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Atmospheric Considerations Regarding the Impact of Heat Dissipation from a Nuclear Energy Center

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OAK RIDGE NATIONAL LABORATORY
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ATMOSPHERIC CONSIDERATIONS REGARDING THE IMPACT OF HEAT DISSIPATION FROM A NUCLEAR ENERGY CENTER

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This study was performed for the Nuclear Regulatory Commission in connection with the development of their Nuclear Energy Center Site Survey report to Congress.

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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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FOREWORD

Section 207 of the Energy Reorganization Act of 1974 requires that the Nuclear Regulatory Commission conduct a nuclear energy center site survey and report its findings to the Congress and the Council on Environmental Quality. The report is to identify possible locations for nuclear energy centers and compare the feasibility of this concept with that of producing an equivalent amount of power at dispersed sites in the same area.

The Nuclear Regulatory Commission contracted with the Oak Ridge National Laboratory to undertake certain phases of this study and to prepare reports on the various tasks when completed. This is one of a series of reports in the fulfillment of this assignment.

ABSTRACT

Potential changes in climate resulting from a large nuclear energy center are discussed. On a global scale, no noticeable changes are likely, but on both a regional and a local scale, changes can be expected. Depending on the cooling system employed, the amount of fog may increase, the amount and distribution of precipitation will change, and the frequency or location of severe storms may change.

Very large heat releases over small surface areas can result in greater atmospheric instability; a large number of closely spaced natural-draft cooling towers have this disadvantage. On the other hand, employment of natural-draft towers makes an increase in the occurrence of ground fog unlikely. The analysis suggests that the cooling towers for a large nuclear energy center should be located in clusters of four with at least 2.5-mile spacing between the clusters. This is equivalent to the requirement of one acre of land surface per each two megawatts of heat being rejected.

1. INTRODUCTION

Although the mechanisms by which man's energy use can modify both the transitory weather patterns and the long-term climate are not fully understood, it is evident that large heat-producing facilities such as nuclear energy centers can cause measurable and perhaps major atmospheric perturbations. There are three scales of possible atmospheric change which should be considered, namely, global, regional, and local.

First, on the global scale, the total energy rejected to the atmosphere from a single NEC will be very small in comparison with the natural solar energy received. Since weather and climate are largely a result of energy inputs to the atmosphere, this suggests that the effect on global climate due to energy release from any one large source, such as a nuclear energy center, will be no greater than an equivalent energy release from a dispersed siting pattern and may not be noticeable on the global scale. The total energy released to the atmosphere from electrical power generation, as well as other energy uses while the entire world experiences continued consumptive growth, gives cause for concern about possible changes in global weather and climate patterns. A number of NECs could have global climatic implications while a single one does not, but these considerations are independent of whether the facilities are sited in nuclear energy centers or at more traditional dispersed locations (with the same total capacity).

On the other hand, it is possible that energy releases on the scale of those from NECs will result in noticeable and perhaps significant atmospheric consequences on the regional and local scales. The energy flux density (the rate of energy release per unit of surface area) and its horizontal gradient are of major interest in estimating the impact on the atmosphere. A feeling for the magnitude of the local or regional meteorological consequences of an NEC may be obtained by considering the heat flux density resulting from the waste heat discharge. Very large values of heat rejection in locations where the surrounding natural heat input to the atmosphere is small can be expected to result in significant increases in convective cloud activity, overall measured cloudiness, and downwind rainfall amounts and possible establishment of preferred locations for thunderstorms, hail, and vortex activity. At present, there are no large (greater than 50 km^2) anthropogenic (man-made) energy sources that exceed the average global solar energy flux at the ground, with the single exception of the concentration on Manhattan Island. Manhattan Island, like most urban areas, has a heat release pattern dissimilar to that probable from an NEC since the heat release is diffuse rather than from concentrated sources. In addition, it is surrounded by very large areas of moderate heat flux. For both of these reasons it is of limited value as an analog for the study of nuclear energy centers.

For meteorological considerations, the value of the heat flux density provides a measure of the primary difference between dispersed siting and the nuclear energy center concept. A nuclear energy center concentrates the heat rejection over a relatively small area in comparison with dispersed siting, which appears as a number of smaller point sources spaced over a wide area.

With an NEC the heat flux density may be reduced by selecting a cooling method that naturally disperses the heat rejection over a wide area; for example, once-through cooling or the use of cooling lakes spreads the heat addition to the atmosphere over a greater area than cooling towers do. Spacing the cooling units, especially if towers are used, over as wide an area as possible (about 1500 sq. miles) will reduce the local or regional atmospheric impact of an NEC.

2. COMPARISON OF ENERGY RELEASES TO THE ATMOSPHERE

2.1 Heat Additions

In the assessment of impacts of nuclear energy centers on the atmosphere, a comparison of the relative magnitude of naturally occurring energy processes in the atmosphere with anthropogenic energy inputs from various sources can be useful. It is important to compare both total energy involved and the energy flux density for each of the several processes and sources. Table 1 lists energy flux densities for a variety of solar and atmospheric natural processes, for energy releases associated with large cities, and for the disposal of waste heat from a variety of power plant situations.

The different groupings in Table 1 should be expected to give different types of impacts on the atmosphere (especially the localized ones), since each group represents a different spacing of large energy sources. For example, the solar energy value quoted is an average and represents an amount that is uniform over a very wide area (in reality the solar energy varies with surface type, latitude, cloud cover, etc.), whereas cities represent a very large number of individual sources having a wide range of source sizes (mostly small). Power plants represent the case of large energy releases at essentially point locations, and even combinations of power plants represent point sources spaced in an area of low energy density background.

The atmospheric phenomena listed in Table 1 draw energy from a very large volume of air which has experienced heat (and moisture) additions during trajectories over wide surface areas. In the case of localized storms, the energy (and possibly vorticity) from large regions is concentrated into smaller regions by atmospheric processes. The direct comparison of solar or atmospheric energies involved in various processes with the energy released by cities and by power plants can result in erroneous conclusions. Certainly, the patterns of energy release of cities and of large power centers are sufficiently different to indicate the possibility of different atmospheric results.

