TENNESSEE VALLEY AUTHORITY
ENGINEERING LABORATORY

RESULTS OF ANALYSIS OF THE BELLEFONTE NUCLEAR PLANT HEAT REJECTION SYSTEM

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Prepared by
Dudley J. Benton

Norris, Tennessee
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EXECUTIVE SUMMARY

An analysis was performed to quantify the impact of design parameters, expected cooling tower performance, and meteorology on the capacity of Bellefonte Nuclear Plant (BLN). This analysis included a parametric study to quantify the impact of the cooling tower performance and condenser cleanliness. The impact of thermal inversions on cooling tower performance was also included. The maximum backpressure alarm setting which would result in a unit trip if a CCW pump were to be lost from service was found to be above the current alarm point. Two potential modifications to the cooling towers in order to increase their performance were also evaluated.

The steam turbo-generator performance was based on TVA heat balances and contractor data. The condenser performance was based on the Heat Exchange Institute (HEI) method. Thirty-two years of historical hourly meteorology from the National Weather Service (NWS) was used to estimate the average expected performance and the incremental changes in generation which can be expected.

Various analyses by the Engineering Laboratory dating back to 1984 indicate that the performance of the towers may be approximately 16 percent less than design. The presence of thermal inversions (which was not considered in the design and specification of cooling towers in the U.S. until the late 1980s) can be expected to further reduce the performance of the towers by as much as 19 percent under adverse conditions. These adverse conditions have been observed at BLN and are quantified in the Final Safety Analysis Report (FSAR). This shortfall in tower performance can be expected to result in a reduction in capacity and generation.

The thermal design of BLN is significantly more robust than any other surviving TVA nuclear plant. The most significant difference being the massive BBC LP turbines which can operate at high backpressure. Even if the cooling towers perform at 84 percent of design--including the impact of thermal inversions--and provided that the condensers are maintained at a cleanliness of 95 percent, backpressure-limited operation should not occur during the average year, but can be expected during a hot year. Should the towers perform worse than this, or the condenser cleanliness not be maintained at this level, or some other deficiency arise such as CCW flow being less than expected, the impact on generation and capacity can be expected to rise sharply.

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RESULTS OF ANALYSIS OF THE BELLEFONTE NUCLEAR PLANT HEAT REJECTION SYSTEM

ASSUMPTIONS

A number of assumptions were made in order to model the operation of BLN and its response to meteorology. The results obtained are contingent on these assumptions which are described in the following sections.

Steam Turbo-Generator Performance

The steam turbo-generator performance was taken from TVA heat balances OTN0800-TA-01, -03, -05, and -08, labeled "Reactor Guarantee", "Maximum Expected," "75% Reactor Guaranteed," "50% ...," and "25% ...," respectively. These span a range of reactor power input from 3777 to 905 MWt. All are computed based on condenser zone backpressures of 2.2 and 3.4 inches Hga. Information on these heat balances were used to quantify reactor power input, generator output, and condenser heat load. The zone A and B condenser heat rejection and rise are not equal; and this is duly accounted for in the analyses.

The effect of condenser zone A and B backpressures on heat rate output was based on the Brown Boveri Corporation (BBC) correction curves, HTGO-11606/1 and /2. The effect of backpressure on generator output at constant heat input was also computed based on these curves by reciprocity. The calculations were checked for consistency and do match exactly for the specific conditions corresponding to the five basic design heat balances.

Limiting Backpressure

The limiting backpressure can have a pronounced effect on the magnitude of the computed impact on generation and capacity (as illustrated in a similar analysis which was performed for Watts Bar Nuclear Plant (WBN) [DJB, TVA Rep. No. WR28-2-85-136, 1992]). A limiting backpressure of 6.5 inches Hga was used in the present analyses (the alarm point). The trip point was taken at 9.2 inches Hga. Considering the magnitude of potential impact on generation, it is essential that the best available instrumentation be installed and maintained at BLN so as to enable operation as close as practical to this limit.

Condenser Performance Calculations

The performance of the condenser was computed based on the currently recommended HEI Standards for Steam Surface Condensers. A change in the HEI calculations was instituted with the 1989 Edition in the water temperature correction factor. Therefore, the present calculations will vary slightly from those of the principal condenser contractor, Southwestern Engineering Company (SEC), in 1974. This change is most significant at low temperatures; and should not significantly affect the calculations for the critical hot weather periods. The HEI method was used even though some differences exist between the physical configuration of the BLN condensers and the ideal upon which the method is based. Addendum I of the Bid Notice [TVA Purchasing No. 38-85052, pg. 1, Item 1] states that the performance penalty shall be $600,000 per 0.1 inch Hga deviation for Zone A and $1,000,000 per 0.1 inch Hga for Zone B above that computed using the HEI method--with no adjustments for performance exceeding that of the HEI method. While this contractual detail does not validate the HEI method, the large monetary penalty does indicate confidence in it on the part of SEC.

Condenser Cleanliness

The design condenser cleanliness for BLN is 95 percent. A range of 70 to 95 percent was used in the present analysis. A cleanliness of 95 percent has been reported by SQN; however, there are many other plants in the Southeast which do not achieve a cleanliness of 95 percent on a continuous basis. Achievement of 95 percent condenser cleanliness at BLN will require proper operation and maintenance of the tube cleaning system.

Cooling Tower Performance

The performance of the cooling towers has been computed based on the manufacturer's curves and the FACTS (Fast Analyzer Cooling Tower Simulator) model [DJB and W. R. Waldrop, "Computer Simulation of Transport in Evaporative Cooling Towers," Journal of Engineering for Gas Turbines and Power, 110:190-196, 1988]. More details on applying the manufacturer's curves and the FACTS performance are given in the Cooling Tower Performance section of the Methodology and Results.

