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NOISE RADIATION FROM ENERGY CENTER COOLING TOWERS

J. Zakaria and F. Moore

December 1976

**POLICY ANALYSIS DIVISION
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973**

**Prepared for the
OFFICE OF SPECIAL STUDIES, UNITED STATES NUCLEAR REGULATORY COMMISSION,
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NOISE RADIATION FROM ENERGY CENTER COOLING TOWERS

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December 1976

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UNDER CONTRACT NO. EY-76-C-02-0016

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Printed in the United States of America
Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy \$5.25; Microfiche \$3.00

May 1978

500 copies

FOREWORD

This study is one of a continuing series of reports on Energy Center Siting sponsored by the U.S. Nuclear Regulatory Commission and the Division of Technology Overview of the U.S. Energy Research and Development Administration, prepared by the Brookhaven National Laboratory Energy Policy Analysis Division.

To date, the Brookhaven National Laboratory energy center research effort has focused on an evaluation of a hypothetical Nuclear Energy Center in New Jersey and the development and application of specific analytical tools necessary for policy assessments. It is to the latter area that this report is addressed.

Other reports in this series include:

Energy Policy Analysis Group, et al. "A Preliminary Assessment of a Hypothetical Nuclear Energy Center in New Jersey", BNL-50465, Nov. 1975.

P.M. Meier and D. Morell "Issues in Clustered Nuclear Siting: A Comparison of a Hypothetical Nuclear Energy Center in New Jersey with Dispersed Nuclear Siting", BNL-50561.

Regional Science Department, University of Pennsylvania, "Regional Economic Impacts of Nuclear Power Plants", BNL-50562.

P. M. Meier "Optimization of Water Conveyance Systems for Nuclear Energy Center", BNL-50563.

S. Linke and D. Chu, "Transmission Studies of Dispersed vs. Clustered Generating Facilities", BNL-50565.

ABSTRACT

Noise radiation from the cooling towers of clustered and dispersed arrays of cooling towers for large power plants is presented, and a procedure presented for the prediction of noise levels at some distance from the rim of single isolated tower. Two types of cooling systems, namely mechanical-draft wet and natural-draft wet cooling towers, are considered, which are assumed to act as the sole source of noise generation in power plants.

The procedure for the prediction of noise levels from single isolated towers is then extended to determine noise levels at some point on the site boundary of energy centers being proposed for the future.

It is concluded that if one wishes to minimize the area impacted by objectionable noise levels, then for concentrated power centers either mechanical-draft or natural-draft towers may be chosen, while for more widely dispersed centers natural-draft systems must be recommended. Special emphasis has been placed upon the A-weighted sound levels, which correlate well with human sound perception. One dimensional free wave spreading and atmospheric absorption are the attenuation factors taken into account.

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NOMENCLATURE

A	Subscript for A-weighting.
A_p, A_p'	Atmospheric absorption and A-weighting parameters. The numerical values are given in the Appendix.
a	Subscript for atmospheric attenuation.
B, B'	Tower constants for natural and mechanical draft towers respectively.
b	Constant = 1/3,000 for L in meters = 1/9,840 for L in feet.
C	Radius of power park site boundary, Figure 6.
c	Sound speed in air.
D	Natural-draft cooling tower parameter.
h, h'	Natural-draft cooling tower parameters.
hp	Rated fan horse power. Its value is 3,625 for a typical mechanical-draft tower for a 600 MW electric generating station.
I	Average intensity of sound.
(i, j)	Grid point, Figures 9, 10 and 17.
k	Number of frequency bands in the noise spectrum.
L	Radius of the innermost circle for the approximation of the location of dispersed towers, Figure 17.
ℓ	Side of the square generating the mesh-work, Figures 9 and 10.
L_ω	Sound power level for mechanical-draft towers.
n	Maximum number assigned to i. Total number of towers = $4 \sum_{i=1}^n (2i - 1)$.
O	Point of interest, Figures 6 and 9.
O'	Point of interest, Figure 17.
P	Sound Pressure
P_A	A-weighted root mean square sound pressure.
p	Number assigned to the frequency band. See also Appendix.
R	Natural-draft tower base radius, Figure 1.
r	Radius of the power park, Figure 6.
S	Distance from the source to the point of interest. Also used as a subscript.

$S(i,j)$	Distance from the grid point (i,j) to the rim of the tower.
SPL	Sound pressure level.
SPL_a	SPL with atmospheric attenuation.
SPL_L	SPL at a distance L from the source, Eq. (38).
SPL_p	SPL in the p th frequency band.
$SPL(i)$	SPL at the point 0 of Figure 17 due to the towers located on i th circle.
$SPL(0)$	SPL at the point 0 due to the towers located at the grid point of Figure 10.
$SPL(0')$	SPL at the point 0' due to the towers located at the grid points of Figure 17.
T	Natural-draft cooling tower parameter.
T_p	Atmospheric attenuation in DB/984 ft. For numerical values see Appendix.
u	Particle velocity, Eq. (1).
Wac	Acoustic power in watts. This will be 1.474 watts for one typical natural-draft tower for a 600 MW electric generating station.
W_p	A-weighting reduction.
W_t	Total acoustic power generated by the eighty towers of a concentrated power center.
X	Distance from the rim of the tower at which a given SPL will occur, Figure 23.
Z_o	Atmospheric impedance = 407 N-sec/m^3 for the assumed conditions.
ρ	Density of air.
$\theta, \theta(i,j)$	Geometrical descriptions appearing in Figures 7 and 10 respectively.
Δ	Difference in DBA re $2 \cdot 10^{-5} \text{ N/m}^2$ predicted at the point 0 and 0' of Figure 9 and 17 respectively, when $n = 1$ and when $n = n$.
Π	Parameter in Eq. (44). Also $= 10 \log_{10} \pi$.
η	Efficiency of conversion from the rated fan power to acoustic power.

Chapter I

INTRODUCTION

1.1 Background

This report is one of several technical studies conducted by the BNL Regional Studies Program in connection with an evaluation of a hypothetical nuclear energy center (NEC) in Ocean County, New Jersey. As such, it addresses only the rather narrow technical area of cooling tower noise; the comprehensive evaluation of all facets of the NEC is reported in a separate study, to which the reader is referred for further background.*

A number of reasons justified the detailed analysis of cooling tower noise. The main reason is that concern over noise emerged very early in our study effort as one of the key public concerns. Since the presence of cooling towers in close proximity to the many beaches of the New Jersey Atlantic coastline raised great apprehension on the part of the recreation industry, some effort was merited in addressing the noise and visibility issues in some detail. Unfortunately the configuration of up to 40 reactors at a single site raised a number of technical problems in noise assessment, and it is to the development of an appropriate noise prediction model that this report is addressed.

It should be pointed out that the intent of our New Jersey NEC analyses, which were conducted in support of the U.S. Nuclear Regulatory Commission Nuclear Energy Center Site Survey (NECSS), was to inject a local and regional perspective into the broad national assessment of energy centers; since only by reference to specific sites could many of the technical, environmental, institutional and socioeconomic issues be adequately addressed. Indeed, in addition to the New Jersey study area a number of other potential areas were selected throughout the U.S. for more specific analysis, each typical of a representative set of siting attributes. Thus neither Ocean County, nor any of the other surrogate sites, is recommended for consideration for actual construction of an NEC; nor does the selection of study areas imply any judgement of desirability.

* P. Meier and D. Morell "Issues in Clustered Nuclear Siting: A Comparison of a Hypothetical Energy Center in New Jersey with Dispersed Nuclear Siting", BNL 50561.

1.2 Scope of Report

In Chapter 2 we present a procedure for the prediction of noise levels at some distance from the rim of the natural-draft as well as mechanical-draft wet cooling towers for a typical 600 MW electric generating station. For natural-draft systems, one wet tower of base radius of 200 ft has been considered. A schematic of such a tower is shown in Figure 1.

The technique for the prediction of noise levels from single isolated towers is extended further in Chapter 3 to noise radiation from energy center cooling towers. Initially the center is assumed to be of 48 GW capacity located at the center of the total site area (the "clustered" case).

At this point it should be mentioned that noise levels below 45 DBA are generally acceptable. If the reactors are more widely dispersed within the energy center, then the noise levels within the area of the dispersed tower sources may fall below 45 DBA, and hence acceptable. This situation is taken into account in Chapter 4 where the listener is placed among and surrounded by power plants, which themselves are much farther apart, or dispersed, than in the clustered case.

Considering the area impacted by a given level of objectionable noise of 45 DBA, some interesting comparisons can be made of the results developed in Chapters 3 and 4, a task addressed in Chapter 5.

Chapter 2

NOISE RADIATION FROM SINGLE ISOLATED TOWERS

In order to analyze the problem of noise radiation from an area with uniformly distributed acoustic power sources, the behavior of sound pressure level (SPL) with increasing distance from a single isolated tower will be studied first. The analytical procedure adopted for the prediction of noise levels is presented in the following pages. Mechanical and natural-draft tower noise has been dealt with separately although the prediction technique is the same for both the cases.

