IMPACT OF ATMOSPHERIC LAPSE RATE ON POWER PLANT PERFORMANCE

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ABSTRACT

The impact of atmospheric lapse rate on the performance of large natural draft cooling towers is quantified experimentally and analytically. Results of simulations are presented for the impact of atmospheric lapse through cooling tower performance on generation for a specific power plant.

INTRODUCTION

The airflow in a natural draft cooling tower results from the difference in density of the air inside and outside of the chimney-like shell. The air inside the tower is buoyant relative to that outside due to evaporation and sensible heating of the air by the water flowing through the tower. In wet towers the buoyant effect of evaporation is greater than that due to sensible heating. This is because the molecular weight of water is 18; whereas the molecular weight of air is 29 (i.e., While in the vapor state, water is considerably lighter than air, other conditions being equal.).

Although the difference in density between the air inside and outside of the tower may be only 5 percent, a significant draft can be induced because of the large distance over which the buoyancy acts on the flow. The shells of large natural draft towers range from 120 to 175 meters tall. While the temperature, moisture content, and density of the air vary inside the tower as a result of its intended function of absorbing heat, the properties of the air outside of the tower also vary. The magnitude of the variation in density of the air outside is smaller than the variation inside the tower; but this too, accumulates over a large vertical distance. A difference of only 0.5 percent outside the tower when compared to 5 percent inside the tower has a relative magnitude of 10 percent.

While there are changes in the moisture content of air in the atmosphere, the focus here will be on the change in temperature and pressure. Atmospheric lapse rate is the change in temperature with elevation. Under normal conditions, the temperature drops roughly 9°C per 1000m, or a lapse rate of -0.009°C/m. If the lapse rate is more negative than this, it is considered favorable; whereas, if it is less negative, or even positive, it is considered adverse. A thermal inversion is said to occur if the lapse rate is positive. The density of the air outside the tower is effected by the temperature and the pressure. The pressure changes slightly due to the hydrostatic effect.

DEVELOPMENT

The variation of temperature and pressure for the "standard" atmosphere as defined by the NACA (1955) and adopted by the ASHRAE (1989) is given in Table 1.

Table 1. NACA Standard Atmosphere

Elevation meters	Temperature °C	Pressure atmospheres
-300	17.0	1.036
-200	16.3	1.024
-100	15.7	1.012
0	15.0	1.000
100	14.3	0.988
200	13.7	0.976
300	13.0	0.965
400	12.4	0.954
500	11.7	0.943
600	11.1	0.931
700	10.5	0.919
800	9.9	0.907
900	9.2	0.897

The lapse rate for this "standard" atmosphere over the first 150 meters above sea level is -0.0066°C/meter. The variation in pressure over this interval is -0.00012 atmospheres/meter. Atmospheres are used for pressure so that the relative magnitude of the variation will be readily apparent. The "standard" atmosphere is a reasonable average, but is not necessarily to be found at any given location. In order to compute the performance of a natural draft cooling tower, it is necessary to be able to compute the local variation in pressure under the existing conditions. The mathematics by which the ideal lapse rate is computed for a given location and conditions is given in the Appendix.

In order to compute the impact of performance on a specific natural draft cooling tower, it is necessary to employ a computer model. The FACTS (Fast Analysis Cooling Tower Simulator) code was used in the present analysis. FACTS is a two-dimensional finite-integral model which accounts for the geometry of the tower, fluid flow, and transfer processes. This computer model ha been validated with field data and presented elsewhere (Benton and Waldrop, 1988).

In order to compute the impact of tower performance and meteorology on the performance of a specific plant, it is necessary to employ another computer code. The MUPIT (Multi-Unit Power plant cooling system analyzer) was used in the present analysis. MUPIT is a quasi-steady model based on overall steam cycle performance curves, condenser performance curves, cooling tower performance curves, and the overall energy flow of the heat rejection system. Steam cycle performance curves are typically supplied by the turbine manufacturer and give the impact on heatrate or capacity as a function of turbine backpressure and heat input. Cooling tower performance curves were based on those supplied by the manufacturer and adjusted for the impact of lapse rate using the FACTS model. Condenser performance was computed based on the Heat Exchange Institute Standards (HEI, 1989). The MUPIT model has been validated with field data and the details presented elsewhere (Benton, 1992 and Miller et al., 1992).