The FACTS model has been extensively verified by third parties including Arkansas Power and Light, Environmental Systems, Houston Lighting and Power, Pacific Gas and Electric, and Southern Company Services. The FACTS model has been validated with field data for a wide range of towers, including several of the same design, vintage, and vendor as the BLN towers. However, there are always some differences between towers even from the same vendor and in the same time period. The FACTS model requires several performance parameters for the tower besides the physical dimensions. Among these parameters is the performance of the fill.

The fill in each of the BLN towers is approximately 1.5 million flat asbestos fiber reinforced cement boards (ACB). The ACB boards are "dimpled" on one side and smooth on the other. No laboratory data are available for this exact type of fill. It has therefore been necessary to extrapolate based on the performance of similar fill. Differences in extrapolation result in changes in expected tower capability on the order of 5 percent. Because the fill contains asbestos fibers, it is likely that laboratory testing would have to be done in Germany or South Africa. The best available calculations have been used in leu of actual laboratory testing.

CCW Water Flow

A CCW flow rate of 410,000 gal/min was used. This value is consistent with the SEC condenser contract.

Makeup Water Temperature

The makeup water comes from the ERCW system and has a design flow rate of 35,000 gal/min with a temperature ranging from 40 to 95 °F. The RCW also feeds into the cooling tower with a flow of 25,000 gal/min and rise of approximately 15 °F. Makeup water was assumed to be at the tower exit temperature plus 15 °F.

Meteorology

The National Weather Service (NWS) hourly record of dry-bulb and dew-point at the Huntsville Airport (HFV) from 1959 through 1990 was used. The NWS data do not include vertical temperature variation, and thus cannot be used to directly compute the lapse rate (variation of ambient temperature with elevation). The lapse rate has a pronounced impact on the performance of natural draft cooling towers, as will be detailed in a subsequent section.

An empirical relationship was used to estimate the occurrence of thermal inversions based on results of a similar analysis for WBN. The TVA weather station near WBN does record the dew-point at 10 meters as well as the dry-bulb at 10, 45, and 91 meters above ground level on an hourly basis, and provided the data base used to generate the empirical relationship. This empirical relationship for thermal inversions was a straight forward multiple linear regression which agreed with the measured data for the average impact to within 2 percent and the standard deviation to within 3 percent.

Quasi-Steady vs. Transient Analysis

Simulations were carried out using historical meteorological data. The response of the plant was assumed to be quasi-steady. That is, the actual transient response is modeled as a sequence of different steady-states. The difference between a quasi-steady and a true transient analysis is that the "short" time response is ignored. "Short" is a relative term and here is a comparative to the time increment for the analysis, which was one hour. This quasi-steady analysis presumes that the plant response will essentially track the environmental conditions on an hour-by-hour basis. Operating experience with similar plants indicates that this characteristic response time is more like 3 hours. A parametric study was conducted in order to quantify the difference in results for different time steps. A comparison for one, two, three, four, six, twelve, and twenty-four hours indicated that there was no significant difference for time steps less than 6 hours.

Capacity Factor

The maximum heat input from the reactor was set at 3621 MWt (this differs slightly from the value of 3619 which appears on the 100 percent heat balance). In the simulations this was held constant unless the backpressure exceeded the alarm point (6.5 inches Hga), in which case the heat input was reduced until this value was not exceeded. All of the results contained herein are based on 100 percent plant availability.

METHODOLOGY AND RESULTS

The methodology and results of the analyses are based on the previously-stated assumptions and are as follows:

Extended Backpressure Correction Curves

The backpressure correction curves provided by BBC only cover from 0.5 to 5.0 inches Hga. These are two sets of five curves corresponding to the five heat input power levels used to develop the five heat balances. In order to apply these corrections in a continuous manner, it was necessary to generate a code module using a bi-variate curve fit for each of the two condenser zones so that the corrections can be built into the various computer codes. Curve-fitting must also be used in order to extend the range of backpressure up to the trip point. The data points taken from the BBC curves and the curve fits are shown in Figures 1 and 2 for Zones A and B, respectively.

Impact of CCW Inlet Temperature on Capacity and Backpressure

A code module was developed which would return generator output and Zone B backpressure as functions of heat input, CCW flow, CCW inlet temperature, and condenser cleanliness. Parameters from the five TVA heat balances were curve-fitted and combined with the HEI calculations as detailed in the section on Assumptions and the extended backpressure correction curves to arrive at the necessary code modules. The results of these modules for a range of heat input are illustrated in Figures 3 and 4.

Cooling Tower Performance

The cooling tower performance curves supplied by the manufacturer, Research-Cottrell (R-C) were curve-fitted using standard least-squares regression in order to provide a code module which would return tower exit water temperature as a function of range (the difference between tower inlet and exit water temperatures), wet-bulb, relative humidity, and water flow rate. Because capability is based on the manufacturer's performance curves, these were used as the basis for this code module. The expected tower performance based on the FACTS model should be applied to the results as indicated subsequently.