2.1 Natural-Draft Wet Tower Noise Estimation

The first step consists of the determination of cooling tower parameters such as dimensions, water flow rate, etc. Ref. (1) suggests two natural-draft wet cooling towers for a 1,200 MW Power Plant. For the present analysis a 600 MW unit is considered for which, also according to Ref. (1), one tower of base diameter 400 ft would be sufficient. The overall dimensions for a counterflow tower, inferred from Ref. (2), for a base diameter of 400 ft, are presented in Figure 1. The cooling water flow rate in this tower from Ref. (1) would be 620 cfs or 17,564 Kgs.

Cooling water flow rate = 17,564 Kg/s = 620 cfs

$h = 60 \text{ ft} = 18.32 \text{ m}$

$T = 37 \text{ ft} = 11.3 \text{ m}$

$D = 14 \text{ ft} = 4.3 \text{ m}$

$R = 200 \text{ ft} = 61 \text{ m}$

Figure 1. Natural-draft wet tower for a 600 MW Power Plant.

At this point a brief review of the theoretical background for the estimation of noise levels might be helpful. It should be emphasized that in the present analysis freely progressing one dimensional sound waves have been assumed. We now define the average intensity of sound, I , as the energy that flows through a unit area in a unit time, in the direction of the sound wave propagation. This intensity is the time average of the product of the sound pressure and the particle velocity measured in the direction of the wave propagation. Thus

$$I = \overline{P \times u} \quad (1)$$

where P = sound pressure in N/m^2

u = particle velocity in m/s associated with the to and from motions of the air molecules, which always occur along a line parallel to the direction of propagation. The product $\overline{P \times u}$ can be shown to be equal to $P_{rms}^2 / \rho c$ or

$$I = \frac{P_{rms}^2}{\rho c} \quad (2)$$

where P_{rms} = root mean square sound pressure

ρ = density of air

c = sound speed in air.

Sound pressure level at some point at a distance S from the source is given, by definition, by the following equation:

$$SPL_S = 10 \log_{10} \left[\frac{P_{rms}^2 \text{ at } S}{(2 \cdot 10^{-5})^2} \right] \text{ DB re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (3)$$

In order to find the sound energy intensity at some distance S from the rim of a natural-draft wet cooling tower, Ellis, in Ref. (3), has developed the following relationship for uniform hemispherical radiation*:

$$P_A^2 = \frac{W_{ac} Z_o}{\pi^2 (S^2 + 2SR)} \tan^{-1} \sqrt{\frac{S + 2R}{S}} (N/m^2)^2 \quad (4)$$

where P_A = A-weighted root mean square sound pressure at S m. from the rim of the tower.

* It is assumed in Ref. (3) that the noise is generated by a ring of falling water around the edge of the pond (Figure 1), and that any noise generated inside this ring is prevented from escaping by reflection, refraction and absorption by the packing and falling water.

$Z_o = \rho c = \text{atmospheric impedance} = 407 \text{ N-sec/m}^3$ for the atmospheric conditions assumed.

$R = \text{base radius of tower in m.}$

$W_{ac} = \text{acoustic power generated by the source in Watts.}$

A brief comment on the behavior of eq. (4) when $S \gg R$ may be helpful.

For this condition eq. (4) reduces to

$$P_A^2 = \frac{W_{ac} Z_o}{4\pi S^2} \quad (5)$$

Eq. (5) appears to describe a spherical radiation of the total acoustic power W_{ac} generated by the splashing of water inside the tower. This contradicts our previous statement that Eq. (4) is derived on the basis of a uniform hemispherical radiation of noise. In fact there is no contradiction at all, for at $S \gg R$, the acoustic power generated at the far side of the tower rim is practically blocked by the structure of the tower from affecting the point of observation. Only that half of the total acoustic power W_{ac} , emanating from the visible side of the tower, actually produces impact at the point of observation. Therefore for S large compared to R , half of the total acoustic energy radiating hemispherically is mathematically equivalent to the total acoustic energy radiating spherically.

The determination of P_A in Eq. (4) can be accomplished by first evaluating W_{ac} . Ellis has presented the following equation which relates the acoustic power W_{ac} with the tower parameters:

$$W_{ac} = Mh \left\{ .95 \cdot 10^{-5} \left(\frac{T}{h} \right)^2 + 1.8 \cdot 10^{-5} \left(\frac{D}{h} \right)^2 \right\} \quad (6)$$

where M is the flow rate of cooling water in Kg/s, and T, h, D are the physical dimensions of tower (see Figure 1). For our tower for a 600 MW power station, from Eq. (6) one obtains

$$W_{ac} = 1.474 \text{ Watts}$$

This implies an efficiency of water pumping power for conversion into sound power of

$$\eta = \frac{1.474}{17,564 \times 18.32 \times 9.8} = .47 \cdot 10^{-6}$$

This value of η is quite reasonable. In fact measured conversion efficiencies stated by Ellis in Ref. (3) for natural-draft wet cooling towers range from 0.37 to 0.81 PPM. The A-weighted SPL can now be found by using the value of W_{ac} from Eq. (6) in Eq. (4), and then substituting P_A from Eq.(4) for P_{rms} in Eq. (3):

$$SPL_S = 10 \log_{10} \left\{ \frac{P_A^2}{(2 \cdot 10^{-5})^2} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (7)$$

The above equation essentially results in the A-weighted, unattenuated SPL. In order to find the A-weighted sound levels with atmospheric attenuation, we first break the SPL_S into the individual sound levels in the octave bands of the spectrum. These octave band levels can then be reduced by the respective DB reduction due to the atmospheric absorption. The resulting sound intensity in each band is then added to yield the net A-weighted and attenuated sound levels actually reaching a distance S from the rim of a natural-draft tower. The overall procedure for the computation of sound levels at some distance from the rim of a natural-draft tower is presented in the following example:

Example 2.1:

Given a point 100 ft (30.5 m) from the rim of the natural-draft tower in Figure 1, one wishes to find the A-weighted sound levels with atmospheric attenuation at this point.

With $S = 30.5$, Eq. (4) yields

$$P_A^2 = .01498 \text{ (N/m}^2\text{)}^2$$

or

$$P_A = .1222 \text{ N/m}^2$$

from Eq.(7) one obtains

$$\text{SPL}_S (S = 30.5) = 75.7 \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (8)$$

The noise spectrum is considered next. It is quite reasonable to assume that the overall shape of the spectrum is nearly the same for different towers and for various distances from the tower source. Table 1, from Ref. (3), is used in our analysis.

Table 1

Natural-Draft Wet Cooling Tower Noise Spectrum

Center Frequency (KHz)	Average octave band levels relative to <u>A-weighted SPL in DB re $2 \cdot 10^{-5} \text{ N/m}^2$</u>						
	.125	.25	.5	1	2	4	8
Level at Tower Rim	-19.4	-19.8	-13.0	-7.8	-6.3	-4.3	-7.2

The A-weighted sound level of Eq. (8) can now be resolved by using Table 1 into sound levels in each frequency band. For example, the sound level in the frequency band of 1 KHz will be $75.7 - 7.8 = 68.9 \text{ DB}$. Table 2 presents the spectrum at $S = 100 \text{ ft}$ from the tower rim.

The effect of atmospheric absorption is now taken into account. Table 3, which includes data for mechanical-draft tower noise atmospheric conditions of 60°F and 70% relative humidity, is extracted from Ref. (4).

Table 2

Noise Spectrum of a Natural-Draft Wet Cooling Tower atS = 100 Ft from Tower Rim (Without Atmospheric Absorption)

Center frequency (KHz)	.125	.25	.5	1	2	4	8
Average Octave	66.3	65.9	62.7	68.9	69.4	71.4	68.5

Table 3

Atmospheric Absorption Rate

Center Frequency (KHz)	.05	.1	.125	.2	.25	.5	1	2	4	8
Atmospheric Absorption	-	-	-	.01	.014	.7	1.4	3.0	7.7	14.4

The sound levels actually reaching a point 100 ft from the rim of the tower of Figure 1, can now be obtained by reducing the levels of Table 2 by the respective atmospheric absorptions presented in Table 3. For example, for an octave band center frequency of 1 KHz, the sound level at a distance S from the rim of the tower will be:

SPL_a , (for a center frequency of 1 KHz)

$$= \underset{\substack{\uparrow \\ \text{Eq. (7)}}}{SPL_S} - \underset{\substack{\uparrow \\ \text{Table 3}}}{1.4 \times S/300} - \underset{\substack{\uparrow \\ \text{Table 1}}}{7.8} \quad (9)$$

where the subscript a in Eq. (9) refers to sound levels with atmospheric attenuation. For the whole spectrum the results are presented in Table 4.

