in workshops on heat dissipation effects, and contacts with researchers investigating cooling tower plumes. It is hoped that this generic report does accurately describe the atmospheric impacts of heat dissipation systems at power plants.

This report does not contain descriptions and critiques of the numerous mathematical models that have been formulated to predict atmospheric behavior. Subsequent efforts in the program will include a critical review of the models that purport to simulate cooling tower plume behavior for predicting such effects as plume length, plume rise, fogging and icing, drift deposition, etc. These studies, to be published separately, will include theoretical analyses of the models and comparisons of predicted results with actual conditions and with one another.

As a result of the National Environmental Policy Act of 1969 (NEPA) and the Calvert Cliffs court decision, the Directorate of Licensing of the U. S. Atomic Energy Commission (now the NRC) entered into a program to write environmental impact statements as a step in the licensing of nuclear power plants and other facilities. As part of this program, a few meteorologists, including the author and meteorological consultants for the utilities, became "instant experts" on the effect of cooling-system effluents on the atmosphere.

Unfortunately, the state-of-the-art in atmospheric understanding and in plume and cloud modeling is such that meteorologists are not now able to make accurate, quantitative predictions on how the atmosphere will react to the large amounts of heat and water vapor it will be forced to accept from limited areas per unit of time from closed-cycle cooling systems. This is largely due to a lack of systematic, detailed observations at operating power plants and to the complexity of the atmospheric processes. The report therefore indicates areas in which more field work, information and model development are needed.

To this end, comments, suggestions and criticisms of the information and/or conclusions in this report will be welcomed by the author:

Dr. James E. Carson
Division of Environmental Impact Studies
Building 11
Argonne National Laboratory
Argonne, Illinois 60439

TABLE OF CONTENTS

Page

- Preface . . . iii
- Nomenclature . . . vii
- Abstract . . . 1

- SCOPE OF THE REPORT . . . 2

- ONCE-THROUGH COOLING SYSTEMS . . . 3
  - Background . . . 3
  - Weather Change . . . 3
    - Local Weather Changes . . . 3
    - Far-Field Meteorological Effects . . . 4
    - Summary . . . 5

- EVAPORATIVE COOLING SYSTEMS . . . 5
  - Background . . . 5
    - General Considerations . . . 5
    - Design Considerations . . . 6
      - Intake Structures . . . 6
      - Blowdown . . . 6
      - Noise . . . 7
    - Environmental Considerations . . . 8
  - Natural-Draft Cooling Towers . . . 9
    - Fogging and Icing . . . 10
    - Visible Plumes . . . 12
    - Cloud and Precipitation Formation . . . 13
    - Drift . . . 14
    - Acid Mist . . . 16
    - Plume Shadowing . . . 17
    - Models . . . 17
    - Summary . . . 19
  - Mechanical-Draft Cooling Towers . . . 19
    - Fogging and Icing . . . 20
    - Cloud and Precipitation Augmentation . . . 21
    - Drift . . . 21
    - Deposition of Fallout . . . 21
    - Models . . . 22
    - Consumptive Water Use . . . 22
    - Summary . . . 22
  - Other Types of Cooling Towers . . . 22
    - Fan-Assisted Natural-Draft Towers . . . 22
    - Circular Mechanical-Draft Towers . . . 23
    - Wet-Dry Towers . . . 24
  - Cooling Ponds and Spray Canals . . . 25
    - Cooling Ponds . . . 25
    - Spray Canals . . . 26
    - Summary, Cooling Ponds and Spray Canals . . . 27
    - Cooling Towers Using Saline Water . . . 28

TABLE OF CONTENTS

Page

DRY COOLING TOWERS 27
Engineering Aspects 27
Atmospheric Effects 30

ENERGY PARKS 31

SUMMARY AND CONCLUSIONS 32

ACKNOWLEDGMENTS 33

REFERENCES 34

TABLE

No.

1 Distribution of Plume Length Classes with Relative Humidity Groups: 1 October 1970 to 30 September 1971 13

NOMENCLATURE

For better understanding, a few meteorological terms are defined here; others are explained in the text.

Aerodynamic downwash: eddy (swirling) airflows created by air moving over a solid object.

Hydrometeor: liquid or solid water particles in the atmosphere (includes fog, cloud and raindrops, and snow crystals).

Hydrosphere: the water portion of the earth, as distinguished from the solid (lithosphere) and gaseous (atmosphere) phases.

Isopleth: a line on a graph or chart drawn through points at which a given quantity has the same numerical value.

Rime ice: a white or milky opaque granular deposit of ice formed by the rapid freezing of small supercooled water drops as they impinge on an exposed object.

Saturation deficit: the difference between the saturation water content of air minus the actual content, given in mass per unit volume.

Surface nocturnal inversion: a stable layer of air next to the ground due to radiational cooling of the surface at night. Inversion refers to any layer in which air temperature increases with height.

ATMOSPHERIC IMPACTS OF EVAPORATIVE COOLING SYSTEMS

Abstract

In areas where sufficient water is available, the once-through cooling system is usually the most economical means of disposing of waste heat from power plants and industry and has the smallest impact on the local air environment. However, shortages of cooling water and/or regulatory actions will require that most new electrical generating stations use closed-cycle cooling systems, such as wet and dry cooling towers, cooling lakes and spray canals. All cooling procedures eventually transfer waste or unusable heat to the atmosphere by radiation, conduction and/or evaporation; but because they involve smaller areas of heat and water vapor transfer to the atmosphere, closed-cycle systems have a much higher potential to modify local weather conditions than a once-through system.

This report summarizes available information on the effects of the various cooling systems on the atmosphere. While evaporative cooling systems do sharply reduce the biological impacts of thermal discharges in water bodies, they do create (at least, for heat-release rates comparable to those of two-unit nuclear generating stations) atmospheric changes. For an isolated site such as required for a nuclear power plant, these changes are rather small and local, and usually environmentally acceptable. However, our understanding of the atmosphere is such that we cannot say with certainty that these effects will remain small as the number of reactors on a given site increases. There must exist a critical heat load for a specific site which, if exceeded, can create its own weather patterns, and thus create inadvertent weather changes such as rain and snow, severe thunderstorms and tornadoes.

Because proven mathematical models are not available, it is not now possible to forecast precisely the extent and frequency of the atmospheric effects of a particular heat-dissipation system at a particular site. Field research on many aspects of cooling system operation is needed in order to document and quantify the actual atmospheric changes caused by a given cooling system and to provide the data needed to develop and verify mathematical and physical models. The more important topics requiring field study are plume rise, fogging and icing (from certain systems), drift emission and deposition rates, chemical interactions, cloud and precipitation formation and critical heat-release rates.

SCOPE OF THE REPORT

One consequence of the second law of thermodynamics is that all engines which convert heat into other forms of energy must dissipate low-grade heat to the environment; in other words, what is frequently called "waste heat" is in fact a necessary part of the energy conversion process.

Until recently, most U. S. electrical generating plants (as well as many industrial plants with large heat loads) have used once-through cooling to dispose of this reject heat. Although the once-through process is the most efficient method of heat dissipation from purely thermodynamic considerations, local water shortages, concern about the biological effects of heated water, and regulatory actions dictate that "closed-cycle" methods be utilized in many situations.

With the growth in worldwide electrical energy production, the number of large power-generating installations is continually increasing, with more and larger generating units per site, aggravating the problem of waste-heat dissipation. And as limitations are placed on the use of rivers and streams for cooling purposes, it is clear that large cooling tower installations will be utilized to a greater degree than in the past. This being the case, careful consideration of the total environmental impact of these cooling systems is a necessary part of the power plant design and site selection process.

Because evaporative or wet cooling towers provide a convenient, dependable, economical and well-understood way of rejecting heat directly to the atmosphere, they are usually chosen as the means of heat rejection for power plants and large industrial plants. Where sufficient level land is available near the plant at moderate prices, cooling lakes or spray canals are sometimes utilized. Occasionally, to meet some stringent condition, such as the lack of cooling water at a mine-mouth plant, a dry cooling system will be installed, even for a large heat-load plant.

In this report, the observed and postulated atmospheric effects of various cooling systems are discussed. The author first treats--as a standard--a simple, once-through cooling system utilizing a large water body as a heat sink, then compares all other systems (the "alternatives") with this standard and with each other. (The term "alternative" system is frequently used for closed-cycle systems, although the once-through system may not be a viable or feasible cooling option in all circumstances.)

Evaporative cooling towers are the most frequently chosen alternatives. Wet or evaporative cooling systems include:

- Natural-draft cooling towers
- Mechanical-draft cooling towers
- Cooling ponds and lakes (with areas up to two to three acres per MWe)
- Spray canals and ponds
- Wet-dry mechanical-draft cooling towers
- Fan-assisted natural-draft cooling towers
- Circular mechanical-draft cooling towers (may have extended vent stacks)

Dry cooling towers of both mechanical-draft or natural-draft designs can be used.

ONCE-THROUGH COOLING SYSTEMS

BACKGROUND

Once-through cooling was used almost exclusively in this country until recent times for the rejection of heat generated in the electric-power and other large industries, and it continues to be a viable cooling option at many power plant sites. In open-cycle or once-through cooling, water for condensing steam is taken from and returned directly to a large body of water, such as a lake, river or ocean. The primary reason for using a once-through system is that it is in most cases the least expensive and most efficient method of disposing of the large amount of reject heat associated with the Rankine cycle. Another desirable aspect is that the water requires little treatment beyond trash and debris removal by the usual bar grates and mechanical screens. In addition, the power industry employs mostly corrosion-resistant systems, so there is little need for water-treatment chemicals except for chlorine as a biocide. Because the cooling water is not recirculated, the temperature rise across the condenser is relatively low (lower than that associated with closed-cycle cooling) and is inversely proportional to the water flow rate: the higher the flow, the greater the thermal efficiency of the unit. The flow rate selected is a compromise between pumping costs and size of the condensers relative to their thermal efficiency.

WEATHER CHANGES

Two scales of weather changes can be expected from thermal discharges into a large water body: local changes due to increased heat and moisture fluxes over the thermal plume, and far-field modifications due to the accumulation of heat energy in the main water body beyond the detectable thermal plume in the water.

Local Weather Changes

Heat and water vapor are transferred to the atmosphere whenever relatively cool air moves over a water surface. As more heat and water vapor will enter the atmosphere from a thermal plume than from the unaffected surrounding water surface, air with a trajectory over the plume will become somewhat warmer, more humid, and less stable than it would otherwise be. If conditions are proper (cold air over very warm water), part of the water vapor from the surface will recondense as the air next to the water mixes with cooler, drier air aloft; the resulting mist is called "steam fog." This fog is created by the same process that allows one to "see his breath" or to see "steam" from a kettle: the nonlinear relation between the saturation vapor content of air and air temperature. Thus, steam fog will occur more frequently (and have a greater density) over a thermal plume than over the main water body. Despite some research, proven techniques for predicting the occurrence, density and area extent of plume-produced steam fog are not now available.[1-6] Further vertical mixing favored by the unstable stratification of air (cold air over a warmer surface) tends to re-evaporate the steam fog droplets; thus the process which creates the fog tends also to dissolve it. It should be noted that natural steam fog and icing are common phenomena over open bodies of water in many areas in fall and winter.

Observations at thermal-discharge areas of power plants confirm that an increase in the frequency and density of steam fog over the immediate plume area is the primary observable effect of once-through cooling systems.[7] Steam fogs over thermal plumes in large lakes or oceans are usually thin and wispy, in turbulent motion, shallow, and move inland only a few tens of meters before evaporating, lifting or becoming quite thin.[7] The wind direction during periods most favorable for steam fog formation over thermal plumes will usually be from the shore toward the lake, moving the steam fog away from land areas. Once-through cooling systems on rivers can generate considerable steam fog downstream of the discharge point. The degree of fogging would depend on many factors, such as the relative flow rate of the stream and the thermal discharge, water temperature increase going through the plant, local weather conditions, shape of the river valley, etc.

Some light rime ice will be deposited on vertical objects (but not road beds) near (a few tens of meters from) the plume discharge point. Observations of ice deposited from freezing steam fog from any source, including cooling ponds and towers, show a similarity to that deposited by natural freezing fog; that is, the ice is so light and friable (easily crumbled) as to pose no problems to vegetation or structures. In any event, plume-produced ice will have an impact identical to ice caused by natural steam fog or natural supercooled fog of similar density. Rime ice deposited by the operation of evaporative cooling systems is quite different in its nature and effects on plant life, traffic and structures than the dense glaze ice formed by freezing rain and drizzle.

Far-Field Meteorological Effects

Most of the heat in a thermal plume will be mixed into the main water body rather than lost to the atmosphere by evaporation, radiation and conduction from the plume itself. It has been argued that the extra heat put into a large lake could be sufficient to modify the weather and climate in the area. However, simple calculations show that the amount of heat generated by power plants is quite small when compared with natural heat-transfer processes (sunshine, evaporation, long wave radiation, etc.).[7-9] For example, it can be shown that if all waste heat from nuclear power plants on Lake Michigan operating at capacity (7000 MWe) for a full year were mixed completely into the lake without losses of energy due to radiation, conduction and evaporation, the temperature of the lake would be increased only 0.022°C (0.04°F).[7] This and other calculations show that the warming of Lake Michigan by thermal discharges, while unidirectional, is much too small to measurably change the average air temperature along its shore.[7-9] Year-to-year fluctuations in cloudiness and air temperatures create much larger fluctuations in lake temperature.[7]

Heat discharges into relatively small lakes (of the order of five to ten acres per MWe) could significantly alter the temperature regime in the water. Atmospheric effects of such thermal discharges would include more steam fog over the water and nearby land in fall and winter, less radiation-advection fog in spring and summer, and slightly warmer water and air at all seasons. The added heat could also delay or prevent the formation of a natural ice cover in winter.

Summary

The waste heat discharged by once-through cooling into a large water body will enter the atmosphere slowly over a large area by conduction, radiation and evaporation. Since the flux densities of heat and water vapor due to power plant heat are very low (except over the thermal plume), no significant meteorological changes will occur. During periods of cold weather, some additional steam fog will form over the thermal plume itself, but this fog will not move more than a few tens of meters from the discharge point before disappearing. The waste heat from a number (say 5 to 20) of large nuclear power units on a large lake (such as one of the Great Lakes) will be much too small to produce a measurable change in the weather and climate of the region. While the atmospheric impact of a once-through cooling system on a large water body is minimal, intake and discharge effects could be such that this cooling option would be environmentally unacceptable and some form of closed-cycle cooling required.

The primary weather change due to once-through cooling drawing from a large water body is a small local increase in fogginess at the plant outfall.[7] As will be seen later, the relative probability of significant local meteorological effects is much larger with the alternative cooling procedures, since these reduce the area of heat and moisture transfer. From the meteorological point of view, the least undesirable way to dispose of waste heat is by using once-through cooling on large water bodies.

EVAPORATIVE COOLING SYSTEMS

BACKGROUND

General Considerations

Process or waste heat from industry and power plants can also be dissipated directly to the atmosphere by means of wet and dry cooling towers, cooling ponds and spray canals.