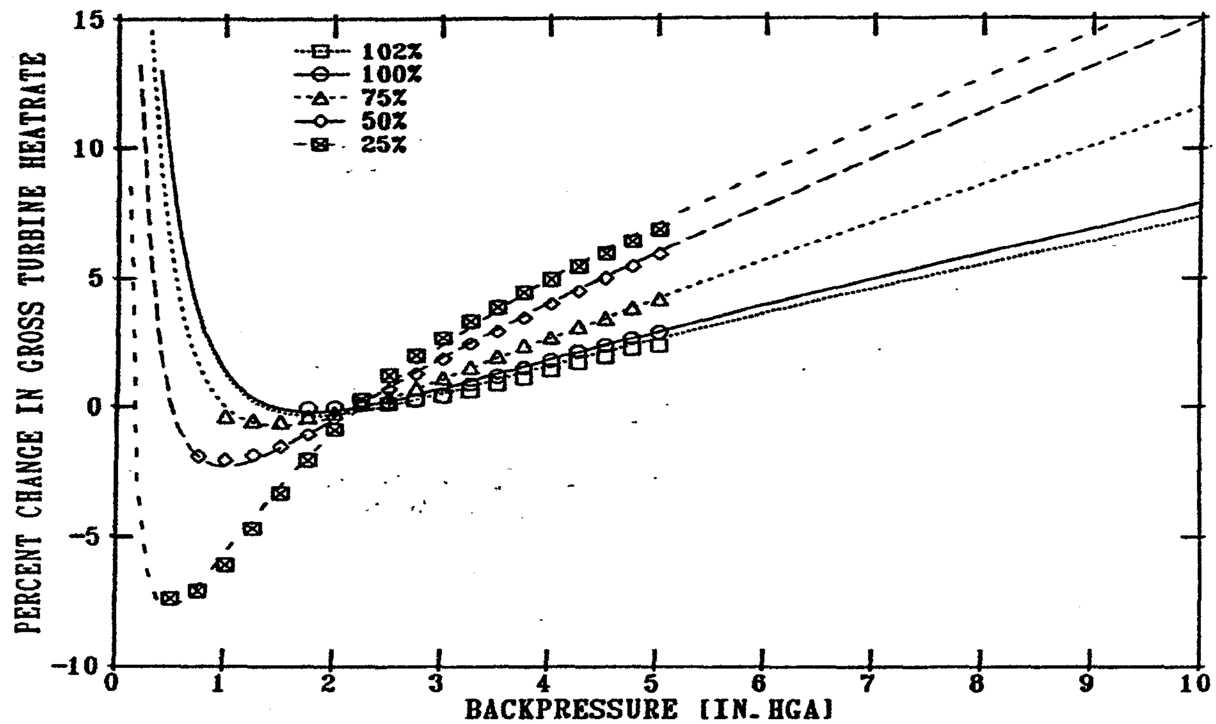

Figure 1. Curve-Fitted Zone A Backpressure Correction Curves

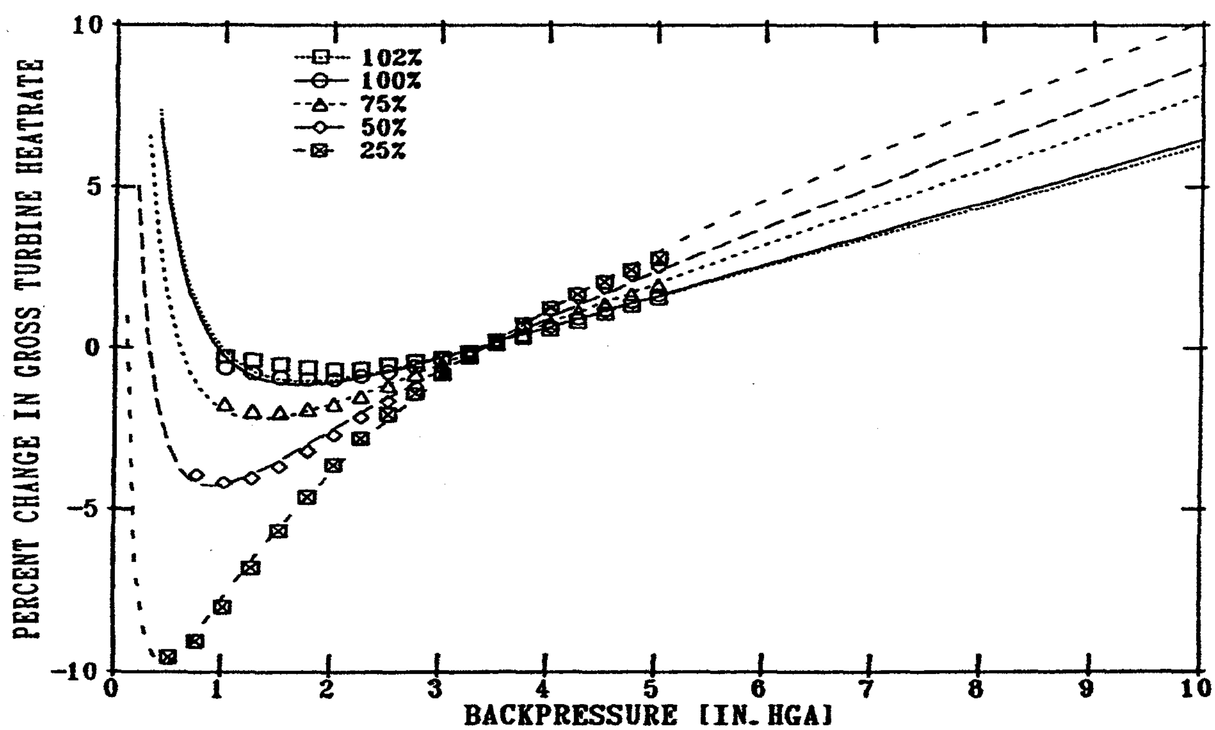

Figure 2. Curve-Fitted Zone B Backpressure Correction Curves

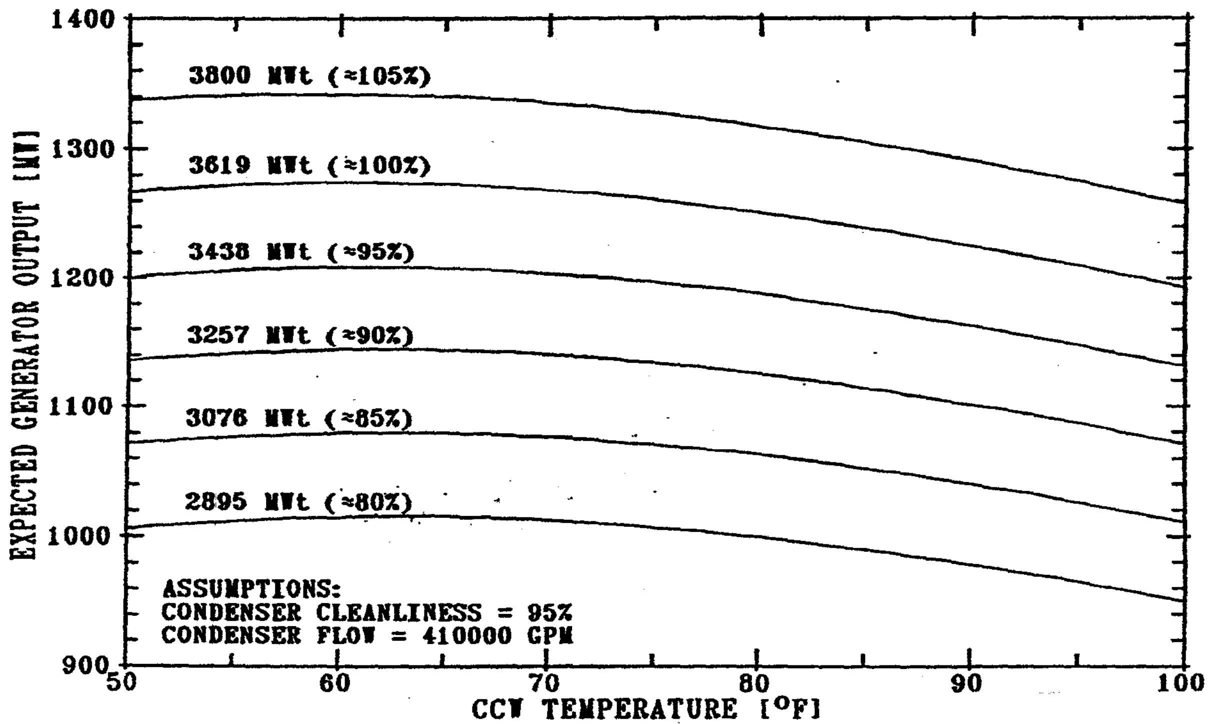

Figure 3. Generator Output vs. CCW Inlet Temperature

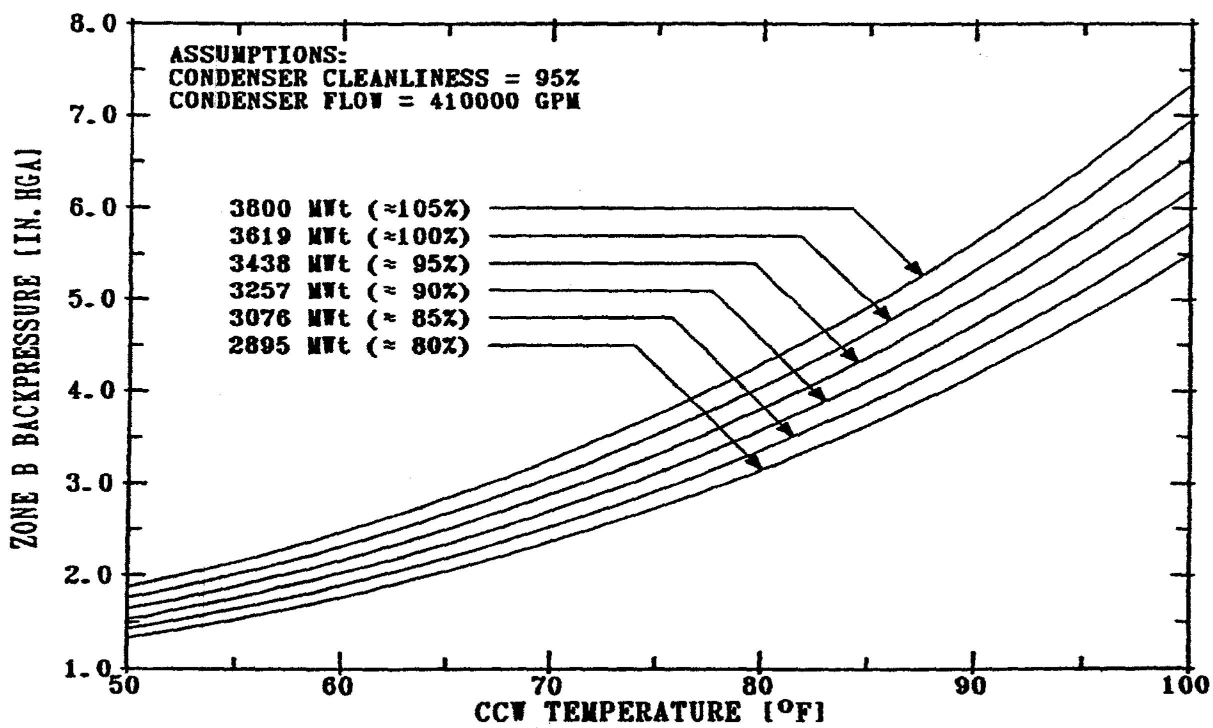

Figure 4. Zone B Backpressure vs. CCW Inlet Temperature

Impact of Wet-Bulb Temperature on Capacity and Backpressure

A code module was developed which would return generator output and Zone B backpressure as functions of reactor power input, CCW flow, CCW inlet temperature, condenser cleanliness, wet-bulb, relative humidity, and tower capability. The code modules returning cooling tower performance, generator output, and Zone B backpressure were combined in order to provide these functions. The results of these modules for a range of heat input are illustrated in Figures 5 and 6.