Table 4

A-Weighted Sound Levels with Atmospheric Attenuation at S = 100 Ft.,
From the Rim of the Natural-Draft Cooling Tower for a
600 MW Station

Center frequency (KHz)	.125	.25	.5	1	2	4	8	DBA re $2 \cdot 10^{-5}$ N/m ²
Octave band levels (DB)	66.3	65.9	62.7	68.9	69.4	71.4	68.5	75.7
Atmospheric absorption (DB)	-	.0014	.0072	.143	.305	.78	1.46	
Predicted levels	66.3	65.89	62.69	68.76	69.09	70.62	67.04	73.9

Finally, Tables 1 to 4 are combined to yield Table 5 representing the overall noise level prediction scheme at a distance S from the rim of a natural-draft wet cooling tower of Figure 1.

Figure 2 shows sound levels calculated in this way for various distances from a natural-draft cooling tower (the mechanical-draft curves will be explained later.)

Figure 3 represents the A-weighted spectra representing the energies actually felt by the human ear at various octave band center frequencies. Note that as S increases, higher frequency contributions disappear from the spectra because of atmospheric absorption.

Table 5

Prediction of A-Weighted SPL With Atmospheric Attenuation for A Natural-Draft Wet Tower
for a 600 MW Power Plant

(S = 100 ft; $SPL_S = 75.7 \text{ DB re } 2 \cdot 10^{-5} \text{ N/m}^2$)

Center frequency (KHz)	.125	.25	.5	1	2	4	8	DBA $2 \cdot 10^{-5} \text{ re } \text{N/m}^2$
$SPL_S \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2$	75.7	75.7	75.7	75.7	75.7	75.7	75.7	75.7
Band level re SPL_S Table 2	-19.4	-19.8	-13.0	-7.8	-6.3	-4.3	-7.2	
Atmospheric absorption Table 3	-	.0014	.072	.143	.305	.78	1.46	
Predicted levels DBA re $2 \cdot 10^{-5} \text{ N/m}^2$	66.3	65.89	62.69	68.76	69.09	70.62	67.04	73.9

Figure 2. Behavior of sound pressure levels (with A-weighting and atmospheric absorption) with increasing distance from single isolated cooling towers. For mechanical-draft towers for a 600 MW Power Plant, rated fan power = 3,625 hp; and an efficiency of conversion from rated fan power to acoustic power = 3 PPM. For natural-draft tower for a 600 MW Power Plant, data used is: one wet tower; cooling water flow rate = $23 \cdot 10^6$ gal per min; pumping head = 60 ft; tower base dia. = 400 ft; efficiency of conversion from cooling water potential energy into acoustic power = 0.47 PPM.

Figure 3. A-weighted noise spectra at S ft from the natural-draft tower for a 600 MW Power Plant.

2.2 Mechanical-Draft Wet Cooling Tower Noise Estimation

Dyer and Miller in Ref. (5) have suggested an efficiency of 3 PPM of the rated fan power for conversion into sound power, as a rough preliminary estimate for the noise generation from mechanical-draft wet cooling towers.

$$L_{\omega} \approx 105 + 10 \log (\text{hp}) \text{ DB re } 10^{-13} \text{ Watts} \quad (10)$$

where

L_{ω} = sound power level of the source,

hp = rated fan horse power.

At S ft from the tower rim, and assuming a free spherical spreading, the SPL according to Dyer and Miller will be:

$$\text{SPL}_S = L_{\omega} - 10 \log_{10} (4\pi S^2) \quad (11)$$

Eqs. (10) and (11) can be combined to give

$$\text{SPL}_S = 10 \log_{10} \left\{ \frac{10^{10.5} \text{ hp}}{4\pi S^2} \right\} \text{ DB re } 10^{-13} \text{ Watts} \quad (12)$$

We should comment on the assumption of free spherical spreading in Eq. (11). On the basis of this assumption, Dyer and Miller (Ref.(5)). developed Eq.(10) for the mechanical-tower noise estimation. The constant number appearing on the right hand side of Eq. (10) is, in fact, a consequence of the assumption of free spherical spreading. This constant number will assume a different value if uniform hemispherical propagation of sound is assumed. Accepting the validity of Eqs. (10) and (11) in the actual physical situation, for a hemispherical spreading Eq. (10) will become

$$L_{\omega} = 102 + 10 \log_{10} (\text{hp})$$

The fact that the efficiency of conversion from the rated fan power to acoustic power is about 3 PPM, as stated by Dyer and Miller, can also be

questioned in this context. Halving this efficiency to 1.5 PPM, and assuming hemispherical spreading would be mathematically equivalent to Eqs. (10) and (11). However, since Dyer and Miller have labeled the spreading of mechanical-draft tower noise as being spherical, we shall use the same term in this context in the present analysis.

We now proceed onwards from Eq. (12). It should be mentioned that in Eq. (7) we obtained directly the A-weighted sound level, while in Eq. (12) we have yet to apply the A-weighting reduction in order to get DBA's instead of simply DB's. Figure 4, from Ref. (6), is a presentation of the sensitivity of the A-weighted measuring instruments. The data from this figure will be used for the A-weighting reduction. To do so, we first break the SPL_S of Eq. (12) into its respective components for the various center frequencies in the spectrum. The rest of the procedure for the prediction of the A-weighted noise levels with atmospheric attenuation is the same as presented in Section 2.1 for natural-draft towers except that an additional reduction of levels will be required in this case to account for the A-weighting.

We now present an example which shows the noise level prediction scheme for the mechanical-draft towers.

Figure 4. The internationally standardized A-weighting curve for sound level meters.

Example 2.2:

Given a point 1,000 ft from a mechanical-draft tower for a 600 MW power station, the total rated fan horse power for such a tower is 3,625 from Ref. (7). With $S = 1,000$ ft and $hp = 3,625$, Eq. (12) gives

$$SPL_S (S = 1,000 \text{ ft}) = 69.6 \text{ DB re } 10^{-13} \text{ Watts.} \quad (13)$$

The next step is to break the SPL of the above equation to get the levels in the octave bands of mechanical-draft tower noise spectrum. This is done by using Table 6 prepared from Ref. (5).

Table 6

Mechanical-Draft Wet Cooling Tower Noise Spectrum

	<u>Average octave band levels relative to the overall level in DB re 10^{-13} Watts</u>							
Center frequency (KHz)	.05	.1	.2	.5	1	2	4	8
Level at tower rim	-5	-6	-8	-11	-15	-17.5	-21	-27

It is worth mentioning that after reducing the SPL_S by the values of Table 6 in a similar manner as we did for natural-draft towers, the resulting DB's for each center frequency would be relative to $2 \cdot 10^{-5} \text{ N/m}^2$. Sound levels for each frequency band obtained as such can then be reduced to the A-weighted levels by using Table 7 which has been prepared from Figure 4.

Table 7

Effect of A-Weighting

Center frequency (KHz)	.05	.1	.2	.5	1	2	4	8
DBA re average octave band levels	-30	-20	-10	-3	-	-	-1	-3

Atmospheric attenuation is applied next by using Table 3. For example, consider the center frequency of 500 HZ. The A-Weighted predicted sound level at S ft from the source, with atmospheric absorption, will be:

$$\text{SPL}_a \text{ (for a center frequency of 500 Hz)}$$

$$= \underset{\substack{\uparrow \\ \text{Eq. (12)}}}{\text{SPL}_S} - \underset{\substack{\uparrow \\ \text{Table 3}}}{.7 \times S/983} - \underset{\substack{\uparrow \\ \text{Table 6}}}{11} - \underset{\substack{\uparrow \\ \text{Table 7}}}{3} \quad (14)$$

Finally, for the whole spectrum, Table 8 shows results for S = 1,000 ft. Various stages involved in the prediction of the noise levels are presented.

The overall results for various S are plotted in Figure 2 along with those for natural-draft towers. Figure 5 is a presentation of mechanical-draft wet tower noise spectrum, corresponding to Figure 3 for natural-draft.

Figure 5. A-weighted noise spectra at S ft from the mechanical-draft tower for a 600 MW Power Plant.