Table 1. Energy flux of solar and natural atmospheric processes, of cities, and of power plants

Process	Area (km^2)	Energy flux density (W/m^2)	Fraction of average solar flux at ground
Solar and atmospheric processes			
Solar energy flux at top of atmosphere	5.1×10^8	350	
Solar energy flux at ground (global average)		160	1
Cyclone latent heat release (assume: half-life, 3 days; rainfall rate, 1 cm/day)	10^6	280	1.75
Great Lakes snowfall squall latent heat release (assume: snowfall rate, 4 cm/hr)	10^4	3,100	19
Thunderstorm latent heat release (assume: half-life, 30 min; rainfall rate, 1 cm/30 min)	10^2	13,600	85
Tornado: kinetic energy (assume: half-life, 10 min)	10^{-2}	10,000	62
Anthropogenic heat from cities			
Manhattan, New York City	5[illegible].8	630	3.94
Moscow	878	127	0.79
Washington, D.C.	173	44	0.28
Los Angeles	3,500	21	0.13
Boston-Washington metropolitan area (projection for AD 2000)	31,200	36	0.23
Sheffield, England	48	19.2	0.12
Waste heat from power plants			
Dresden and Braidwood (over area for city of 1 million people)	230	35.3	0.22
Summit, Salem, Hope Creek (12 x 5 miles)	155	73.8	0.46
Typical cooling pool (assume 2 acres/MWe generation)		247	1.54
Typical cooling tower (Chalk Point design data)[a]	8.9×10^{-3}	128,000	800
48,000-MWe NEC with area of 48,000 acres	194	495	3.1

[a] R. J. Niebo, "Brackish Water Cooling Towers Studied," *Electr. World*, Aug. 1, 1973, pp. 58-59.

Sources: S. R. Hanna and S. D. Swisher, "Meteorological Effects of the Heat and Moisture Produced by Man," *Nucl. Safety* 12(2): 114-122 (1971); R. M. Rotty, Institute for Energy Analysis, Oak Ridge, Tenn., "Atmospheric Thermal Pollution," paper presented at Climatology Conference and Workshop of the American Meteorological Society, Asheville, N.C., Oct. 8, 1974.

On the other hand, the changes that result at large distances downwind probably are independent of the nature of the source and depend only upon total quantities released. The distance at which differences between point sources and diffuse sources are discernible depends on atmospheric variables (including winds, stability, and water vapor content), as well as the strength of the source.

As was indicated above, it is probable that during the next few decades the most significant impact of additional energy released to the atmosphere will occur locally or regionally, and hence the concentrated releases from an individual nuclear energy center may have impacts quite unlike those of releases from major cities or from dispersed siting of power plants.

Even though the impacts can be different under many situations, it is informative to examine the climate of cities as an indication of the magnitudes of changes that can result from heat additions to the atmosphere. As a rough measure of magnitudes, the rate of heat rejection from a 5000-MWe electrical generating station corresponds to the average rate at which energy is used in the United States for each million people. In addition to heat releases, the paving and building materials in the cities, contrasting with the natural vegetation of surrounding rural areas, add to the effects of greater energy release and cause a shift in the balance of radiative equilibrium.[1,2]

The standard review of urban climate that is now accepted by most others (e.g., refs. 3, 4) was initially presented over ten years ago by Landsberg.[5,6] Research has since confirmed the values that he tabulated in his papers. Table 2, which describes the climate changes produced by cities, is taken from Landsberg's work.

Nearly all investigations relating to "urban heat islands" confirm that the magnitude of the heat island is dependent on city size (one measure of total energy released). There is no documentation of changes in heat island effects resulting from high or low energy flux density, but some of the elements in Table 2 may prove to be sensitive to concentration of heat releases in addition to total magnitude of heat release.

Table 2. Climatic changes produced by cities

Element	Compared with rural environs
Temperature	
Annual mean	1.0 to 1.5 F° higher
Winter minima	2.0 to 3.0 F° higher
Relative humidity	
Annual mean	6% lower
Winter	2% lower
Summer	8% lower
Dust particles	10 times as many
Cloudiness	
Clouds	5 to 10% more
Fog, winter	100% more
Fog, summer	30% more
Radiation	
Total on horizontal surface	15 to 20% less
Ultraviolet, winter	30% less
Ultraviolet, summer	5% less
Wind speed	
Annual mean	20 to 30% less
Extreme gusts	10 to 20% less
Calms	5 to 20% more
Precipitation	
Amounts	5 to 10% more
Days with >0.2 in.	10% more

Source: After H. E. Landsberg, "City Air — Better or Worse," in *Symposium: Air over Cities*, U.S. Public Health Service, Taft Sanitary Engineering Center, Cincinnati, Ohio, Technical Report A62-5, p. 122 (1962).

2.2 Water Vapor Additions

Nearly all systems for disposal of waste heat from power plants also add large amounts of water vapor to the atmosphere. Only in the case of dry cooling towers is the bulk of the heat transferred to the atmosphere as sensible heat. The amount of water vapor added to the atmosphere in the cooling of a power plant is dependent on the cooling system selected and the ambient atmosphere. Even in "traditional" once-through cooling, the heat must eventually be transferred from the natural water body to the atmosphere. This heat transfer is a very complex combination of several modes of heat transfer. The evaporation of water from the surface and the convection of heated air and moisture are the most important modes in summer; radiation assumes a greater role in winter as evaporation is reduced.

In the case of evaporative cooling towers, it is typical (as an annual average) for 75 to 80% of the heat transfer to be latent heat and 20 to 25% to be sensible heat. In the summer the latent fraction is usually higher and in the winter lower than this average by large amounts. Assuming an 80% latent heat fraction and a 75% load factor on the power plants, one 48,000-MWe nuclear energy center will evaporate water at the rate of 28×10^9 ft^3/year (or 200×10^9 gal/year). This annual water vapor addition is 0.05% of the average water vapor content of the earth's atmosphere.[7] It is obvious that the atmosphere will not provide long-term storage for water vapor from evaporative cooling processes (lest the atmospheric composition be appreciably changed in a relatively short period), and hence the added vapor must result in additional precipitation somewhere downwind of the NEC. It is impossible to determine how much of this precipitation will occur at any particular location, and depending on the location of a particular site, much of it may occur over the oceans.