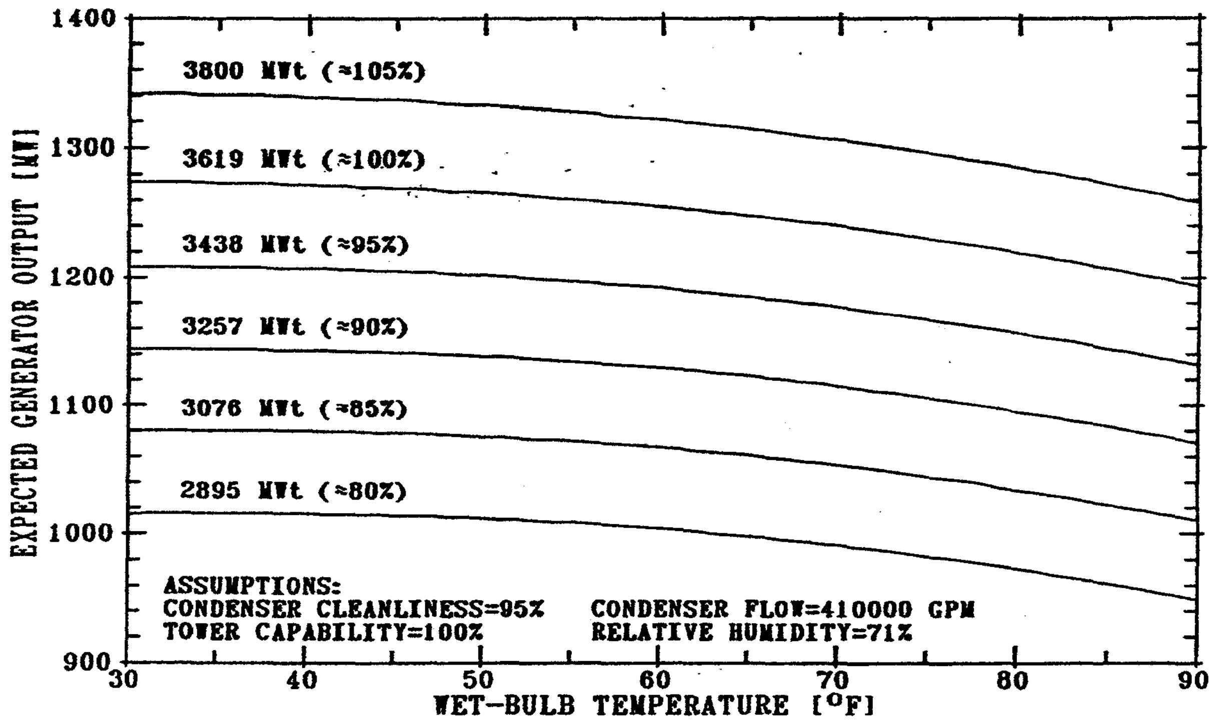

Figure 5. Generator Output vs. Wet-Bulb Temperature

Impact of Thermal Inversions on Tower Performance

A thermal inversion is an adverse atmospheric lapse rate. The lapse rate is the change in ambient air temperature with elevation. Under normal conditions, the ambient temperature decreases with increasing elevation. A thermal inversion is said to occur if the ambient temperature increases (or does not decrease as rapidly as would normally be expected) with increasing elevation.

The impact of thermal inversions (or lapse rate in general) on tower performance was computed using the FACTS computer model. These results are shown in Figure 7, which also shows field data and a curve-fit which was obtained by Ben Sherlock of EBASCO (as part of the review of the WBN heat rejection system [DJB 1992]) from a cooling tower manufacturer. The computer model results compare reasonably and are well within the scatter of the field data.