RESULTS

Capability is a common measure of tower performance. Capability is the ratio of the measured water flow to the design or contract water flow which should result in the same inlet and exit water temperatures at the same ambient (typically ground level) dry- and wet-bulb temperatures. The capability is expressed as a percentage. A capability greater than 100 percent indicates a tower that performs better than expected; whereas a capability less than 100 percent indicates a tower that performs below expectation. Figure 1 shows the impact of atmospheric lapse rate on cooling tower performance, expressed as capability. The figure shows computer model results, field data, and a least-squares curve-fit of the field data. There is significant scatter in the data ($r^2=0.78$); however, the intersection with 100 percent capability for field and computer model are nearly coincident at -0.0095 and -0.0097° C/m, respectively. This coincidence confirms the preference of pressure over temperature in the "standard" atmosphere and the isentropic lapse rate over the "standard" atmosphere lapse rate as discussed in the Appendix.

While the National Weather Service (NWS) has maintained many sites (typically airports) and collected much atmospheric data which is available in computer format, they, unfortunately, do not measure lapse rate. The NWS does, however, infer thermal inversion conditions from soundings. These soundings are only qualitative and are not done on a hourly basis; thus NWS airport data must be supplemented. The Tennessee Valley Authority (TVA) does, however, maintain atmospheric data collection stations at its nuclear plant sites. Among other parameters, the TVA met stations record dry-bulb at 10-, 45-, and 91-meters above ground level on 15-minute intervals. The occurrence of adverse and favorable lapse rates at one particular TVA site, Bellefonte (BLN), for one particular year, 1988, is shown in Figure 2 as percent impact on cooling tower performance vs. day of the year. Because the relationship is essentially linear, lapse rate and impact on tower capability are merely different scales as indicated in the figure.

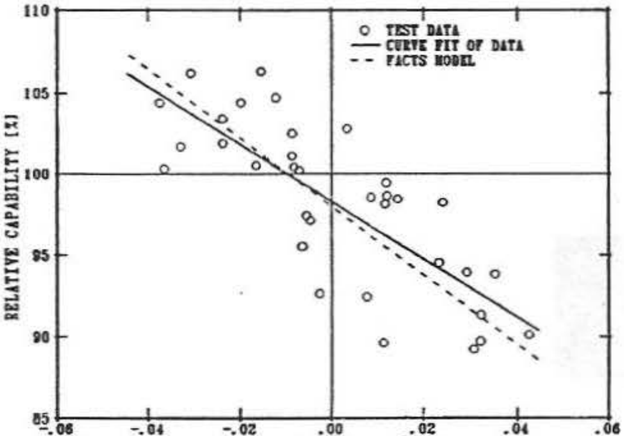

Figure 1. Impact of Lapse Rate on Tower Performance

This peppered-looking scatter plot shows 8784 hourly capability calculations based on measured lapse rate and computed tower performance. This figure reveals that the impact of lapse rate is greatest in the spring and fall and least at the typically hottest time of the year (late July and August). The average impact of adverse lapse rate on cooling tower performance for the period of available record was found to be -7 percent. The 95 percent confidence interval extends from +2 to -13 percent (i.e., this interval contains, on the average, 95 out of 100 occurrences). The extremes were found to be +4 and -19 percent impact. The figure also shows that impacts of -5 percent can be expected often, even in August.

The Bellefonte Nuclear Plant is located on the Tennessee River in northeast Alabama. Whether or not this site is typical as to atmospheric lapse rate with the Southeast is not known quantitatively. Comparison of sites around the U.S. is not possible using only available NWS data as these do not include vertical temperature profiles on the order of 100 meters which is needed to get the proper scale for the natural draft cooling towers.