Another way of looking at this water quantity is to consider the equivalent annual evaporation that would be required over the entire area of the nuclear energy center site to add the same amount of water to the atmosphere. For a 48,000-MWe center with an area of one acre per electrical megawatt, this amount of water is equivalent to an annual average evaporation of 13.4 ft over the total 48,000-acre area. As an aid in putting this amount of evaporation in perspective, the annual evaporation from reservoirs in Tennessee averages 3 ft.[8] A particular reservoir at Nashville loses 39 in. (3.25 ft) per year through evaporation,[9] and the amount in the vicinity of the Kentucky Lake surrogate site is 37 in. (3.08 ft).[10] Thus, a 48,000-MWe nuclear energy center may add over four times as much water vapor to the atmosphere as a 48,000-acre lake in the same location, or as much as one 200,000-acre lake. With cooling towers the moisture is injected high in the atmosphere and therefore can have different consequences. Also in large NEC's the additional cloud cover will reduce natural evaporation, thus reducing the total gain in moisture content of the atmosphere.

Essentially the same amount of water must be added to the atmosphere for cooling 48,000 MWe of capacity at dispersed sites as for the cooling of a 48,000-MWe energy center. The difference between the two is simply the concentration of the release. In the case of dispersed siting there is usually a greater opportunity for atmospheric diffusion processes to reduce areas of very high specific humidity.

3. PROBLEMS ASSOCIATED WITH STABLE, STAGNANT ATMOSPHERES

In an ambient atmosphere that is stable, water vapor added at low levels, as from large cooling ponds or lakes or from mechanical-draft cooling towers, can result in increased humidity, fogging, etc. No cooling-system-induced fog (at ground level) has been observed in cases in which natural-draft cooling towers have been employed. The release of the moisture at elevations greater than 100 m (and in a buoyant plume) requires a very unusual atmospheric situation if fog is to be induced by such a release.

3.1 Increased Occurrences of Fogging and Icing

There are several examples of local fogging and icing resulting from lakes and ponds used in the cooling of large power plants. Extrapolating these experiences to the scale of a 48,000-MWe energy center indicates that frequent and persistent periods of fog would be produced. Either this adversity must be accepted by locating the cooling system where fog will not interfere with other activities, or natural-draft cooling towers must be used to reject the large amounts of water vapor at elevations well above the surface.

In an atmosphere that is stagnant but well mixed to altitudes equal to or exceeding the height of the plume rise, a large group of wet cooling towers could, under rare circumstances, result in an increase in fog occurrence. Austin has studied a 15-month sample of data for Montgomery, Alabama, for the summertime (when frequent periods of stagnant conditions exist over the southeastern United States).[11] He found only 20 cases of surface relative humidity equal to or greater than 97%. (Presumably the water vapor from cooling towers will cause fog on the days when the saturation deficit is low.) Of the 20 occasions, only 4 showed a temperature decrease with elevation while the relative humidity remained near 100% in the atmospheric layer between the surface and 515 m (1690 ft) elevation. The other cases showed a distinct gradient of relative humidity with height, and most of any additional moisture injected into the atmosphere above 100 m elevation will be diffused upward rather than downward to the surface.

The 2.17 x 10^{12} g/day average water added to the atmosphere by cooling a 48,000-MWe nuclear energy center is sufficient to make up a saturation deficit of 1 g/kg throughout a volume of 2.17 x 10^{12} m^3 — a cylindrical volume of air 52,000 m (32 miles) in diameter standing 1000 m (3300 ft) high. (By comparison saturated air at 20°C contains 17.3 g of water per cubic meter.)

As Austin pointed out, conditions conducive to the observation of surface fog caused by elevated releases of large amounts of moisture occur very infrequently.[11] The combination of a well-mixed lower atmosphere and very light and variable winds can, on rare occasion, occur to the extent that the very large amounts of water evaporated in towers cooling an NEC will augment fog production. Dispersal of the plants reduces the quantity of water being injected into the atmosphere at a single location, and hence not so large a volume can be saturated. Currently operating natural-draft towers (with up to three in a cluster) have not given any evidence of augmenting surface fog, and similar observations can be expected for dispersed siting arrangements. If meterological conditions exist which could produce fog, the probability of meeting these conditions is increased with dispersed siting.

3.2 Role of Buoyant Plumes from Natural-Draft Towers in Producing Fog

A given amount of moisture added to the atmosphere is less likely to result in saturated conditions as the volume of the atmosphere to which it is added is increased. Mixing the water vapor with a very large volume of air (with an appreciable vertical as well as horizontal extent) could therefore reduce the possibility of fog formation. This is the principle offered to explain why fog has not been observed in association with natural-draft cooling towers. The warm and nearly saturated air is released at an elevation of 100 or so meters above the ground, and the buoyant rise of the plume continues to push the moisture still higher above the ground. This is roughly equivalent to releasing the moisture at an elevation of several hundred meters, and both horizontal and vertical diffusion serve to dilute the water vapor concentration and reduce fog possibilities.

When the quantity of added water is increased, as in the case of the development of a large nuclear energy center, the volume of air that can be saturated increases. Added cooling tower height and/or greater plume rise becomes important in increasing the effective volume of air that must be saturated.

When cooling towers are placed within a few tower diameters of each other, the plumes may merge and reinforce each other, resulting in a higher plume rise. This mechanism has been suggested as a method for getting the moisture higher into the atmosphere and reducing the fog problem even further.[12]

On the other hand, clustering several towers closely enough to give plume reinforcement requires that the horizontal area over which the water is injected be reduced. The augmentation in plume rise is not linear with the number of towers, and clustering additional towers may reduce the total volume through which the water vapor is mixed (in contrast to locating additional towers a mile or two away). Koenig suggests that, while this mechanism provides augmented buoyancy, the overall plume rise from clustering natural-draft towers will have little effect on the fog problem.[13]

In clustering cooling towers, care is generally exercised to assure that towers are not aligned in such a way as to form an aerodynamic wall that gives an associated downwash region to the lee of the towers under certain (high) wind conditions. This is a problem when mechanical-draft towers are used, but no downwash problems have been experienced with natural-draft towers. (The experience with natural-draft towers to date is limited to clusters of three or fewer, but other engineering considerations will keep these towers far enough apart to avoid the aerodynamic wall situation.)

4. PROBLEMS IN AN UNSTABLE ATMOSPHERE

Meteorologically, cooling towers in a nuclear center can be regarded as a family of strong, buoyant point sources.[14] It is concluded that heat releases of the magnitude and with the concentration required in connection with nuclear energy centers will add to the convective activity and will increase the amount of convective cloudiness.

