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Preliminary Report

Effect of Cooling Tower Effluents on Atmospheric Conditions in Northeastern Illinois

by F. A. HUFF, R. C. BEEBE, D. M. A.JONES,
G. M. MORGAN, JR., and R. G. SEMONIN

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CONTENTS

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INTRODUCTION

Because of ecological considerations, controversy presently exists over the use of Lake Michigan and other natural water bodies for the discharge of waste heat from large electric power plants now under construction *or* planned for the near future. This problem has become especially acute in the case of a 2200-megawatt nuclear power plant of the Commonwealth Edison Company now nearing completion at Zion, located on Lake Michigan in the northeastern part of the state (figure 1). This plant was designed for once-through-cooling utilizing lake discharge of the waste heat, but this method of cooling has met opposition from several sources. An alternative method of solving the thermal pollution problem is through the use of large cooling towers which dissipate the huge quantities of waste heat directly into the atmosphere. However, this alternative then raises concern about the environmental consequences of the effluent discharged into the atmosphere from the towers.

At the request of the Illinois Pollution Control Board the State Water Survey carried out a 2-month investigation to assemble and evaluate information on the potential effects of cooling tower effluents on atmospheric conditions with major emphasis on the Zion installation. Because of time limitations, this preliminary investigation was restricted to 1) an extensive literature review of existing information on the topic, and 2) limited in-house research involving three studies of selected meteorological factors pertinent to evaluation of the cooling tower problem.

The first study under the in-house research involved determination of the relative magnitude of heat and moisture outputs that would be associated with Zion cooling towers in comparison with 1) the size of naturally occurring fluxes of heat and moisture in the atmosphere, and 2) man-made heat emissions from large urban areas.

The second study was concerned with the potential weather effects from interaction between the lake breeze and cooling tower plumes, a special problem where large bodies such as Lake Michigan are involved. The third study involved application of existing cloud modeling techniques to aid in evaluating the potential for tower plumes to initiate, trigger, *or* intensify the development of clouds and precipitation downwind of the Zion plant. In this preliminary investigation, we made an attempt also to

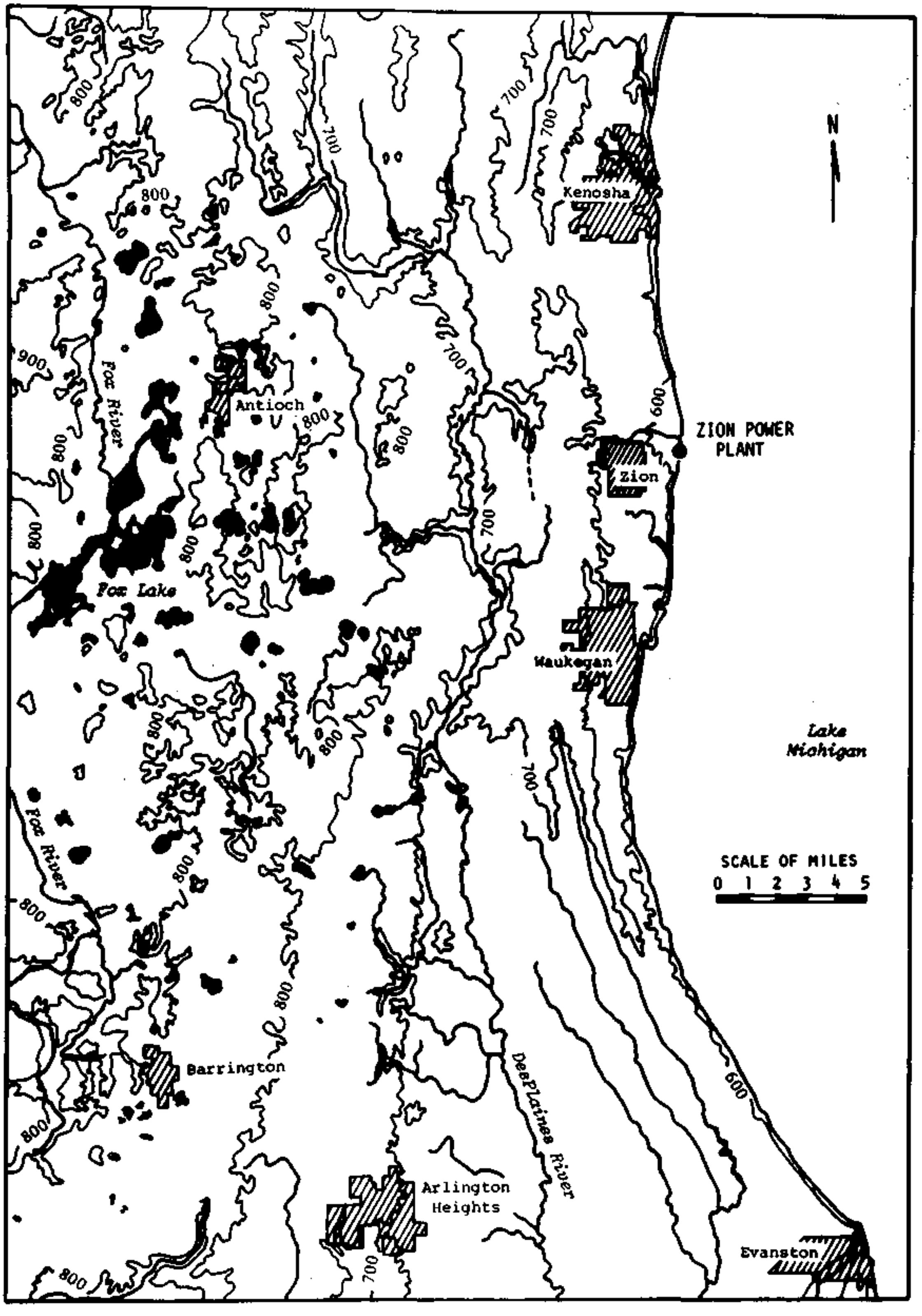

Figure 1. Location of Zion Power Plant
(Elevations in feet above msl)

assess atmospheric effects according to 1) natural-draft and mechanical-draft towers, and 2) wet and dry cooling methods.

This report summarizes the results of the various phases of the 2-month study and presents conclusions and recommendations derived from the limited investigation.

Definition of Terms and Tower Design Data Used

A *natural-draft cooling tower* is one that depends upon a chimney or stack to induce air movement through the tower. A *mechanical-draft tower* is one which uses fans to move ambient air through the tower. Hyperbolic is a term used to describe the most common shape of natural-draft towers. *Wet-type or evaporative cooling towers* are those in which the cooling water is brought in direct contact with a flow of air and the heat is dissipated mainly by evaporation. They may be either of the natural-draft or mechanical-draft type. *Dry-type towers* are those in which the waste heat is dissipated to the air by conduction and convection rather than by evaporation as in the wet-type.

Drift is the entrained water carried from the cooling tower by the exhaust air. *Blowdown* is the continuous or intermittent wasting of a small amount of the circulating water to prevent an increase of solids in the water due to evaporation. *Dry-bulb temperature* is the air temperature as read on an ordinary thermometer. *Wet-bulb temperature* is that temperature to which air can be cooled adiabatically to saturation by the addition of water vapor, that is, the theoretical limit to which water can be cooled through evaporation. *Relative humidity (percent)* is the ratio of the amount of water vapor actually present in the air to the greatest amount it could hold if saturated at that temperature and pressure. *Btu* is the abbreviation for the British thermal unit and is the unit of heat energy commonly used by engineers.

In this report, *local meteorological effects* refer to those occurring within distances of 5 miles or less. *Mesoscale effects* are those involving distances of 5 to 50 miles. *Large-scale effects* are those extending over distances greater than 50 miles. For example, if a cooling tower effluent affected fog formation only within 5 miles of the plant, it would be considered a local effect in our terminology.

All computations involved in the in-house studies discussed in this report have been based upon design criteria for cooling towers furnished by the Commonwealth Edison Company. Of several possible designs, the most acceptable from the standpoint of possible FAA height restrictions at the Zion site was used in our studies. This design consists of three hybrid wet-type towers with an outlet height of 250 feet, discharge diameter of 180 feet, and fan-forced discharge velocity of 1110 feet/minute. Only two towers will be in operation at any one time. Average heat rejection to the atmosphere for each tower would be approximately 8.3×10^9 Btu/hour.