Table 8

Prediction of A-Weighted SPL With Atmospheric Attenuation for Mechanical-DraftWet Towers for a 600 MW Power Plant(S = 1,000 Ft.; $SPL_S = 69.6 \text{ DB re } 10^{-13} \text{ Watts}$)

Center frequency (KHz)	.05	.1	.2	.5	1	2	4	8	DBA re $2 \cdot 10^{-5} \text{ N/m}^2$
$SPL_S \text{ DB re } 10^{-13}$ Watts	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	
Band level re $SPL_S \text{ Table 6}$	-5	-6	-8	-11	-15	-17.5	21	27	
A-weighting reduction Table 7	-30	-20	-10	-3	-	-	-1	-3	
Atmospheric absorption Table 3	-	-	-	-0.7	-1.4	-3.1	-7.8	-14.6	
Predicted levels DB re $2 \cdot 10^{-5} \text{ N/m}^2$	34.6	43.6	51.6	54.9	53.2	49.0	39.8	25.0	58.9

2.3 Discussion

Before proceeding on to the radiation of noise from energy center cooling towers, we should comment briefly on our predictions for single isolated towers. In Ref. (8) Capano has presented his experimentally measured sound pressure levels at varying distances from cooling tower sources. The mean values of Capano's measured envelope of data for a range of different mechanical- and natural-draft wet towers are plotted in dotted lines in Figure 2. Owing to the lack of data presented in Ref. (8) we are not in a position to interpret or generalize Capano's results. The dotted curves, however, give us some idea about what would be the overall behavior of sound pressure levels at increasing distances from the tower sources. When we compare our predicted curves (obtained as described in Sections 2.1 and 2.2 for a 600 MW power plant) with the measured (dotted) ones, we notice that for small distances from towers the overall shape of our curves is quite different from Capano's measured data. This becomes less significant for higher distances. The discrepancy arises mainly because of the assumptions involved in the mathematical analysis. These assumptions apply less accurately at small distances from tower rim. Our predicted results show that at small distances from tower rim the noise levels due to the mechanical-draft towers will be considerably higher than natural-draft tower noise levels. This implies that acoustic power generation from mechanical-draft towers will be much greater than the generation from their natural-draft counterparts. It will be interesting to note the difference stemming from acoustic power generation from the two types of cooling systems being considered. As noted in Section 2.1, the acoustic power generated from natural-draft towers for a 600 MW power plant would be 1.474 Watts. This power when substituted in Eq.(4) will lead to the A-Weighted sound levels. Acoustic power resulting in the unweighted SPL can be obtained by following the procedure opposite to that of the A-Weighting reduction scheme. This reduction scheme is illustrated in Section 2.2 for mechanical-draft towers. In this way, for natural-draft towers, the acoustic power leading to the unweighted sound levels was calculated to be 4.36 Watts. Correspondingly, for mechanical-draft towers, from Section 2.2 this power will be 8.1 Watts*.

* 3 PPM conversion of the rated fan horsepower of 3,625 for a 600 MW plant leads to an acoustic power of 8.1 Watts.

or about twice as great.

The above mentioned discrepancies between our estimates and Capano's measurements lead us to the point where we can suggest that there is a need for further investigation of both experimental and theoretical prediction procedure for noise levels, so that improved techniques could be devised for a better comprehension of the overall problem of noise radiation from cooling towers.

We note also from Figure 2 that noise levels of our natural-draft towers exhibit a shallower slope for distances up to 100 ft as compared to the mechanical-draft tower noise. This can be explained by considering both atmospheric absorption and the sensitivity of the A-weighted measuring instruments simultaneously.

Atmospheric absorption increases linearly with distance and is greater at higher frequencies (see Table 3). The A-weighted sensitivity, Figure 4, is greatest in the range of 1 to 2 KHz. Therefore the higher frequency noise due to the splashing of water of natural-draft wet towers is sensed more efficiently by an A-weighting device. But at large distances, beyond 1,000 ft, the atmospheric absorption becomes predominant, causing the SPL to fall more rapidly. In the case of mechanical-draft tower noise, the A-weighting has less effect owing to the presence of lower frequencies. The almost uniform slope is thus due to the spherical attenuation of the acoustic energy intensity.

The environmental impact of noise radiation from single towers can be studied by first devising, according to Ref. (9), a Community Noise Equivalent Level (CNEL). In our case, since the noise will be continuous (24 hrs a day), the CNEL correction to the predicted data will be zero. The same reference gives permissible levels for the following categories:

	<u>DBA</u>
A - ultra critical areas (24 hrs)	38
B - suburban residential (24 hrs)	43
C - urban residential (24 hrs)	48

Noise levels which do not exceed 45 DBA more than 30 min. per 24 hrs,

have been classified in Ref. (10) as acceptable. With this information available, we observe from Figure 2 that for single isolated towers* for a 600 MW power plant, a level of 45 DBA is reached at a distance of 2,500 ft from natural-draft and at a distance of 3,800 ft from mechanical-draft towers. These are therefore the safe distances from sources at which noise levels will not create any problem. It also appears that natural-draft systems will be much quieter.

*See Figures 1 and 2 for relevant physical parameters of towers.

Chapter 3

NOISE RADIATION ENERGY CENTER COOLING TOWERS

The noise problem from energy center cooling towers can be analyzed by the assumption of an energy center as an area of distributed acoustic power sources. This is done by averaging the total acoustic power over the whole area and then dividing the area into smaller elements. Each element, or strip, can be thought of as a separate noise-generation source. And then by adopting the same technique as for the single towers, we can find the total sound intensity reaching at some point of interest by integrating the intensities from each area element over the entire area of power park.

It has been suggested that an energy center of 48 GW capacity would occupy a site of some 75 sq. miles. We assume for simplicity that this site is circular, of radius C . We then consider that power stations are uniformly distributed over a smaller concentric circular area of radius r . Figure 6 presents the overall configuration, with the shaded area representing the energy center, acting as a uniform source of acoustic power. We are interested in the total sound pressure level at the point O located on the site boundary. The shaded area shown in Figure 7, drawn along an arc of radius S , is a presentation of an area element mentioned above. All the sources in this area element will thus be approximately equidistant from O , and may as well be considered as a single acoustic generation source of strength:

$$W_{ac} = 2S\theta \left(\frac{W_t}{\pi r^2} \right) dS \quad (15)$$

where W_t is the total acoustic power radiation from the power park of area πr^2 . The radius of the 75 sq. mile power park is

$$C = 25,800 \text{ ft.}$$

Figure 6. Overall configuration of the site containing 48,000 MW of power generation.

Figure 7. Geometrical configuration of site for the purpose of problem analysis.

and, for purposes of later integration, we record the geometrical relation

$$\theta = \tan^{-1} \frac{\sqrt{4C^2S^2 - (S^2 - r^2 - C^2)^2}}{S^2 - r^2 + C^2} \quad (16)$$

3.1 Natural-Draft Wet Towers

The acoustic power resulting in the A-weighted SPL, for one wet tower of Figure 1, was found in Section 2.1 to be 1.474 Watts. For 48 GW, it will be 80 times as great, or $W_t = 117.92$ Watts. It was shown in Section 2.1 that for $S \gg R$, Eq. (4), derived on the basis of uniform hemispherical spreading, reduces to:

$$P_A^2 = \frac{W_{ac} Z_o}{4\pi S^2} \quad (17)$$

where Z_o , as stated earlier, is the atmospheric impedance. It will be seen later in this section that distances S involved in the analysis will be great as compared to R . Therefore, more conveniently, we shall use Eq. (5) instead of Eq. (4) for the present power park case.

For any area element of Figure 7, Eqs. (15) and (5) give

$$P_A^2 = \frac{117.92 Z_o \theta(dS)}{2\pi r^2 S} \quad (18)$$

where r and S are in meters, and θ is given by Eq. (16).

The A-weighted SPL at a distance S from any element area source is then found by using Eq. (18) in Eq. (3):

$$SPL_S = 10 \log_{10} \left\{ \frac{58.96 Z_o \theta(dS)}{\pi^2 r^2 S (2 \cdot 10^{-5})^2} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (19)$$

Note that Eq. (19) is analogous to Eq. (7) developed for single isolated towers. Following the steps of Section 2.1 for a center frequency of,

for example, 8,000 Hz, Eq. (19) and Tables 1 and 3 yield the following equation for the A-weighted SPL with atmospheric attenuation:

$$SPL_a = 10 \log_{10} \left\{ \frac{58.96 Z_o \theta(dS)}{\pi^2 r^2 S (2 \cdot 10^{-5})^2} \right\} - 7.2 - \frac{S \times 14.4}{300} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (20)$$

Writing Eq.(20) in a different form:

$$SPL_a \text{ (for 8 KHz)} = 10 \log_{10} \left\{ \frac{58.96 Z_o \theta(dS)}{\pi^2 r^2 S 10^{[(14.4S/3000)+.72]} (2 \cdot 10^{-5})^2} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (21)$$

From Eqs.(7) and (21), the intensity of sound for a center frequency of 8 KHz reaching the point 0, at a distance S m. from the area strip of Figure 7, will be:

$$I = \frac{P_A^2}{Z_o} = \frac{58.96 \theta(dS)}{\pi^2 r^2 S 10^{[(14.4S/3000)+.72]}} \text{ Watts} \quad (22)$$

For any r, and C being constant (= 25,800 ft), Eq. (22) can be integrated over the area πr^2 to give the total sound intensity at the point 0 for 8 Khz.

$$\text{Total } \frac{P_A^2}{Z_o} \text{ for 8 KHz} = \frac{58.96}{\pi^2 r^2} \int_{C-r}^{C+r} \frac{10^{-[(14.4S/3000)+.72]} \theta dS}{S} \quad (23)$$

In this way intensities for all center frequencies in the spectrum can be found and the total sound level can then be computed by summing all such sound intensities as given by Eq. (23):

$$\text{Total } \frac{P_A^2}{Z_o} \text{ for the whole spectrum} =$$

$$\begin{aligned}
& \frac{58.96}{\pi^2 r^2} \int_{C-r}^{C+r} \left\{ 10^{-1.94} + 10^{-[(.014S/3000)+1.98]} + 10^{-[(.7S/3000)+1.3]} \right. \\
& + 10^{-[(1.4S/3000)+.78]} + 10^{-[(3S/3000)+.63]} + 10^{-[(7.7S/3000)+.43]} \\
& \left. + 10^{-[(14.4S/3000)+.72]} \right\} \left(\frac{\theta}{S} \right) dS \quad (24)
\end{aligned}$$

Net DBA's reaching at the point 0 for the some value of r are then calculated by using Eqs. (7) and (24):

$$\text{SPL}_a = 10 \log_{10} \left\{ \frac{P_A^2 \text{ (from eq. (3.8))}}{(2 \cdot 10^{-5})^2} \right\} \text{DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (25)$$

The integral of Eq. (24) was evaluated by the help of the computer by taking $dS \approx 45$ ft. The results are plotted in Figure 8 for r ranging from 6,000 ft to 25,000 ft.