4.1 Increased Precipitation

Landsberg has observed that as a part of the climate changes produced by cities (Table 2), the amount of precipitation is increased by 5 to 10%.[6] Of greater significance here is the estimate that the number of days with more than 0.2 in. of precipitation is increased by 10%. This suggests that cities cause an increase in convective activity and that on days conducive to showers, rainfall is augmented.

A study of long-term weather records for nine urban areas shows that in seven cases there was a 9 to 17% increase in the summer precipitation, either over the city or downwind.[15,16] A summary of this study is shown in Table 3.

Recent studies of radar echo initiations reinforce the concept of increased convective activity over and downwind from large cities.[17] In a 17-storm sample during the summers of 1972 and 1973, an unusually high number of radar echo initiations occurred over the industrial complex just south of Wood River, Illinois (9 times the network average). Other areas of high frequency of echo initiations were in and east of St. Louis. Particularly in South St. Louis the statistics showed unusually high values — 5 times the network average.

It should be pointed out, however, that cities also add a variety of aerosols to the atmosphere, and some of these significantly affect downwind precipitation patterns. Whether it is just the heat, just the aerosols, or the combination of both, it has been demonstrated that cities are influential in initiating convective activity and in producing showers. It has not been established that the particular cells initiated

Table 3. Summary of urban effects on summer rainfall at nine cities

City	Observed effect	Maximum change[a]		Approximate location
		Millimeters	Percent	
St. Louis	Increase	40	15	16-20 km downwind
Chicago	Increase	50	17	50-55 km downwind
Indianapolis[b]	Indeterminate			
Cleveland[c]	Increase	35	15	40-80 km downwind
Washington	Increase	28	9	Urban area
Baltimore[d]	Increase	43	15	Urban and northeastward
Houston[e]	Increase	33	17	Near urban center
New Orleans[e]	Increase	45	10	Northeast side of city
Tulsa	None			

[a]Maximum change from surrounding area.

[b]Sampling density not adequate for reliable evaluation.

[c]Estimated orographic effect subtracted (maximum actually 27% greater than city).

[d]50-65 km downwind from Washington — not included in original study.

[e]Urban effect refers only to air mass storms — apparently little or no effect in frontal storms.

Source: F. A. Huff and S. A. Changnon, Jr., "Precipitation Modification by Major Urban Areas," *Bull. Am. Meteorol. Soc.* 54(12): 1220-1232 (1973).

grow to produce major storms or extremely large rainfall amounts. In fact, Changnon has concluded, "A strong localized effect to induce initiation of precipitation process is suggested, but the echos induced are not major rain producers."[18]

Studies on thunderstorms and hail associated with cities show increased numbers of thunder days and hail days in recent years in and downwind from the cities listed in Table 3, with the exception of Indianapolis and Tulsa, the smallest of those listed.[16]

While the heat releases from a nuclear energy center are not truly analogous to those associated with a city, as was pointed out earlier, the increase in convective cell formation in and around cities leads one to expect that energy center heat rejection could give rise to a major increase in convective cloud activity, with an associated increase in precipitation in localized areas. However, rural siting of large and small energy centers would reduce the problem of urban heat island effects.

4.2 Other Heat Releases and Increased Convective Activity

It was initially pointed out by Hanna and Gifford that large heat releases from very large power generating stations may, under some conditions, produce convective effects that have the potential to generate thunderstorms and possibly concentrate vorticity.[19] In discussing the effects of heat and moisture produced by man, Hanna and Swisher used the concept of energy rate per unit area to compare natural atmospheric processes with man's energy releases.[20] Rotty also indicated that the heat flux density, as well as the total energy release, is an important consideration in estimating the extent and severity of the results in the atmosphere.[21] As comparable sources releasing heat of this large magnitude, Hanna and Gifford suggested large fires and certain geophysical phenomena,[19] and Rotty expanded the number of examples to include some additional fire examples and some deliberate experimental attempts to modify the weather through heat addition.[21] A summary of the phenomena and the meteorological consequences of each is presented in Table 4.

Table 4. Effects of large heat additions to the atmosphere

Phenomenon	Energy rate (MW)	Area (km^2)	Energy flux density (W/m^2)	Meteorological consequences	Reference
Large brush fire	100,000	50	200	(Relatively small energy flux rate, very large area.) Cumulus cloud reaching to a height of 6 km formed over 1/10 of area of fire. Convergence of winds into the fire area	1
Forest fire whirlwind				Typical whirlwind: central tube visible by whirling smoke and debris. Diameters few feet to several hundred feet. Heights few feet to 4000 ft. Debris picked up: logs up to 30 in. in diameter, 30 ft long	2
World War fire storm		12		Turbulent column of heated air 2-1/2 miles in diameter. Fed at base by inrush of surface air. One and a half miles from fire, wind speeds increased from 11 to 33 mph. Trees 3 ft in diameter were uprooted	3
Fire at Hiroshima				(10-12 hr after A-bomb.) "The wind grew stronger, and suddenly — probably because of the tremendous convection set up by the blazing city — a whirlwind ripped through the park. Huge trees crashed down; small ones were uprooted and flew into the air. Higher, a wild array of flat things revolved in the twisting funnel." The vortex moved out onto the river, where it sucked up a waterspout and eventually spent itself	4

Table 4 (continued)

Phenomenon	Energy rate (MW)	Area (km^2)	Energy flux density (W/m^2)	Meteorological consequences	Reference
Surtsey Volcano	100,000	<1	100,000	Permanent cloud extending to heights of 5 to 9 km. Continuous sharp thunder and lightning, visible 115 km away (phenomenon probably peculiar to volcano cloud with many small ash particles). Waterspouts resulting from indraft at cloud base, caused by rising buoyant cloud	5
Surtsey Volcano	200,000	1	200,000	Whirlwinds (waterspouts and tornadoes) are the rule rather than the exception. More often than not there is at least one vortex downwind. Short inverted cones, or long, sinuous horizontal vortices that curve back up into the cloud, and intense vortices that extend to the ocean surface	6
French Meteotron	700	0.0032	219,000	"Artificial thunderstorms, even tornadoes, many cumulus clouds...substantial downpour. Dust devils"	7
Meteotron	350	0.0016	22,400	15 min after starting the burners, observers saw a whirl 40 m in diameter...whirlwind so strong burner flames were inclined to 45°	8
Single large cooling tower	2,250	0.0046	484,000	Plume of varying lengths and configurations	

Table 4 (continued)

Phenomenon	Energy rate (MW)	Area (km^2)	Energy flux density (W/m^2)	Meteorological consequences	Reference
Array of large cooling towers (48,000-MWe NEC, area 48,000 acres)	96,000	194	495	Unknown	
Array of large cooling towers (48,000-MWe NEC, 8000 acres)	96,000	32	3000	Unknown	

References:

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7. J. Dessens, "Man-Made Thunderstorms," *Discovery* 25(3): 40-43 (1964).
8. J. Dessens, "Man-Made Tornadoes," *Nature* 193(4820): 13-14 (1962).