Water loss to the atmosphere is estimated at 14,700 gallons/minute for each tower in spring, summer, and fall, lowering to approximately 11,000 gallons/minute in winter.

Acknowledgments

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PART 1. SUMMARY AND CONCLUSIONS

RESULTS OF LITERATURE REVIEW

Basically, the literature search revealed a discouraging lack of information on how effluents from large cooling towers, such as those which would be required at Zion, affect atmospheric conditions in their vicinity. Research with respect to this problem has been hampered by the lack of well-organized and properly conducted field studies to collect the meteorological data necessary to promote and accelerate needed research. In turn, the lack of data collection can be attributed partly to the short operational history of large cooling towers in the United States.

Fog and Icing

In the literature, more attention has been given to fog and icing associated with plumes from evaporative cooling towers than to any other weather effects. A primary reason for this is that such effects are readily observable and immediately troublesome. However, there still has been too little done to define these effects accurately. The majority opinion appears to be that fog and icing are usually minor problems with natural-draft towers employing evaporative cooling, since these towers usually extend to heights of 350 feet or more into the atmosphere so that the plume seldom, if ever, sinks to ground level. Mechanical-type towers release their effluent at a much lower level (50-75 feet) and in a much more turbulent condition due to fan-forced ejection, so that there appears to be a high probability of tower-induced fog and icing at or near the ground on occasions. However, the frequency of such occurrences cannot be assessed accurately with existing observational data.

Clouds and Precipitation

Quantitative data on the effects of cooling tower plumes on clouds and precipitation were found to be extremely meager in the published literature. Occasional observations of light drizzle or snow attributed to tower effluents have been reported. Also, there have been several reports of tower plumes contributing to cloud formation downwind; apparently, these are usually stratus-type clouds and observations of cumulus developments have been rare. A few mathematical calculations have been made to determine the cloud and precipitation producing potential of cooling tower plumes, but no meteorologically acceptable analyses have been made to assess quantitatively the possibility that these plumes augment precipitation and cloud systems associated with naturally occurring storms.

Severe Weather

A search was made for any observed and/or calculated effects of tower plumes on severe weather events, such as thunderstorms, hail, tornadoes, and heavy rainstorms. Very little was found and this was of a highly speculative nature. However, from consideration of atmospheric physics and dynamics, one would expect that any severe weather event resulting from cooling tower effluents would be attained only through a triggering or stimulation effect. That is, the additional heat and/or moisture fed into a developing storm cloud could conceivably produce an imbalance that would result in intensification into a severe weather state. However, the severe weather effect, if any, must be strictly conjectural at this time.

In general, we conclude from available information in the literature that a very distinct void exists in our knowledge of the effects of cooling tower plumes on clouds and precipitation with regard to both initiation and stimulation of these weather events. From climatological observations and cloud physics research it is known that cumulus clouds and rain showers or thunderstorms can be triggered by small inputs of energy. Consequently, it is extremely important that research be initiated to combine existing knowledge of plume and cloud properties into mathematical models that will provide reliable quantitative estimates of the plume effect on downwind clouds and rainfall.

Comparison of Cooling Tower Types

Most of the information in the recent literature relating to meteorological effects associated with cooling tower effluents concerns the natural-draft type employing evaporative cooling. The engineering profession apparently considers these to be the best alternative to waste heat discharge into water courses. To date, no large dry cooling towers have been constructed in the United States. Consequently, dry cooling towers present an environmental problem about which little is known. Qualitatively, the large quantities of heat released to the atmosphere from dry cooling towers could produce increases in convection and turbulence and likely initiate or stimulate the development of cumulus clouds. However, the literature provides no information, and knowledge is not adequate to define in quantitative terms the meteorological significance of the tower heat release. Therefore, no further attempt has been made in this report to present a comparative evaluation of tower-induced atmospheric effects between wet and dry towers.

Similarly, actual quantitative measurements of the differential effects of natural-draft and mechanical-draft tower effluents on atmospheric conditions apparently have not been made. Except for one study by *McVehil* (1970), only qualitative comparisons were found. Qualitatively, there appears to be general agreement that the mechanical type is more likely to produce fog and icing problems. With their higher level discharge, the natural-draft type would be expected to become involved more readily in cloud and precipitation producing processes in the atmosphere.

STUDIES SPECIFIC TO ZION

Relative Magnitude of Heat-Moisture Output from Towers

Calculations of the typical ingestion of moisture from both small shower clouds and thunderstorms indicated that the cooling tower releases of moisture into the atmosphere at a Zion-type installation would be very small compared with the natural fluxes in storm clouds. However, it appears quite possible that the cooling tower addition to existing convective clouds might be sufficient occasionally under a favorable set of atmospheric conditions to intensify natural cloud processes, resulting in additional precipitation downwind and possibly other undesirable intensification of naturally occurring weather events.

Comparisons of available estimates of heat produced by the urban areas of St. Louis and Chicago with the heat output from cooling towers associated with a Zion-type plant indicated that the Zion peak output would be approximately 16 percent of the total St. Louis output and 5 percent of the Chicago production. This suggests that the atmospheric heat output at Zion would represent a strong potential for affecting the local weather, although reliable quantitative estimates are not possible at this time.

Tower Effluent-Lake Breeze Interaction

An investigation was made of possible meteorological effects from the interaction between cooling tower effluents in the Zion region and the lake breeze which annually occurs on 40-45 percent of the days at Zion. Large, deep lakes have a strong influence on the climate within several miles of their shorelines, and the lake interaction with the atmosphere varies between seasons. From an examination of the known meteorological characteristics of the lake breeze circulation, it was concluded that its interaction with Zion cooling tower effluents would likely result in additional snowfall under certain synoptic weather conditions.

In spring, analyses indicated that there are days on which the Zion plume would thicken an existing naturally occurring fog, but most of the time this fog would not persist more than 1 to 2 miles inland. Only very occasionally would a weather situation exist in which convective storms could be intensified by the lake breeze-tower plume interaction. Again, the general conclusion must be that accumulated knowledge is insufficient at this time to define in quantitative terms the effects of the interaction of cooling tower plumes with a lake-influenced atmosphere.

Cloud Modeling

Numerical cloud modeling techniques were employed in an effort to gain additional knowledge on the meteorological consequences of cooling tower effluents on clouds and precipitation in the Zion area. Results of this research must be considered first approximations only, in view of limitations in the theory involved both in current cloud models and in the interaction between a cooling tower plume and the atmosphere. In our brief study, particular attention was given to investigating atmospheric conditions in which the moist plume from an evaporative cooling tower might provide a mechanism (trigger) to enhance organized convection in the form of cumulus clouds and/or intensify precipitation downwind from the plume release point. Typical synoptic weather conditions were selected for the various seasons for use with the cloud model.

Results of the abbreviated model study indicated that under steady light rain conditions, the water vapor flux from Zion towers could lead to a small increase in storm rainfall (trace amounts) within a few thousand feet of the tower. However, when these increases are added to the normal annual amounts from steady rains, the addition is insignificant, amounting to only a fraction of 1 percent annually. The model computations indicated that the tower plume would affect snowfall for a distance of approximately 2 miles inland in the presence of storms with onshore winds, and that the total annual snowfall would be increased 1 to 2 inches within this lake-effect zone. Indications were found that the tower plume could also trigger thunderstorms under certain favorable weather conditions. However, since there exists such a void in the measurement of meteorological parameters in conjunction with the operation of large cooling towers, it is not possible to calculate with a high degree of confidence the specific increases in thunderstorms and other severe weather events that might be triggered by cooling tower effluents.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

At this time meteorologists have not acquired adequate information to define in quantitative terms the meteorological consequences of the large amounts of heat energy and water vapor that are released into the atmosphere from cooling towers associated with nuclear power plants. The interaction between tower effluent and the atmosphere is very complex and dependent upon local conditions of climate and topography. Consequently, estimates of the environmental effects, such as undertaken for the Zion area in this report, must be recognized as speculative to a large extent, and they will remain so until extensive measurement and research programs are carried out to obtain the needed knowledge. The time to do this is now, not in 1980 or later, when the problems (whatever they may be) associated with cooling tower effluents will have increased many times with the rapidly increasing demands for electric power.