Evaporative or wet cooling towers are effective, reliable and economical heat-dissipation systems. In wet cooling towers, most (60% in winter, 90% in summer, averaging about 75%) of the heat is transferred to the atmosphere by evaporation, with the remaining cooling accomplished by sensible heat transfer.[10] There are two basic types of wet cooling towers: natural- and mechanical-draft. Each has its advantages and disadvantages, and the type selected for a specific site will depend in no small part on local climatological and site considerations. For example, natural-draft cooling towers (NDCTs) usually cost more to construct, but are less expensive to operate and maintain, than mechanical-draft units (MDCTs) of the same capacity. Weather conditions for optimal NDCT performance include low-to-moderate air temperatures with high relative humidities.[11] MDCTs are more flexible in operation, give adequate cooling in hot or very dry climates, and can be designed for lower approaches.[11-13] The relative operating costs of the two basic types of towers are in part a function of fuel costs (to produce the power used to operate the fans).

In this country, MDCTs and cooling ponds (CPs) have been widely used for decades; in the past ten years, however, the NDCT has been introduced for many large power plants, especially those in the cooler parts of the nation. In Europe, the NDCT has been in use for several decades and is the most widely used cooling system for large heat loads. Until recently, the selection of an alternative cooling system has resulted from the unavailability of sufficient cooling water at the site rather than concern for the environmental aspects of heated water on natural bodies of water.

All alternative cooling systems can be used in either the closed- or open-cycle mode of operation. In the latter, sometimes called "helper," mode a supplementary cooling device is used to dissipate most of the plant's reject heat to the atmosphere before returning all of the cooling water to its source without recirculation. Such systems are most frequently used at power plants where the cooling system is needed only during part of the year to keep effluent water temperatures below a seasonal standard; the Monticello Nuclear Plant in Minnesota has such a system, using MDCTs in summer only. Because the helper cycle does not reduce the volume of water needed to cool the plant, all of the intake and some of the discharge impacts of once-through systems remain, and a large source of water is required.

However, most plants with cooling towers, spray canals and ponds are operated in the closed-cycle mode at all times, with most of the cooling water being recycled through the condensers. Closed-cycle cooling greatly reduces the volume of water taken from the local water body, thus decreasing intake effects. A small part of the cooling water flow (one to two percent) is usually returned to its source as blowdown in order to keep the level of dissolved solids low.

While closed-cycle cooling systems do reduce the thermal load on local water bodies, they also create their own set of environmental impacts (such as fogging and icing, noise, plumes, drift, greater water use, impact on esthetics, etc.) which, for particular sites, may be unacceptable (especially those plants forced to change from once-through to closed-cycle cooling after construction has begun or during plant operation).

Design Considerations

Intake Structures

The use of closed-cycle wet cooling systems reduces but does not eliminate the need for a reliable source of water to replace losses from evaporation, drift, leaks and blowdown. The water supply could be a large lake or a river; in many locations, a dam and reservoir may be needed to ensure an adequate supply of makeup water at all times. Such an impoundment will have its own environmental impacts. The intake structure, screens, pumps, intake flow velocity, etc., should be designed to have a minimal impact on the aquatic biota.

Blowdown

Closed-cycle evaporative cooling usually reduces but does not eliminate thermal and chemical discharges into water bodies. Because evaporation is the principal means of heat dissipation in a wet cooling system, dissolved solids present in the makeup water will be concentrated. In addition, chemicals are usually added to maintain water quality or to control biologic growths. In a few plants, the intake water is sufficiently pure that no chemical additions, except chlorine to control biological growths, are required. The blowdown and drift from cooling towers may also contain erosion materials--such as asbestos and copper--from the cooling system pipes, condenser surfaces and cooling tower fill. Unless some of these materials are removed, a saturation level will be reached and some of the chemicals will be deposited inside the condensers or on other surfaces, reducing the efficiency of the system. An equilibrium concentration below the saturation value is usually maintained by continually purging water from the system. This purge consists in part of droplet loss (drift or windage) from the tower and leakage from the circulating-water piping system. Since these losses are insufficient to maintain the dissolved solids concentration at a satisfactory level for operation, the operator must remove additional water (typically one to three percent of the circulating water flow) from the system; this purge is referred to as "blowdown." Makeup water must be added to the system to compensate for all losses.

Unless a water purification system is added to the blowdown system, the total chemical discharge to the aquatic medium is increased both in amount (owing to chemicals added to the cooling water to control pH, algae, corrosion and scaling) and in concentration. In a few cases, the blowdown is completely evaporated or otherwise used so that the water quality of the receiving water body is not degraded; such procedures increase both the costs and the consumptive use of water.

In general, blowdown problems become more severe as water quality standards become more restrictive and the sizes of installations increase. To minimize the thermal impact of blowdown, water should be withdrawn from the cool-water basin of the tower, a procedure that increases slightly the cost of cooling system operation; such withdrawal is required by U. S. Environmental Protection Agency (EPA) guidelines.[14,15]

Noise

The noise characteristics of large cooling tower installations must also be considered in an overall assessment of the plant's impact. Techniques are available for evaluating cooling tower noise and measuring the noise level of the surrounding environment. Although quantitative data in this area are few, most observers of these large installations have not reported significant noise problems beyond the areas immediately surrounding the towers. For example, noise levels of 65 to 75 dBa have been measured at a distance of 100 meters from a group of eight NDCTs in England; even though these towers are in a "neighborhood of domestic dwellings," this noise level has been accepted by the public.[16]

In general, the noise associated with mechanical-draft towers can be attributed to a combination of sounds resulting from the operation of the motors, fans, and gear drives, and from the falling water striking the fill and cold-water basin. In the case of natural-draft towers and spray cooling systems, the most significant source of noise is the falling water.

In evaluating noise problems, parameters of importance (in addition to the total noise or sound-pressure level of towers) include the sound intensity by octave band-number; direction and distance from the tower; local weather conditions (which affect sound propagation); attenuation by acoustic barriers, trees, etc.; outdoor background noise levels; and types of activity of people near the tower who would be affected.

A complete analysis of cooling tower noise problems is beyond the scope of this report; for more information the reader is referred to recent publications.[17-20] Field measurements of cooling tower noise indicate that its sound impact is minimal when there is adequate distance between the tower and the community. These observations indicate that, at a distance of 1000 to 2000 feet, the noise from the cooling tower is below the noise level of the general community.[16,18,20] Techniques to lower the sound level are available. Fan noise in MDCTs can be reduced by about 10 dB by reducing fan-tip speed from 12,000 ft/min to 8,000 ft/min (Ref. 14, p. 653). Baffles can also be used to lower sound to acceptable levels (Ref. 14, p. 655).*

Environmental Considerations

The use of closed-cycle cooling systems does not eliminate thermal discharge problems; it merely transfers most of the thermal burden from the hydrosphere to the atmosphere and may itself create adverse impacts. The primary factor to be considered in evaluating a cooling system at a specific location is its *impact* rather than *effect*; how the discharges affect people, fauna, flora and the environment is more important than the atmospheric processes involved. Thus, merely predicting the frequency, extent and severity of a specific event (such as fogging and icing from a MDCT) is insufficient; some effort must be made to estimate how these effects will impact people, traffic, flora, etc.--which is usually a much more difficult problem. The atmospheric effects of a cooling system depend primarily on the type of cooling system selected and local climate; a system's impact will be controlled to a considerable degree by the height of release of the effluents and the location of the cooling device with respect to roads, homes, trees, farms and fields, etc.

The recent literature contains a large number of papers on the environmental impacts of alternative cooling systems. Unfortunately, only a few describe observations made at operating power plants; far too many are based on guesses or derived from mathematical models that have never been tested or verified by observations at operating plants, and all too often predict atmospheric effects (such as frequent ground-level fog from NDCTs) that do not in fact occur. (For more discussion of this point, see Ref. 21.) A survey of the literature written prior to 1970 yields much speculation but very little factual information on cooling-tower effects. Statements with the dubious usefulness and authority of "cooling towers have the *potential* to cause fogging and icing" were found all too frequently. In addition, some of the facts presented are incorrect (e.g., drift rates of about 0.2% were given for new towers, a value more than two orders of magnitude too high).

A number of major reports (or collections of papers) on the atmospheric effects of cooling towers have been published. These include *Cooling Tower Environment-1974* (Ref. 22); the July 1974 issue of *Atmospheric Environment* (15 papers on experience with natural-draft cooling towers in Great Britain);

---

*More information on sound baffling is given later, in the report section on fan-assisted natural-draft cooling towers.

"Cooling Towers," Am. Inst. Chem. Engineers (Ref. 23); "Dry and Wet/Dry Cooling Towers for Power Plants," Am. Inst. Mech. Engineers (Ref. 24); "Industrial Waste Guide on Thermal Pollution," Federal Water Pollution Control Administration (Ref. 12); "Plume Behavior and Potential Environmental Effects of Large Dry Cooling Towers," Gulf General Atomic Company (Ref. 25); "Cooling Towers," March 1973 issue of *Power* (Ref. 11); "Effect of Cooling Tower Effluents on Atmospheric Conditions in Northeastern Illinois," Illinois State Water Survey report (Ref. 26); "The State-of-the-Art of Salt Water Cooling Towers Applicable to Nuclear Electric Power Generating Plants," Report WASH-1244 (Ref. 27); "Cooling Tower Plume Modeling and Drift Measurement," Am. Soc. Mech. Eng., 1975 (Ref. 28); Proceedings of the International Atomic Energy Agency Symposium, Oslo, Norway, August 1974 (Ref. 29); Proceedings of the 9th World Energy Conference, Detroit, September 1974 (Ref. 30), and three summary articles by Parker and Krenkel (Refs. 31-33).

The atmospheric effects of evaporative heat dissipation systems can be separated into four major areas of concern:

- Visible plumes
- Fogging and icing caused by plumes
- Wetting, icing and salt deposition caused by drift
- Augmentation of clouds, precipitation and/or severe storms (tornadoes)

Other items for potential concern are: consumptive water use; shadowing by the plume; percolation of cooling water into the ground; interactions of plumes with other pollutants (such as SO_2) to form acid mists; critical heat-release rates for a specific site; noise; esthetics; intake effects; and the chemical, thermal and scouring impacts of the blowdown.

The question of the *degree* of weather modification by cooling tower plumes, either wet or dry, cannot be satisfactorily answered at this time due to our lack of understanding of the atmospheric processes involved and the inadequacy of available modeling techniques. Meteorologists have not as yet been able to develop satisfactory models of cumulus clouds. Cloud modeling with the added effect of wet or dry cooling tower plumes is an even more difficult problem. Very little information is currently available on the possible effects of large plumes on severe weather events such as thunderstorms, hail, severe rainstorms and tornadoes. Some observers think that severe thunderstorms, and even tornadoes, can be caused by cooling tower effluents during very unstable weather situations.

Because all evaporative systems add large quantities of heat and water vapor to the atmosphere per unit of area and time (the flux density of heat and water vapor from a cooling tower is three orders of magnitude greater than that for once-through systems), they have a much higher potential for altering local weather conditions than does a once-through system. Cooling ponds and spray canals, with their larger areas of heat and moisture transfer, have intermediate fogging potentials.

NATURAL-DRAFT WET COOLING TOWERS

The design of an electric power generating station must combine a number of components into the best possible combination (usually in terms of the cost required to generate a unit of energy). Hence, there are trade-offs or compromises between the design of one component and the balance of the plant. The engineer designing a natural-draft cooling tower for a particular power plant has a number of parameters to consider in selecting the optimum design. These include design wet-bulb temperature, approach (the difference between the temperature of the cooled water leaving the tower and the ambient wet-bulb temperature), and range (difference in temperature of the water entering and leaving the tower). Decreasing the approach, for example, increases the size and cost of the tower but produces water and a somewhat more efficient power plant. Increasing the cooling range decreases the water flow and the size of condensers, while lowering thermal efficiency. A low wet-bulb design temperature results in a smaller tower, but at the expense of plant performance on hot, humid summer days. The designer attempts to balance all of the parameters into an optimum, or least costly, combination. In order words, there is no such thing as the ideal NDCT design suitable for all power plants and all climates.

The primary atmospheric effect created by the operation of natural-draft cooling towers is the generation of visible plumes that remain aloft; the primary impact of NDCTs is the esthetic or visual effect of their massive structure and associated visible plume.[16,21,34-36]

Observations at operational NDCTs indicate that the visible plume usually begins inside the tower itself, due to recondensation of water vapor in the rising airstream--a process not discussed in most papers and models on cooling tower plumes. The warm, saturated air leaving the tower then mixes with cooler, drier ambient air. Because of the nonlinear relationship between saturation vapor pressure and air temperature, the mixture of these two bodies of air will usually be supersaturated, and the excess moisture will continue to condense in the form of an elevated visible plume. Because of its vertical momentum and buoyancy, the visible plume usually continues to rise well above the top of the tower, where it either evaporates and disappears or merges with an existing cloud layer. NDCT plumes will punch through all but the most intense inversion layers.

Because NDCTs dissipate large amounts of heat and water vapor from a small area per unit of time, there exists a potential for creating inadvertent weather modifications. These atmospheric effects are discussed below.

Fogging and Icing

For evaporative or wet cooling systems, the primary atmospheric effect will be the generation of visible (water droplet) plumes due to the recondensation of the water evaporated into the air. If this plume is formed at or near ground level, or descends to the surface by either plume meander or dispersion, ground-level fog and ice may be generated.

Fog affects the environment by reducing visibility and by wetting and icing surfaces. The impact of cooling-system fog on most human activities (such as highway traffic) depends primarily on horizontal visibility. Unfortunately, the term "fog" means different things to different people. To some, fog exists only when "one cannot see his hand in front of his face." The international definition of fog, and the one used by the U. S. National Weather Service (NWS) in its synoptic (six-hourly) weather codes, is a hydrometeor consisting of a visible aggregate of minute water droplets or ice crystals suspended in the atmosphere near the earth's surface which reduces visibility to less than one kilometer (0.62 mile).[27] The NWS uses the term "dense fog" for conditions in which the visibility is less than 400 meters (0.25 mile). The official term for conditions in which the horizontal visibility is one kilometer or more is "mist."[27] Contrary to international usage, the NWS, in its hourly (airways) weather observations, describes as fog a condition of six miles or less visibility due to water drops or ice crystals; the exact reduction in visibility is given in another portion of the weather report. The "fogging" effects discussed in the literature on cooling systems seem to refer to any reduction of horizontal visibility due to thermal discharges, including those which would have only a very minor effect on man's activities, such as highway traffic.

If the air temperature is below 32°F, this fog exists as supercooled water (not ice or snow) and will be deposited primarily on vertical surfaces as friable rime ice with a very low density and little structural strength. Wetting and icing of structures and biota downwind of cooling towers can be caused by both drift deposition and impaction of recondensed water drops in the visible plume. This wetting can cause damage or corrosion to structures as well as promote disease in plants. Drift droplets will contain whatever chemicals and pathogens are in the circulating water; these materials will be deposited on plants, soils and structures, and thus may impact the local environment.