The data presented in Table 4 offer credence to the concept that there is some (as yet unknown) combination of total energy addition and the flux density of the energy which is effective in enhancing the natural processes in the atmosphere that produce thunderstorms and concentrate vorticity. (Another criterion for concentration of vorticity in the atmosphere is presented in the following section.) The data in Table 4 do not suggest that any of the phenomena listed caused what would normally be regarded as a major tornado. It also appears likely that in most of the cases in which vortex activity was noted, the atmosphere was already in a state favorable to vortex formation, and the energy source simply provided a preferred location. These data do strongly support the idea that large energy releases with high energy flux densities will serve to augment the natural convective processes and thus enhance the activity in the vicinity of nuclear energy centers.

In a convective atmosphere, energy and water vapor are entrained in a rising air column and add to the tendency for cloudiness. Plumes from large cooling towers can act as a stimulant in the convective process, but the energy and water vapor entrained into a developing cumulus cloud system may be many times the amounts from the initiating cooling tower — especially in the systems that grow into major rain producers. Orville has suggested that the heat and moisture from cooling towers entrained into a mesoscale meteorological system will be a small perturbation compared with the total vapor and heat processed by the system.[22] (In this case the mesoscale system consists of ten or more major convective cells, each of which processes 10 to 100 times the output of 40 cooling towers.)

The heat rejection from nuclear energy centers will have its greatest impact on those occasions when the heat and moisture from the cooling towers act as initiating or trigger mechanisms for processes that draw in the larger energy and moisture amounts present in the ambient atmosphere. The combination of the NEC inputs with properties of the atmosphere can cause convective activity to occur earlier in time, to occur at a different location, to develop convective clouds on occasions when convective clouds would otherwise not occur, and perhaps to increase the violence associated with major thunderstorms. Some meteorologists have suggested that starting more convection, and starting it earlier, may reduce the number of very large thunderstorms that are formed. The possibility of this and the spacing of the heat rejection systems to do this are unknowns and require extensive further study.

4.3 Possible Vorticity Concentration

In discussing the possible consequences of clustering many cooling towers in a small area at River Bend, Louisiana, Hanna and Gifford expressed concern about vorticity concentration.[19] Briggs, in connection with his work on buoyant plumes, has suggested a criterion that might be used to predict whether a large source of buoyancy flux will serve as a mechanism for concentrating the natural atmospheric vorticity.[12]

A workshop on heat rejection from nuclear energy centers and its impact on the atmosphere was held by NRC on June 2 and 3, 1975. Attendees at the workshop pointed out the differences between an array of natural-draft cooling towers and the models used in developing the Briggs criterion, as well as examples of heat rejection systems (cooling towers) that perform in ways contrary to the criterion.

Heat rejection systems that spread the heat addition to the atmosphere over a wide area, for example, once-through cooling, cooling ponds, and lakes, result in low buoyant vertical velocities (heat flux densities a few times the global average solar flux at the ground), which result in no greater tendency to concentrate vorticity than exists in the natural atmosphere. Clusters of large numbers of cooling towers result in large vertical velocities (high heat flux density) over large surface areas, and the possible consequences of such arrangements are unknown. In view of the unknown consequences, the NRC June 1975 workshop favored "spreading out" the heat rejection as a safety precaution, although it was unwilling to accept any quantitative criteria or spacing limits.

5. IMPACTS ON AIR TRAFFIC SAFETY

As increasing numbers of cooling towers are used to provide power plant cooling, concern arises for the proximity of these towers to airports and other areas of medium- to high-density aircraft operation. It is assumed that nuclear energy centers will not be located in areas that coincide with approach patterns to any airport for reasons other than atmospheric considerations, but this alone does not assure that large heat disposal systems will have no effect on aircraft safety.

5.1 Air Turbulence as It Affects Aviation

Although mathematical formulation of turbulence is possible under a variety of physical situations, the problem in buoyant plumes and in convective clouds is sufficiently complicated that it is more productive to measure the effects of turbulence by aircraft instrumentation. In connection with the licensing of the Douglas Point Nuclear Generating Station, Potomac Electric Power Company presented the results of a series of aircraft flights, both helicopter and fixed-wing, through cooling tower plumes at Keystone (near Shelosta, Pennsylvania) and at Paradise Steam Plant (near Central City, Kentucky).[23] The effect of plume impact on aircraft operations was assessed by flying an Aero-commander 680E and a Bell 206B Jet Ranger helicopter repeatedly through the plumes. In all, 235 traverses through the plumes were reported, and during the 158 horizontal traverses made in the Bell 206B helicopter, vertical acceleration measurements were made and the peak values reported.

The highest value of vertical acceleration was 1.2 times g (upward) and occurred on one of the 20 horizontal traverses made through the most dense, visible portion of the plume. This particular traverse was at an elevation of 560 ft above the cooling tower top and 180 ft downwind of the tower. On only one other traverse did the vertical acceleration reach 1.0 times g acceleration — the traverse at 460 ft above the tower and 180 ft downwind. On both of these occasions the reported time in turbulence was 4 sec. On all other traverses the vertical acceleration was considerably less; most values were below 0.5 times g. In general, higher vertical acceleration values were obtained at lower elevations and nearer the tower, as expected, and maximum downward accelerations were numerically smaller than the upward values. During most of the helicopter traverses, a single cooling tower was operating, providing the cooling for a 1100-MWe-capacity coal-fired unit. The traverses experiencing the greatest acceleration were made below a 1400-ft elevation.