Although it was not the purpose of this report to compare the meteorological consequences of lake and atmospheric dissipation of waste heat, the authors consider it appropriate at this point to present several relevant facts pertaining to this problem. First, it is much more difficult to establish the meteorological consequences of atmospheric dissipation of waste heat from large nuclear power plants than it is to evaluate the meteorological ramifications of once-through-lake cooling on Lake Michigan. This is because in both time and space the lake is much more stable with respect to its meteorological properties. For example, the day-to-day fluctuations in temperature in the atmosphere are very much greater than in the lake water. Secondly, lake cooling spreads out the heat dissipation over a much longer time period than cooling towers, and, therefore, localized effects on the weather are likely to be less pronounced with lake cooling than with cooling towers. Strictly from the meteorological standpoint, it appears that environmental effects *are* likely to be no greater, and probably smaller, with dissipation of waste heat into Lake Michigan compared with atmospheric release from cooling towers.

PART 2. DESCRIPTION OF INDIVIDUAL STUDIES

LITERATURE REVIEW

The literature review revealed a discouraging lack of well-organized measurement programs and research upon which to assess reliably the meteorological consequences of large cooling tower effluents. Furthermore, this problem is rapidly becoming more critical as the electric power industry continues its rapid growth and ecological objections to once-through-cooling increase. *Carson* (1970) has pointed out that only a very limited number of research and field studies have been conducted to date on the meteorological aspects of thermal pollution, and these have been in conjunction with studies related to biological processes rather than atmospheric effects.

In the following pages, the results of our literature search have been summarized. Effort has been made to cite a sufficient portion of the large amount of literature reviewed to portray the status of present knowledge adequately but to avoid excessive repetition of similar findings, conclusions, and opinions. Results of the literature search have been grouped according to weather element.

Fog and Ice

In the literature, more attention has been given to fog and ice associated with the plumes from evaporative cooling towers than to any other weather element. A primary reason for this is that such effects are readily observable and immediately troublesome. The majority opinion appears to be that fog and ice are usually minor problems with natural-draft towers employing evaporative cooling, but that tower-induced fog may occur frequently enough to be objectionable when mechanical-draft towers of the wet type are employed.

Unfortunately, this prevailing opinion has resulted to a considerable extent from questioning of plant operating personnel. More scientifically acceptable approaches to the problem have been undertaken in several cases by private concerns employed by power companies and the Federal Water Quality Administration (FWQA). However, it must be emphasized that precise calculations of cooling tower effects on fog and other weather events cannot be achieved because of 1) insufficient observational data from tower operations and 2) inadequate understanding of the atmospheric behavior of moist plume discharges and their meteorological ramifications. Consequently, any conclusions must be somewhat speculative and can lead to dissimilar evaluations, as will be illustrated later. In the following paragraphs, some representative assessments of the fog and icing problems obtained from the literature reviews are presented.

In a report recently published by *FWQA* (1970) on the feasibility of alternative means of cooling for thermal power plants near Lake Michigan, the following conclusion is reached:

> "While it is generally agreed that cooling towers are potential fog producers, it is also generally agreed that they are not probable fog producers. Most authorities agree that low profile mechanical draft towers are more likely to produce a fog condition than tall, natural draft towers."

The report further states that according to studies of fog potential derived by *E G & G* (1970), Lake Michigan is located in an area of "moderate potential." Therefore, some concern over potential fogging is justified. However, they point out that the classifications of high, moderate, and low potential by E G & G are relative rather than absolute definitions. Thus, location in an area of high potential would not necessarily mean that fog would be a problem -- this would depend upon specific site and local climatic conditions.

Using the criterion for fog given by E G & G, the FWQA report shows calculations of the probability of a cooling tower fog for selected points in the Lake Michigan area. At Chicago, their calculations indicate that weather conditions associated with a high probability existed approximately 0.1 percent of the time, a moderate probability was present 4.2 percent of the time, and the probability was low 95.7 percent of the time. The report emphasizes that analyses such as summarized above are very general and unsophisticated, although they do indicate that weather conditions in the Lake Michigan area are seldom severe enough to cause extensive fog conditions in the vicinity of wet cooling towers. It further emphasizes that for proposed power plant sites, adequate meteorological data should be collected during the site selection phase so that accurate predictions of fog potential can be made.

Travelers Research Corporation (1969) prepared a report for the Toledo Edison Company concerning weather effects of a natural-draft cooling tower proposed for Locust Point on Lake Erie, with special emphasis on the possibility of precipitation and icing in the path of the tower effluent plume. On the basis of their calculations for a natural-draft hyperbolic tower required to remove 6.21×10^9 Btu/hour at a height of 370 feet, they conclude that a visible plume would touch the ground (tower-induced fog) less than 2 percent of the time on an annual basis. They indicate that icing could occur at ground level approximately 3 percent of the time during the winter months, but that precipitation would not be a problem because of drift eliminators in the tower and low exit velocities. Other calculations indicate that the tower would emit a highly visible but *elevated* plume that would exist for 1.2 to 2.3 miles downwind, on the average, but might persist as far as 20 miles downwind in cold weather, or an estimated 6 percent of the time on an annual basis.

In a report prepared for the Commonwealth Edison Company, *McVehil* (1970) finds the problem of cooling tower effluents in the Lake Michigan area of greater consequence than indicated by the reports published by *Travelers Research Corporation* (1969), *E G & G* (1970), and *FWQA* (1970). McVehil indicates that his results, based upon conditions at Zion (figure 1), the area of our primary interest, must be considered contrary to the general conclusion that fog would not be a problem in the Lake Michigan area. He then points out that he has utilized observed meteorological conditions for the Zion area and proposed specifications for cooling tower equipment that would be required, whereas the report of *FWQA* (1970) emphasizes that their methods of estimating fog frequency were simplified and general, and not necessarily applicable to any specific site.

Since McVehil's findings are so relevant to our present problem, the following summary of his findings has been abstracted verbatim from his report:

> "All evaluations have been made assuming the operation of two generating units, with a total heat load for cooling equipment of 14.3×10^9 BTU/hour. The required evaporation in cooling towers will average 18,000 gal/min. Fog potential was calculated for mechanical-natural draft towers (3 towers) and pure natural draft towers of 350 ft height (5 towers) and 500 ft height (3 towers).
>
> The results show that fog at the surface should be expected somewhere around the plant on a maximum of 650 hours per year. The maximum frequency at any one point on the ground was calculated to be 90 hours per year from 1-1/2 to 2-1/2 miles north of the plant site. These maximum fog frequencies would result from mechanical draft cooling towers. Natural draft or combination cooling towers would produce somewhat lower fog frequencies, the numbers decreasing with increasing height of the towers. Maximum ground-level fog frequencies for these towers range from 40 hours for 500 ft towers to 100 hours for 250 ft towers.
>
> Fog should be expected on some few days during the year in any direction from the plant and with any type of cooling tower. The fog would occasionally persist for 10 miles or further downwind from mechanical draft towers. Plumes from taller towers would frequently extend much further in the free atmosphere; when the plumes contact the ground it would be at distances of 3 to 15 miles. Fog persistence will typically be two to four hours, and individual fog episodes can be expected to occur on 100 to 150 days per year with mechanical draft towers, and on 5 to 30 days per year with hybrid or natural draft towers.
>
> Most cooling tower fog will be produced in the winter, and during the hours between 3 and 9 AM. Since fog will typically form at temperatures below freezing, icing in fog plumes is to be expected. Visibility in the fog will usually be from 200 to 1000 ft, and occasionally less. For purposes of comparison, the normal frequency of dense natural fog in the Zion area is about 20 days per year."

Higgins (1969), in a paper presented at the 62nd Meeting of the Air Pollution Control Association (APCA), reports that calculations made with various atmospheric diffusion models indicate fog may occur as far as 20 miles from a cooling tower under very adverse weather conditions. However, he points out that it is difficult to support or refute such calculations since conditions conducive to natural fog formation are also those under which cooling tower problems would arise. He states further that the whole matter is very complex and very dependent on local conditions, and there apparently have been no properly conducted field studies on this problem. In siting towers, he emphasizes that consideration should be given to nearby highways and airports, prevailing winds, frequency of severe weather conditions, and local topography. The evaluation by Higgins appears to place the problem in its proper light; that is, at the present level of knowledge, the definition of the weather effects from cooling tower effluents must be largely speculative rather than quantitative in nature.