Figure 8. Variation of sound pressure levels at the site boundary with Radius of Power Park.

3.2 Mechanical-Draft Wet Towers

Using a 3 PPM efficiency of rated fan power for conversion into acoustic power (see Section 2.2), the total acoustic power generation from the area of the 48 GW energy center will be 80 times of that from a 600 MW power plant. The SPL at a distance S from any element area source, for an assumed uniform spherical spreading, can be found from Eq. (12):

$$SPL_S = 10 \log_{10} \left\{ \frac{10^{10.5} (dhp)}{4\pi S^2} \right\} \text{ DB re } 10^{-13} \text{ Watts} \quad (26)$$

where S is in feet, and dhp is the rated fan horsepower existing within the area element being considered. Also,

$$dhp = \frac{3625 \times 80}{\pi r^2} 2S\theta (dS) \quad (27)$$

where units of r and S should be the same. The rest of the procedure for the prediction of SPL at 0 is the same as presented in Section 3.1. In this case, however, an additional A-weighting reduction is required in each frequency band. The data to be used is presented in Section 2.2. The results for r ranging from 6,000 ft to 25,000 ft, are plotted in Figure 8 along with those for natural-draft towers for comparison.

3.3 Discussion

Figure 8 shows that mechanical-draft tower noise is nearly constant over the range of r considered. While natural-draft tower noise has initially a shallow slope with r, it increases more rapidly with greater r than does the mechanical-draft tower noise. Considering the natural-draft towers first, we notice that noise level at the site boundary increases significantly beyond an r of about 10,000 ft, or as the shortest distance from the periphery of the area source to the point 0 decreases. This happens because at large radii, (C-r) is small, and sound energies emanating from the far side of the park are relatively ineffective; thus the major effect is due to the nearer area elements.

But as r is decreased, $(C-r)$ increases and the effect of dispersed sources becomes insignificant and the area source behaves more like a point source. This results in an almost constant noise level of about 35 DBA for r less than 8,000 ft.

For mechanical-draft tower systems the atmospheric absorption is negligible, A-weighting rejects about 16 DB's and is the major reason why actual sound levels are considerably lower than the unweighted, unattenuated levels (Figure 6). The impact of scattered sources, as is the case of natural-draft towers, becomes insignificant at smaller r , resulting in about a constant SPL of 43 DBA.

Finally, we should indicate briefly the possible range of park radii for which sound levels at the site boundary (Figure 6) would not exceed 45 DBA^{*}. For mechanical-draft tower systems this level will be reached at a park radius of 17,500 ft. This radius will be about 24,500 ft for natural-draft towers.

* See Section 2.3.

Chapter 4

COOLING TOWER NOISE WITHIN THE ENERGY CENTER

In the two previous chapters we analyzed the noise radiation from a single isolated tower, and that from an energy center as measured at a point beyond its boundary. Thus no attention was paid to the SPL existing within the energy center shown shaded in Figure 6. If, however, the restriction of the site boundary is removed and the towers are more widely dispersed, then it will be interesting to know the noise levels within the area over which the towers are spread. We shall, therefore, now investigate the generation of noise from the cooling towers of a dispersed array of 600 MW power stations. Whereas in Chapter 3 the listener was outside the concentrated power plant system, in this chapter the listener is placed among and surrounded by power plants, which themselves are much farther apart, or dispersed, than in the previous case. In this analysis we shall consider that the array of towers may extend indefinitely around a point where we shall be interested in finding the total noise impact. Each of the towers considered will be a typical tower for a 600 MW station described in Chapter 2.

4.1 Geometrical Configuration of Array of Towers

In this section we shall present the analysis when the location of the dispersed towers has been approximated by the mesh points of a square grid. Considerable emphasis has been placed upon the grid size (degree of dispersion), the area over which the towers are spread, and their effect on noise levels at the observing point.

The mesh points of the square grid mentioned above are shown in Figure 9. Point 0 is located at the center of the innermost square and will be our point of interest where we would like to know the SPL due to the surrounding towers. It should be noted that the cooling tower array may extend indefinitely on all sides of the point 0. For the

Figure 9. Grid points for a square mesh work, representing the location of the array of dispersed towers as the sources of noise generation. The dimension l is the distance between the center points of towers as shown.

geometrical analysis we designate each of the grid points as (i,j) , where i is the number assigned to each square with the point 0 on its center. The innermost square being $i=1$. The next bigger $i=2$, and so on (note that in Figure 9 only the squares $i=1$ and 2 are shown). j is the number given to the grid points located on the i -th square. For the top left corner grid point we will have $j=1$, and then j increases as we move along the grid points on the i -th square in the clockwise direction. In fact, due to symmetry, we would be interested only in the first i number of grid points for the i -th square (Figure 10).

The distance $S(i,j)$ from the rim of a natural-draft tower located at the point (i,j) to the point 0 will be given by the following formula:

$$S(i,j) = \frac{l(i - 0.5)}{\cos[\theta(i,j)]} - R \quad (28)$$

where $\theta(i,j) = (i - j + 0.5)/(i - 0.5)$

Now we shall assume that a mechanical-draft tower will be spread over the same ground area if substituted for a natural-draft tower, and hence $S(i,j)$

Figure 10. Geometrical configuration of the extending array of towers. For this figure the value of n will be 3.

for mechanical-draft towers will also be given by Eq. (28).

4.2 Estimation of Noise Levels at the Point 0

We shall consider the dispersed array of natural- and mechanical-draft towers separately and then present the results together in a graphical form. Noise levels at the point 0 will be calculated for the following conditions:

- 1) Increasing n, i.e. $n = 1, 2, 3, \dots$, while keeping l fixed.
- 2) Increasing l and repeating the procedure with increasing values of n.

Natural-Draft Tower Array: Corresponding to Eq. (4), here we shall use the following equation for the A-weighted root mean square sound pressure emitted by a natural-draft tower located at the grid point (i,j) of Figure 10:

$$P_A^2(i,j) = \frac{W_{ac} Z_o}{\pi^2 (S^2(i,j) + 2S(i,j)R)} \tan^{-1} \sqrt{\frac{S(i,j) + 2R}{S(i,j)}} \quad (29)$$

where $S(i,j)$ for the point (i,j) is obtained from Eq. (28). We also know by the definition of SPL that:

$$\text{SPL}(i,j) = 10 \log_{10} \left\{ \frac{P_A^2(i,j)}{(2 \cdot 10^{-5})^2} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (30)$$

In order to apply atmospheric attenuation to a particular $\text{SPL}(i,j)$ given by Eq. (30), we must first find the SPL's for the individual center frequencies in the noise spectrum. And then following the procedure described in Section 2.1 we can compute the DBA's with atmospheric attenuation at the point 0 due to the tower at (i,j) . Finally, the noise level at the point 0 due to the array as a whole can be found as follows:

$$\text{SPL}(0) = 10 \log_{10} \left\{ 4 \sum_{i=1}^n \sum_{j=1}^{2i-1} \left[10 \cdot 1 \text{ SPL}_a(i,j) \right] \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (31)$$

The term within the brackets of eq. (31) is simply a sum of the sound intensities, due to $4 \sum_{i=1}^n (2i - 1)$ towers constituting the array of towers under study, divided by the reference sound pressure of $2 \cdot 10^{-5} \text{ N/m}^2$. The subscript a, refers to the atmospheric attenuation as stated earlier in Example 2.1.

Eq. (31) was evaluated by the help of the computer. For each ℓ , n was taken up to 20 although the impact of n higher than about 7 is relatively insignificant in terms of $\text{SPL}(0)$. The results are presented in Figure 11 for ℓ ranging from 600 to 15,000 ft. Figure 12 shows theoretically predicted SPL at the point 0 for the two types of dispersed tower sources with increasing ℓ .

Mechanical-Draft Tower Array: Corresponding to Eqs. (10) and (11) of Section 2.2, we shall have the following equations for a mechanical-draft tower located at the grid point (i,j) of Figure 10:

$$I_w(i,j) = 105 + 10 \log_{10} (\text{hp}) \text{ DB re } 10^{-13} \text{ Watts} \quad (32)$$

$$\text{SPL}(i,j) = I_w(i,j) - 10 \log_{10} [4\pi S^2(i,j)] \text{ DB re } 10^{-13} \text{ Watts} \quad (33)$$

Figure 11. Sound levels at the point O (Figure 10) due to a dispersed array of natural- and mechanical-draft tower sources. A description of a typical tower for a 600 MW electric generating station is presented in Sections 2.1 and 2.2.