Fourteen occasions when the Aero-commander 690E penetrated the plume at distances from 50 to 360 m directly above the cooling tower are reported by Hosler.[24] In no case did the pilot or crew experience even moderate turbulence, and on most penetrations only a slight uplift was detected.

It was concluded that the turbulence in the plume 500 ft or more above the tower outlet will be similar to that at the base of (or in) a cumulus (not cumulonimbus) cloud.[23,24] The liquid water content, drop size distribution, and air motions are almost identical in the plume and in small cumulus clouds.

If the cooling towers associated with a large nuclear energy center are spaced to avoid large areas of very high energy flux density, for example, clusters of no more than four towers close enough to give merging plumes, then the conclusions of the previous paragraph can be assumed. On the other hand, locating more towers within a few tower diameters of each other may give larger vertical currents and turbulence affecting aviation. The spacing of clusters of four towers at 2-1/2-mile distances (as assumed for the NEC) to avoid the merging of plumes from clusters would appear to offer sufficient insurance.

5.2 Aircraft Icing

Icing on an aircraft may be defined as the buildup of ice that adheres to aircraft surfaces as the result of deposition of airborne water particles or water vapor.

Detailed information has been obtained on spectra of droplet sizes in cooling tower plumes during aircraft penetrations as low as 50 m directly above the cooling tower and up to 360 m above the cooling tower.[24] Nearly all of the drops are less than 100 mμ in diameter even in the core of the plume, and most are very small, in the range from a few to 50 or 60 mμ in diameter. Liquid water content in the cloud rarely exceeded a few tenths of a gram per cubic meter (largest measured was 1.4 g/m^3). This low water content combined with the small drop size results in almost negligible liquid water deposition on the aircraft. (At no time during the aircraft flights into the plumes did the windshield become completely wet.)

Except for cases where the cooling tower has triggered the formation of a major cloud, the time that an aircraft is likely to be in the plume or cloud from a cooling tower is short. This, added to the arguments of the paragraph above, makes it unlikely that aircraft icing resulting from cooling plumes will be a major problem.

A nuclear energy center should not result in major turbulence or icing problems for air transportation. Any major cloud formations initiated by the NEC will have the same characteristics to be avoided (by aircraft) as other clouds of the same type and size. The only other region of possible significant impact on aircraft is in the immediate vicinity of the cooling towers (within 100 m), and it is assumed that this region will normally be avoided.

6. DRIFT AND ATMOSPHERIC SALT CONCENTRATIONS

When cooling towers are used in the heat dissipation system, fine droplets of the cooling water are dispersed into the atmosphere via the cooling tower plume. These water droplets, referred to as drift, are of the same composition as the cooling tower water and therefore carry dissolved solids (salts), suspended solids, water treatment chemicals, and, in fact, everything that was present in the cooling water. The drift rises with the tower plume and then begins to settle out downwind from the cooling tower, giving rise to airborne salt deposition and buildup of concentrations on the ground.

Modern cooling towers are routinely equipped with high-efficiency drift eliminators, which can reduce the discharge to less than 0.002% of the water circulation rate. No adverse environmental effects of drift have been reported from such installations now operating. A few recent instances of adverse environmental effects, such as the accumulation of salt on buildings, power lines, parked cars, and vegetation near cooling towers, have been attributed to defective or poorly designed drift eliminators, for example, at the Ratcliffe plant in England.[25] The following analysis of groupings of plants into NECs indicates further that the drift from groups of cooling towers is not expected to result in adverse effects.

The drift analysis of an NEC surrogate site in the inland United States indicates that salt deposition reaches a peak between 0.5 and 1.0 mile from a point source and is a small fraction (about 0.15) of the peak value at 2.5 miles (the proposed spacing between modules in the NEC).[26] It is concluded, therefore, that the local ground deposition from an NEC would be dominated by the nearest module and would not differ greatly from the deposition from a dispersed site. However, the fraction of the drift that carries farther than one module spacing, which would consist of the finer particles, would be additive for the modules, producing a dispersion of fine particles downwind from the NEC estimated to be several times as wide and possibly two or three times as concentrated as from a single dispersed site. Since the deposition rate from such a fine dispersion would be less, by about an order of magnitude, than the deposition rate local to a module, it is not expected to produce noticeable effects on the ground. However, a meteorological effect might be possible.

The drift pattern obtained depends somewhat on the type of cooling tower employed. The types that are most suitable for very large heat loads, which are therefore most likely to be used in an NEC, include the natural-draft tower, the fan-assisted natural-draft tower, and the circular mechanical-draft tower. These three types (the "round towers") produce very similar plumes, large and characterized by an appreciable buoyant plume rise. The main difference between them lies in the effective height at which the plumes are discharged, which generally decreases in the order of the list above. Greater height generally gives greater dispersion and lower local deposition of drift.

Conventional rectangular mechanical-draft towers are widely used at present, but because of plume recirculation and other problems, the trend is away from this type in favor of the various round towers for large heat loads. The drift from conventional mechanical-draft towers is deposited locally to a greater extent than the drift from round towers because of a smaller plume rise.

Spray ponds also generate drift, but the droplets are of coarse size and discharged at low altitude, so that effects are very localized. Essentially no interaction between such installations in an NEC would be expected.

The remainder of this discussion will concentrate, therefore, on the drift associated with the large buoyant plumes from towers of the round types. If the shorter rectangular towers should be used, the drift effects would be similar but more localized around each cluster of towers.

6.1 Characteristics of Drift

Drift from modern towers with high-efficiency drift eliminators is characterized by low discharge rates and small droplet size. Tower manufacturers will guarantee drift rates of 0.002%, based on the circulation rate of water in the tower, and drift rates of 0.001% have been measured in tests.[27] A drift rate of 0.002% is equivalent to about 30 ppm in the discharge air. Drift eliminators are most efficient in removing the larger drops, so that the resulting drift droplet size distribution is heavily weighted toward smaller droplets. Recent measurements on a tower test section, as shown in Table 5, indicate that over half the weight of droplets is in the range of less than 60 μm diameter. Because of these factors of low drift rate and small droplet size, the local drift deposition from modern towers is much less than from older installations. The remaining fine drift droplets, however, may be transported long distances by the plume.