In their report prepared for FWQA, *E G & G* (1970) outlines areas having high, moderate, and low potential for adverse cooling tower effects, based upon results obtained from atmospheric model computations utilizing climatic data. They find the Lake Michigan area to be one with moderate potential. However, they point out that the local microclimate of a given region can vary considerably from the larger scale features, so that each site should be evaluated on the basis of local parameters. They indicate that local topographic features can be significant. Valleys with local moisture sources, such as ponds, rivers, and lakes, will increase the fogging potential, whereas hilltops with their greater roughness will tend to disperse the tower plume more efficiently. They conclude also from their model computations that typical summer conditions (warm, unstable air) will not lead to downwind propogation of the plume, and that late fall and winter are the primary periods of interest because of the prevalence of stable air and relatively cold temperatures.

Aynsley (1970a), who has been associated recently with cooling tower studies performed under National Air Pollution Control Administration sponsorship at the 1800-megawatt Keystone plant in Pennsylvania, evaluates the fogging and icing problem as follows:

> "Local fogging and winter icing can be a hazard with towers, especially forced draft units under certain weather conditions. Hyperbolic towers have much larger point emissions of heat and water vapor and certainly have the potential to form dense, extensive fogs."

He points out that local fog and icing are apparently not a problem with natural-draft towers, since their plumes tend to puncture and ventilate natural temperature inversions and reach greater heights than mechanical-draft towers.

Decker (1969), in evaluating meteorological aspects of cooling tower effluents, indicates that modern cooling towers have apparently caused few complaints of fog except in downwash conditions (tower plume forced downward). He points out that this hazard apparently has a low probability of occurrence and that suitable sites greatly exceed the number of unfavorable sites which trap or concentrate the fog. He concludes that it should be relatively easy to select a favorable site for a natural-draft tower, and perhaps elevated sites for mechanical-draft towers would also be relatively easy to obtain. The natural-draft tower has an inherent advantage over the mechanical-draft tower because of the greater height of the effluent discharge.

Broehl (1968) made a field investigation (interview trip) to four Appalachian cooling tower installations to investigate environmental effects from cooling towers of large steam electrical plants. Towers visited had a total of 6.5 years of operating time. He concludes that:

> ". . . the plume from large, natural-draft towers does not produce, even under the most adverse weather conditions, ground level fog, since the plume does not drop below the top of the tower for an extended distance."

He further concludes from his interviews and personal observations that the plume will not exceed 400 feet in length most of the time. For a small amount of time, it will be 1000 to 2000 feet long, and plume lengths of 1 to 5 miles occur only rarely.

Zeller et at. (1969), reports on a trip to seven thermal power plants in the United States. From their interviews with operational personnel, they reach the same general conclusion as Broehl; that is, ground fog and icing from evaporative cooling towers have not increased, although some towers are in the vicinity of frequent natural occurrences of ground fog.

Comparison of Tower-Induced Fog Frequency Derived from Modeling Studies

In view of the considerable amount of literature on fog associated with cooling towers and some disagreement on the magnitude of the problem, an effort was made to obtain a more precise evaluation of the problem through an analytical comparison of results from several of the more scientifically oriented studies reviewed in the literature search. Several investigators have attempted to estimate the frequency of tower-induced fogs through use of atmospheric models in conjunction with climatological data on wind and atmospheric stability. Three of these studies were used in our comparative analyses.

A model developed by *E G & G* (1970) considers the effects of buoyancy; mixing; the initial diameter, velocity, water content, and temperature of the tower plume; and information from atmospheric soundings. Case studies with this model show that the plume from natural-draft towers can reach the ground only under certain extreme conditions.

A version of this method was employed by combination with local climatological data in the Zion study by *McVehil* (1970) discussed previously.. The McVehil report has a rather pessimistic tone, but this results primarily from undue attention to low-profile, mechanical-draft cooling towers having an outlet height of only 60 feet. From the meteorological standpoint, it does not appear that this type should be given serious consideration at Zion or any location where fog could be a serious problem. McVehil indicates that the highest point frequency of fog caused by the 60-foot mechanical-draft cooling towers should be approximately 90 hours/year and occur at distances of 1.5 to 2.5 miles north of the plant site. This maximum point frequency is 14 percent of his estimated areal frequency of 650 hours/year.

For the 250-foot hybrid towers, McVehil estimates from 25 to 100 hours of tower-caused fog per year, and the distance at which it will be most frequent is 12 kilometers (~ 7 miles). He concludes that the geographical distribution will be similar to that for the mechanical-draft case, except with fog occurring at greater distances. Therefore, one would estimate point values of 3.5 to 14 hours/year of tower-caused fog with the 250-foot towers, based upon the point/areal conversion factor of 14 percent. Data for Chicago Midway Airport indicate an average point frequency of 620 hours/year for all fog conditions and 420 hours/year with visibilities less than 3 miles. McVehil indicates approximately 160 to 260 hours/year of natural fog with visibility less than 1 mile at Zion. Therefore, the additional point frequency of 14 hours/year or less of tower-caused fog does not appear very significant.

E G & G placed Zion in an area of moderate cooling tower fog potential. The shores of Lake Erie are in the same area of moderate potential. *Travelers Research Corporation* (1969) uses a diffusion model to perform an analysis of fog potential at the Davis-Besse Nuclear Power Station at Locust Point on Lake Erie. They find that fog should occur somewhere around the site (370-foot tower) less than 2 percent of the time per year, or approximately 175 hours/year. This is somewhat more than was found for the 250-foot Zion towers, but is of the same general order of magnitude.

Visbisky et al. (1970) using a "cumulus model" estimates a fog risk of 25 hours/year at an airport located 8 miles from two cooling towers at Three Mile Island, Pennsylvania. This site is on the border between areas of high and moderate potential for cooling tower fog, according to E G S G.

Comparing results of the three modeling studies of fog-producing potential by evaporative cooling towers, it is concluded that the problem is not a serious cause for objecting to the use of natural-draft towers with waste heat ejection at heights of several hundred feet. However, the use of low-level mechanical-draft towers with forced ejection of waste heat in a rather turbulent state below 100 feet should be avoided where ground fog creates a problem.

Clouds and Precipitation

In the literature reviewed for this report quantitative data pertaining to the effects of moist plumes from cooling towers on clouds and precipitation are extremely meager. Occasional observations of light drizzle or snow have been reported in the vicinity of towers, such as mentioned by *Culkowski* (1962), *Federal Water Pollution Control Administration* (1968), *Zeller et al.* (1969), and *Decker* (1969). A few calculations have been attempted to determine the cloud and precipitation producing potential of cooling tower plumes, but as pointed out by H*anna and Swisher* (1970), no analysis has been made of the possibility of these plumes augmenting precipitation from naturally occurring storms.

Analyses of *E G & G* (1970) indicate that moist tower plumes can initiate cloud formation. In their studies at Keystone, Pennsylvania, *Visbisky et al.* (1970) find that tower plumes will contribute to local cloud formations at times in varying degrees, depending upon atmospheric conditions. They conclude, however, that any cloud effect at Keystone did not appear to have a significant effect upon airport operations approximately 2 miles northwest of the plant.

Carson (1970) states that the extra heat and water vapor from cooling towers may create cumulus clouds and that the possibility of tower plumes acting as a trigger to produce extra cumulus congestus clouds and precipitation miles downwind of the release must be considered. In reviewing findings of Central Electricity Generating Board of Great Britain, Carson points out that they had found no reports of drizzle downwind from cooling towers. Cumulus clouds are sometimes formed, but they have not observed showers or precipitation being generated by the tower plumes. However, they did observe that sunshine could be altered in the area, since the visible plume may persist for a number of miles.

Aynsley (1970a), in discussing studies at Keystone, states:

> "There are frequent occasions when tower plumes can be seen to evaporate and then re-condense to some extent at higher altitudes further downwind. Under stable conditions with higher humidities, the plumes will persist after leveling off and appear downwind as stratus cloud coverage, or merge and reinforce existing cloud coverage. Initiation of cumulus clouds is a rare occurrence and on such occasions, clouds triggered by the towers only precede natural cloud formations."

In general, it must be concluded from available information in the literature that a very distinct void exists in our knowledge of the effects of cooling tower plumes on clouds and precipitation, with regard to both initiation and stimulation of these weather events. From climatological observations and cloud physics research it is known that cumulus clouds and rain showers or thunderstorms can be triggered by relatively small inputs of energy. As an example, *Changnon* (1968a) has shown that areas downwind of Chicago have experienced 20 to 40 percent increases in precipitation due to urban-industrial effects. Hence, the possibility that cooling tower effluents could modify the rainfall distribution on a localized scale must be considered.