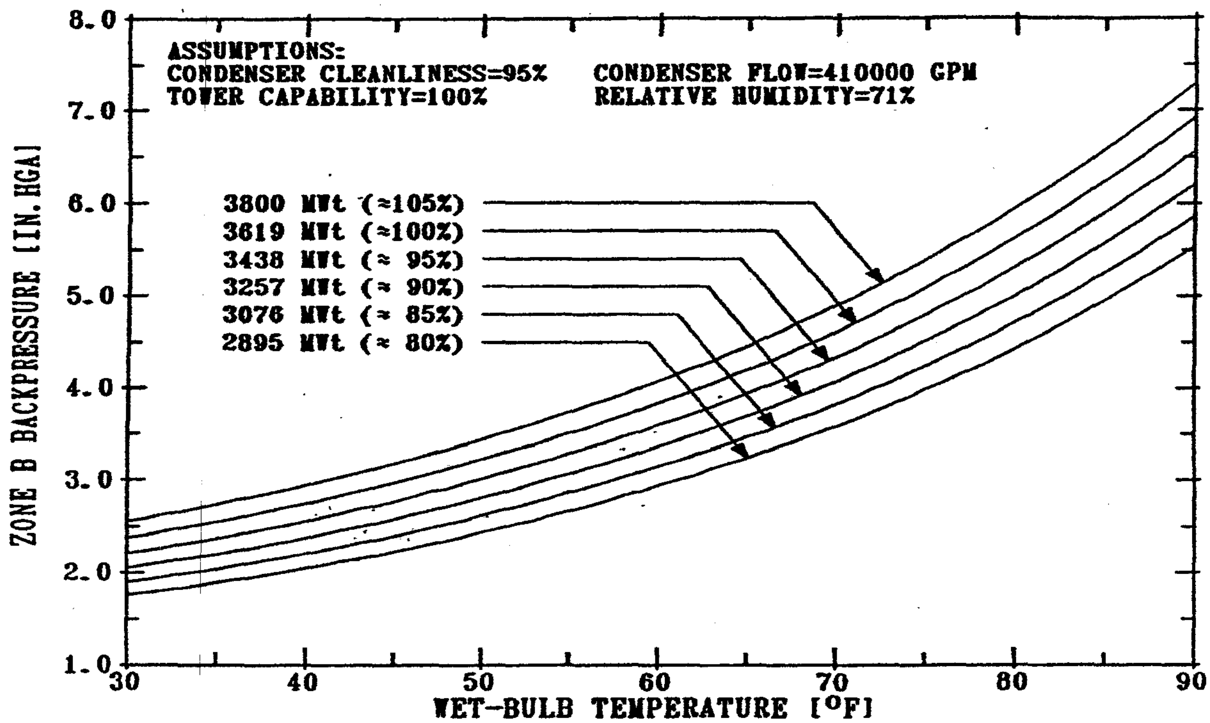

Figure 6. Zone B Backpressure vs. Wet-Bulb Temperature

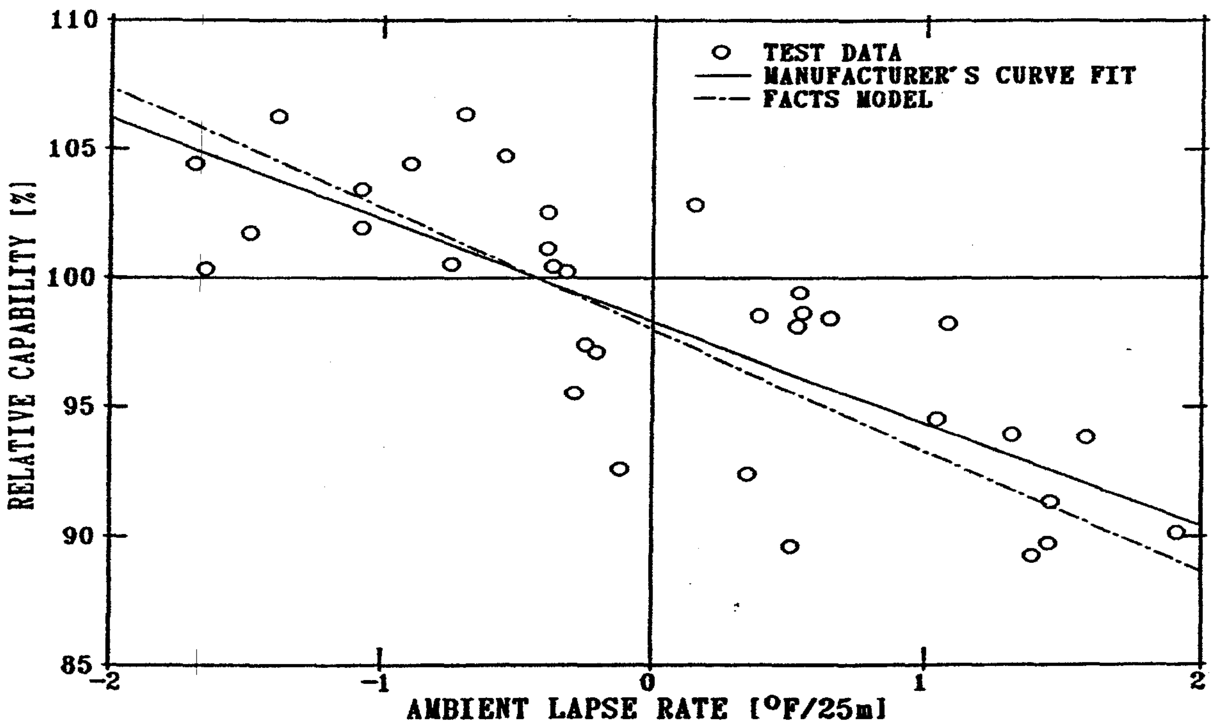

Figure 7. Impact of Lapse Rate on Cooling Tower Performance

The occurrence of thermal inversions at BLN and the associated computed impact on tower performance is illustrated in Figure 8. This scatter plot is for 1988 and shows that thermal inversions do occur and impact tower performance for much of the year, particularly in the spring and fall months. Fortunately, these rarely occur in August. Over the entire 32-year period, the average impact of thermal inversions was found to be equivalent to a 7 percent loss in tower performance. In order to include 95 percent of the impact, this loss must be considered to be 13 percent (i.e., the bottom of the 95 percent confidence interval).