Table 5. Mass distribution of drift droplet sizes

Range of diameters (μm)	Fraction of total mass in group (duplex eliminator)
<60	0.55
60–120	0.22
120–180	0.05
180–225	0.04
225–325	0.08
325–425	0.06

Source: J. D. Holmberg, "Drift Management in the Chalk Point Cooling Tower," *Cooling Tower Environment — 1974*, CONF-74302 (1974).

Salt drift is measured both as an airborne concentration and as an average deposition rate on the ground. Airborne concentration is most useful for considering acute exposures. For example, acute exposures of vegetation to salt drift (natural or man-made) occur during periods of high winds; given the airborne salt concentration and the wind velocity, the impingement of drift on a given front of vegetation can be calculated. Average deposition rates over relatively long periods of time (usually per year) are generally used in evaluating chronic effects.

Airborne concentrations and deposition rates of salt drift are usually predicted by the use of mathematical models.[28] A number of these models are quite elaborate; for example, a model developed at ORNL can use many years of weather data (from NOAA tapes) to yield annual deposition rates based on calculations of the plume rise, droplet evaporation rates, and droplet fall rates.[29] Because of the difficulty in obtaining drift data in the field, however, none of the models have been adequately verified against field data. A comprehensive program of field measurements from a natural-draft cooling tower using brackish water is presently under way (the Chalk Point Cooling Tower Project of the State of Maryland Power Plant Siting Program).[30] This and perhaps other data should be available to verify models for drift calculations for an NEC. Data on liquid droplet deposition near operating power plant cooling towers were presented in the 1973 symposium "Environmental Effects of Cooling Towers."[25]

The amount of drift salts emitted from a tower is controlled by two main factors: the design of the tower, particularly the drift eliminators, and the concentration of salts in the tower water. The concentration of salts depends in turn on the quality and treatment of the makeup water and the concentration factor.[26] Salt drift from an existing tower can be reduced, if necessary, by decreasing the concentration factor, that is, by increasing the makeup and blowdown rates. The prevention of significant drift effects, on the other hand, lies largely in the adequate design of the tower and the provision of good-quality makeup water.

6.2 Effects of Drift

The primary potential effect of drift is damage to vegetation. Potential secondary effects are increase in the salinity of soils and/or groundwater and related ecological effects. A further potential effect is the airborne spreading of contaminants in the tower water. "Potential" should be emphasized, because, to date, environmental effects of drift from operating towers have been small or nondetectable.

The source of makeup water for the tower is very important in assessing the impact of drift. Where freshwater makeup is used, the total dissolved solids in the tower water can be kept relatively low by operating with reasonable concentration factors. The predominant ions in solution are likely to be calcium and sulfate, with smaller amounts of magnesium, sodium, and chloride. Under these conditions, drift does not appear to damage the environment. No references have been found in the literature to any instances of damage to vegetation due to drift from freshwater towers.

Where salt water or brackish water is used for makeup, the total dissolved solids concentration in the tower water is relatively high even for low concentration factors. The predominant ions in solution are usually sodium and chloride, with smaller amounts of calcium and magnesium. The drift from saltwater towers is essentially the same as natural ocean salt drift found in seacoast areas.

The acute effects of natural salt drift are well known. After periods of high winds from the ocean, foliage directly exposed suffers necrosis. These effects have also been demonstrated in laboratory experiments. Chronic effects (e.g., growth stunting) are also observed. Vegetation with low salt tolerance does not become established in coastal areas. Salt tolerance has also been the subject of controlled studies. Among cultivated plants, tobacco and beans are examples of plants with low salt tolerance.[30] In areas where salt water may be used for makeup, the natural vegetation is likely to be salt-tolerant, but cultivated crops may not be.

There are almost no data available on the effects of operating saltwater towers. In Britain, no damage to vegetation is reported from the operation of small saltwater towers at Fleetwood in a coastal area.[31]

Secondary effects are likely to be highly site-dependent. In the eastern United States the normal rainfall is sufficient to avoid the buildup of salt in the soil, even around saltwater towers. The amount of salt entering the groundwater from drift has likewise been shown to be negligible in relation to the natural salt levels in groundwater.[32] The possible transport of contaminants, such as sewage waste, in cooling tower drift is a hypothetical problem, but no reports of the spread of dangerous contaminants via cooling tower drift have appeared in the literature. Viruses, fungi, and bacteria are present to some extent in the usual sources of water. However, cooling tower basins are normally chlorinated regularly (to control algae), and drift is well exposed to the oxygen of the air. Both factors would destroy many pathogens. Treated sewage effluent has been proposed as a source of cooling water in water-short areas; presumably such a water source would be carefully monitored for pathogens. In the absence of scientific data on the potential spread of contaminants in cooling tower drift, it would seem prudent to select a source of makeup water that was free of dangerous contaminants. In summary, potential secondary effects of drift should be carefully considered on a site-related basis, but so far no serious problems have appeared.

7. SELECTION AND SPACING OF COOLING SYSTEMS

The disposal of waste heat to the atmosphere can have a number of different types of impact on the local and mesoscale climate and weather. The severity of an impact can often be reduced by selecting a cooling system that avoids that particular impact, although this may result in increasing the possibility of some other impact. For example, the use of large cooling ponds or lakes spreads the heat rejection over a wide area, giving a low heat flux density, thus reducing the possible augmentation of severe convective activity but significantly increasing the fogging problem as compared with the use of natural-draft cooling towers.

If natural-draft cooling towers must be used, the severity of the impact can be reduced by locating and spacing the towers in the most effective way. There is no way to design cooling systems that reject these large quantities of heat (and moisture) without giving some adverse impacts. In general, spacing the cooling system over as wide an area as possible tends to minimize the severity of the impact on the atmosphere.

7.1 Spacing to Minimize Fogging and Surface Temperature Effects

The mitigation of the increased tendency for fog may be accomplished by providing thorough mixing with a large volume of ambient (drier) air, so that the frequency with which saturated conditions occur at the ground is reduced.