Most reports on NDCTs written more than a few years ago state that they have the "potential" to cause ground-level fogging and icing. Observations at operating units indicate that they rarely if ever do.[[illegible],[illegible],16,[illegible],[illegible],38–[illegible]] The warm, moist plume enters the atmosphere at heights of 100 meters or more, continues to rise hundreds of meters more, and either evaporates or merges with a natural cloud layer before reaching ground level. In England, it has been observed that two or three times per year "a few detached fragments" of visible plume have touched the ground; this condition occurs only with high humidity when strong winds create aerodynamic downwash downwind of a complex of eight closely spaced, relatively short (375 ft) NDCTs.[[illegible],[illegible]4]

In an unpublished 1968 report,[42] the Central Electricity Generating Board of Great Britain presented its findings on the environmental effects of cooling towers. No measurable change in relative humidity was detected downwind. The visible plume sometimes persisted for a number of miles downwind, altering sunshine in the area. No drizzle or drift was observed from the towers. The report states that cumulus clouds were sometimes formed but that no cases of showers or precipitation generated by the plumes were observed. More recent observations in England, Europe and the United States confirm these conclusions. The April 1974 issue of *Atmospheric Environment* contains a more complete and more recent summary of the British experience with NDCTs.

Photographs taken at cooling tower sites sometimes show ground-level fog completely separate from the rising plume from the towers.[[illegible],[illegible]] The surface fog is caused by natural processes, such as nocturnal radiation; rivers and reservoirs used to supply makeup water to the towers often aid in its formation.

Thus, observations at operating NDCTs provide evidence that this type of cooling tower does not cause fogging and icing in level-terrain areas.

Visible Plumes

Under certain weather conditions (low temperature, high humidity, moderate wind speed and stable atmosphere), the visible plume from a cooling tower may extend for many miles.[32,41,43,54] Colbaugh[41] measured plumes extending 16 kilometers from the 2250-MWe Paradise, Kentucky, coal plant. Even longer plumes (up to 43 miles) have been observed and reported.[33,42]

The length and other dimensions of the plume, such as its plume rise, width, depth, and height of base above ground, will depend primarily on existing weather conditions (air temperature, saturation deficit, wind speed and atmospheric stability). Because the ability of air to hold water vapor is quite low at low temperatures, plumes will be most pronounced during the winter season. Bierman et al.[63] published the first climatology of plume lengths. They photographically measured the length of the plume from a cooling tower complex in Pennsylvania for six months (January 31 through July) in 1969. Pictures were taken during the early morning hours, normally the time of day with the longest visible plumes. It was found that the plumes evaporated completely on 81.5% of all days during the period of study. Of these, 87.3% disappeared within five stack heights or 1625 feet of the tower, and only 2.6% extended more than 15 stack heights or 4875 feet. The plume merged with an existing overcast on 16.5% of all days. On the remaining days (2.0%), the plumes were classified as "special cases," such as cloud-building. Smith et al.[42] made 244 plume-rise and length measurements at three power plants in Ohio and West Virginia, with generating capacities up to 2900 MWe-fossil, during November 1973 through August 1974. Of these, 163 (67%) disappeared within a half-mile of the plant. Only 16 (6.5%) extended to distances greater than two miles. Later data indicate that one plume extended 70 kilometers (43 miles).[33]

A more complete climatological study of plume lengths was made at the coal-fired plant at the Ratcliffe-on-Soar power plant in England.[45,64] This plant uses eight towers to cool its four 500-MWe units. Photographs were taken three times (at about 0900, 1400 and 1700 local time) each day for one year. (Some photographs were not usable because of a variety of problems, including fog, low clouds and merging of the cooling tower and stack plumes.) The plume length measurements were subdivided into three length classes and into three relative humidity classes, as shown in Table 1. On a seasonal basis, 50% of the measured plumes were persistent (i.e., longer than 900 meters) in winter; only 10% were persistent in summer. Persistent plumes were not observed at high wind speeds (10 mps or higher), but neither were high humidities. Moore[45] concludes that relative humidity (measured at 12 m) is as good a predictor of plume length (at least for this one power station) as the mathemetical model given in Reference 61. Extreme caution should be exercised in using a relationship such as that in Table 1 as a predictive tool or model; this table should not be used for power plants with different power levels and climates. Also, humidity (specifically, saturation deficit) at plume level (1000 to 3000 ft) would be a far superior moisture parameter.[37,44]

There have been no reported cases of visible plumes reaching the ground during the five years of operation of the 2250-MWe steam plant at Paradise, Kentucky (Ref. 41 plus recent personal communication). According to observers of meteorological conditions in the vicinity of the Keystone, Pennsylvania, Power Plant (1800 MWe), no surface fogs or icing have been observed in its

Table 1. Distribution of Plume Length Classes with Relative **Humidity** Groups: 1 October 1970 to 30 September 1971[a]

Measured Humidity Group	Plume Length Class Short, <300 m	 Medium, 300-900 m	 Persistent, >900 m
Low <75% r.h.	46	2	0
Medium 75-90% r.h.	10	13	11
High >90% r.h.	0	3	15

As percentages of 717 observations.

[a] *Based on measurements taken three times each day at the Ratcliffe-on-Soar power plant in England, Reference 61.*

four years of operation (personal communication). The same conclusions have been reported in England,[16,21,34,38,42,43,54,55] Switzerland[50-53] and the United States.[35,36,40,41,45-49,59] Hosler[48] does report one occasion on which the visible plume from an NDCT did reach the ground in a mountainous terrain area; however, this is the only reported case. Horizontal visibility at ground level at this location was about one mile. Nevertheless, contrary to actual observations taken at tower sites, many theoretical analyses still predict frequent tower-induced ground-level fog.[21,62,63]

Cloud and Precipitation Formation

The visible plume from a cooling tower is in fact an artificial cloud. The extra heat and water vapor can, under proper meteorological conditions, create cumulus clouds. Aynsley,[47] Spurr,[21,34,43] Smith et al.[49] and others have observed that the updraft from an NDCT can create cumulus clouds after the initial visible plume has evaporated. Aynsley concludes that this is a "rare occurrence," and that these man-made clouds only precede natural cloud formation. Experience in England indicates that NDCTs do create clouds but not precipitation.[16,21,38,42,43] The state-of-the-art in cloud physics is such that meteorologists cannot now say with any degree of certainty that there will or will not be a measurable increase in rainfall due to cooling tower plumes.[26,64-67] It is possible that the plume from a cooling tower could somehow trigger an existing atmospheric instability and create extra cumulus congestus clouds and precipitation miles downwind of the release point. As the number and size of cooling towers on a given site increase, the probability of significant alteration of cloudiness and precipitation patterns will increase (see Energy Parks). There should be a small (of the order of a few percent) increase in precipitation when natural rain or snow fall through a cooling plume.

There are several reported occurrences of snow or ice crystals being generated by MDCT plumes; in all cases, the amounts of snow were very small.[7,68,69]

Until recently, there were no such observations for NDCTs. (This doesn't mean that the phenomena did not occur at NDCT sites, it means that no one had really been looking for it.) Aircraft observations made in Ohio and West Virginia during the winter of 1975-1976 indicated at least ten cases in which some snow fell from the visible plumes of NDCTs.[39] In all ten cases, the surface air temperature was -12°C or lower. Kramer et al.[39] discuss in detail one situation (January 18, 1976) where up to one inch of very light fluffy snow fell from a cooling tower plume in otherwise clean air. The air temperature at this time was -12°C at the surface, -18°C at plume height. The supercooled plume rose to the base of an inversion at 1600 meters. The supercooled water droplets began to change to ice crystals about 5 kilometers downwind of the towers; snowfall at ground level extended from 13 to at least 43 kilometers.

This study indicates that at least two other factors contribute to the lack of reports of snow from cooling towers: the distance between the towers and the snow, and the fact that tower-induced snows often occur when natural clouds are present and when natural snow would be expected.[39] The report dramatically indicates the need for thorough observational studies at cooling towers.

Although there are many examples of cloud generation from cooling tower operation, no cases of rain showers or liquid precipitation generated by cooling tower plumes have been observed and reported in the literature. The lack of reports of rainfall from cooling tower plumes may be due only to the fact that no one has been looking for it, as was the case with snowfall observations. It is quite possible that a cooling tower will modify the pattern of rainfall in the area, but it will not alter the total precipitation for the region, as the water vapor emissions from the tower are very small compared with natural fluxes. Whether single towers or small groups (two to four nuclear units) of cooling towers do modify precipitation patterns will remain an unanswered question until data from operating power plants become available. Separating the signal (change in rainfall patterns) from the noise of the random spatial variability of natural processes will be difficult.

Drift

A small fraction of the cooling water (of the order of 0.005% or less for NDCTs with modern drift eliminators in good repair) is entrained in the air before leaving the towers. These water droplets, which contain whatever microorganisms and dissolved and suspended chemicals are present in the circulating water, are called "drift" or "carryover." Most of these drops will evaporate before reaching the ground, leaving their impurities suspended in the atmosphere. Under some conditions, such as high relative humidity or drizzle, some of the drops will fall to the ground and may create or contribute to wetting, fogging and/or icing and the deposition of salt residue. The possible health hazards of microorganisms in drift are now under investigation by Argonne and others.

Methods for measuring drift rate, drop-size spectrum and drift deposition rates can be found in References 70 through 78. Experience at operating towers indicates that low drift rates are possible only if the drift eliminators are in good repair; even minor failures or defects in this system will cause large increases in the drift rate.

It should be remembered that the guaranteed or quoted drift rate, usually expressed as a percentage of the circulating water flow, is valid only at design wet-bulb conditions; this design temperature is often taken as the value exceeded five percent of the hours in a four-month summer season. At lower wet-bulb temperatures, which occur 95% or so of the time in summer, the airflow through the tower will be greater than at design conditions. It is not clear how the drift rate will vary at higher airflows, as the effectiveness of the eliminators will also increase.

Experience at such towers indicates that the fallout of water and chemicals under most weather conditions is too small to be felt or measured except in the immediate vicinity of the tower, and that no environmental problems are created.[16,21,34,42,43,46,50-52,73] Measurements in England indicate that the maximum deposition rate of liquid water observed downwind of a cooling tower complex for a 2000-MWe fossil plant with state-of-the-art drift eliminators in good repair is only 0.0008 inch per hour about 300 meters downwind, an amount too small to cause road wetting or to be felt.[21,42,43,73]

The environmental *impact* of drift depends not on what comes out of the top of a cooling tower (the drift) but on what falls to the ground (drift deposition). Due to an almost complete lack of representative data on drift deposition rates at various distances from the tower as functions of tower design and weather conditions, no satisfactory, *proven* models to predict drift deposition rates and impacts have been developed.[28] Hopefully, studies now in progress at the Chalk Point nuclear power plant on the Patuxent River in Maryland will help resolve the problem.[76-78]

In some areas, drift could cause icing of road surfaces, etc. During periods of high wind, some of the circulating water can be blown out of the base of a cooling tower; this process is called "blowout" or "stripping."[16,73] This could cause problems very close to the tower, especially for saltwater towers.

The question of biological damage due to the deposition of salts by drift from freshwater cooling towers has generated considerable interest and controversy, despite the total lack of any cases of such damage being observed and reported. This controversy is fueled in part by a series of mathematical models which predict very large wet deposition values, a condition that is not observed. Part of the confusion and controversy is due to use of the word "salt." To most people, salt means sodium chloride ($NaCl$) only. Most of the solid material in the drift from a freshwater cooling tower is calcium sulfate ($CaSO_4$), a material that has a much smaller effect on plants. A typical value for the salt or total dissolved solids (TDS) level in the cooling water for freshwater towers is of the order of 1000 ppm, a value below that of some irrigation waters. Most of the salts falling on plant leaves will be washed off by natural rain, reducing the biologic effect of deposition.

A review of the literature indicates that salt deposition due to drift from freshwater cooling towers fitted with state-of-the-art drift eliminators will be very small and that most all of the drift droplets that do fall to the ground will do so within one or two thousand feet of the towers, a conclusion consistent with two recent EPA reports.[14,15] Thus, no adverse environmental impacts are expected due to salts in the drift from freshwater cooling towers.

Salt deposition due to drift from cooling towers using salt or brackish water for makeup could lead to serious environmental problems.[22,27,76-82] The question of adverse biological impacts of salts from saltwater cooling tower drift remains unsettled, due to a lack of careful, systematic efforts to measure drift deposition rates and plant damage. Experience with saltwater NDCTs at Fleetwood, in England, shows no evidence of destruction of vegetation due to drift.[21,27] Observational programs now under way at brackish-water NDCTs in Maryland,[76-78] New Jersey[79] and Florida[80] should resolve the problem. The biological impact of salt deposition is, of course, related to the type and salt tolerance of the vegetation in the area, the season of the year, and the amount of natural rainfall (which washes the salt from the leaf surfaces). Salt can also increase corrosion of metal surfaces in man-made structures. Plants growing near the seacoast are subject to a natural salt load, whereas plants further inland are not. The *added* salt burden will be the item controlling the impact of salts on the biota. Roffman et al. have published a series of papers on the drift from saltwater cooling towers.[27,81,82] Additional papers on saltwater cooling towers include References 83 through 85. For more information on cooling tower drift and its biological effects, the reader is referred to the April 1974 issue of *Atmospheric Environment* and to the book *Cooling Tower Environment-1974* (Ref. 22).

Acid Mist

It has been argued on theoretical grounds that the water droplets in a visible cooling tower plume could merge with stack gases from fossil-fired plants, that sulfuric acid droplets would be formed, and that this "acid mist" would fall to the ground and cause damage to human health, the biota and man-made structures.

Hundreds of wet cooling towers have been operating at fossil-fired power plants for decades both in the United States and Europe without any indication of significant adverse impacts due to "acid mist" from merging plumes. While this lack of reports of damage is not proof that the phenomenon does not occur (since no systematic observations have been made), the problem is probably a minor one. This conclusion is in agreement with a recent EPA report[14] and studies in England.[38,73] Smith[86] has made a theoretical analysis of acid mist conversion and deposition rates.

The statements above do not mean that acid rains and mists from the use of high-sulfur fuels do not occur or are not a problem, but the real question remains "how does the presence of a cooling tower plume *alter* the sulfur dioxide cycle in the atmosphere?" The plume from a fossil-fuel plant already contains all of the ingredients needed to cause acid droplets and acid rain (SO_2; particulates to act as catalysts; water vapor from the hydrogen in the fuel; and, in cold weather conditions, water droplets from the condensation of this water vapor). When coal, oil or gas is burned, the hydrogen in the fuel will be converted to water vapor. For most coal deposits, about one pound of water vapor is created for each two pounds of fuel burned. In burning high-sulfur (4%) coals, 20 or more water molecules are created for every molecule of SO_2. These two gaseous effluents are completely mixed in the stack gas, along with the catalytic agents to promote oxidation.

Natural weather processes (fog, clouds, drizzle, rain and snow) provide the liquid water needed to convert SO_2 into sulfuric acid and bring the acid to the ground. In other words, the real problem in evaluating cooling tower-fossil plume interactions is to isolate the effect of a (small?) perturbation on a chemical process common to all fossil-fueled plants, with or without cooling towers. Limited data collected in England indicate that acid droplets observed in an NDCT plume were due mostly to ambient SO_2 entrained in the plume and not to merging of the plant's stack and tower effluents.[73] Acid drops with values between pH 2 and pH 3 have been observed in Pennsylvania.[47,87]

Observations and photographs at power plants show that plumes from cooling towers frequently merge with the stack effluents, especially during periods favoring long, visible plumes. This merging may occur with most wind directions, tower heights and plume rises, due to the widening of both plumes with distance.