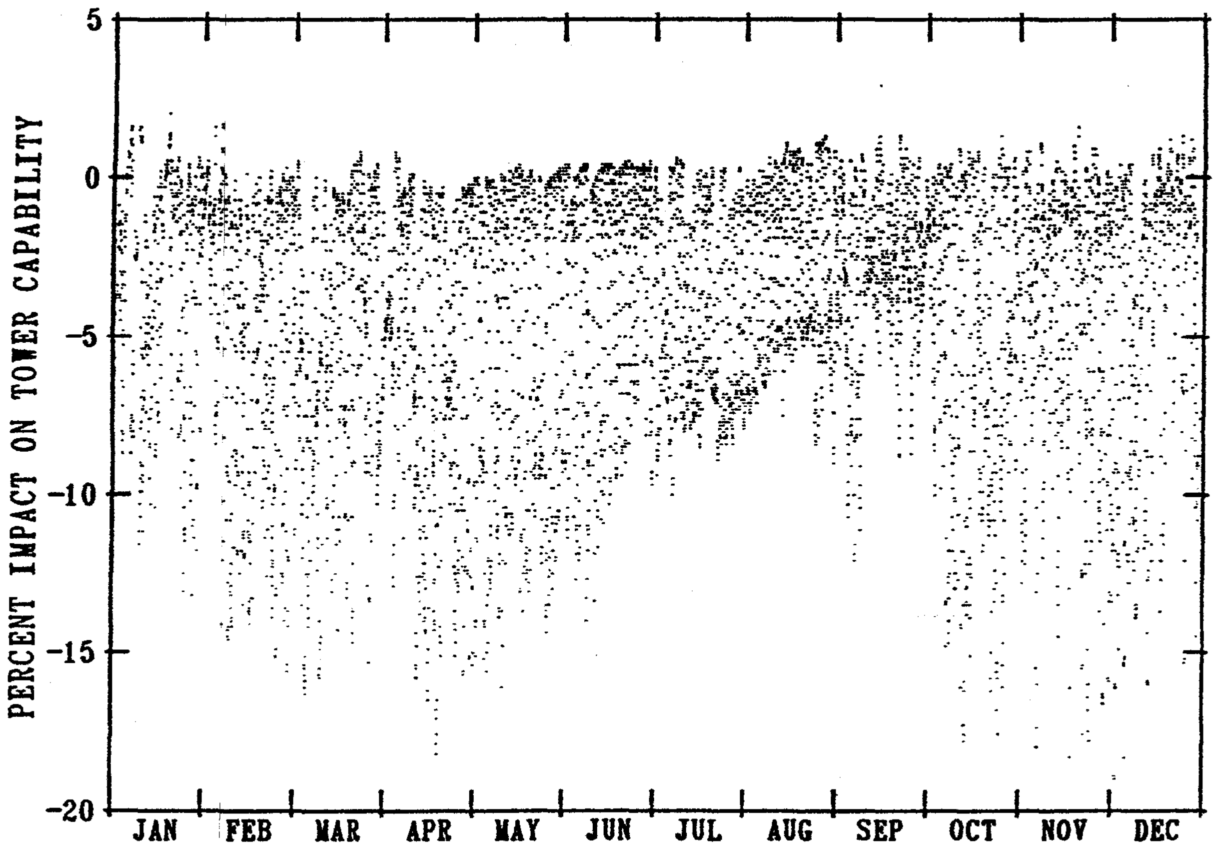

Figure 8. Occurrence and Impact of Thermal Inversions at BLN (1988)

Lost Generation, Capacity, and Backpressure-Limited Operations

The capability of a cooling tower is defined as the ratio of the actual water flow to that indicated by the manufacturer's performance curves at the same range and meteorological conditions. A tower which is found to cool the same water flow to a lower temperature or a greater water flow to the same temperature than expected is said to have a capability in excess of 100 percent. The reverse is said of a tower having a capability less than 100 percent. While this definition may not seem to be useful, it is widely used in the industry and under certain restrictions, multiple towers can be added in a manner analogous to flashlight batteries, where water flow is analogous to current and temperature is analogous to voltage. Tower capability is always referenced to the manufacturer's performance curves.

Capability is a better indicator of performance for mechanical draft towers than for natural draft, as the tower exit water temperature for mechanical draft towers is a monotonic function of the water flow rate (i.e., increasing water flow rate always results in higher exit water temperature). The heat load drives the airflow in a natural draft tower. Heat load is the product of the water flow rate and range. Therefore, with natural draft towers, the exit water temperature is not a monotonic function of the water flow. In fact, for a given tower design, meteorology, and range, there is an optimum water flow rate (i.e., a flow rate which will result in a minimum exit water temperature). For this reason, natural draft tower performance calculations based on capabilities much in excess of 100 percent are not necessarily informative and may yield results which are counter-intuitive to the idea of ever increasing performance with increased capability. The capability used in this parametric study was limited to 120 percent.

In order to quantify the impact of tower capability and condenser cleanliness on capacity and generation, it is necessary to factor in the occurrence of external conditions. It is not sufficient to stop with Figure 2 and conclude that a particular air temperature will result in a certain impact. The frequency of occurrence is essential to computing this impact. This process is complicated by the fact that environmental factors such as dry-bulb, wet-bulb, and lapse rate do not vary simultaneously. In order to capture the impact of the natural variation of these parameters, it is preferable to directly use historical data. The 32-year NWS data set for HFV used in these simulations contained 32x365.25x24=280,512 hourly values.

The capability was varied from 70 to 120 percent in steps of 10; while cleanliness was varied from 70 to 95 percent in steps of 5. The total number of simulated conditions for the basic parametric study was 6x6x280,512=10,098,432. A sample of the results for the design capability of 100 percent and the design cleanliness of 95 percent are listed in Table 1. The table lists the computed parameters by year as well as the minimum, average, maximum, and 95 percent confidence interval. The average results from all 36 cases are listed in Table 2.