BLN is a closed-cycle nuclear plant. Most of the condenser cooling water is recirculated through the cooling tower and back to the condenser. BLN uses large evaporative natural draft cooling towers. About 2.5 percent of the cooling water is evaporated during the cooling process. The evaporative cooling process, like distillation, leaves behind most of the impurities in the

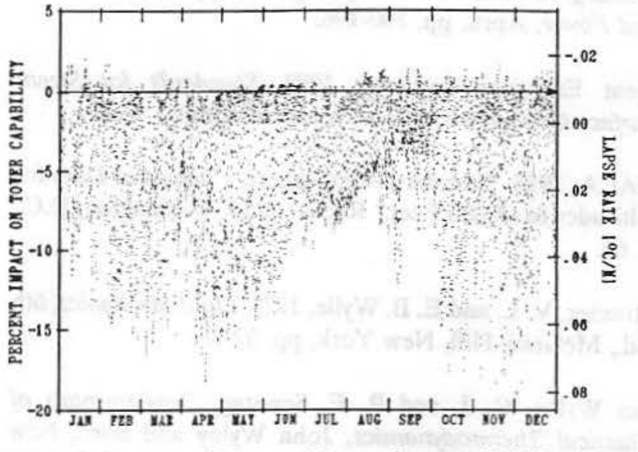

Figure 2. Impact of Thermal Inversions at BLN for 1988

water (e.g., carbonates and sulfates). These build up in the system as the evaporated water is replenished with water containing more impurities; thus, in addition to that which is evaporated, some water is discharged (about 2 percent) in order to control this concentrating effect. Because most of the water is recirculated and very little is supplied from the river, the cooling system operating temperature is essentially fixed by the cooling tower performance and the atmospheric conditions.

Nuclear power plants are designed and operated such that the thermal heat input from the reactor to the steam system is limited. This is in contrast to a coal-fired plant where more coal or higher heating value coal can be burned in order to increase output, even if this comes at the expense of optimum economy. The electrical power output of a nuclear plant operating at full reactor power level will thus vary directly with the thermal efficiency of the steam system which is directly dependent on the temperature of the condenser cooling water. The temperature of the condenser cooling water for a closed-cycle plant is directly dependent on the cooling tower performance; thus, the electrical power output of this type plant is ultimately dependent on the cooling tower performance and atmospheric conditions.

The electrical power output of such a plant is not a linear function of any one variable. Figure 3 shows the generator output as a function of thermal heat input from the reactor and condenser cooling water inlet temperature. This figure is based on reactor, steam system, and condenser design and is specific to BLN, though not unique in a qualitative sense. It is typical for such plants to exhibit an optimum performance point at about 15° C and fall off more rapidly with increasing than decreasing condenser cooling water temperature.

Lapse rate impacts generation for a power plant which depends on natural draft cooling towers for heat removal. On the average, a decrease in tower performance of 10 percent for this plant configuration translates into