Obviously, the question of acid mist formation by cooling tower plumes needs further study, primarily field studies at operating fossil plants.[35] A field program to examine this phenomenon at the Chalk Point plant in Maryland is now under way.[76,77]

Plume Shadowing

The visible plume from an NDCT will reduce the amount of sunshine reaching the ground near the unit.[49-52] The amount of sunshine loss will depend on a large number of parameters: plant heat load, season of the year (shadowing will be a maximum in winter), time of day (plumes are longest at dawn), local climate (temperature, humidity, natural cloudiness, wind speed), etc. The impact will be very site-specific: people and crops shadowed, seasonal effects, wind direction, etc.

Bøgh[52] and Junod et al.,[50] using computer models to simulate visible plumes, have computed the minutes of sunshine lost per day due to plumes for specific power plants in Switzerland and Germany. Reductions of up to 20 minutes per day very near the plants were calculated. The one-minute-per-day isopleth of lost sunshine extends only about six miles from a plant. These calculations appear to be reasonable.

Models

A large number of analytical models have been generated to make quantitative predictions of natural- and mechanical-draft cooling tower plume parameters: plume rise, length of visible plume, fogging and drift deposition. A few of these have been referenced above,[22,26-28,38,48,50-53,61-63,70-73,79,81,82,86] and many more are available.[88-118] This list is incomplete, and many of the models are proprietary. Several recent models (especially for drift deposition) were presented at a March 1974 Atomic Energy Commission symposium, the proceedings of which (*Cooling Tower Environment--1974*) are available.[22] The April 1974 issue of *Atmospheric Environment* also contains many papers on drift and plume models.

A survey of the cooling tower environmental impact analysis requirements indicates there is an urgent need for the generation of mathematical and physical models that have been shown to accurately simulate cooling tower plume effects. At the moment, more numerical models are not needed, but data to test them are in very short supply. For example, more than a dozen models to simulate drift fallout rates from the NDCTs exist; but due to a complete lack of drift fallout data of good quality, none has as yet been shown to simulate nature accurately.[28] Yet, important design decisions are being made on the basis on these untested, perhaps invalid, models.

While meteorologists have found mathematical models very useful in studying atmospheric processes, the primary function of such models in environmental impact statements is to simulate cooling tower effects at other locations and for other atmospheric conditions. Therefore, the models for this application should be simple and easy to apply, inexpensive to run on the computer, and have been shown by tests with independent data to accurately simulate nature.

Unfortunately, some of the models now available are known to be inaccurate. Most models for NDCTs predict that the visible plume will begin outside of the tower due to mixing with ambient air, while in fact the plume begins inside the tower just above the drift eliminators. Most of the older models for NDCTs predicted frequent downwind fog, despite a complete lack of such fog at actual tower sites. Many but not all models for MDCTs call for much ground fog at some distance from the tower because of dispersion of the plume downward after an intial rise, a process that has never been observed and reported. Observations indicate that the primary if not the only cause of fog at such towers is aerodynamic downwash next to the towers, a condition not simulated by most models. Finally, some models have been tested using the same set of observational data used to establish the values of adjustable parameters in the model; models must be tested against independent data.

Physical models, such as wind tunnels, can also be used to simulate cooling tower plume behavior; again, prototype data are needed to verify the applicability of the models.[110,119]

The American Society of Mechanical Engineers (ASME) recently published a critical review of the mathematical models for predicting plume lengths, fogging and drift from cooling towers.[28] This report contains a list of many but not all of the available models, and some of the assumptions used, and briefly discusses the limited verification procedures used by the model developers. ASME tested only a very limited number of models and was not able to test others because of their proprietary nature.

Among the conclusions in the report are:

1. With reference to cooling tower plumes, "no mathematical models exist that have been adequately validated by field measurements for a variety of tower types and meteorological conditions."

2. No specific plume model type was proven to be superior to others.

3. Some of the models proposed "were capable of reasonably good predictions of observed plume characteristics when the model coefficients were tuned for a best fit"; that is, after an empirical curve-fitting parameter was used to modify the original calculated value.

4. "A major problem in prediction of plume effects is characterization of the source, determination of aerodynamic effects and the combination of plumes from multiple sources."

5. "A number of fairly complex mathematical models exist for prediction of transport and deposition of cooling tower drift. No adequate field data have been collected for verification or calibration of the models. The proposed models often produce conflicting predictions, and there is no general agreement on the best way to model turbulent dispersion of drift particles or the mechanism of droplet escape from the vapor plume. It is concluded that there is no single model that can be accepted as providing reliable drift predictions at present."

6. "None of the [drift] models have been compared to any kind of representative field data [because they do not exist]. Therefore, there is no basis for stating that any model even roughly corresponds to reality."

7. Estimates of drift deposition rates from the various models differ by more than an order of magnitude.

The ASME report[28] confirms the widely held opinion that the primary reason for the lack of proven models is the shortage of quality field data collected at operating cooling towers under a variety of meteorological conditions.[36] At present, a number of field studies are being conducted at operating NDCTs both in Europe and the United States; the data from these observational programs are now becoming available for model development and validation. The U. S. Energy Research and Development Administration (ERDA) and NRC are presently funding model comparison studies at both Oak Ridge and Argonne National Laboratories.

Summary

Experience with hundreds of towers (there are about 300 in Great Britain alone[38]) proves that the natural-draft cooling tower is an effective and reliable cooling device that produces a minimal environmental impact, provided it is properly designed and maintained.[16,21,38] Such towers do not cause fogging or icing, and the drift effects are minor and limited to areas quite near the tower. Their primary adverse impact is visual: their bulk--it is hard to conceal a structure 500 feet or more tall--and visible plumes that remain aloft.[16,21,38]

Because of the limited amount of data taken at operational cooling towers, none of the models for cooling tower effects has been properly tested by using independent data from a variety of climatic areas. Therefore, it is not now possible to indicate which, if any, of the available formulae do simulate natural conditions accurately.

MECHANICAL-DRAFT COOLING TOWERS

Compared to natural-draft units, the mechanical-draft tower has several advantages, such as lower capital costs, greater control over cold-water temperatures, smaller approach, greater cooling range, and greater flexibility in use.[11-13,120] Mechanical-draft towers, with their low level of release (20 to 30 m) and more rapid entrainment, do cause ground-level fog. Therefore, attention must be paid to site selection to minimize fog over highways and structures, and other adverse impacts.

Mechanical-draft units are better suited to areas with summer peak loads and high ambient wet-bulb temperatures, such as the Gulf Coast. Natural-draft cooling towers should not be used in areas with hot, dry summers, or in deserts, since the evaporative cooling within the tower may be so great as to destroy the density difference and thus stop the airflow through the tower.[11] Natural-draft units should not be built in areas with frequent, strong winds, such as the hurricane belt along the Gulf and Atlantic coasts.

Observations to date indicate that properly designed, maintained and located MDCTs do not create significant adverse effects, except for the region quite close (of the order of 1000 to 2000 ft) to the towers.

Fogging and Icing

The fog potential of these shorter, induced-ventilation towers is much greater than that of natural-draft units for the following reasons:

- Mechanical units release their water vapor at much lower elevations (50 to 80 ft, compared to 350 to 500 ft for NDCTs) where winds are weaker, the saturation deficit is usually less and surface nocturnal inversion may be present.

- The plumes are frequently trapped in the building wake eddies generated by aerodynamic downwash.

- Much higher entrainment rates (and hence lesser plume rise) are generated owing to smaller exit diameters, higher exit air speeds and the additional turbulence created by the fan.

Although wet mechanical-draft towers have been used for decades to cool power plants, little quantitative data are available on the water droplet plumes they generate (the work of Meyer et al.[108] being a recent exception), and even fewer references exist on significant adverse impacts due to their operation.[7,10,12,14,27,45,46,120-132] Several studies have reported light, friable rime icing from cooling tower operation, but there are no known reports of severe icing on adjacent roads or structures as the result of operating modern MDCTs. The primary cause of surface fogging and icing near an MDCT is aerodynamic downwash, which brings the plume to the ground very near the tower. A recent study of the plumes from the Oak Ridge, Tennessee, induced-draft towers (about 2000 MWt) indicates that during a seven-month period (December 1972 through June 1973), downwash was observed on 65% of all days (the photographs were taken during the afternoons) and occurred whenever the wind speed was more than 3 m/sec and wind direction was more than 10° from the long axis of the towers.[96,123-125] This fog either evaporated completely or lifted because of buoyancy once it escaped the tower cavity region, typically about 100 meters downwind. With the wind direction along the long axis of the towers (within ±10°), no downwash was observed with winds up to 5 m/sec. The greatest distance over which fog due to downwash was observed at Oak Ridge was 0.5 kilometer.[123] EPA studies indicate "mechanical draft towers may cause problems, but in most cases fogging and icing would be on-site (i.e., within 1000 to 2000 ft of the tower)."[14]

Thus, while downwash does cause fogging and icing near the tower, proper tower siting will confine the problem to the plant site.

Cloud and Precipitation Augmentation

The visible plume from a cooling tower is a cloud. Hanna and Perry[124] report that, on rainy days, the plume sometimes forms a stratus-type cloud that may extend for tens of kilometers below the natural overcast layer, and that a cumulus cloud can form in the updraft created by a cooling tower plume after the initial plume has evaporated completely. In the Oak Ridge study, it was concluded that some form of cloud development was initiated on 10% of all days.[123-125] Very light snow caused by cooling-tower discharge was reported in Tennessee[69] and in Indiana.[68]

Drift

Because of higher exit speeds in mechanical-draft towers, the drift rate is usually higher than in natural-draft units. However, drift rates as low as 0.0008% are possible.[80] In any event, almost all of the drift that falls to the ground will do so within 300 to 1000 feet of the towers.[96,123-125,128-132] In studies conducted at the gaseous diffusion plant in Oak Ridge, Tennessee, drift measurements were made on individual cells of both counterflow and crossflow towers.[96,123-125,130-132] Observations were made using three separate measurement techniques (LIDAR, sensitive paper and isokinetic samples).[70,71,80] The results of these tests indicate that the average drift flux from the crossflow tower was 3.8 g/m^2-sec, or approximately 0.1% of the recirculating water flow rate.[132] It should be pointed out that these are old (25 years) units with somewhat defective drift eliminators. Measurements made at a counterflow tower yielded an average drift concentration of 0.04 g/m^2-sec, or 3.5×10^{-4}% of the recirculating water flow.[132] The large difference in the values obtained at the two installations is thought to be due to the condition of the entrainment separators in the cells under test rather than to inherent characteristics of the towers. Measurements made at modern MDCTs using state-of-the-art drift eliminators indicate drift rates of about 0.008%;[128,129] even lower values are technically feasible.[80]

Deposition of Fallout

At Oak Ridge, studies were also conducted on the deposition flux and air concentration of drift chemicals in the cooling tower surroundings. Samples of grasses, trees and soils were analyzed to determine the amounts of cooling water treatment chemicals (such as chromium and zinc) they contain.[130-132] Although the tests definitely indicated concentrations of these chemicals above background levels at distances up to 2400 meters, it was observed that the amount decreased exponentially with distance. In the case of soil, the results indicated that background levels were not exceeded beyond 400 meters. Tests conducted with tobacco plants, which are sensitive to chromium, showed that little or no effects were observed at distances beyond 600 meters. In addition to the tests described above, observations of the surroundings in the near vicinity of the tower have shown no detectable damage from over 20 years of cooling tower operation.[130-132]

Models

Most models for predicting plume dimensions and surface fogging from mechanical-draft units include a prediction of plume rise (due to buoyancy and initial momentum) followed by a dispersion-of-moisture calculation from this "virtual" or effective stack height. Many of the models available predict frequent fogging some distance (1 to 10 km) from the tower due to downward dispersion. However, the limited amount of quantitative data concerning such towers indicate that this type of fog rarely if ever occurs (better, is rarely seen and is not reported). Fogging from MDCTs is almost exclusively due to aerodynamic downwash, a process ignored in many models.[1,2]

Consumptive Water Use

The consumptive water use is the same in both mechanical- and natural-draft cooling towers. On an average annual basis, about 75% of the heat transfer is due to evaporation; the rest, to conduction. In winter, the evaporative heat rate is as low as 60% of the total; it is about 90% in summer.[10]

Summary

In 1974, 80% of all orders for power-plant cooling towers were for mechanical-draft units, and 20% for NDCTs.[133] Ten years ago, the ratio was about 50:50. The survey showed that the average cooling range for MDCTs ordered in 1974 was 22.3°F, compared with 26.8°F for NDCTs; the average approach to wet-bulb for MDCTs was 13.9°F, compared with 17.3°F for NDCTs. The trend toward the greater use of MDCTs results in part from their lower total cost.[134]

MDCTs do cause surface fogging near (within 2000 ft of) the towers; this fog then either evaporates or lifts. The drift rate for a tower equipped with modern drift eliminators is 0.008% or less; most of the drift droplets that do fall to the surface will do so within 1000 feet of the tower. Thus, a properly sited and maintained MDCT can be used to dissipate heat from a power plant or other large source without creating a significant environmental impact, except in an area within 1000 to 2000 feet of the tower.

Mostly because of a shortage of quantitative empirical data, none of the mathematical models advanced for predicting plume parameters and drift for MDCTs has been shown to simulate nature accurately.[28]

OTHER TYPES OF COOLING TOWERS

Fan-Assisted Natural-Draft Towers

The fan-assisted natural-draft type of tower (FANDCT), a relatively new design concept, combines certain features of both mechanical- and natural-draft towers.[11,135-139] Several FANDCT designs exist, including both crossflow and counterflow arrangements for the fill.[135] In some, the multiple fans can be turned off on all but the warmest days or during low-load periods, and the unit will operate as a natural-draft tower. In others, the fans are used at all times for additional cooling capacity for a given size cooling tower. Thus, a shorter (compared with a pure NDCT) tower can be used to dissipate the same amount of waste heat. While no units of this type have been constructed in the United States to date, several are now operating in Europe. For example, in a typical English fossil-fired power plant, eight natural-draft cooling towers (each about 374 ft tall with a base diameter of 302 ft) are used to cool a 2000-MWe-fossil power complex.[illegible] The physical bulk of these towers and their visible plumes have created an adverse esthetic impact. In an effort to reduce this impact, a single FANDCT of the same height and shell diameter is now being built at the 1000-MWe-fossil Ince "B" power plant in England. This single tower will be able to do the cooling of the four NDCTs it will replace.[illegible] In this design, the fill will be outside the shell in a typical crossflow arrangement in a circle 564 feet across; 35 fans will provide the necessary airflow, and will use 0.6% of the power produced by the plant.

Another tower design consists of a concrete shell similar to, but shorter than, that of a pure counterflow natural-draft unit, with a circle of fans around the base to augment airflow.[illegible] For a given heat load, such a tower will be about one-half as tall and two-thirds the diameter of a natural-draft unit.[illegible] Wind tunnel tests for proposed FANDCTs at the Biblis Nuclear Power Plant in Germany indicated frequent fogging downwind from 170- (52 m) and 220-feet (67 m) tall units. A tower height of 268 feet (82 m) was required to ensure that "ground-touching plumes will be extremely rare."[52] Bøgh has stated that "although the assisted draught cooling towers gave higher ground impacts than the natural draught towers, their environmental influence can still be considered as being well within tolerable limits. . . ."[52]

The drift rate from FANDCTs will depend in part on the effectiveness of the drift eliminators. However, because of the higher exit air speeds, the drift rate could be greater than that of a natural-draft tower. Tests made in a large test cell indicate that, with proper engineering of the drift eliminators, drift is negligible.[illegible] Drift rates for FANDCTs of as low as 0.002% of the circulating water may be obtained and guaranteed; the cost penalty for such low drift rates is, however, lower than that of an NDCT of same capacity.[135]

One would suspect a FANDCT to be noisier than an NDCT, as the fans and motors would add to the noise generated by the falling water. However, Lefevre and Gilbert report that FANDCTs are not necessarily noisier, and that sound attenuation barriers can be added to make them very quiet.[135] They state that FANDCT noise levels are equal to, or actually less noisy in operation than, conventional MDCTs. Noise-absorbing baffles have been used to lower the levels at the Biblis plant to 19 dBa at 1800 meters (5900 ft).[135] Noise levels reported by Lefevre and Gilbert[135] at 500 feet from various types of cooling towers, in dBa, are: counterflow NDCTs, 61; counterflow fan-assisted units at peak load, 66; counterflow fan-assisted units with low-noise fans, 63; counterflow fan-assisted units with low noise fans, motors, gears and baffles, 45; and induced-draft counterflow (inline or clustered) units, 66.