Figure 12. Change of noise levels at the point O with l for the configuration of the dispersed tower sources of Figure 10, $n = 15$.

Knowing $SPL(i,j)$ from Eq. (33) we can calculate $SPL_a(i,j)$ by the method illustrated in Example 2.2. Eq. (31) can then be used for the prediction of $SPL(0)$. The results are presented in Figures 11 and 12 along with those for natural-draft towers for comparison.

4.3 Noise Level Contour

The next step in this chapter will be to find the distribution of SPL 's within the area of the mesh of grid points. It should be noted that if the point 0 is displaced from its central position then the problem no longer remains symmetrical and extra computation is required to find $S(i,j)$. To make the problem simpler we consider only the innermost square (i.e., $i=1$), and calculate the net SPL at various sub-grid points within this square, Figure 14. Then applying a correction for the SPL at each sub-grid point, we can account for the situation if the mesh were indefinitely extended. We can easily deduce an estimate of such a correction by observing Figure 11, which shows that as n increases from $n = 1$, there is only a small difference of noise levels, and that the levels become sufficiently constant beyond $n = 13$. Thus by keeping $n = 1$, noise levels at any point within this square can be calculated by hand methods and the small increase of levels, as depicted by Figure 11, can then be added to our results for each sub-grid point to account for large n . We are assuming, of course, that these corrections will be the same throughout the area under consideration, for a particular ℓ . These corrections, which we shall call Δ , were computed numerically and are presented in graphical form in Figure 13. We do not intend to present an analytical expression for Δ because the algebra involved becomes very tedious. Section 4.4 and the Appendix explain the behavior of Δ with the degree of dispersion of towers.

It should be emphasized that in the construction of Figure 13, the atmospheric absorption effect of that part of the noise spectrum lying below 200 Hz was also taken into account. This additional atmospheric absorption at very low frequencies, however, will have a negligible effect on the curves of Figure 13 for ℓ below of about 30,000 ft.

Figure 13. The value of Δ with increasing l , n being fixed at 15. The configuration is that of Figure 10 for the dispersed array of natural- and mechanical-draft towers acting as sources of acoustic power.

Figure 14. Location of the sub-grid points.

Example 4.3:

Consider, as an example, the dispersed array of natural-draft towers, each tower being that of Figure 1. We shall attempt to compute the noise level contour for the case when $\ell = 4,000$ ft. The correction to be applied at each of the sub-grid points will be 1.5 DBA from Figure 13. Due to symmetry only 8 sub-grid points shown in Figure 14 need be considered. Figure 15 presents the noise levels at the points 1 thru 8, due to each of the towers A, B, C and D if considered separately. The overall sound levels, including the correction of +1.5 DBA, are stated within the parenthesis for each of the eight sub-grid points. Finally, a sketch of the SPL contour, extrapolated from the data presented in Figure 15, is shown in Figure 16.

4.4 Simplified Geometrical Approximation for the Dispersed Array of Towers

We shall now make another approximation for the location of the randomly spread towers, and consider a simpler geometry, where the towers will be located on the circumference of concentric circles of radii which are integer multiples of some number (Figure 17). This approximation, being simpler, helps to explain the variation of Δ with system dimensions, as compared to the square grid approximation of Section 4.1.

Consider that the towers are located on the circumference of concentric circles of radii i times some value, say L , where $i = 1, 2, \dots, n$. Consider also that on the circumference of the circle of radius $L \times i$, we place $4(2i - 1)$ towers. It should be noted that under the present circumstances we are simply replacing the i -th square of Figure 10 with i -th circle, having on its circumference the same number of towers as on the i -th square of the previous geometry. We would now be interested in finding the increase of sound levels at the center O' , Figure 17, when n is increased from 1 to some higher number. It is worth mentioning at this point that having introduced the circles instead of squares we have considerably simplified the geometry of the configuration because now all the towers on the i -th square will be equidistant from the central point O' .

Figure 15. Noise level contour computation scheme. The numbers in parenthesis include the correction of +1.5 DBA for $\ell = 4,000 \text{ ft}$, $n = 15$.

Figure 16. Theoretically predicted noise level contours associated with a dispersed array of natural-draft towers. A schematic of a typical tower for a 600 MW power station is shown in Figure 1. For the geometry of the distribution of tower sources see Figures 9 and 10, $n = 15$.

Figure 17. Alternative geometrical configuration for the dispersed array of towers. Note that the total number of towers located on the i th circle will be $4(2i - 1)$. $L \times i$ is the shortest distance from the observing point O' to the rim of the tower associated with the i th circle.

Natural-Draft Tower Array: Considering natural-draft towers first, we recall Eq. (30) which for single towers can be written as:

$$SPL_S = 10 \log_{10} \left\{ \frac{P_A^2}{(2 \cdot 10^{-5})^2} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (34)$$

and similarly SPL in each frequency band can be found by the following equation:

$$SPL_p = 10 \log_{10} \left\{ \frac{P_A^2}{(2 \cdot 10^{-5})^2} \right\} - A_p \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (35)$$

where SPL_p is the SPL in the p -th frequency band, and A_p 's are the relative reduction of levels for each band.

Taking atmospheric attenuation into account, Eq. (35) can be further modified as:

$$SPL_p = 10 \log_{10} \left\{ \frac{P_A^2}{(2 \cdot 10^{-5})^2} \right\} - A_p - \frac{L}{300} T_p \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (36)$$

where L is in meters and T_p is the atmospheric absorption in DB re $2 \cdot 10^{-5}$ N/m²/300 m in the p -th frequency band. A_p and T_p are stated in Table 9. We can now write Eq. (36) in the following form:

$$SPL_p = 10 \log_{10} \left\{ \frac{P_A^2}{(2 \cdot 10^{-5})^2 10^{.1 A_p} b T_p^L} \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (37)$$

where $b = \text{constant} = 1/3,000$.

Table 9

Spectrum, Atmospheric Attenuation, and A-Weighting Data

A_p = Spectral reduction in DB

T_p = Atmospheric absorption in DB/984 ft

W_p = A-weighting reduction in DB

Natural-Draft Towers

Band Number	A_p	T_p
p	A_p	T_p
1	19.4	.0049
2	19.8	.014
3	13.0	.7
4	7.8	1.4
5	6.3	3.0
6	4.3	7.7
7	7.2	14.4

Mechanical-Draft Towers

Band Number	$A_p' = A_p + W_p$		
p	A_p	W_p	T_p
1	5	30	.000793
2	6	20	.00317
3	8	10	.01
4	11	3	.7
5	15	--	1.4
6	17.5	--	3.0
7	21	1	7.7
8	27	3	14.4

It should be mentioned that although we used the values of A_p and T_p in Chapters 2 and 3, we did not introduce these symbols (i.e. A_p , T_p , etc.). In this chapter, however, we shall frequently refer to these symbols instead of their numerical values to simplify the mathematical expressions.

We can now recover the total SPL which actually reaches a point located at a distance L from the source by using Eq. (37).

$$SPL_L = 10 \log_{10} \left\{ \sum_{p=1}^k \left[\frac{P_A^2}{(2 \cdot 10^{-5})^2 10^{.1A_{p10}} 10^{bT_p L}} \right] \right\} \text{DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (38)$$

Since we are considering 7 frequency bands for natural-draft tower noise, k will be 7 for such towers.

We can now use Eq. (38) for the array of towers presently under consideration, and because $4(2i - 1)$ towers are located on the i-th circle of radius $L \times i$, the SPL at the central point 0' due to the array on the i-th circle will be:

$$SPL(i) = 10 \log_{10} \left\{ \sum_{p=1}^k \left[\frac{4(2i - 1) P_A^2}{(2 \cdot 10^{-5})^2 10^{.1A_{p10}} 10^{bT_p iL}} \right] \right\} \quad (39)$$

The A-weighted root mean square sound pressure, P_A , in Eq. (39) is given by Eq. (29), which, for L large compared to R, reduces to the following equation for a natural-draft tower located on the i-th circle of Figure 17:

$$P_A^2 = \frac{W_{ac} Z_o}{\pi i^2 L^2} \left(\frac{\pi}{4} \right) \quad (40)$$