The higher the elevation (above ground) that the water vapor is injected into the atmosphere, the greater the vertical mixing and diffusion required before the injected water vapor can affect the saturation ratio (ratio of water vapor content of the air to the water content for saturated conditions) at the ground. Cooling ponds, lakes, and canals with or without spray modules rely on density-induced vertical motion to carry the water vapor away from the surface, and hence the effective vertical dimension of the mixed volume may be small. Cooling towers provide a vertical discharge velocity and usually an elevated source of the water injection into the atmosphere. Natural-draft towers are better than mechanical-draft towers in eliminating additional fog because of their added height. Clustering towers can add to the rise of the buoyant plumes through plume reinforcement and thus add to the elevation of the effective moisture release point.

At present, there are no natural-draft cooling towers in this country that have been demonstrated to cause increased frequency of fog occurrence. Under certain atmospheric conditions a large number of natural-draft cooling towers (as with an energy center) could cause augmented fogging, while single towers would not. This will occur very infrequently, and, in general, the use of natural-draft towers eliminates the fogging problem.

The total volume of air receiving the injected water vapor can be increased by clustering the cooling towers to obtain augmented plume rise, but it is doubtful whether much advantage can be realized in clustering towers of the 2400-MWt size beyond three or four per cluster. Under atmospheric conditions conducive to increasing the saturation ratio at the surface by moisture additions from cooling tower plumes, the relatively small amount of enhanced plume rise from tower additions beyond three or four will produce little change in the already very small possibility of ground-level fogging.

7.2 Spacing to Minimize Convective Activity

The concept of an array of cooling towers as a family of strong buoyant point sources and therefore as an enhancement to convective activity in the vicinity of a nuclear energy center was presented in Sect. 2. If the heat (and moisture) additions can be spread over a wide surface area, the effect of increasing convective activity can be minimized.

The rejection of 96,000 MW of heat by spreading it uniformly over an area sufficient to give a heat flux density no greater than that of Manhattan Island (i.e., three to four times the average solar flux at the ground) is not likely to give augmentation to convective activity of any more significance than that of very large cities (see Sect. 4.1). To provide such a heat flux density, the surface area of a 48,000-MWe NEC must be approximately 48,000 acres. The problem then becomes that of spreading the heat uniformly over such a large area to be analogous to cities.

Convective activity is initiated by uneven addition of heat or by obstructions in the flow field (flow over a row of hills, etc.). In the case of Manhattan Island the heat release is relatively uniform over the entire surface, in comparison with that of a nuclear energy center using cooling towers, where the heat release is by a group of point sources spaced over a large area. The nonuniformity of heat release should result in greater convective activity, and since cooling towers must be used in finite sizes, a uniform value for heat flux density over very large areas is impossible. (Use of cooling ponds and lakes, in addition to, or in place of, cooling towers, tends to spread the heat more uniformly.)

Orville has suggested that another way to evaluate the areal requirements of an energy center cooling system is to compare natural atmospheric moistening rates with those of energy centers of different areas.[33,34] Since atmospheric convective activity is also dependent on the availability of large moisture amounts, water vapor additions from energy centers contribute to the convective activity. Orville suggested that a convergence rate of 10^{-4} sec^{-1} (or greater) should be taken as a critical value. On this basis, the natural advection of water vapor in the atmosphere from mesoscale convective processes is found to be 10^{6} g sec^{-1} km^{-2}. This value should be compared with the moistening rate per unit area resulting from the energy center. Table 6 shows the moistening rate for various areas on the assumption of a 48,000-MWe nuclear energy center with its estimated moisture release of 2.8×10^{7} g sec^{-1}. Comparing the values in the table with the 10^{6} g sec^{-1} km^{-2} associated with strong natural convective activity suggests that areas of about one acre per megawatt (electrical) are needed to assure that the cooling system will have a small effect compared with the natural atmospheric mesoscale dynamics.

Table 6. Moistening rates for 48,000-MWe energy centers (2.17×10^{12} g/day or 2.5×10^{7} g/sec water evaporation rate for cooling)

Area		Moistening rate density (10^6 g sec^{-1} km^{-2})	Ratio to natural strong convection
Acres	Square kilometers		
74,100	300	0.083	0.08
47,500	192	0.13	0.13
24,700	100	0.25	0.25
12,350	50	0.50	0.5
6,175	25	1.0	1.0

Although the estimation of the atmospheric impact from large heat additions cannot be quantified with a high level of confidence on the basis of present knowledge, it is clear that spreading the heat over wide areas provides some reassuring analogs. With areas of about one acre per megawatt (electrical) the heat flux density is about the same as that of Manhattan Island, and the moisture rate density is about 13% of that of the natural atmosphere on highly convective days. Pushing these values higher by using smaller areas for heat rejection pushes the evaluation of possible impacts toward increased conjecture.

The use of natural-draft cooling towers will not spread the heat uniformly, but their use is so likely that special attention should be given to the location or spacing of the towers within the large area needed to reduce the heat and moisture flux densities within acceptable limits. One arrangement to be considered assumes several small clusters of cooling towers spaced over the nuclear energy center site at distances sufficient to assure that each cluster acts as an individual source instead of merging into one gigantic source. Spacing clusters of four units (9600 MW of heat rejection per cluster) over a 48,000-acre (75-sq-mile) site to provide 48,000 MWe output results in devoting 7.5 sq miles to each cluster (or a square 2.5 miles on a side). Locating a cluster near the center of each square gives a spacing of 2.5 miles between clusters.

With a 2.5-mile spacing, the plumes from a cluster of towers are not likely to merge with plumes from adjacent clusters (at least until the plumes are past the stages of their greatest buoyant activity). The moisture is also added at several locations within the convective field and in aggregate is a small part of that being advected from the ambient atmosphere by convection.

7.3 Direction and Distance from Urban Areas

The possibility that a nuclear energy center will serve as a source (or at least a triggering mechanism) for severe convective activity (thunderstorms or hailstorms) cannot be totally eliminated on the basis of current understanding of the associated atmospheric processes. In the eastern half of the United States the most violent convective storms occur on days when the atmosphere is very warm and humid as a result of air flow from the southwest advecting moisture from the Gulf of Mexico. Storms that are triggered in this flow pattern generally move in a northeasterly direction. For example, a map of the severe outbreak of tornadoes on April 3-4, 1974, indicates damage paths running from the southwest toward the northeast.[35]

Energy centers, like all power plants, must be carefully sited for a large number of reasons. In view of the large heat and moisture additions from an energy center, giving a potential for preferred locations for increased convective activity, this additional consideration should enter the siting criteria.

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