Thus, the environmental impacts of fan-assisted towers will be comparable to those of natural-draft units.

Circular Mechanical-Draft Towers

As with FANDCTs, a variety of circular mechanical-draft cooling tower designs exist. One counterflow design uses one very large fan (up to 85 ft in diameter) to pull air through fill similar to that in natural-draft counterflow units. A large number of towers of this type are now in use in Europe, with unit sizes of up to 300 MWe-fossil per tower. Because of their high stacks (up to 150 ft), some of the force drawing air through the tower is due to the natural-draft effect. Another design uses a fill arrangement similar to that in crossflow natural-draft units, but replaces the hyperbolic shell with a number (up to 16) of fans similar to those used in mechanical-draft towers. One such tower is now operating at a 500-MWe-fossil plant in Gulfport, Mississippi.[143] One cooling tower vendor is now offering a counterflow circular tower with both forced draft (fans and motors located on the periphery of the unit pushing air across the fill) and induced draft (fans and motors inside the tower structure pulling air through the fill).[135] The latter arrangement would be somewhat quieter, as the fan placement would direct the noise upward, not outward.

The primary advantage of circular towers over the standard MDCT layout is the better aerodynamic characteristics of the rounded structure, which reduce downwash (and therefore fogging and icing) and recirculation.[51,52,113,140] Because these towers combine the heat output of many cells of a conventional mechanical-draft unit into one plume and (in some designs) discharge it at higher elevations (up to approximately 150 ft), ground-level fogging will be less than that of conventional MDCTs, but more than that of the much higher FANDCTs or NDCTs. The more compact site layout could reduce construction and pumping costs.

Wet-Dry Towers

In the wet-dry type of tower, a dry cooling section is added to a conventional evaporative cooling tower. Most design concepts, and all operating wet-dry units, are pure mechanical-draft types,[11,24,141-148] although a wet-dry natural-draft tower is feasible.[149] The design is an attempt to combine some of the best features of both wet and dry cooling towers (little or no fogging in winter, lower consumptive use of water, economical cooling in summer, etc.) and decrease the disadvantages of each (especially the high capital and operating costs of dry-only units for summer conditions). Experience with wet-dry towers is very limited, as only a few cells are now operational.

Four basic water and flow patterns are possible: airflow in series or parallel, and water flow in series or parallel. In one design (the only one now in use), all or part of the hot water first passes through the dry section of the tower and then through the wet section; airflow is through either the wet or the dry section, or both, with adjustable louvers used to control the two parallel airflows.[11] The airflows mix inside the tower prior to discharge. The effluent air thus has a higher temperature and a lower absolute humidity than that from a standard MDCT, lowering the potential for fogging, icing and long plumes. The amount of fogging and plume reduction will depend on the relative sizes of the two cooling sections. Such towers can be designed to operate with dry-only cooling below a certain temperature, say 40°F. It is expected that they would operate as wet-only units in summer. Thus, water conservation would result primarily in winter, which may or may not be important at a specific location.

Wet-dry mechanical-draft cooling towers are larger and more costly to build and operate than pure wet mechanical-draft units of similar capacity.

The dollar cost would be 25 to 100% more, depending on the exact design.[142] Utilization of a combined wet-dry system can be of great advantage in areas where the incremental contribution of cooling tower moisture to the atmosphere could increase the occurrence of fog in the vicinity of the cooling towers to an unacceptable degree. The reduction of fogging at a specific site may be sufficient to justify the higher costs involved.

COOLING PONDS AND SPRAY CANALS

Before the final complete plant design (fuel, location, boiler design, cooling system, dollar and ecological costs, etc.) is selected, the environmental impact of all feasible alternate cooling systems, including cooling ponds and spray canals, should be considered.

Cooling Ponds

In areas where land is relatively inexpensive and sufficiently level, cooling ponds and/or spray canals may be used to dissipate the plant's thermal discharges. Experience at operational plants with cooling ponds indicates that the ponds are effective and reliable heat sinks.[7,12,120] They are also the least expensive of the alternative cooling systems to install and operate over the lifetime of the plant in most areas where land can be purchased at current farm-land price levels.[7,150] Further, ponds have a considerable thermal inertia; that is, the power plant waste heat need not be dissipated to the atmosphere at the same rate that it is produced--as is the case with cooling towers. There is no noise or drift associated with cooling pond operation, and the ponds can also be used for recreation. Their primary disadvantage is the large water surface area needed to dissipate the energy. Seepage could be a problem at some locations.

There is a rule-of-thumb that at least one acre of water surface is needed to cool a 1-MWe-fossil plant effectively, and as much as 1.5 acres are needed for a similar light-water reactor.[7,11] A smaller pond will cool a plant at the expense of higher pond temperatures, higher back pressure in the turbines (hence, lower plant efficiency), and a greater impact of steam fog on the local atmosphere due to a warmer water surface. Larger ponds will provide cooler water and less steam fog, but at the expense of greater land-use area and greater total consumption of water.[151]

The primary meteorological effect of a cooling pond is the generation of steam fog over and near the pond.[7,152,153] Steam fog is created whenever the air above the pond is sufficiently cold and humid that it cannot retain the water vapor evaporating into it from the heated water surface.[1-6] The frequency, intensity and inland penetration of pond-induced steam fog are items of concern in pond site selection. Fog over ponds used for recreation could also be a problem; however, weather conditions during steam fog periods are not favorable for boating, fishing or swimming. Observations made at existing cooling ponds indicate the steam fog is usually shallow, wispy and in turbulent motion, and that it does not penetrate inland more than 100 to 500 feet before evaporating, becoming quite thin, or lifting to become stratus.[7,12,45,152-154] Steam fog has been observed two miles downwind of the Four Corners Power Plant in New Mexico.[2] The reference does not indicate the density of this fog, however. Elevated plumes (stratus) 11 miles long were observed.[2] It would appear that, because the water vapor is released over large areas, ponds are not a major source of dense fog despite the release of the water vapor at ground level. A cooling pond should be located so that the induced fogs (and freezing fogs) do not affect roads and bridges. Experience at the Dresden Nuclear Power Plant in northern Illinois indicates that a buffer distance of 500 to 1000 feet is sufficient.[152] Some of the water droplets will be removed by vegetation (a row of evergreens, for example) and other surfaces as the fog moves across the nearby land areas, causing a local increase in humidity and dew, but reducing fog density downwind of the "fog sweeper."[illegible] The potential for creating steam fog and icing (as well as the thermal effectiveness of the pond) depends on pond size, plant load and local weather conditions, such as air temperature and humidity, wind speed and sunshine. Therefore, the utility will have to study local weather conditions before selecting this cooling system for a specific plant.

It should be remembered that natural steam fog is fairly common in much of the nation because of the frequent passage of cold air masses over open water. Because of higher water temperatures, steam fog will sometimes form over the heated water in cooling ponds when conditions do not favor natural steam fog. During periods of subfreezing temperatures, some of the droplets will freeze and create a layer of low-density rime ice on nearby (i.e., within a few hundred feet) vegetation and structures.[illegible] Observations at existing ponds indicate that this rarely, if ever, causes problems with power lines or vegetation because of the nature of the rime ice deposited.[illegible] In any event, the ice will be similar in nature to that produced by natural steam fog.

Water consumption from a cooling pond cannot be estimated by a simple calculation, as all components of the water budget for the pond area must be considered.[10,151] These include water gains by precipitation and runoff and losses by seepage. If the pond or lake existed prior to its use as a cooling facility, the consumptive use for cooling alone (forced evaporation) is total lake evaporation minus natural evaporation. Water losses due to forced evaporation on an existing water body are probably less than that from a wet cooling tower, since the pond also loses significant amounts of heat by conduction and radiation. For new ponds, the natural evapotranspiration of the area covered by the pond must be subtracted from total pond evaporation in order to calculate the net consumptive water use. It is generally assumed that a new cooling pond evaporates more water than cooling towers of similar capacity.[151]

Spray Canals

In a spray cooling system, pumps are used to send a spray of heated water droplets into the atmosphere to increase the area of contact between water and air, thus increasing the rate of cooling by conduction and evaporation. One type of system now in service sends the water about 20 feet upwards in a 40-foot-diameter circle. The primary advantage of a spray system over a cooling pond is the much smaller water area needed to cool a given plant load: about five percent of that needed for a cooling pond of similar capacity.[11,12,120] However, to reduce recirculation and ensure maximum cooling efficiency, the sprays should be spread over a large area, such as a meandering canal.[157-159] If the spray modules are placed in rows, as in a canal, they should be aligned at right angles to the prevailing winds if at all possible. Additional land between the canal and plant boundary is needed to reduce fogging impacts.

Spray cooling systems have a higher probability of creating dense fogs than a cooling pond or once-through system, since, for a given heat load, a much smaller volume of air is modified by the sprays. The fogging potential of a spray canal is lower than that of an MDCT, however.

The visible plume created by a spray canal contains some drift droplets in addition to drops of recondensed vapor. These drift droplets will be much larger than those produced by condensation, and add considerably to the wetting and icing potential of the visible atmospheric plume.[illegible] The drift rate from a spray cooling system will depend on many factors, such as wind speed and the design of the spray units. Because there are no drift eliminators, the drift rate can be quite large in strong winds. However, because of the low height of release, the low vertical velocity of the droplets as they leave the spray heads and the large size of the droplets, most of the drift will quickly fall to the surface near the spray units.[illegible]

In contrast to cooling towers and ponds, which have been used for decades, there has been little operating experience with large spray cooling systems, especially in winter, the season of greatest fogging and icing potential. Most information on the thermal performance of sprays is proprietary, the recent work of Porter et al. of Illinois Institute of Technology being an exception.[illegible] Power plant operation with a spray cooling canal at the Dresden Plant in northern Illinois indicated no serious environmental or fogging problems after three seasons of use.[illegible] Similar experiences with spray canals have been noted in Michigan[illegible] and New Hampshire.[illegible] As with cooling ponds, the fogging and icing effects decrease rapidly with distance. Hoffman concludes that a distance of 600 feet from the canal to public roads and switchyards is sufficient to preclude any hazardous conditions from arising.[illegible] From the limited experience to date, it is reasonable to expect that spray cooling systems will create more severe icing conditions very near the spray canal during winter than would MDCTs and cooling ponds, with drift being the primary cause of the difference.

Quantitative estimates of fog and icing potential from spray canals are not now possible, since the properties of the air downwind of spray units (temperature, liquid water content, droplet size distribution, etc.) are unknown functions of ambient weather conditions (wind speed, air temperature, humidity, stability), water temperature, and characteristics of the spray heads (nozzle opening number of spray, droplet sizes and their location with respect to the wind direction, etc.). For most wind conditions, the air will be in contact with the water from the spray for a shorter period than it would be in a cooling tower, and a larger volume of air will be modified while cooling a given plant load. Sprays are noisier than cooling ponds because of the pumps, falling water and lack of baffling.

Hori reports that a belt of evergreen trees acts as a "fog sweeper," reducing the area affected by spray canal induced fogging.[155,156] Such a shelter belt would also cut the wind speed across the sprayed water, reducing both drift and thermal performance.

Summary, Cooling Ponds and Spray Canals

In general, experience has shown that cooling ponds are effective, inexpensive and environmentally acceptable cooling systems as long as they are located a sufficient distance (of the order of one-quarter to one-half mile) from public roads, etc., the exact distance depending in part on plant loading (heat dissipation per acre), local weather conditions, and the type of vegetation between the water and the roads structures, etc. Experience with large spray cooling systems is limited, and adequate studies of their thermal performance and environmental impacts have not as yet been conducted and or made available for evaluation. Most information on the thermal performance of spray systems is proprietary. Data that are available indicate that sprays are environmentally acceptable if there is a large enough (of the order of one-quarter to one-half mile) buffer zone.

Cooling Towers Using Saline Water

Because a large fraction of the total electric power generation for this country is located near centers of population, many of the installations now proposed or under construction are to be located close to the east and west seaboards. To provide the necessary cooling for the large number of power plants anticipated, it will be necessary to use salt- or brackish water as a means of cooling in some plants. When cooling towers are used, the environmental aspects of drift and blowdown must be evaluated.

Although there has been very little experience with saline water in recirculating cooling water systems in this country, the English Central Electricity Generating Board (CEGB) has operated two natural-draft evaporative cooling towers using saltwater at its 90-MWe Fleetwood Power Station for about 21 years.[illegible] These towers are about 250 feet high 184 feet in diameter at the base, and circulate water at about 50,000 gpm each. Salt concentration is about 40,000 ppm. No significant environmental effects due to salts in the drift have been observed at this power plant.[illegible] The measured drift rates from these old towers is of the order of 0.03 to 0.06% of the circulating water flow. A network of 11 deposition gauges was used for a one-year period to determine chloride deposition. No measurable increase above the natural background level (about 900 kg/km^2-mo or 8 lbs/acre-mo) was detected.[illegible] Trees, lawns and pastures near the towers show no signs of damage due to drift. Based on their long experience at the Fleetwood Station, CEGB representatives state that they have not observed adverse effects and have not had complaints from their neighbors.[illegible] Of course, care must be used in extrapolating from this small plant to a group of much larger generating units. A saltwater NDCT with a drift rate of less than 0.002% is now in use in New Jersey.[79]

Several theoretical investigations have attempted to determine the effect of the saltwater deposition patterns in areas located close to the seashore and the environmental aspects of sea spray on biological growth in these areas. The early literature contains descriptions of injury to plants after strong winds off the ocean.[165] It was observed as early as 1805 in England that greater leaf injury occurred when there was no rain associated with such winds.

In the studies for the proposed Forked River Nuclear Power Plant, on the New Jersey coast, the environmental effects of salt drift from an NDCT were calculated.[illegible] Initial measurements were made at a power plant where a counterflow tower of similar design was in operation.[illegible, 72] The characteristics of drift from this installation were then used to model the potential effects of a tower using seawater as makeup. The following conclusions were reached concerning the Forked River installation.