Temperature and Humidity

Information on how cooling tower effluents affect temperature and humidity locally has received little attention in the literature. This is probably because these weather elements have had little apparent effect except insofar as they contribute to the fog and icing problem.

Some information on humidity effects was obtained from an unpublished report of the *Central Electricity Board* (unofficial publication, 1968) of Great Britain. They report on one series of measurements made for one week at a power station in which hourly measurements of humidity were made. They did not detect any significant increase in humidity at 100 to 500 yards downwind of the tower using psychrometric measurements. In another study, they made continuous humidity measurements at a point 500 yards from a bank of cooling towers over a period of 8 months. It was not possible to observe any increase in humidity when the instrument was in the lee of the towers, compared with those times when the wind blew in other directions. However, they conclude that in areas where very low temperatures are experienced, the addition of water vapor in the wake of cooling towers could significantly affect the relative humidity, although at all times this effect would be partially offset by the addition of sensible heat.

Aynsley (1970a) in reporting on aerial measurements of humidity in moist plume emissions from natural-draft towers at the 1800-megawatt plant at Keystone, Pennslyvania, states:

> ". . . measurements of cooling-tower plume profiles indicate that humidity increases can be detected for many miles downwind."

There has not been sufficient attention given to temperature and humidity measurements to define either the frequency or magnitude of their downwind effects.

Severe Weather Events

As part of the literature review, a search was made for any observed and/or calculated effects of tower plumes on severe weather events such as thunderstorms, hail, tornadoes, and severe rainstorms. Very little was found and this was of a highly speculative nature. For example, *Csapski* (1968), on the basis of certain observations and calculations of large thermal emissions, foresees that:

> ". . . severe thunderstorms and even tornadoes can be caused in very unstable weather situations by dry and clean heat emission."

It is quite evident that any severe weather event resulting from cooling tower effluents could be attained only through a triggering or stimulation effect. That is, the additional heat and/or moisture fed into a developing storm cloud could conceivably produce an imbalance that would result in its intensification into a severe weather state. Again, past urban studies provide evidence that sizeable alterations in the distribution of severe weather events can be wrought inadvertently. For example, *Changnon* (1969) has shown that 20 to 40 percent increases in the number of thunderstorm and hail days over and downwind of Chicago and St. Louis have resulted from the combined effects of urban-industrial heat and aerosol releases. Thus, severe weather effects, if any, resulting from cooling tower operations must be strictly conjectural at this time, but the possibility of their occurrence cannot be eliminated.

Scientific Opinions

Listed below are selected quotations and stated opinions of individuals and organizations prominent in the evaluation of power plant cooling problems. These statements have been abstracted from various technical papers and reports published recently. They portray quite vividly the void in our knowledge on the meteorological consequences of waste heat dissipation which makes evaluation of cooling tower effects largely speculative at this time.

Dr. E. Wendell Hewson, Oregon State University

In a paper published in the Bulletin of the American Meteorological Society, *Hewson* (1970) reviews possible meteorological problems that could be encountered from water vapor released from cooling towers and cooling ponds. He states:

> "Until research has been conducted on the particular types of problems presented by cooling towers and cooling ponds, it will not be possible to determine whether the possible meteorological problems listed below are insignificant or important in any given situation."

He then goes on to treat qualitatively the possible effects of cooling towers and ponds on various meteorological elements such as precipitation, humidity, and temperature.

Dr. William P. Lowry, Oregon State University

Lowry (1970) in discussing environmental effects of nuclear cooling facilities concludes that:

> "The scientific and engineering professions do not now have either the information or the experience necessary even to begin operational avoidance or reduction of the fogging problem which we know exists in connection with industrial cooling tower and pond facilities."

E G & G, Incorporated

A 1970 report prepared for the Federal Water Quality Control Administration by *E G & G,* a leader in atmospheric research, states that:

> "Clearly, a firm understanding of environmental modification by cooling towers will have to be established by proper measurements in the vicinity of operational towers, in order to validate and refine the theoretical concepts."

They further point out that:

> "Besides proper meteorological measurements, ecological monitoring will also be necessary to evaluate the total influence of the tower effluents on the environment."

Dr. Eric Aynsley, IIT Research Institute

In a paper presented at a Cooling Tower Institute Meeting, *Aynsley* (1970b), who has been very active in environmental studies of cooling tower effluents, makes the following statement in his concluding remarks:

> "In conclusion it can be stated that there are a number of effects, mechanisms and interactions occurring both with cooling tower plumes and tower plumes mixed with nearby stack emissions. As yet, there is no simple answer and there remains many unanswered questions, the problem appearing more complex than was initially thought."

Dr. James E. Carson, Argonne National Laboratory

Carson has been involved in assessing the meteorological effects of nuclear power plants in the Lake Michigan area and has served as a consultant in our present study of cooling tower effects. In a recent paper *Carson* (1970) points out:

> "Meteorologists do not know how the atmosphere will react *quantitatively* to the large amounts of heat energy and water vapor that it will be forced to absorb as the result of waste heat from nuclear power plants."

Steven R. Hanna and Searle D. Swisher, Atmospheric Turbulence and Diffusion Laboratory, ESSA

In a paper concerned with the meteorological, effects of the heat and moisture produced by man *{Hanna and Swisher,* 1970), these scientists conclude that present research efforts concerning energy budgets and atmospheric effects of such sources are for the most part inadequate, but that this problem must be understood if we are to disperse waste heat and moisture with minimum effect on the environment. In discussing moisture pollution, they point out that research with respect to fogs and drizzle from evaporative cooling towers has been fragmentary.

George E. McVehil, Sierra Research Corporation

In a report prepared for Commonwealth Edison Company, *McVehil* (1970) summarizes available knowledge on the effects of dry cooling towers on atmospheric conditions as follows:

> "Dry cooling towers represent an environmental situation about which least is known. Certainly the large quantities of heat released to the atmosphere will result in an increase in convection, turbulence, and cumulus clouds. Whether these will produce any significant meteorological consequences is a problem that is beyond the scope of this study, and very possibly beyond current knowledge of atmospheric processes."

John T. Higgins, Division of Air Resources, New York State Department of Health

In a paper regarding the thermal pollution problem, *Higgins* (1969) discusses the fogging problem and states that calculations made with various atmospheric dispersion models indicate that during very adverse weather conditions fog could be found as far as 20 miles from a cooling tower. He then goes on to assess the evaluation problem as follows:

> "Unfortunately, it is rather difficult to support or refute these calculations as the conditions which are conducive to natural fog formation are also the ones which are likely to create cooling tower problems. The whole matter is extremely complex and very dependent on local conditions. It does not lend itself to laboratory study and properly conducted field studies are, to the author's knowledge, nonexistent."

SPECIFIC STUDIES RELATING TO ZION TOWERS

In the limited period of time (2 months) available to complete this preliminary report, three specific studies were undertaken to assist in evaluation of potential cooling tower effects on atmospheric conditions in the Zion region. The first of these studies involved an evaluation of the relative magnitude of the heat and moisture output to the atmosphere that would be associated with cooling tower operations at Zion. Comparing this potential output with the size of naturally occurring heat and moisture fluxes in the atmosphere can provide useful information to assist in the evaluation. of potential weather problems created by tower effluents. Also, it is useful to compare the waste heat output from large cooling towers with that generated by urban areas which are known to affect temperature and precipitation conditions within and downwind of their built-up areas.

The second study was an investigation of the potential effects from interaction of cooling tower effluents and lake-related weather. Large water bodies, such as Lake Michigan, influence local weather conditions in their vicinity, and this could conceivably be a factor of considerable importance in the Zion region.

The third study was concerned with numerical modeling of potential cloud development and precipitation enhancement associated with the Zion tower effluent, since it is possible that this effluent may act as a mechanism to enhance naturally occurring cloud and precipitation systems. Results of the three studies described in the following pages must be considered preliminary in nature because of the severe time limitation imposed in accomplishing the various analyses required.

Relative Magnitude of Heat-Moisture Output from Zion Towers

The modifying effects of cooling towers on clouds and precipitation are very difficult to assess. Before attempting to do so, it is useful to examine the energy output, mass flux, and other meteorologically related properties of the Zion plant and compare them with similar properties of atmospheric systems.