Eqs. (39) and (40) can be combined to give

$$SPL(i) = 10 \log_{10} \left\{ \sum_{p=1}^k \left[\frac{(2i - 1) W_{ac} Z_o}{\pi i^2 L^2 (2 \cdot 10^{-5})^2 10^{.1A_{p10}} 10^{bT_p iL}} \right] \right\}$$

or

$$SPL(i) = 10 \log_{10} \left\{ \sum_{p=1}^k \left[\frac{B(2i - 1)}{i^2 L^2 10^{.1A_{p10}} 10^{bT_p iL}} \right] \right\} \quad (41)$$

where

$$B = \text{constant} = \frac{W_{ac} Z_o}{\pi (2 \cdot 10^{-5})^2}$$

For n circles, i.e. $i = 1, 2, \dots, n$, the total SPL at $0'$, $SPL(0')$, can be easily computed by the help of Eq. (41):

$$SPL(0') = 10 \log_{10} \left\{ \sum_{i=1}^n \left[\sum_{p=1}^k \left(\frac{B(2i-1)}{i^2 L^2 10^{.1A_p - bT_p iL}} \right) \right] \right\} \text{DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (42)$$

The difference Δ , of the SPL experienced at $0'$ when $n = 1$ and when $n = n$ will be

$$\begin{aligned} \Delta &= 10 \log_{10} \left\{ \sum_{i=1}^n \left[\sum_{p=1}^k \left(\frac{B(2i-1)}{i^2 L^2 10^{.1A_p - bT_p iL}} \right) \right] \right\} \\ &- 10 \log_{10} \left\{ \sum_{p=1}^k \left(\frac{B}{L^2 10^{.1A_p - bT_p L}} \right) \right\} \\ \text{or} \quad \Delta &= 10 \log_{10} \left\{ 1 + \frac{\sum_{i=2}^n \frac{2i-1}{i^2} \sum_{p=1}^k \frac{1}{10^{.1A_p - bT_p iL}}}{\sum_{p=1}^k \frac{1}{10^{.1A_p - bT_p L}}} \right\} \end{aligned} \quad (43)$$

Identifying the second term in brackets as Π ,

$$\Pi \equiv \frac{\sum_{i=2}^n \frac{2i-1}{i^2} \sum_{p=1}^k 10^{-0.1A_p - bT_p iL}}{\sum_{p=1}^k 10^{-0.1A_p - bT_p L}} \quad (44)$$

It is obvious that

$$\Pi = \Pi(n, L)$$

since A_p and T_p are constants. We may note that if $n = 1$, then $\Pi = 0$ and Eq. (43) gives $\Delta = 0$.

Eq. (43) is perhaps the most comprehensive form for Δ without making drastic simplifications. We shall therefore stop at this point in this section. However, a further "discussion of the form of Δ " is given in the Appendix.

Mechanical-Draft Tower Array: For mechanical-draft towers we first combine Eqs. (32) and (33) to get

$$SPL_S = 10 \log_{10} \left\{ \frac{10^{10.5} h_p}{4\pi L^2} \right\} \text{ DB re } 10^{-13} \text{ Watts} \quad (45)$$

where L is in feet. Corresponding to Eq.(35) for natural-draft towers, we shall have the following equation for mechanical-draft systems:

$$SPL_p = 10 \log_{10} \left\{ \frac{10^{10.5} h_p}{4\pi L^2} \right\} - A_p' - \frac{LT_p}{984} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (46)$$

where $A_p' = A_p + W_p$; W_p being the additional DB reduction required for the A-weighting. A_p and W_p are given on Table 8. Proceeding onwards from Eq.(46), one obtains, finally;

$$SPL(0') = 10 \log_{10} \left\{ \sum_{i=1}^n \left[\sum_{p=1}^k \left(\frac{B'(2i-1)}{i^2 L^2 10^{.1A_p'} 10^{bT_p i L}} \right) \right] \right\} \text{ DBA re } 2 \cdot 10^{-5} \text{ N/m}^2 \quad (47)$$

where

$$B' = \frac{10^{10.5} h_p}{\pi},$$

and $K = 8$ for mechanical-draft towers, and since the units of L are in feet, the constant b will be 1/9,840. The expressions for Δ and Π will be the same as Eqs.(43) and (44), respectively, except that A_p is to be replaced by A_p' .

Finally, for this geometrical configuration, Figures 18, 19, and 20 are presented for comparison with Figures 11, 12 and 13 for the geometry of Section 4.1.

We now show an example in which we compare the predicted sound levels for the geometrical approximation for the location of the towers of Figures 9 and 17.

Figure 18. Sound levels at the point 0' (Figure 17) due to a dispersed array of natural- and mechanical-draft towers.

Figure 19. Change of noise levels at the point 0' with L for the configuration of the dispersed tower sources of Figure 17, $n = 15$.

Figure 20. The quantity Δ obtained from Eq. 43 is plotted against L for the configuration of Figure 17. The value of n is 15.

Example 4.4:

Suppose we are given the actual physical situation of Figure 9. Keeping the location of the nearest four towers from the point 0 fixed, the corresponding L , using the simplified analysis of this section, will be

$$L = \frac{\ell}{2 \cos 45}.$$

For example if $\ell = 1,000$ ft, L will be 707 ft. From Figure 12 for an ℓ of 1,000 ft, we will predict 70 DBA for natural and 73.7 DBA for mechanical-draft towers. From Figure 19 for an L of 707 ft, the corresponding numbers are 69.5 and 73.6 respectively. For $\ell = 10,000$ ft, L will be 7,070 ft, and we read the following data from Figures 12 and 19:

Table 10
Comparison of the Predicted Results by Using the Dispersed Tower Array
Approximations of Figures 9 and 17

Type of Towers	$\ell = 10,000$ ft (Figure 12)	$L = \ell/2 \cos 45 = 7,070$ ft (Figure 19)
Mechanical	47.3 DBA	48.7 DBA
Natural	40.0 DBA	37.8 DBA

For most purposes, it seems that one may use either of the two geometrical descriptions (Figure 9 or 17) for a homogeneous array.

Chapter 5

COMPARISON OF COOLING TOWER NOISE

Consider first the noise levels within the area of the energy center, given a total capacity of 48 GW, and with 80 cooling towers. These towers can be assumed to be uniformly distributed over the area of the energy center illustrated in Figure 6, and their locations can be approximated by the geometry of Figure 10. It should be noted that a total of 80 grid points, each of which will represent the location of one tower around the point 0 in Figure 10, cannot be obtained by taking either n equal to 4 or 5. The computation of the noise levels at the point 0 has therefore to be done by averaging the results for $n = 4$ and $n = 5$.

The overall picture of the location of the towers will be as shown in Figure 21. It should be recalled that the maximum radii r for which noise levels at any point on the site boundary will not exceed 45 DBA or $2 \cdot 10^{-5} \text{ N/m}^2$, were predicted to be 17,500 and 24,500 ft for mechanical- and natural-draft towers respectively. It can be estimated from the geometry of Figure 21 that a radius r of 17,500 ft corresponds to an ℓ of 3,500 ft for mechanical-draft towers. For natural-draft towers, for an r of 24,500 ft the value of ℓ will be 4,900 ft. We now look at Figure 22* which shows the variation of noise levels at the point 0 (Figure 21) with ℓ . By the help of this figure and Figure 11, we can easily predict the minimum noise levels which can be expected within the area of the power park. For an ℓ of 3,500 ft for mechanical-draft towers, this minimum level will be 57 DBA. This number will be 48.3 for natural-draft towers for an ℓ of 4,900 ft.

We shall now illustrate an example for finding the noise levels at the site boundary, and the minimum noise levels within the area of the energy center, given the value of r .

*The data for this figure was obtained by taking the average of the results with $n = 4$ and $n = 5$.

Figure 21. Location of towers within the power park. For a site area of 75 square miles the value of C will be 25,800 ft.

Figure 22. Change of noise levels at the point O of Figure 21 with l . This data has been averaged for $n = 4$ and $n = 5$.

Example 5.1:

Let $r = 15,000$ ft and $\ell \approx r/5 = 3,000$ ft. From Figure 22 we read the following data presented in Table 11 for $\ell = 3,000$ ft.

Table 11

Prediction of SPL at the Center of the Energy Center

(Point 0 of Figure 21)

$\ell = 3,000$ ft, $r = 15,000$ ft, $n = 4.5$

<u>Type of Towers</u>	Noise Levels at 0 from Figure 21
	<u>DBA re $2 \cdot 10^{-5}$ N/m²</u>
Mechanical	60.0
Natural	55.3

From Figure 11, for $n = 4.5$ and $\ell = 3,000$ ft, the values of Δ will be approximately 2 DBA and 1.3 DBA for mechanical- and natural-draft towers respectively. The minimum noise levels within the area of the energy center can now be predicted as shown in Table 12.

Table 12

Prediction of Minimum Noise Levels in the Energy Center

$\ell = 3,000$ ft, $r = 15,000$ ft, $n = 4.5$

<u>Type of Towers</u>	Minimum Noise Levels
	<u>DBA re $2 \cdot 10^{-5}$ N/m²</u>
Mechanical	$\sim 60 - \Delta/2 = 59$
Natural	$\sim 55.3 - \Delta/2 = 54.7$

Next we can predict the noise levels at the site boundary from Figure 8.

Figure 23. Diagonal distance X from the rim of the tower. This distance for a fixed DBA is plotted against l in Figure 24.