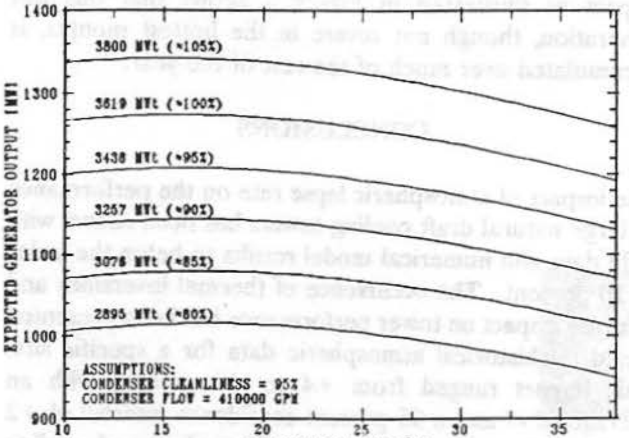

Figure 3. Generator Output for BLN vs. CCW Inlet Temperature

approximately 1° C hotter condenser cooling water and a reduction in capacity (MW) of 0.5 to 5.0 percent (The impact of tower performance on plant capacity is not a linear relationship.). Because adverse lapse rates occur at various times of the year, the impact on tower performance cannot be directly converted into an impact on generation. The impact on generation depends on the frequency, duration, and time of occurrence. Thus, quantifying the impact on generation requires historical simulations in order to capture the variability of atmospheric parameters. The impact of atmospheric conditions on generation for BLN can be calculated by using the computer code, MUPIT, which produced the curves shown in Figure 3, along with the cooling tower model, FACTS, which produced the dashed line in Figure 1, and the historical weather data.

This historical simulation for BLN over the period of available record consisted of hourly data for 32 years (280,512 operating points). Complete details of this simulation, which included the variation of a number of parameters besides atmospheric lapse rate, are given in Benton (1992). Comparing Figures 2 and 3 reveals that the strongest thermal inversions (i.e., largest negative impact on cooling tower performance) occur in the spring and fall when the condenser cooling water temperatures are in the vicinity of the optimum point (i.e., the flat part of the curves in Figure 3). The steep part of the curves in Figure 3 (i.e., where the impact on generation is greatest) corresponds to the summer conditions in Figure 2, where the strong thermal inversions are not seen. This rather fortuitous situation, tends to diminish, but not eliminate the impact of thermal inversions (at least for this particular plant in this particular location). The largest impact of thermal inversions seen during the simulations was a capacity loss of 5 megawatts. The cumulative loss in generation over the worst year on record was found to be 10,000 megawatt-hours/year. The distribution of impact as illustrated in Figure 2 shows that this lost generation, though not severe in the hottest months, is accumulated over much of the rest of the year.

CONCLUSIONS

The impact of atmospheric lapse rate on the performance of large natural draft cooling towers has been shown with field data and numerical model results to be on the order of 10 percent. The occurrence of thermal inversions and inferred impact on tower performance has been presented based on historical atmospheric data for a specific site. This impact ranged from +4 to -19 percent with an average of -7 and a 95 percent confidence interval of +2 to -13. Computer models for power plant and cooling tower performance have been used with historical atmospheric data in a simulation to determine the impact on the capacity and generation of a particular nuclear power plant. This impact was found to be no more than 5 megawatts (out of 1265) and 10,000 megawatt-hours/year (out of 11,000,000). This impact is quite small, but does represent a particular system at a particular site and is not necessarily representative of all such plants.

NOMENCLATURE

symbol	meaning
g	acceleration of gravity
k	isentropic exponent
R	ideal gas constant
P	pressure
T	temperature
Z	elevation

greek

ρ	density

subscripts

0	ground level or $Z=0$
1	first arbitrary state
2	second arbitrary state

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APPENDIX: IDEAL LAPSE RATE

Moist air essentially behaves as an ideal gas mixture under the operating conditions of natural draft cooling towers. The pressure, P, temperature, T, and density, ρ, of an ideal gas are related by Equation 1,

$$P=\rho RT \tag{1}$$

where R is the gas constant. The hydrostatic pressure variation is given by Equation 2,

$$\frac{dP}{dZ}=-\rho g \tag{2}$$

where Z is the elevation, and g the acceleration of gravity.

If the ideal variation of temperature with elevation is presumed to be linear and equal to that given by the NACA standard, then Equations 1 and 2 can be combined and integrated to yield an expression for pressure as a function of elevation. Similarly, if the pressure is assumed to vary as given by the NACA standard, a different expression can be derived for temperature as a function of pressure. If either one of these two approaches are taken, the resulting derived parameter (i.e., pressure in the first case and temperature in the latter) will not agree with the NACA standard.