The Zion plant will produce 2200 megawatts of electrical power, and assuming an efficiency of one-third, it will release approximately 4400 megawatts to the atmosphere as heat if cooling towers are used. This is sufficient energy to produce clouds and, possibly, more severe weather phenomena based upon the Meteotron experiment by *Desserts and Desserts* (1961) in southwestern France. This device consists of 100 oil burners distributed over an area of 410 by 410 feet. Each burner consumes about 13 quarts of oil per minute and the total heat released to the air is given at 700 megawatts. Under favorable conditions of lapse rate, winds, and relative humidity, cumulus clouds form over the burner and "cumulus streets" can be generated. On several occasions, small funnel clouds or whirlwinds have been formed. These results are achieved with less than 20 percent of the power of the Zion cooling towers. In fact, most of the cooling towers in use in the United States dissipate many times more power to the air than does the Meteotron.

Why haven't the existing cooling towers generated easily observed cumulus clouds? The reason would appear to lie in the fundamental difference in the modes of adding the heat to the air by the Meteotron and the wet cooling towers. The Meteotron adds heat to the air at high temperatures with open flames which results in large buoyancy forces and high vertical velocities, creating strong convergence at ground level. The energy output from wet cooling towers is mostly stored as latent heat of evaporation, leaving the emitted air at fairly low temperatures, with resulting lower buoyancy forces and lower vertical velocities. The energy stored as latent heat in the outflow of wet towers will eventually be given back to the air by condensation; fortunately, from the standpoint of minimizing atmospheric effects, this process will be distributed over some time and accompanied by mixing and considerable dilution.

Mass Flux from Towers. Each of the three 250-foot cooling towers designed for possible use at Zion has an exit diameter of 180 feet and the air leaves the tower exit with a speed of 1110 feet/minute, or about 5 meters/second. The area of each tower mouth, A, is 2370 square meters (~ 25,000 square feet), and two of these, at most, will be used at any one time. For an air density $p_a = 10^{-3}$ grams/cubic centimeter and a velocity, V, at the exit of the tower of 5 meters/second, the mass flux of air, F_a, for each tower is:

$$F_a = p_a V A = 14.9 \text{ tons/second}$$

For a two-tower operation, the mass flux would then be approximately 30 tons/second. In wet cooling at summer peak load, the water evaporated into the air amounts to 29,400 gallons/minute, or about 2.2 tons/second.

Storm Cloud Fluxes. It is interesting to compare these fluxes with those through the bases of two cumulus clouds of different size and strength. The first considered was a shower cloud or thunderstorm which is assumed to have an updraft diameter of 1 kilometer, vertical velocity averaged over the updraft of 2 meters/second, and cloud base mixing ratio of 5 grams/kilogram. Assuming again that $p_a = 10^{-3}$ grams/cubic centimeter, the air and water fluxes are:

$$F_a = 1650 \text{ tons/second}$$

$$F_w = 8.3 \text{ tons/second}$$

Thus, this medium-sized storm cloud ingests nearly four times as much water and 55 times as much air as passes out of the exits of two Zion towers at summer peak load.

The second cloud considered was a large thunderstorm of the type which produces hail. The updraft diameter is estimated to be 5 kilometers, with a base level updraft of 10 meters/second, and a cloud base mixing ratio of 10 grams/kilogram. With the same assumptions as in the previous case, the fluxes of air and water through the base are:

$$F_a = 165{,}000 \text{ tons/second}$$

$$F_w = 1650 \text{ tons/second}$$

Compared with these fluxes associated with natural atmospheric phenomena, the cooling tower fluxes are very small indeed.

From the foregoing flux comparisons, it may be deduced that the Zion cooling towers could contribute a significant amount of water to small cumulus clouds and showers, and hence contribute to the precipitation rate during periods when such clouds are influenced by the towers. The air and water fluxes of the towers are of insignificant magnitude compared with those of large thunderstorms.

Urban Heat Fluxes. Climatological studies have shown that cities influence the distribution of temperature and precipitation within and downwind of their urban areas. For example, *Changnon* (1968a) found a notable increase in precipitation, number of rain days, thunderstorm days, and hail days at La Porte, Indiana, 30 miles east of a large complex of industries at Chicago. Another study (*Changnon,* 1969) has shown the existence of urban-produced thunderstorms in St. Louis and Chicago. *Huff and Changnon* (1970) found an increase in the frequency of heavy rainstorms downwind from these two large urban areas. *Landsberg* (1956) has discussed urban effects on both precipitation and temperature.

In view of known urban effects on certain weather elements, it was considered desirable to compare the potential Zion tower output of waste heat with that from large urban areas. For this comparison, rough estimates were obtained of the heat produced through all combustion processes, including industry, power generation, domestic heating, and automotive fuel consumption, for the metropolitan-industrial areas of St. Louis and Chicago (including northwestern Indiana and Lake County, Illinois). These estimates were based upon 1962 data available for St. Louis and 1957 data published for Chicago. The estimated heat outputs to the atmosphere are shown in table 1. These estimates show that Zion (at peak load) would release about 16 percent of the heat generated by the St. Louis urban area and approximately 5 percent of that produced by Chicago.

The Illinois Water Survey is presently engaged in research to investigate further the magnitude and causes of urban effects on nearby weather conditions. Although the mechanisms of these effects have yet to be defined in detail, the city heat output from combustion processes is considered a contributing factor *(Changnon,* 1968a). Consequently, the relative size of the proposed heat output at Zion in table 1 appears rather large in its potential for affecting the regional weather. It must be pointed out, however, that the city combustion output is more of the dry, high-temperature type and may therefore involve greater buoyancy and vertical motion than the evaporative cooling tower output.

Table 1. Comparison of Heat Outputs from
Cooling Towers and Urban Areas

Location of emission	Computational basis	Heat output (*Btu/hr*)
Zion Towers	Summer peak load	8.8×10^9
St. Louis	Average yearly output	55×10^9
Chicago	Average yearly output	180×10^9

Water Vapor Fluxes. How does the water vapor output from the potential Zion towers compare with the amounts of water encountered in natural precipitation? Using the Commonwealth Edison estimates of 14,700 gallons/minute ejected from each cooling tower, one finds that this would be equivalent to 19.5 inches of precipitation annually if all the water vapor released from continuous operation of one tower was condensed and fell to the surface over an area of 25 square miles. If two towers were in continuous operation annually, the above figure would double to 39 inches. However, the above assumption is very unrealistic, since the plume is simply evaporated into the air most of the time.

Again, assume all the tower output of water vapor is deposited as rain, but this time extend the distance to 60 miles with the water deposited over a sector bounded by a 45^o angle extending from the tower. Then the total contribution to surface precipitation from each tower would be only *0.4* inch annually. If the distance is extended to 600 miles, a more realistic assumption, the annual contribution would be less than 0.01 inch per tower. Since one would not expect the water released to the atmosphere by the towers to be precipitated back to the ground as precipitation within short distances most of the time, it is highly unlikely that the tower water output from the Zion towers would contribute appreciably to the total annual precipitation at any given point.

Another useful comparison is that between naturally occurring atmospheric water vapor fluxes and the water vapor ejection from the potential Zion towers. Again, use the two-tower values of 29,400 gallons/minute *or* 2.2 tons/second to cover the extreme case. For comparison, the flux of atmospheric water vapor through a vertical section, *A,* can be calculated with air at a specific humidity, *q,* moving at a speed, *V,* normal to the section. First, let *A* be 1 kilometer high by 10 kilometers wide (approximately 4 square miles). Then, assume a specific humidity, *q,* of

10 grams/cubic meter; this is representative of near saturation conditions at a mild temperature of 57 F, or air with a relative humidity of 50 percent at a warm temperature of 77 F. Let *V* = 10 meters/second (23 mph). Then the naturally occurring flux would be 1100 tons/second, or about 500 times the vapor output from two towers.

Next, assume *q* is 1 gram/cubic meter which represents near saturation at a cold winter temperature of -4 F or a relative humidity of 50 percent at a temperature of 14 F. Then, the atmospheric flux through the section defined above is 110 tons/second, or approximately 50 times the two-tower moisture output.