The accumulation of airborne salt on aboveground vegetation such as leaves and branches is proportional to the near-ground air concentration of salt. Measurements made in the vicinity of the Forked River installation indicate that the concentration of natural sea salt in the air ranged from an annual average of one $\mu g/m^3$ at a distance of ten miles inland to about 70 $\mu g/m^3$ at the shore itself. Under consistent on-shore wind conditions, short-term natural sea-salt concentration can be 20 $\mu g/m^3$ ten miles inland and 500 to 1000 $\mu g/m^3$ near the shore. The study, relying on measurements of the drift rate and drift drop size distribution made on the Homer City, Pennsylvania, station cooling tower, indicates that the annual average near-ground air concentrations of tower salt will be less than ten percent of that from the bay and ocean. The highest annual average near-ground air concentration of tower salt is about 0.1 $\mu g/m^3$, about a factor of 100 below the level of 10 $\mu g/m^3$, which might have a long-term effect on the growth of a principal species of vegetation in the area.[84,92]

The effect of airborne salt on the surface- and groundwater, soil and plant life is related to the deposition rate of salt on the surface of the ground. Measurements indicate that the annual sea-salt deposition rate averages from 300 kg/km^2-mo at a distance of ten miles inland to 3500 kg/km^2-mo near the shore. About one-half to three-quarters of this occurs normally in rainfall. The average natural sea-salt concentration in rainwater is estimated to vary from about 10 to 20 ppm immediately inland from the shore to about two ppm ten miles inland. Comparable tower salt concentration in rainfall in the area within a three-mile radius of the tower is estimated to average a fraction of one ppm. Obviously, the downstream contribution will be less. Investigations made in the area of the Forked River plant indicate that the incremental effects of cooling tower operations on airborne salt concentration, salt in rainfall, and dry deposition rates will result in no significant related effects on subsurface water, groundwater, and soil, or indirect effects on fish, land animals and subsurface structures.[84,92]

Observations of the rate of salt deposition from drift from brackish water NDCTs and of the biological impact of this salt are being conducted at two locations along the Atlantic Coast.[76,77,79] Preoperational estimates of these parameters for the Chalk Point, Maryland, plant are included in a series of reports in Reference 22; no serious impacts are expected. Nester[83] reports no serious problem due to salt drift from a small mechanical-draft tower in New Jersey.

DRY COOLING TOWERS

ENGINEERING ASPECTS

The use of dry (nonevaporative) cooling towers for power-plant heat rejection has been the subject of much study during the past few years.[24,25,166-185] Increasing interest in the use of dry-type cooling systems by both the steam-electric power generating and process industries is evident. The use of such cooling systems will allow greater freedom in plant siting by eliminating the need for large water supplies. In these systems, all heat transfer takes place as a sensible heat-transfer process across an air-metal interface rather than by evaporation. Because the advantage of latent heat evaporation is not available, the heat-transfer area in dry-cooling systems must be extensive; airflow through a dry tower is about three times that through a wet tower of similar capacity.

Dry cooling towers now being used in Europe and Africa are limited to fossil plants in the 220-MWe or smaller categories.[166] A 330-MWe coal plant using dry towers is now being constructed at the Wyodak Station, near Gillette, Wyoming.[171]

Dry cooling towers remove heat from a circulating fluid through conduction to air being circulated past the heat-exchanger tubes. The theoretical lowest temperature that a dry cooling system can achieve is the dry-bulb temperature of the air, which is always higher than or equal to the wet-bulb temperature, the theoretical lowest temperature that a wet cooling tower can achieve. As a result, a dry cooling tower is a less efficient cooling system, which leads to increased cost and size of the cooling equipment. Turbine back pressures will be increased, as will the range of back pressures over which the turbines must operate. This will result in a reduced station capacity for a given boiler system and quantity of fuel used. Because of high capital and operating costs, higher back pressures in the turbines and poor fuel economy, dry towers are not now an attractive alternative cooling technique for power plants with large heat loads, except in areas where adequate water is unavailable or too expensive. Dry towers are in widespread use in the chemical and petroleum industries, where high condensate temperatures are tolerable.

Studies have been undertaken to determine the incremental increased cost of adding dry cooling towers to conventional power systems. Dry cooling can be expected to add a small incremental cost to the production of power as finally distributed to the buyer. When considered at the retail level for household service, including all costs of generation and transmission, the increase in cost for power production using dry-type heat-rejection systems with a power plant optimized for dry cooling could be as low as two to five percent, depending on the rate prevailing in the particular system.[172] Much higher cost estimates can also be quoted (e.g., see Ref. 44).

E. S. Miliaras recently published a comprehensive book on the engineering aspects of dry cooling systems for large heat loads.[166]

ATMOSPHERIC EFFECTS

It is frequently stated or assumed that dry towers, either of the natural- or mechanical-draft types, would have little if any local atmospheric effects. Dry towers will not, of course, create fogging or icing. However. the possibility exists that the updraft from such a tower could release an existing atmospheric convective instability and create showers, thunderstorms and severe storms.[25,44,65,186] Huff, a cloud physicist, recently stated: "At this time, for example, it is not evident whether a dry or wet tower plume is more likely to initiate clouds with a given rate of energy discharge to the atmosphere."[65] Hanna and Gifford[187] find the probability of cloud forming due to a dry-tower plume nearly the same as that for a wet cooling tower, if other factors (heat discharge rate, atmospheric conditions) were equal. Due to poorer efficiency, a plant of given size would discharge more waste heat with dry towers than with wet units. Boyack and Kearney[25] state that ". . . a sailplane pilot, reported that the thermal updraft over the Ibbenbüren plant [150 MWe-fossil] is by far the strongest and most persistent updraft in northwestern Germany, far outweighing the effect of naturally originating thermals produced by terrain and slope differences. Frequent cloud formation has also been observed by sailplane pilots over or downwind from the Ibbenbüren plant."

In a wet cooling tower, 10 to 40% of the waste heat is in the form of sensible heat, with the lower value typical of summer conditions. All of the heat from a dry tower is in the form of sensible heat. Hence, the effluents from dry towers create much larger updrafts than effluents from evaporative towers of equal electrical capacity, especially in summer when the probability of large thunderstorms is greatest. Most of the liquid water in a cumulus or cumulonimbus cloud generated by updrafts from a wet cooling tower comes from the condensation of ambient water vapor entrained into the rising air column, not from the cooling tower effluent. Thus, the cloud-building and precipitation augmentation of a cooling tower effluent are due to the buoyancy and vertical momentum of the effluents. Meteorological conditions in the atmosphere above the cooling tower tops will control plume rise and cloud generation. On a dry day with a stable atmosphere, or on a very windy day, no large clouds will be generated. However, on days when the atmospheric conditions favor natural cumulus cloud activity, the buoyancy of the cooling tower plumes could initiate or augment convective activity.

Some people believe that dry cooling towers can produce desirable weather effects that could be an asset to the local environment.[25,186] Some believe that the large heated plumes from dry cooling towers can be used to disperse fog in the near vicinity. It is also possible that plumes from both natural- and mechanical-draft dry cooling towers can be expected to penetrate ground-level and most elevated inversions under normal conditions. One advantage of this method of heat release is the possibility of venting pollutants trapped below the inversion by pushing them up through the stable layers. However, this cleansing action could be expected to be small unless there were a large number of 1000-MW or larger power plants located within a single basin.[25,186]

Other possible objections to dry cooling towers include the noise and visual size of the towers. The noise level from a large array of fans in a mechanical-draft dry tower would be higher than that from a wet tower of equal capacity. Boyack and Kearney state that an NDCT for a 1000-MWe nuclear plant at sea level would be 713 feet tall, with top and base diameters of 547 and 783 feet, respectively.[25,186] At an elevation of 3000 feet, these values, in order, change to 918, 577 and 783 feet. Thus, dry NDCTs would be much larger than evaporative NDCTs for a given generating load. Dry mechanical-draft towers would also be larger than wet MDCTs, covering an area 1250 × 354 feet, standing 115-feet tall and using forty-eight 60-foot-diameter fans. Freezing of the cooling water inside dry towers is a serious problem.[171,174]

ENERGY PARKS

"Energy parks"--consisting of a large number of electric generating stations in a limited geographical area--are now being seriously considered as a solution to the energy problem.[187-190] Energy centers with capacities of 5000 MWe (nuclear) are now being constructed; power parks of 10,000 to 50,000 MWe are being considered. Martin[191] has examined local weather data near a

2000-MWe-fossil plant using eight natural-draft cooling towers and found no evidence of weather changes due to the thermal plumes. Hanna and Gifford[187] indicate that, while clouds are formed by cooling tower plumes, no significant changes in rainfall in the areas of study have been reported. This conclusion seems to be valid for power plants using natural- or mechanical-draft cooling towers in currently operating power plants, with capacities up to 3000 MWe-fossil or 2000 MWe-nuclear. Whether it is a valid conclusion for larger heat outputs is not known.

The state-of-the-art in atmospheric modeling and understanding is such that meteorologists are not able to predict quantitatively how the atmosphere will react to the large amounts of heat energy and water vapor that it will be forced to absorb from small areas as the result of the disposal of waste heat from energy parks. Conceivably, critical heat-release rates may exist which, when exceeded, may lead to significant meteorological effects, such as the generation of thunderstorms and severe storms in convectively unstable, subtropical conditions.[[illegible],64-66,187] The possibility of such inadvertent weather modifications should be examined very carefully before any energy parks are constructed. Energy parks using once-through cooling systems on the ocean would have very little if any atmospheric effects. Those using cooling ponds would have a much lower probability of creating significant atmospheric effects than would plants using cooling towers, due to their large area and the low level of heat and vapor releases. The NRC has recently published a report on the technical and meteorological aspects of power parks.[[illegible]]

SUMMARY AND CONCLUSIONS

The amount of heat energy contained in the cooling water from large nuclear power stations is small in comparison with amounts involved in natural heat processes. Because the heat energy from plants with once-through cooling systems will enter the atmosphere slowly over a large area, changes in weather will be small and impossible to isolate in the natural variability of weather elements. An exception will be an increase of steam fog in fall and winter at the point of discharge.

Evaporative cooling towers and lakes are effective heat sinks which sharply reduce the impact of thermal discharges on water bodies. However, they do create their own atmospheric impacts which, for an isolated site such as required for the exclusion area of a nuclear plant, are rather minor and usually acceptable.

Mathematical models to simulate plume and drift behavior are available, but none has been shown to be accurate and reliable under all weather conditions, due primarily to a lack of plume and drift data from operational power plants. Since some data on plume effects are now being collected, efforts to validate and improve models should be increased.

The primary reason meteorologists are not able to make accurate, quantitative estimates of the atmospheric effects of cooling-system operation is the lack of systematic, detailed observations made at operating power plants. Therefore, the primary research need to eliminate this information void is a series of major field experiments at power plants with mechanical-draft and natural-draft cooling towers, spray canals, once-through cooling and cooling ponds. The primary results of these field observations would be to clearly identify and quantify the environmental problems caused by cooling systems, and to indicate which of the postulated issues are in fact nonproblems and need not be considered further. Another result of equal importance would be the construction of a suitable data base that would allow mathematical and physical models to be developed and adequately tested. These models could then be used to predict with accuracy and confidence conditions at proposed power plants in other areas. As a result, multimillion-dollar design decisions, which are now being based on very poor information, would be supported on a more accurate and complete assessment of cooling-system effects. The observations would also be used to formulate "rules-of-thumb" that could be used in determining the environmental acceptability of a specific cooling system on a given site. For example, if more thorough observations show that fog from MDCTs and cooling ponds does, in fact, always or almost always evaporate or rise above the surface within a short distance, then no model would be needed to accept such a cooling system on another site. But "how far is far enough" remains a valid question requiring a quantitative answer that can only come through observations over a wide range of meteorological conditions at operating plant cooling systems.

Specific areas for which additional field studies as well as theoretical analyses are urgently required include: (1) plume rise and the dimensions of the visible plumes from all types of cooling systems; (2) fogging and icing from mechanical-draft cooling towers, cooling ponds and spray canals; (3) drift emission and deposition rates and the effects of salt deposition on plants and structures; (4) interaction of cooling tower plumes with other pollutants, especially SO_2; (5) generation of clouds and precipitation; (6) critical heat-release rates for a given site; and (7) physical (laboratory) model studies in wind tunnels. The field observations should also identify nonproblem areas: i.e., environmental objections to cooling systems raised by theoretical and other arguments which are not observed or are of relatively low importance, such as fogging and icing from natural-draft cooling towers, drift effects, acid misting, noise, etc. More complete information on research needs are given in References 35, 67 and 190.

Because of the legal nature of environmental hearings, the results of these studies should be published in a series of reports, with condensed versions published in the open literature, preferably in a refereed journal. The research above would quantify the effects of the operation of the various cooling tower options and allow the utilities and regulatory agencies to weigh the advantages and disadvantages of each cooling system more accurately and then to select the best total power plant design for a given site.

ACKNOWLEDGMENTS

This document was prepared at Argonne National Laboratory under the auspices of the U. S. Nuclear Regulatory Commission. Comments and critiques received from Drs. F. Vaslow, T. J. Policastro, G. J. Marmer, and C. Luner, of Argonne, are gratefully acknowledged.

This generic report is in part based on a report prepared by Dr. Eric Aynsley* and the author in the fall of 1972, titled "Environmental Effects of Water Cooling for Power Plants: A Status Report." For a variety of reasons, this report was never published. The contributions of Dr. Aynsley to this revised document are acknowledged with thanks. The contributions to several sections of this report--especially those dealing with water quality, noise, and dry cooling towers--by Mr. T. Shapiro of Union Carbide-Nuclear Division, Oak Ridge, Tennessee, are also acknowledged with thanks.

**A consultant to the Laboratory; present address: Particle Data Laboratories, Elmhurst, Illinois.*

REFERENCES

1. P. E. Church, *Steam-fog over Lake Michigan in winter*, Trans. Am. Geophys. Union, 26:353-357, 1945.

2. E. L. Currier et al., *Cooling pond steam fog*, J. Air Poll. Cont. Assoc., 24:860-864, 1974.

3. P. M. Saunders, *Sea smoke and steam fog*, Quart. J. Royal Meteorol. Soc., 90:156-165, 1964.

4. R. A. Cox, *Predictions of fog formation due to a warm lagoon proposed for power plant cooling*, Atmos. Environ., 7:363-368, 1973.

5. F. A. Huff and J. L. Vogel, *Atmospheric effects from waste heat transfer associated with cooling lake*, Illinois State Water Survey, Urbana, December 1973.

6. Y. J. Tsai and D. R. DeHarpporte, *A method for predicting fog produced by cooling ponds*, Paper presented at AEC Specialty Conference, Ithaca, NY, Aug. 16-18, 1972.

7. J. E. Carson, *The atmospheric effects of thermal discharges into a large lake*, J. Air Poll. Cont. Assoc., 22:523-528, 1972.

8. J. P. Asbury, *Evaluating the effects of thermal discharges on the energy budget of Lake Michigan*, Report ANL/ES-1, Argonne National Laboratory, 1970.

9. J. E. Carson, *Atmospheric effects of waste heat discharges into a large lake*. In: Proceedings of the Second Federal Conference on the Great Lakes (sponsored by the Interagency Committee on Marine Science and Engineering of the Federal Council for Science and Technology), March 25-27, 1975, pp. 306-318. (Published by the Great Lakes Basin Commission, Box 999, Ann Arbor, MI 48106.)

10. *Reviewing environmental impact statements--power plant cooling systems, engineering aspects*, Report EPA-660/2-73-016, National Environmental Research Center, U. S. Environmental Protection Agency, Corvallis, OR, October 1973.

11. *Cooling Towers*, Power, 117:S-1 to S-24, March 1973.