Figure 24. Change of the diagonal distance X from the rim of the natural-draft tower (Figure 23) at which the noise levels of 40, 45 and 50 DBA will be reached, has been plotted against l .

Figure 25. Change of the diagonal distance X from the rim of the mechanical-draft tower (Figure 23), at which the noise levels of 40, 45 and 50 DBA will be reached, has been plotted against l .

Figure 26. Total area of the dispersed sites of eighty 600 MW power stations with natural-draft cooling towers. Noise levels will always be greater than 45 DBA within this area.

Figure 27. Total area of the dispersed sites of eighty 600 MW power stations with mechanical-draft cooling towers. Noise levels will always be greater than 45 DBA within this area.

Table 14

Estimation of Eighty Dispersed 600 MW Power Station Sites

Given l , SPL exceeding 45 DBA are unacceptable

Type of Towers	l (ft) <u>given</u>	X (ft) <u>Figure 24</u>	X + R (ft) <u> </u>	$\pi \left(\frac{X+R}{5280} \right)^2 \times 80$ <u>sq. miles</u>
Mechanical	14,000	4,670	4,870	214.1
	∞^*	3,800	4,000	144.24
Natural	14,000	2,600	2,800	70.68
	∞	2,500	2,700	65.72

* $l = \infty$ means that effects of all the other towers have to be neglected. The corresponding data for X has been recorded from Figure 2.

Table 13

Prediction of SPL at the Energy Center Site Boundary for a
Given r

<u>Type of Towers</u>	<u>Noise Levels at some Point on the Site Boundary (DBA re $2 \cdot 10^{-5}$ N/m²)</u>
Mechanical	44.0
Natural	36.5

Consider next the case of increasing dispersion. We are removing the restriction of the site boundary, and increasing r to such values that noise levels within the area over which the towers are spread, fall below 45 DBA and are hence acceptable. The distances X (Figure 23) from the rim of the towers at which noise levels will reach 40, 45 and 50 DBA, have been plotted against ℓ in Figure 24. It should be noted that as ℓ is increased, X decreases, and so does the area affected by noise. Considering that noise levels of below 45 DBA are generally acceptable, we can estimate the area of the site for each 600 MWe generating station. Figures 26 and 27, constructed for natural-and mechanical-draft towers respectively, show the total area in which the noise levels will exceed 45 DBA. This total area is, of course, associated with a power generation of 48 GW(e), and should be studied in comparison with the area of the power park site of 75 sq. miles. The estimation of the areas of Figure 26 has been presented in an example illustrated below:

Example 5.2:

Suppose $\ell = 14,000$ ft and ∞ . It should be recalled that a mechanical-draft tower was assumed to occupy the same ground area if substituted for a natural-draft tower. The radius R for a typical natural-draft tower for a 600 MW power station was stated in Section 2.1 to be 200 ft. We thus construct the following table:

It is worth noting from Figure 26 that for natural-draft towers an ℓ of 10,250 ft yields an area of 75 sq. miles over which noise levels will always exceed 45 DBA. This ℓ thus corresponds to the area of the alternative energy center site. Decreasing ℓ will increase the total area of the 80 sites quite rapidly, and will thus be undesirable. Increasing ℓ beyond 10,250 ft will certainly decrease this area but not dramatically.

On the other hand, for mechanical-draft towers, from Figure 27 we note that no matter how large we make the ℓ , the total affected area will always be above 150 sq. miles. Thus, this affected area will always be more than twice the site area of the alternative concentrated energy center.

Chapter 6

CONCLUSIONS

1. Stating the conclusions for the single isolated cooling towers for a 600 MW power station, in Chapter 2 we saw that mechanical-draft towers will be noisier than their natural-draft counterparts. For moderate distances from the tower we may generalize that the mechanical-draft systems will be about 4 DBA louder. The acoustic power generated from the mechanical-draft tower under consideration was shown in Chapter 2 to be twice of that from the natural-draft tower for a 600 MW station. Knowing that sound levels of below 45 DBA are generally acceptable, it will be interesting to note the distances from the tower rim at which this level is reached. These distances from Figure 2 will be 2,500 and 3,800 ft for natural- and mechanical-draft towers respectively. These will therefore be the safe distances from single isolated towers* at which noise levels are not likely to pose any problem.

2. For concentrated power centers we found in Chapter 3 that for some range of power park radius r , Figure 6, noise levels at the site boundary will not exceed 45 DBA, and hence will be acceptable. These energy center radii from Figure 8 are 17,500 and 24,000 ft for mechanical- and natural-draft tower systems respectively.

3. Last but not least, we compare the results for the concentrated energy center with the randomly dispersed array of electric generating stations. The basis of comparison is the area affected by a level of noise from the cooling towers exceeding 45 DBA. With natural-draft towers, in the limit of infinitely wide dispersion, the area impacted by noise levels of 45 DBA or higher is about the same as the corresponding concentrated energy center. In the case of mechanical-draft towers, in the limit of infinitely wide dispersion, this impacted area is about twice the corresponding park area of 75 square miles.

* See Figures 1 and 2 for relevant tower parameters.

Hence we conclude that if concentrated energy centers are chosen, and judged by noise at the boundary of 75 square mile sites, then either mechanical- or natural-draft towers may be used. In the case of natural-draft systems, however, a somewhat greater degree of dispersion within the 75 square mile site area will be possible. On the other hand, if more widely dispersed energy centers are desirable, then natural-draft systems should be chosen if one wishes to minimize the total area impacted by objectionable noise. Conversely, if mechanical-draft towers are to be employed, then concentrated energy centers would provide the least area impacted by unacceptable noise due to cooling systems.

APPENDIX

DISCUSSION OF THE FORM OF Δ

An important conclusion to be drawn from Figure 11 is that increasing n has but little effect on noise levels at the point 0. This effect, plotted in the form of Δ in Figure 13 attains its maximum at an ℓ of about 30,000 ft, beyond which it decreases uniformly, eventually approaching zero at very large ℓ . The curves for mechanical- and natural-draft towers are almost identical for ℓ greater than 30,000 ft. For smaller ℓ , however, the difference between the values of Δ for the two types of dispersed tower sources is worth noting and is obviously due to the difference in the respective noise spectra. In order to further comprehend the oscillating behavior of Δ with ℓ for the values below about 30,000 ft, we should now discuss Figure 20, which exhibits similar trends as Figure 13. As we look at the numerator of Eq. (44) we realize that for some band number p , i.e., for $p = 1$ thru k , the following quantity

$$10^{-0.1A_p - bT_p iL} \quad (48)$$

will become maximum for i and L fixed. Similarly, for this p , the following term will be minimum:

$$0.1 A_p + bT_p iL \quad (49)$$

But when we are summing Eq. (48) for $p = 1, 2, \dots, k$, i.e.

$$\sum_{p=1}^k 10^{-0.1A_p - bT_p iL} \quad (50)$$

The most important contribution to the magnitude of the summation will be the value of that term of the summation which is maximum out of a total of k terms. Now, when i and L are changed, (48) might attain its

maximum at another p , which will eventually affect the magnitude of the summation (50) as already explained. The fact that as i and L are increased the quantity (48) attains its maximum at a different p , characterizes what we might call a fluctuating behavior of Δ with either ℓ or L .

At large L , the first term of the quantity (49) will become relatively insignificant compared to the magnitude of the term $bT_p iL$, even for the smallest of T_p in the spectrum. Under such circumstances it can easily be shown that eq. (44) can be approximately represented as:

$$\Pi = \sum_{i=1}^n \frac{2i-1}{i^2} 10^{bT_p L} (1-i) \quad (51)$$

where T_p in Eq. (51) must be the minimum value of T_p for $p = 1, 2, \dots, k$. For example from Table 9, this value of T_p will be .0049 and .000793 for natural- and mechanical-draft towers respectively. From Eq. (51) the following result immediately follows:

$$\frac{d\Pi}{dL} \sim \sum_{i=1}^n \frac{2i-1}{i^2} bT_p (1-i) e^{bT_p L(1-i)} \quad (52)$$

The right hand term in Eq. (52) will always be ≤ 0 for all $i \geq 1$. It can also be shown from Eq. (51) that for very large L we have

$$\Pi \sim \frac{1}{L} \quad (53)$$

Hence Π , and consequently Δ , will uniformly approach zero for L tending to infinity.

We can summarize our discussion about the behavior of Δ by saying that as the degree of dispersion of towers is increased from lower values, Δ increases or decreases depending on how various frequencies in the noise spectrum are affected by attenuation due to the atmosphere and A-weighting. The value of Δ will reach its maximum for some degree of dispersion of the tower array. Beyond this maximum Δ will gradually approach the value

of zero mainly because of atmospheric absorption at lower frequencies.

It is also interesting to note from Figures 13 and 20 that mechanical-draft towers which are already known to be noisier when considered in the form of a dispersed array. This conclusion, of course, applies exclusively for values of l below about 30,000 ft for the square geometry, and an L of below 20,000 ft for the circular geometry. Beyond these ranges, however, the total affect of dispersed tower sources will be the same for the two types of cooling systems.

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