Thus, it is clear, as *Hanna and Swisher* (1970) point out, that the amount of water introduced into the atmosphere by the cooling towers at a single plant is insignificantly small compared with the natural atmospheric fluxes of vapor, except on a small scale close to the tower or in the immediate vicinity of the plume. However, if the number of Zion-type plants increases substantially about Lake Michigan in the future, the total discharge of heat and moisture from large cooling towers (if employed as the primary cooling method) might become sufficient to assume a significant role in determining regional weather characteristics. For example, one cannot calculate with a high degree of confidence at this time what the meteorological consequences would be of the addition of 25,000 to 50,000 megawatts from nuclear power plant facilities that might be in operation 20 to 30 years from now in the lake region.

Potential Effects from Interaction of Cooling Tower Plumes and Lake-Related Weather

The siting of electrical power generating plants on and near the shores of large, deep lakes raises meteorological problems not encountered at plants located elsewhere. The strong influence that such lakes have upon the climate over and within several miles of their shorelines would be a factor in the dispersion and dissipation of the effluent from wet or dry cooling towers along the shores of the lakes. Lake interaction with the surrounding atmosphere is different from season to season, depending upon whether the lake's waters are cooler or warmer than the environmental air over the adjacent land areas.

Lake Breezes. The most obvious effect of Lake Michigan upon the climate of the surrounding shores occurs when the lake waters are warming and lake breezes are prominent. These begin in May and continue into September. A lake breeze has been found to occur at Chicago Midway Airport 8 miles inland from the shore on 36 percent of the days during this period, and it is estimated that lake breezes occur 40-45 percent of the days at Zion (*W. A. Lyons,* personal communication).

According to Lyons, the lake breeze can begin anytime between 0630 CST and 1900 CST, but they most frequently start between 0800 and 0900 CST.

Depending primarily on the strength and direction of the gradient wind, they may penetrate anywhere from a few blocks to 25 miles inland. A typical penetration is 5 to 10 miles. The depth of the inflow layer can range from 300 to 3500 feet, but most frequently it is from 1500 to 2000 feet. Maximum inflow speeds are 10 to 15 mph. There is a distinct return flow layer aloft that is generally about twice as deep as the inflow, with half the velocity. The surface winds frequently turn from northeast to south-southeast during the day because of the Coriolis effect. Although the peak frequency of lake breezes is in the warm season, they can occur during any month.

The lake breeze has a convergence zone 1-2 miles wide at its leading edge in which updrafts are relatively strong (lake breeze frontal zone). A temperature inversion occurs at the top of the inflow layer. Circulation is such that the air moves inland at low levels, rises rapidly in the updraft zone, returns to the lake aloft, sinks to the inflow layer offshore, and returns inland again. The lake breeze is almost always associated with strong insolation which promotes mixing in the lower levels of the atmosphere. Consideration of the lake breeze characteristics outlined above indicates that moist plumes released from 250-foot cooling towers at the Zion lakeshore site would be confined to the inflow layer below the inversion; however, they should mix rapidly with the ambient air, so that the visible tower plume (stratus-type cloud) would be dissipated within several miles inland.

The effect of the lake breeze on the initiation and/or intensification of cumulus clouds would depend upon several factors, primarily the synoptic wind flow and the depth of the lake breeze inflow. Thus, when the large-scale synoptic flow has a westerly component of movement (SW, W, NW, etc.), the most common occurrence, cumulus forming inland would simply advect over the lake breeze front. However, the disruption of their feeding plume by flow over this front should cause them to dissipate quite rapidly. There is a possibility that the tower plume could initiate convective clouds if it could puncture the overlying temperature inversion associated with the lake breeze circulation. Nonetheless, it is believed that the strong wind shears encountered between the inflow and outflow layers of this circulation would inhibit growth of the moist tower plume into an organized cumulus cloud in most cases (see following section on numerical modeling for more information on this subject).

Convective Storm Interactions. Approximately once or twice a year when the large-scale synoptic flow is from the north and there is a lake breeze interacting with it, a convective zone will move from the north or northwest with the lake breeze convergence zone becoming the area of most active convection *(Lyons,* 1966). Conceivably, the tower plume from the Zion plant could be venting into this convergence zone at the time that convective storms move across the area from the north. However, as pointed out by Lyons (personal communication), lake breeze fronts tend to be rather far inland when the above storm condition occurs, so that the tower plume would be greatly diluted by mixing as it flowed inland toward the convergence zone. Consequently, it is not anticipated that Zion cooling tower plumes would be of much importance in modifying the naturally occurring storms under this situation. However, the possibility that the diluted tower plume might occasionally trigger further intensification of these storms cannot be completely eliminated.

Snowfall Effects. Any augmentation of the snowfall from synoptic weather systems passing through the Zion area would depend upon the level in the atmosphere where the major interaction between the tower plume and the snow mechanism occurs. It seems most likely that the effect of the plume upon snow systems would be in the lower atmosphere where the plume would act as a "feeder" cloud to augment the amount of snow falling underneath the tower plume (*Bergeron,* 1969). The augmentation is most likely to take place as riming on the snow crystals. The total amount of snowfall would be dependent upon the duration and intensity of the synoptic snowfall; the longer the snow falls and the greater the intensity, the more liquid water droplets would be captured by the snow crystals falling through the plume. Quantitative estimates of additional snowfall amounts from tower emissions are presented in the next section.

Other Cold Season Effects. Several times during fall and winter a cold arctic high pressure system descends into the United States east of Lake Michigan. The air then has a northeasterly trajectory across the lake. When this occurs, the snow squall pattern normally occurring along the eastern or southeastern shore is found on the western side of the lake. This synoptic situation appears to be one in which environmental conditions may be optimum for cooling tower plumes to trigger additional convection. Potential plume effects when this synoptic weather condition exists in the Zion region are examined further in the following section dealing with numerical modeling.

Another weather system of some interest during winter is the land breeze. If there are clear skies and light winds (less than about 5 mph), offshore flow will develop during the night. However, it appears this layer is extremely shallow, even less than 300 feet at times. Thus, when the surface wind flow indicates a plume should move offshore, it would often puncture the existing radiation inversion and enter the onshore flow aloft. Normally, this should not cause much of a problem, since the tower plume would be shielded from the surface by the underlying inversion as it moved inland.

Fog Effects. Lyons (personal communication) has pointed out an instance in which the Zion plume would, of necessity, thicken an existing heavy fog. This fog occurs during the spring warming of the lake when the near-shore water is warming, but the center of the lake is still cold and a thermal bar exists between the two temperature regimes. An air stream advected from the east over the cold pool in the center of the lake becomes stabilized before passing over the near-shore warm water, picking up moisture from the water along with some turbulence but capped by a stable temperature inversion above. The Zion plume would likely be trapped below this inversion and travel inland with the lake fog. in general, the fog does not persist more than a mile or two inland because of surface heating over the land, except on cloudy days or during the night. The moist tower plume would generally be mixed from the inversion to the surface.

A fog situation similar to the above may develop during the spring warming season when the land winds are blowing along the lake shore, particularly from the north. Cool, stable air which migrates from the lake with the lake breeze is near saturation, and stratus are likely to form at the low temperature inversion capping the stable air. The tower plume would be trapped within the cool air, and there is a strong probability of mixing from the surface to the inversion in the near-saturated air.

Conclusions. With lake breezes in the warm season, visible plumes of moisture released from 250-foot cooling towers at Zion would usually be confined to the lower 1500-2000 feet of the atmosphere and would dissipate through mixing with the ambient air within several miles inland. The lake breeze circulation is such that it would normally tend to inhibit the growth of existing convective clouds and contribute to eventual dissipation. Only rarely would synoptic weather conditions exist in which the tower plume could conceivably contribute to intensification of convective storms occurring in the lake breeze convergence zone. There are usually several occasions in late fall and winter when northeasterly circulation over the lake associated with arctic outbreaks could be conducive to intensification of existing storm systems. Moist tower plumes associated with land breeze circulations are not expected to affect significantly local weather conditions. Under certain synoptic weather conditions, the tower plumes can be expected to thicken an existing heavy fog. Also, there are occasions in the spring warming season when the tower plume may reach the ground through mixing in the onshore inflow layer beneath the temperature inversion.