12. *Industrial waste guide on thermal pollution*, National Thermal Pollution Research Program, Federal Water Pollution Control Administration, Corvallis, OR (revised), 112 pp., September 1968.

13. K. K. McKelvey and M. Brooke, *The Industrial Cooling Tower*, American Elsevier Publishing Co., New York, 429 pp., 1959.

14. *Development of document for effluent limitations guidelines and new source performance standards for the steam electric power generating point source category*, EPA 440/1-74 029-a, U. S. Environmental Protection Agency, Washington, DC, October 1974.

15. *Steam electric power generating point source category, effluent guidelines and standards*, Federal Register, pp. 36186-36211, Oct. 8, 1974.

16. D. B. Leason, *Planning aspects of cooling towers*, Atmos. Environ., 8:307-312, April 1974.

17. I. Dyer and L. N. Miller, *Cooling tower noise*, Noise Control, 3:44-47, 1959.

18. G. A. Capano and W. E. Bradley, *Radiation of noise from large natural draft and mechanical draft cooling towers*, Paper 74-WA/HT-55, Am. Soc. Mech. Eng. Meeting, New York City, Nov. 17-27, 1974. Also: *Noise prediction techniques for siting large natural draft and mechanical draft cooling towers*, Paper 155, Am. Power Conf., Chicago, April 22, 1976.

19. R. M. Ellis, *Cooling tower noise generation and radiation*, J. Sound Vibr., 14(2):171-182, 1971.

20. *Comments on EPA's proposed § 304 guidelines and § 306 standards of performance for steam electric power plants*, The Edison Electric Institute et al., June 26, 1974 Attachment III, *Study on the cost of backfitting from open to closed cycle cooling*, Sargent and Lundy Engineers, Appendix G.

21. G. Spurr, *Meterology and cooling tower operation*, Atmos. Environ., 8:321-324, April 1974.

22. *Cooling Tower Environment-1974*, ERDA Symposium Series, CONF-740302, 638 pp., USERDA Technical Information Center, Office of Public Affairs, Washington, DC, 1975.

23. *Cooling towers*, Chemical Engineering Progress, Tech. Manual, Am. Inst. Chem. Eng., 145 pp., 1972.

24. R. L. Webb and R. E. Barry, eds., *Dry and wet/dry cooling towers for power plants*, Papers presented at Winter Annual Meeting of ASME, Detroit, Mich., November 1973. Am. Soc. Mech. Eng., 153 pp., 1973.

25. B. E. Boyack and D. W. Kearney, *Plume behavior and potential environmental effects of large dry cooling towers*, report by Gulf General Atomic Co. for U. S. Atomic Energy Commission, Contract AT (04-3)-167, Project Agreement No. 47, 167 pp., February 1973.

26. F. A. Huff et al., *Effect of cooling tower effluents on atmospheric conditions in northeastern Illinois*, Circ. 100, Illinois State Water Survey, Urbana, 1971.

27. A. Roffman et al., *The state-of-the-art of salt water cooling towers applicable to nuclear electric power generating plants*, Report WASH-1244, Westinghouse Electric Corp., Pittsburgh, PA, for U. S. Atomic Energy Commission, Contract AT(11-1)-221, February 1973.

28. G. E. McVehil and K. E. Heikes (known to be authors), *Cooling tower plume modeling and drift measurement. A Review of the state-of-the-art.* Am. Soc. Mech. Eng., 170 pp., 1975.

29. *Symposium on the physical and biological effects on the environment of cooling systems and thermal discharges at nuclear power plants*, Proc. International Atomic Energy Agency, Oslo, Norway, Aug. 26-30, 1974.

30. Proceeding of the 9th World Energy Conference, Division 2, Environment and the Energy Supply, Detroit, MI, Sept. 22-27, 1974.

31. F. L. Parker and P. A. Krenkel, *Thermal pollution: status of the art*, Report No. 3, Dept. Env. and Water Resources Engineering, Vanderbilt Univ., Nashville, TN, December 1969.

32. F. L. Parker and P. A. Krenkel, eds., *Design and operation of cooling towers*, Vanderbilt Univ. Press, Nashville, TN, 1969.

33. F. L. Parker and P. A. Krenkel, *Physical and engineering aspects of thermal pollution*, CRC Press, Cleveland, OH, 1970.

34. G. Spurr and R. A. Scriven, *United Kingdom experience of the physical behaviour of heated effluents in the atmosphere and in various aquatic systems*, Paper ABA-SM-187/38, Proc. International Atomic Energy Agency Symposium, Oslo, Norway, August 1974.

35. J. E. Carson, *Meteorological effects of evaporative cooling towers--research needs*, Paper 74-WA/HT-58, Am. Soc. Mech. Eng., New York City, November 1974 (preprint available).

36. P. T. Brennan et al., *The observed rise of visible plumes from hyperbolic natural draft cooling towers*, Atmos. Environ., 10:425-431, 1976. Also: *Behavior of visible plumes from hyperbolic cooling towers*, Paper presented to Am. Power Conf., Chicago, April 22, 1976.

37. R. E. Huschke, *Glossary of Meteorology*, Am. Meteorol. Soc., Boston, 638 pp., 1959.

38. D. J. Moore, *Recent CEGB research on environmental effects of wet cooling towers*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 205-220, 1975.

39. M. L. Kramer et al., *Snowfall observations from natural-draft cooling tower plumes*, Science, 193:1239-1241, September 24, 1976.

40. D. J. Broehl, *Field investigation of environmental effects of cooling towers for large steam electric plants*, Portland General Electric Co., 1968.

41. W. C. Colbaugh et al., *Investigation of cooling tower plume behavior*. In: "Cooling Towers," Chemical Engineering Progress (eds.), AIChE, New York, pp. 83-86, 1972.

42. *Environmental effects of cooling towers*, Great Britain Central Electricity Generating Board, Planning Department, 3 pp., June 21, 1968.

43. G. Spurr, *The magnitude of the problem of thermal discharge from nuclear power plants*, Report PL. SP/EG/3/72, Great Britain Central Electricity Generating Board, September 1972.

44. R. M. Rotty, *Waste heat disposal from nuclear power parks*, Tech. Memo. ERL ARL-47, National Oceanic and Atmospheric Administration, September 1974.

45. R. W. Zeller et al., *Report on trip to seven thermal power plants*, prepared for Pollution Control Council, Pacific Northwest Area, 1969.

46. F. W. Decker, *Probabilities of cooling system fogging.* In: "Cooling Towers," Chemical Engineering Progress (eds.), AIChE, New York, pp. 91-93, 1972.

47. E. Aynsley, *Cooling-tower effects: studies abound*, Electr. World, 42-43, May 11, 1970.

48. C. L. Hosler, *Wet cooling tower plume behavior.* In: "Cooling Towers," Chemical Engineering Progress (eds.), AIChE, New York, pp. 27-32, 1972.

49. M. E. Smith et al., *Cooling towers and the environment*, Am. Elec. Power Corp., New York, October 1974.

50. A. Junod et al., *Meteorological influences on atmospheric cooling systems as projected in Switzerland.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 239-264, 1975.

51. P. Bøgh et al., *A new method of assessing the environment influence of cooling towers as first applied to the Kaiseraugst and Leibstadt Nuclear Plants*, International Nuclear Industries Fair (Nuclex 72), October 1972.

52. P. Bøgh, *Experience with combined wind tunnel/plume model analysis of cooling tower environmental impact.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 265-290, 1975.

53. P. Bøgh, *Development on the cooling system, heat use and thermal efficiency in nuclear power plants*, Kerntechnik, 17 (9/10), 443-439, 1975.

54. R. C. Scorer, *Air Pollution*, Pergamon Press, London, 151 pp., 1968.

55. J. M. Burnett et al., *The cooling of power stations*, Paper 2.2-5, Proc. IX World Energy Conference, Division 3, September 1974.

56. R. D. Woodson, *Cooling towers*, Sci. Am., 224(5):70-78, May 1971.

57. H. Bartels and J. W. Caspar, *German cooling tower experience and the meteorological consequences of thermal discharges from nuclear power plants*, Paper IAEA-SM-187/23, Proc. International Atomic Energy Symposium, Oslo, Norway, August 1974.

58. J. I. Reisman and J. C. Ovard, *Cooling towers and the environment--an overview*, Proc. Am. Power Conf., 35:713-725, 1973.

59. M. L. Kramer et al., *Cooling towers and the environment*, Paper 75-17.3, Air Poll. Cont. Assoc., Boston, MA, June 1975.

60. G. F. Bierman et al., *Characteristics, classification, and incident plumes from large natural-draft cooling towers*, Proc. Am. Power Conf., 33:535-545, 1971.

61. F. R. Barber et al., *The persistence of plumes from natural draught cooling towers*, Atmos. Environ., 8:407-418, 1974.

62. J. V. Wilson, *ORFAD, a computer program to estimate fog and drift from wet cooling towers*, Report ORNL-TM-4868, Oak Ridge National Laboratory, January 1975.

63. *Potential environmental modifications produced by large evaporative cooling towers*, Water Pollution Control Research Series, EPA WQO, Report No. 16130 DNH 01/71, EG&G, Inc., 1971.

64. E. W. Hewson, *Moisture pollution of the atmosphere by dry cooling towers and cooling ponds*, Bull. Am. Meteorol. Soc., 51:21-22, January 1970.

65. W. P. Lowry, *Environmental and effects of nuclear cooling facilities*, Bull. Am. Meteorol. Soc., 51:23-24, January 1970.

66. F. A. Huff, *Potential augmentation of precipitation from cooling tower effluents*, Bull. Am. Meteorol. Soc., 53:639-644, July 1972.

67. W. C. Ackermann, *Research needs on waste heat transfer from large sources into the environment*, report to National Science Foundation, Grant GI-30971, Illinois State Water Survey, Urbana, p. 37, December 1971.

68. E. M. Agee, *An artificially induced local snowfall*, Bull. Am. Meteorol. Soc., 52:557-560, 1971.

69. W. M. Culkowski, *An anomalous snow at Oak Ridge,* Tennessee, Monthly Weather Rev., 90(5):194-196, May 1962.

70. F. M. Shofner et al., *Measurement and interpretation of drift-particle characteristics*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 427-454, 1975.

71. G. O. Schrecker et al., *Prediction and measurement of airborne particulate concentrations from cooling-device sources in the ambient atmosphere*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 455-482, 1975.

72. A. Martin and F. R. Barber, *Some water droplet measurements inside cooling towers*, Atmos. Environ., 8:325-336, 1974.

73. A. Martin and F. R. Barber, *Measurement of precipitation downwind of cooling towers*, Atmos. Environ., 8:373-381, 1974.

74. B. R. Gardner and H. J. Lowe, *The research and development background to the environmental problems of natural draught cooling towers*, Atmos. Environ., 8:313-320, 1974.

75. V. M. Morton and P. M. Foster, *The design of droplet and sampling devices for measurements in cooling towers*, Atmos. Environ., 8:361-372, 1974.

76. J. Pell, *The Chalk Point cooling tower project*, Paper IAEA-SM-187/41, Proc. International Atomic Energy Agency Symposium, Oslo, Norway, August 1974.

77. J. Pell, *The Chalk Point cooling tower project.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 88-127, 1975.

78. J. D. Holmberg, *Drift management in the Chalk Point cooling tower.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 128-146, 1975.

79. M. E. Waner and M. R. Lefevre, *Salt water natural-draft cooling design consideration*, Proc. Am. Power Conf., 36:442-453, 1974.

80. G. O. Schrecker and C. O. Henderson, *Salt water condenser cooling: measurements of salt water drift from a mechanical draft wet cooling tower and spray modules, and operating experience with cooling tower materials*, Paper 154, Am. Power Conf., Chicago, April 22, 1976.

81. A. Roffman and R. E. Grimble, *Drift deposition rates from wet cooling systems.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 585-597, 1975.

82. A. Roffman and L. D. VanVleck, *The state-of-the-art of measuring and predicting cooling tower drift and its deposition*, J. Air Poll. Cont. Assoc., 24(9):856-859, 1974.

83. D. M. Nester, *Salt water cooling towers.* In: "Cooling Towers," Chemical Engineering Progress (eds.), AIChE, New York, pp. 115-117, 1972.

84. J. C. DeVine, Jr., *The Forked River program: A case study in saltwater cooling.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 509-557, 1975.

85. C. D. Henderson and S. H. Dowdell, *Test program on environmental effects of saltwater mechanical cooling devices.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 501-509, 1975.

86. D. B. Smith, *Fallout of sulfuric acid*, testimony presented at USAEC hearing, Bailly Nuclear Plant, AEC Docket No. 50-367, 1973.

87. J. Stockham, *Cooling tower study*, IITRI Report No. C6187-3, EPA Contract EPA-22-69-122, January 1971.

88. P. M. Foster, *Droplet growth inside and outside cooling towers*, Atmos. Environ., 8:583-402, 1974.

89. K. S. Rao et al., *A dynamic plume model for the prediction of atmospheric effects associated with cooling tower operation*, Paper 75-04.5, Air Poll. Cont. Assoc., Boston, June 1975.

90. D. J. Moore, *The prediction of the rise of cooling tower plumes*, Atmos. Environ., 8:403-406, 1974.

91. S. R. Hanna, *Rise and condensation of large cooling-tower plumes*, J. Appl. Meteorol., 11:793-799, 1972.

92. R. A. Burns et al., *Program to investigate feasibility of natural-draft salt water cooling towers*, Appendix B to Forked River Nuclear Power Plant Environmental Report, Docket No. 50-363, January 1972.

93. C. L. Hosler, J. Pena and R. Pena, *Determination of salt deposition rates from drift from evaporation cooling towers*, Trans. ASME, Series A, J. Eng. Power, 96:283-291, July 1974.

94. J. A. Pena and C. L. Hosler, *Influence of the choice of the plume diffusion formula on the salt-deposition rate calculation.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 573-584, 1975.

95. K. G. Baker, *Water cooling tower plumes*, Chem. Proc. Eng., 48(1)56-58, 1967.

96. S. R. Hanna, *Fog and drift deposition from evaporative cooling towers*, Nucl. Saf., 15:190-196, 1974.

97. G. W. Israel and T. J. Overcamp, *Drift deposition model for natural-draft cooling towers.* In: ERDA Symposium Series CONF-740302, "Cooling Tower Environment-1974," pp. 614-628, 1975.

98. S. M. Laskowski, *A mathematical transport model for salt distribution from a saltwater natural-draft and cooling tower.* Part 1 in ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 598-613, 1975. Part II in Proc. Am. Meteor. Soc. Symp. on Atmospheric Diffusion and Air Pollution, Santa Barbara, CA, pp. 412-419, September 1974.

99. W. A. Bowman and W. G. Biggs, *Meteorological aspects of large cooling towers*, Paper 72-128, presented at 65th Annual Meeting of Air Poll. Cont. Assoc., Miami Beach, June 1972.

100. F. B. Kaylor et al., *Prediction and verification of visible plume behavior associated with wet plume discharges*, Paper presented at AIChE 68th National Meeting, Houston, TX, February 1971.

101. R. V. Calabrese et al., *Prediction of temperature and moisture distributions in cooling tower plumes*, Proc. Am. Meteorol. Soc. Symp. on Atmospheric Diffusion and Air Pollution, Santa Barbara, CA, pp. 400-407, September 1974.