In order to resolve this discrepancy, the concept of an isentropic atmosphere is introduced (i.e., the assumption that under "ideal" conditions the atmosphere is isentropic). In an isentropic atmosphere a particle of air can move up or down without generating any entropy due solely to this translation. For an isentropic process involving an ideal gas, the following holds (van Wylen and Sonntag, 1973, and most any other Thermodynamics text):

$$\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)}=\left(\frac{\rho_2}{\rho_1}\right)^{(k-1)} \qquad (3)$$

where the subscripts **1** and **2** indicate two arbitrary state points and **k** is the isentropic exponent (viz., the ratio of the constant pressure and volume specific heats).

Equations 1 through 3 can be solved to obtain relationships for temperature and pressure as functions of elevation. White (1979) provides several pages of discussion relative to lapse rate and derives various formulae. Streeter and Wylie (1975) provide a derivation of the isentropic lapse rate.

$$T(Z)=T_o\left[1-\frac{Z}{R}\left(\frac{k-1}{k}\right)\right] \qquad (4)$$

$$P(Z)=P_o\left[1-\left(\frac{Z}{R}\right)\left(\frac{k-1}{k}\right)\right]^{\left(\frac{k-1}{k}\right)} \qquad (5)$$

This last equation can be differentiated in order to obtain the isentropic lapse rate:

$$\frac{dT}{dZ}=-\frac{T_o}{R}\left(\frac{k-1}{k}\right) \qquad (6)$$

The isentropic lapse rate corresponding to the same conditions as the "standard" atmosphere in Table 1 is -0.0097° C/m (a difference of 50 percent). The isentropic variation of pressure with elevation is -0.00012 atmospheres/meter. This is the same pressure variation as the "standard." Field measurements agree with the isentropic lapse rate rather than the "standard". The "standard" and isentropic variation in temperature and pressure with elevation are illustrated in Figures 4 and 5, respectively.

Figure 4 shows that there is a considerable difference between the isentropic and "standard" variation in temperature with elevation. Figure 5 shows that the isentropic variation in pressure, which is the essential quantity, is virtually the same as the "standard."

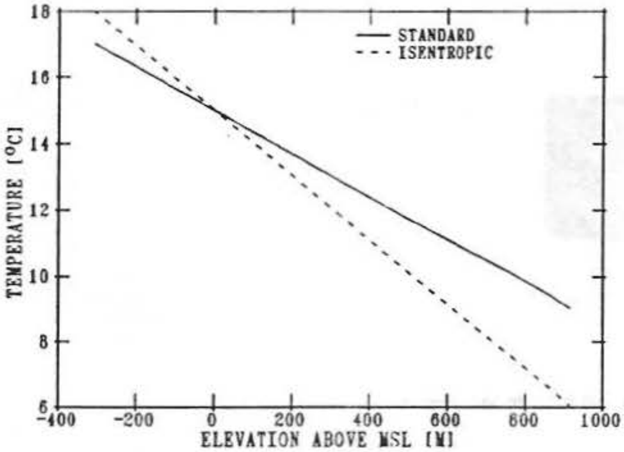

Figure 4. Variation of Temperature with Elevation

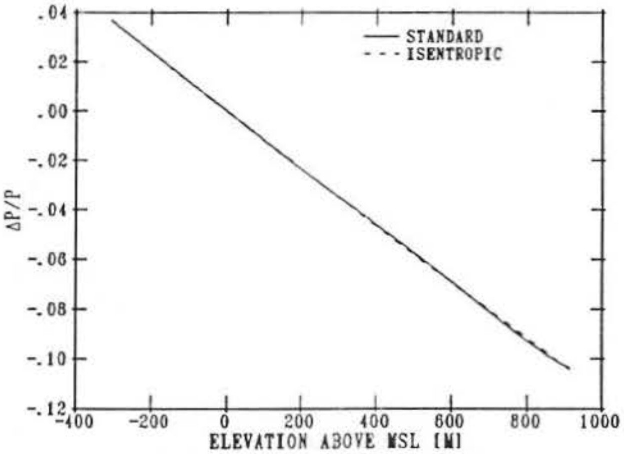

Figure 5. Variation of Pressure with Elevation