Numerical Modeling of Cloud Development from Cooling Tower Effluent

The following section discusses efforts to use a computer to solve the thermodynamic and hydrostatic equations applicable to the cooling tower effluent. The basis for the calculations, as described by *Weinstein and Davis* (1968), is the temperature and moisture difference between the plume and the environment which gives rise to buoyant, moist air parcels and the formation of water droplets (plume cloud). The computer calculations show the vertical variation of the plume temperature, rise velocity, and water content, but do not show the effect of the horizontal wind on the tower plume. The model does not incorporate time variations in either the environmental temperature structure or the plume characteristics. The model was used with various meteorological conditions which may be expected to occur in the Zion area, including those in which the moist plume might act to enhance precipitation and/or organized (potentially severe) cumulus convection. The current limitations of the theory involved in cloud models and in the interaction between the atmosphere and the cooling tower plume necessitate that the following results be considered first approximations.

Model Description and Limitations. The cloud model predicts in-cloud parameters such as liquid water content, vertical velocity, rate of precipitation exiting the cloud base, and the maximum vertical extent of the cloud. The model incorporates the concept of convection as an entraining jet. While this concept may be questioned for atmospheric cloud processes, it is directly applicable to cooling tower effluents. The numerical results from the model have been used to predict maximum cloud tops with significant accuracy *(Semonin,* 1970). Therefore, the results should be reliable for the maximum plume rise for the assumed stability conditions of the atmosphere. Since the model does not allow for wind shear, it does not predict the downstream extent of the plume cloud.

Time permitted computations for only a few representative weather conditions in the modeling study. As shown in table 2, computations were made on a seasonal basis for typical synoptic weather conditions, along with several special situations of particular interest, namely, snowstorms, thunderstorms, and onshore winds (lake breeze effects).

In table 2, only those synoptic conditions marked with asterisks represent situations under which precipitation would occur naturally. The winter average day refers to one which is cool and dry and has little or no cloudiness. The spring average day is similar to the winter average synoptically, but not as cold or dry. The atmosphere is vertically stable and winds are from a westerly direction. The winter snowstorm is typified by a surface high pressure system to the east resulting in onshore winds and snow on only the west side of Lake Michigan. This situation occurs 11 times per year, on the average, and accounts for approximately 25 percent of the annual snowfall in the Zion area *(Changnon,* 1968b).

The spring-early summer day is one on which the atmosphere is relatively stable and cooling of low-level air over the cold lake creates fog with an onshore wind. The summer average day has the upper levels dominated by a quasistationary ridge with light surface winds from north to east. The atmosphere is basically stable but insolation generates cumulus clouds. The average summer night is synoptically the same as the summer day, but radiational cooling results in a low-level temperature inversion and high relative humidity near the ground. The thunderstorm day is one on which the atmosphere is potentially unstable and relatively strong convection occurs. The "after thunderstorm passage" refers to a condition in which the lower atmosphere has become cooler and more stable due to spreading downdrafts, but relative humidities are high up to the 600-millibar level.

Model Results. Table 2 summarizes the model computations. Fall was not included but should conform closely to the results for spring and spring-early summer. It should also be pointed out that with the exception of the situations marked with asterisks, the model did *not* predict a cloud to form unless the cooling tower effluent was present. However, it was found that on days of potential thunderstorm activity or continuous snow the cooling tower effluent may interact with naturally occurring atmospheric phenomena to enhance precipitation or trigger intense moist convection. Table 2 indicates that the tallest plume clouds are produced in winter. The average cloud top height in summer is approximately 2000 feet compared with about 3000 feet for the rest of the year.

Table 2. Results of Cloud Modeling Computations"

Season	Synoptic weather condition	Maximum vertical speed in plume cloud (*ft/sec*)	Height of plume cloud top (*ft*)
Winter	Average day	25	3000
Winter	Snowstorm**	35	5500
Spring	Average day	22	2000
Spring-early summer	Onshore flow	25	3000
Summer	Average daytime	20	1800
Summer	Average nighttime	22	2000
Summer	Thunderstorm day**	27	2800
Summer	After thunderstorm passage**	33	3700

*Values presented in this table are based on effluent exit temperatures and tower dimensions provided by Commonwealth Edison and an assumed initial plume radius of 45 meters (approximately 140 feet).

**Potential precipitation enhancement and/or triggering of developed cumulus convection.

Moisture budget computations indicate that water vapor flux from a Zion-type cooling tower into steady light rain could lead to a small increase of rainfall within a few thousand feet of the tower. However, the storm amounts would be only 0.001 to 0.002 inch. Reference to climatological studies of rainfall distributions *(Huff and Schickedanz,* 1970) indicates the net effect would be insignificant, resulting only in an increase of a few hundredths of an inch in the annual precipitation totals (fraction of 1 percent).

The above argument does not hold for the vapor contribution from the cooling tower into a snowstorm. Since the winter atmosphere is colder and holds much less water vapor than it does in the other seasons, the relative contribution of water vapor to the atmosphere from cooling towers is much greater. If one considers the liquid water formed within the plume cloud and couples this with a pre-existing "lake effect snowstorm" *(Changnon,* 1968b), the result is a 20 percent increase in naturally occurring snowfall rate over the land within a semicircle of 2 miles in radius centered at Zion. From Changnon's data on the frequency and intensity of lake-effect storms, it is estimated that the Zion towers would enhance the annual snowfall by 1 to 2 inches in the above zone.

Snowfall enhancement would also result from the proposed cooling towers interacting with non-lake-effect snowstorms; however, this addition was not considered quantitatively in this brief study, since the snow would be carried over the lake by the offshore winds associated with these snowstorms.

In contrast to the above cases, precipitation resulting from the plume cloud in the absence of macroscale storm systems is presumed negligible. On cool moist days in spring, summer, and fall, the plume cloud would probably produce light misty rain and local fog. In winter on fairly calm days, light snow can be expected to fall. It was not possible to derive a frequency estimate of these light precipitation phenomena in the time alloted to the numerical modeling.

Cloud bases in Illinois in the warm season are typically 4000 to 6000 feet above the ground, and it is expected that the tower plume would frequently extend to near the cloud base level. On a potential thunderstorm day, the plume cloud is predicted to rise to about 3000 feet with a maximum speed of almost 30 feet/second. The plume cloud may interact dynamically with the atmosphere to initiate a thunderstorm under favorable conditions (such as a day of high humidities and little wind shear in the lower 10,000 feet). As shown in the previous section of this report on heat-moisture output from the Zion towers, the energy contribution of the plume cloud would be small compared with the energy associated with a well-developed thunderstorm. However, it is most likely that the energy flux of the plume cloud is at least of the order of magnitude (and possibly greater) of the meteorologically undetectable trigger mechanisms which generate much of our violent spring and summer weather.

The frequency of the plume cloud entering an already developed, pre-existing thunderstorm updraft is estimated to be on the order of 1 to 5 times a year in the Zion region. The small increase in flux of heat and water into the thunderstorm should have the effect of increasing the storm size by a corresponding amount. The conversion of non-severe thunderstorms to severe by the plume's interaction with its mesoscale envelope should occur only infrequently when a unique set of dynamic conditions evolve. It is fortunate that the thunderstorm steering level in the Zion area is normally from the west so that any severe weather which might be induced by the tower plumes would usually be carried over Lake Michigan and not the densely populated areas to the south, west, and north.

No nuclear power plants as large as that under construction at Zion (2200 megawatts) are in operation in the United States, and the smaller ones that are in existence have not been instrumented properly to detect any storm enhancement or triggering effects. Therefore, it is very difficult to predict the increase in thunderstorms and associated severe weather that might result from plume interactions with existing atmospheric storm systems.

Conclusions. The numerical modeling provided quantitative estimates of how high a plume cloud ejected from the 250-foot Zion towers would rise. Among the several synoptic conditions considered, it was found that the top of the moist plume (plume cloud) could vary between 1800 and 5500 feet, the height being strongly a function of the relative humidity. Other results indicated that the enhancement of warm season rainfall by Zion tower plumes would probably be negligible, but an average annual increase of 1 to 2 inches of snowfall could be expected within a distance of 2 miles inland from the power plant. Analyses performed with the typical spring-early summer condition (onshore flow) indicated that the lake breeze (discussed in the previous section of this report) would not normally trap the tower plume cloud near the ground to enhance inland fogging. Also, the subsidence inversion due to the return lake breeze flow aloft would deplete the vertical momentum of the tower plume and weaken its potential as an initiator of cumulus convection. That is, the lake breeze interaction with the tower effluent is not expected to increase significantly convective cloudiness and rainfall in the Zion area. From the limited modeling undertaken in conjunction with this report, it is not possible to evaluate quantitatively the potential triggering or enhancement of thunderstorms and other severe weather events by cooling tower effluents.

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