102. Y. J. Tsai and C. H. Huang, *Evaluation of varying meteorological parameters in cooling tower plume behavior*, Proc. Am. Meteorol. Soc. Symp. on Atmospheric Diffusion and Air Pollution, Santa Barbara, CA, pp. 408-411, September 1974.

103. P. R. Slawson et al., *Some observations on cooling-tower plume behavior at the Paradise steam plant*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 147-160, 1975.

104. P. R. Slawson, *Buoyant moist bent-over plumes*. In: "Cooling Towers," Chemical Engineering Progress (eds.), AIChE, New York, pp. 87-90, 1972.

105. P. R. Slawson et al., *Natural draft cooling tower plume behavior at Paradise steam plant* (Part I), TVA Report E-AQ-76-1, August 1975.

106. J. Taft, *Numerical model for the investigation of moist buouant cooling-tower plumes*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 180-204, 1975.

107. J. L. Lee, *A numerical study of wet cooling tower plume*, Trans. Am. Nucl. Soc., Environ. Sci., 32-33, 1973.

108. J. H. Meyer et al., *Mechanical-draft cooling tower visible plume behavior: measurements, models, predictions*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 307-352, 1975.

109. W. G. N. Slinn, *An analytical search for the stochastic-dominating process in the drift-deposition problem*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 483-500, 1975.

110. T. J. Overcamp and D. P. Hoult, *Precipitation in the wake of cooling towers*, Atmos. Environ., 5:751-756, 1971.

111. G. T. Csanady, *Bent-over vapor plumes*, J. Appl. Meteorol., 10:36-42, 1971.

112. J. P. Trepp, *Two-dimensional hydrodynamic model for cooling tower plumes*, Paper IAEA-SM-187/3, Proc. International Atomic Energy Symposium, Oslo, Norway, August 1974.

113. K. R. Wilbur et al., *Measurement and characterization of cooling tower drift*, Paper 74WA/HT-60, Am. Soc. Mech. Eng., New York City, Nov. 17-22, 1974.

114. T. M. L. Wigley and P. R. Slawson, *On the condensation of buoyant moist, bent-over plumes*, J. Appl. Meteorol., 10:253-259, 1971.

115. T. M. L. Wigley and P. R. Slawson, *A comparison of wet and dry bent-over plumes*, J. Appl. Meteorol., 11:335-340, 1972.

116. T. M. L. Wigley, *Condensation in jets, industrial plumes and cooling tower plumes*, J. Appl. Meteorol., 14:78-86, 1975.

117. J. Weil, *The rise of moist, buoyant plumes*, J. Appl. Meteorol., 13:435-443, 1974.

118. H. R. A. Weesels and J. A. Wisse, *A method for calculating sizes of cooling tower plumes.* Atmos. Enviror., 5:743-750, 1971.

119. J. F. Kennedy and H. Fordyce, *Plume recirculation and interference in mechanical-draft cooling towers.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 58-87, 1975.

120. *Feasibility of alternative means of cooling for thermal power plants near Lake Michigan*, National Thermal Pollution Research Program and Great Lakes Regional Office, U. S. FWQA, August 1970.

121. H. Veldhuizen and J. Ledbetter, *Cooling tower fog: control and abatement*, J. Air Poll. Cont. Assoc., 21:21-24, 1971.

122. W. A. Hall, *Elimination of cooling tower fog from a highway*, J. Air Poll. Cont. Assoc., 12:379-383, 1962.

123. S. R. Hanna, *Meteorological effects of the mechanical-draft cooling towers of the Oak Ridge gaseous diffusion plant.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 291-306, 1975.

124. S. R. Hanna and S. G. Perry, *Meteorological effects of the cooling towers at the Oak Ridge gaseous diffusion plant. I. Description of source parameters and analysis of plume photographs and hygrothermograph records*, ATDL Contribution No. 86, Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge National Laboratory, December 1973.

125. S. R. Hanna, *Meteorological effects of the cooling towers at Oak Ridge gaseous diffusion plant. II. Fog occurrence and drift deposition*, ATDL Contribution No. 88, Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge National Laboratory, March 1974.

126. C. Waselkow, *Design and operation of cooling towers.* In: "Engineering Aspects of Thermal Pollution," F. L. Parker and P. A. Krenkel, eds., Vanderbilt Univ. Press, Nashville, TN, pp. 249-281, 1969.

127. A. Blum, *Drizzle precipitation from water cooling towers*, Engineer, 198:128-130, August 1948.

128. G. W. Wistrom, *Cooling towers overcome polluter image*, Electr. World, 181:36-37, May 1, 1974.

129. G. K. Wistrom and J. C. Ovard, *Cooling tower drift: its measurement, control, and environmental effects*, Paper presented at Cooling Tower Institute Meeting, Houston, TX, Jan. 29, 1973.

130. F. G. Taylor et al., *Environmental effects of chromium and zinc in cooling-water drift.* In: ERDA Symposium Series CONF-740302, "Cooling Tower Environment-1974," pp. 408-426, 1975.

131. A. J. Alkezweeny et al., *Measured chromium distributions resulting from cooling-tower drift.* In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974" pp. 558-572, 1975.

132. P. A. Jallouk, G. J. Kidd and T. Shapiro, *Environmental aspects of cooling operation*, Report K-1895, Union Carbide, Nuclear Division, February 1974.

133. T. Kolflat, *Application considerations for central station cooling tower installations*, Proc. Am. Power Conf., 37:575-581, 1975.

134. K. A. Oleson et al., *Economics favor mechanical-draft towers*, Electr. World, 182:40-43, July 15, 1975.

135. M. R. Lefevre and J. Gilbert, *Operating experiences with fan assisted natural draft cooling towers*, Paper 157, Am. Power Conf., Chicago, April 22, 1976.

136. T. J. Flanagan and M. W. Golay, *Augmentation of cooling tower performance*, Trans. Am. Nucl. Soc., pp. 31-32, 1973.

137. D. J. W. Richards, *Engineering research aspects of assisted draught cooling towers*, Atmos. Environ., 8:425-432, April 1974.

138. I. W. Hannah, *Civil engineering aspects of environmental effects of cooling towers*, Atmos. Environ., 8:433-436, April 1974.

139. H. Frühauf, *Overall plant configuration-Biblis nuclear power station*, Nucl. Eng. Internat., 607-612, August 1975.

140. J. B. Dickey et al., *The operating debut of the round mechanical draft cooling tower*, Proc. Am. Power Conf., 37:582-590, 1975.

141. L. Heller, *Wet/dry hybrid condensing system.* In: "Dry and wet/dry cooling towers for power plants," R. L. Webb and R. E. Barry, eds., Am. Soc. Mech. Eng., pp. 88-98, November 1973.

142. E. P. Hanson, *Dry towers and wet/dry towers for the indirect power plant cycle.* In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 109-118, November 1973.

143. K. W. Li, *Analytical studies of dry/wet cooling system for power plants.* In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng. pp. 99-108, November 1973.

144. R. D. Landon and J. R. Houx, *Plume abatement and water conservation with the wet-dry cooling tower*, Proc. Am. Power Conf., 35:726-742, 1973.

145. K. A. Olesen and R. J. Budenholzer, *Economics of wet/dry cooling towers show promise*, Electr. World, 78:32-34, Dec. 15, 1972.

146. A. M. Rubin and P. S. Klanian, *Visible plume abatement with the wet/dry cooling tower*, Power Eng., 79:54-57, 1975.

147. J. I. Reisman and N. E. Dolan, *The wet/dry cooling tower: an effective plume control method*, Paper 74WA/HT-57, Amer. Soc. Mech. Eng., New York City, Nov. 17-22, 1974.

148. V. C. Patel et al., *Optimum design of dry-wet combination cooling towers for power plants*. In: ERDA Symposium Series, CONF-740302, "Cooling Tower Environment-1974," pp. 24-57, 1975.

149. P. Bøgh and N. Bhargava, *Combined dry/wet cooling towers: their environment promise and their problems*, Report, IAEA-SM-187/44, Proc. International Atomic Energy Agency, Symposium, Oslo, Norway, pp. 45-62, 1974.

150. A. G. Christianson and B. A. Tichenor, *Energy penalties--wet closed-cycle cooling systems for electric power plants*, Paper presented at AIChE Meeting, Washington, DC, Dec. 1-5, 1974.

151. L. G. Hauser and K. A. Oleson, *Comparison of evaporative losses in various condenser cooling water system*, Proc. Am. Power Conf. 32:519-527, 1970.

152. J. R. Murray and D. W. Trettel, *Report on meteorological aspects of operating the cooling lake and sprays at Dresden Nuclear Plant*, Report 1001-5 to Commonwealth Edison Co., Chicago, Aug. 1, 1973.

153. J. E. Carson, *The atmospheric consequences of thermal discharges from power generating stations*, Ann. Report, Radiological Physics Div., Argonne National Laboratory, pp. 250-269, 1971.

154. F. W. Decker, *Background study for pond cooling for industry*, Report RLO-2218-1, for USAEC, Contract AT(45-1)-2218, Oregon State Univ., Corvallis, March 31, 1970.

155. D. J. Portman, *Spray canal fog in the vicinity of Quad Cities Nuclear Power Station*, Report to Commonwealth Edison Co., Chicago, June 1973.

156. T. Hori, ed., *Studies on fogs in relation to fog-preventing forest*, Tanne Trading Co., Ltd., Shapporo, Japan, 440 pp., 1953. Cited by Portman (Ref. 155).

157. A. W. Elgawhary, *Spray cooling system design*, Chem. Eng. Progr., 71(7), 83-87, July 1975.

158. A. M. Elgawhary, *Design considerations and thermal performance of spray cooling systems for large power plants*, Paper 74e, AIChE 67th Annual Meeting, Washington, DC, December 1974.

159. A. M. Elgawhary and A. M. Rowe, *Spray pond mathematical model for cooling fresh water and brine*. In: ASME HT-Vol. 4, Environmental and Geophysical Heat Transfer, Am. Soc. Mech. Eng., 1971.

160. L. C. Neale, *Field studies of a spray module*, Paper presented at U. S.-Japan Seminar on Engineering and Environmental Aspects of Waste Heat Disposal, Tokyo, Japan, April 15-19, 1974.

161. P. A. Frohwerk, *Spray modules cool plant discharge water*, Power, 115:52-53, September 1971.

162. D. P. Hoult, *Spray pond fog and salt deposition*, Paper 74-10, presented at Air Poll. Cont. Assoc. Meeting, Chicago, June 1974.

163. D. P. Hoffman, *Spray cooling for power plants*, Proc. Am. Power Conf. 35:702-712, 1973.

164. R. W. Porter, U.-M. Yang and A. Yanik, *Thermal performance of spray cooling systems*, Paper presented at the Spray-Cooling Workshop, Am. Power Conf., Chicago, April 23, 1976.

165. S. G. Boyce, *The salt spray community*, Ohio University, Ecological Monographs, 23, 1, 1954.

166. E. S. Miliaras, *Power plants with air-cooled condensing systems*, MIT Press, Cambridge, MA, 237 pp., 1974.

167. J. P. Rossie and E. A. Cecil, *Research on dry-type cooling towers for thermal electric generation: Parts I and II*, Report 16130 EES 11/70, U. S. Environmental Protection Agency, Government Printing Office, Washington, DC, Part I, 322 pp. and Part II, 101 pp.

168. J. P. Rossie et al., *Electric power generation with dry-type cooling systems*, Proc. Am. Power Conf., 33:524-534, 1971.

169. K. A. Oleson et al., *Dry cooling for large nuclear power plant*, Report Gen-72-004, Power Generation Systems, Westinghouse Electric Corp., February 1972.

170. G. J. Silversti and J. Davids, *Effects of high condenser pressure on steam turbine design*, Proc. Am. Power Conf., 33:319-328, 1971.

171. R. C. Norton et al., *Dry cooling design characteristics of a large power plant*, Proc. Am. Power Conf., 37:591-597, 1975.

172. *Cost comparison of dry type and conventional cooling systems for representative nuclear generating plants*, AEC Report TID 26007, R. W. Beck and Associates, March 1972.

173. L. Heller, *The indirect (Heller) system*. In: Power plants with air-cooled condensing systems, E. S. Miliaris, ed., MIT Press, Cambridge, MA, pp. 16-35, 1974.

174. P. J. Christopher and V. T. Forster, *Rugeley dry cooling tower system*, Proc. Inst. Mech. Eng., 84:Part I, pp. 197-221, 1969-1970.

175. F. K. Moore, *On the minimum size of natural-draft cooling towers for large power plants*, Paper 72-WA/IT-60, Am. Soc. Mech. Eng. Winter Meeting, Nov. 26-30, 1972.

176. F. K. Moore, *On the minimum size of a large dry cooling tower with combined mechanical and natural draft*, J. Heat Transfer, 95:383-389, August 1973.

177. F. K. Moore and T. Hsieh, *Concurrent reduction of draft height and heat-exchange area for large dry cooling towers*, J. Heat Transfer, 96:1-7, 1974.

178. H. H. Von Cleve et al., *Economics and operating experience with air-cooled condensers*, Proc. Am. Power Conf., 33:511-523, 1971.

179. L. Forgó, *Past and future of dry cooling for power stations*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 1-12, November 1973.

180. J. P. Rossie, *Dry cooling towers*. In: Energy and Production and Thermal Effects, B. J. Gallagher, ed., Proc. Symp., Sept. 10-11, 1973 (Ann Arbor Science Publishers, Ann Arbor, MI), pp. 99-112, January 1974.

181. F. K. Moore, *The minimization of air heat-exchange surface areas of dry cooling towers for large power plants*. In: Dry and wet/dry cooling towers for power plants, Am. Soc. Mech., Eng., pp. 13-24, November 1973.

182. B. M. Johnson and D. R. Dickinson, *On the minimum size for forced draft dry cooling towers for power generating plants*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 25-34, November 1973.

183. J. P. Rossie and W. A. Williams, Jr., *The economics of using conventional nuclear steam turbine-generators with dry cooling systems*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 49-56, November 1973.

184. M. W. Larinoff, *Dry cooling tower power plant design specifications and performance characteristics*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 57-76, November 1973.

185. P. Leung, *Dry cooling tower plant operation: an economic loading approach*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 77-84, November 1973.

186. D. W. Kearney and B. E. Boyack, *Plume behavior and potential environmental effects of large dry cooling towers*. In: "Dry and wet/dry cooling towers for power plants," Am. Soc. Mech. Eng., pp. 35-48, November 1973.

187. S. R. Hanna and F. A. Gifford, *Meteorological effects of energy dissipation at large power parks*, Bull. Am. Meteorol. Soc., 56(10):1068-1076, October 1975.

188. L. R. Koenig and C. M. Bhumralkar, *On possible undesirable atmospheric effects of heat rejection from large electrical power centers*, Report R-1628-RC, Rand Corp., December 1974.

189. S. R. Hanna and S. D. Swisher, *Meteorological effects of the heat and moisture produced by man*, Nucl. Saf., 12:114-122, 1971.

190. *Nuclear Energy Center Site Survey--1975*, Report NUREG-0001, Five Parts plus NUREG-0001-ES, *Executive Summary*, plus NUREG-001, Appendix A, Part 1, *U. S. Map, Coarse Screening Results*, U. S. Nuclear Regulatory Commission, Office of Special Studies, January 1976.

191. A. Martin, *The influence of a power station on climate--A study of local weather records*, Atmos. Environ. 8:395-400, 1974.