The average impact on generation is illustrated in Figure 9. This is a contour map of lost generation in GWHR/yr (1 gigawatt-hour/year = 1000 megawatt-hours/year). The zero contour line passes through the design point (capability=100, cleanliness=95). Table 1 indicates that the 95 percent confidence interval on lost generation for the reference case is ±15 GWHR/yr. This means that 95 years out of 100, the increment in generation can be expected to lie within a loss of 15 and a gain of 15 GWHR/yr (as compared to the design point) with an average of zero.

For a capability of 100 percent and a cleanliness of 90 percent, Figure 9 indicates that the average lost generation will be 11 GWHR/yr (The +10 contour line is very near this point. It can also be computed from Table 2 in the column labeled "tlos" by subtracting the base case: 182-171=11.). The 95 percent confidence interval is ±15 GWHR/yr (this is listed in Table 2). This means that 95 years out of 100, the increment in generation can

TABLE 1
Sample Simulation Results

year	step	cap	ccf	gmax	genr	tlos	blos	lmax	lmin	loth	lobp	nhrs
1959	1	100	95	11178	10995	183	0	1276	1217	59	0	0
1960	1	100	95	11208	11038	171	0	1276	1216	60	0	0
1961	1	100	95	11178	11014	164	0	1276	1221	55	0	0
1962	1	100	95	11178	11005	173	0	1276	1218	58	0	0
1963	1	100	95	11178	11011	166	0	1276	1220	56	0	0
1964	1	100	95	11208	11038	170	0	1276	1214	62	0	0
1965	1	100	95	11178	10998	180	0	1276	1217	59	0	0
1966	1	100	95	11178	11004	174	0	1276	1207	69	0	0
1967	1	100	95	11178	11016	162	0	1276	1220	56	0	0
1968	1	100	95	11208	11041	167	0	1276	1216	60	0	0
1969	1	100	95	11178	11010	168	0	1276	1214	62	0	0
1970	1	100	95	11178	10998	180	0	1276	1217	59	0	0
1971	1	100	95	11178	11005	173	0	1276	1220	56	0	0
1972	1	100	95	11208	11045	163	0	1276	1219	57	0	0
1973	1	100	95	11178	10996	182	0	1276	1221	55	0	0
1974	1	100	95	11178	11006	172	0	1276	1224	52	0	0
1975	1	100	95	11178	11003	174	0	1276	1221	55	0	0
1976	1	100	95	11208	11062	147	0	1276	1223	53	0	0
1977	1	100	95	11178	11001	177	0	1276	1219	57	0	0
1978	1	100	95	11178	11010	168	0	1276	1219	57	0	0
1979	1	100	95	11178	11018	160	0	1276	1220	56	0	0
1980	1	100	95	11208	11036	172	0	1276	1212	64	0	0
1981	1	100	95	11178	11017	161	0	1276	1221	55	0	0
1982	1	100	95	11178	11001	177	0	1276	1218	58	0	0
1983	1	100	95	11178	11021	156	0	1276	1214	62	0	0
1984	1	100	95	11208	11041	167	0	1276	1220	56	0	0
1985	1	100	95	11178	11000	178	0	1276	1217	59	0	0
1986	1	100	95	11178	10992	185	0	1276	1214	62	0	0
1987	1	100	95	11178	11005	173	0	1276	1216	60	0	0
1988	1	100	95	11208	11041	167	0	1276	1217	59	0	0
1989	1	100	95	11178	11001	177	0	1276	1217	59	0	0
1990	1	100	95	11178	10993	184	0	1276	1217	59	0	0
min:	1	100	95	11178	10992	147	0	1276	1207	52	0	0
avg:	1	100	95	11185	11014	171	0	1276	1218	58	0	0
max:	1	100	95	11208	11062	185	0	1276	1224	69	0	0
95±:	1	100	95	23	31	15	0	0	6	6	0	0

LEGEND

max_heat_input = 3621 MWt
step = time step in hours
cap = tower capability in percent
ccf = condenser cleanliness factor in percent
gmax = maximum (name plate) total generation in GWHR/yr
genr = total generation in GWHR/yr
tlos = total lost generation due to thermal inefficiency in GWHR/yr
blos = total lost generation due to limited backpressure in GWHR/yr
lmax = maximum capacity in MW
lmin = minimum capacity in MW
loth = maximum lost capacity due to thermal inefficiency in MW
lobp = maximum lost capacity due to backpressure in MW
nhrs = number of hours of backpressure-limited operation
95± = 95 percent confidence interval (2-sided, sample size=32)
GWHR = gigawatt-hour = 1000 MWHR

be expected to lie within a loss of 26 (-11-15=-26) and a gain of 4 (-11+15=+4) over the design point with an average loss of 11 GWHR/yr. For a capability of 90 and a cleanliness of 95 the result is 28±16 (This point is between the 20 and 30 contours, closer to the 30. It can also be computed from Table 2 in the column labeled "tlos" by subtracting the base case: 199-171=28.). In this case, a 10 percent change in capability is worth 2.5 times as much as a 5 percent change in cleanliness (or each percentage point of capability is worth slightly more than a percentage point of cleanliness).

TABLE 2

Summary of Simulation Results

cap	ccf	genr	tlos	blos	lmax	lmin	loth	lobp	nhrs
70	70	10735±50	411±21	39±24	1274±4	1048±44	95±6	133±38	963±387
70	75	10784±42	382±20	20±15	1274±3	1076±45	90±6	110±39	589±307
70	80	10820±38	356±20	9±10	1275±2	1102±46	86±6	88±40	330±226
70	85	10848±36	333±19	4± 6	1275±2	1126±46	83±6	67±41	166±167
70	90	10870±34	314±19	1± 3	1275±1	1148±47	80±6	48±42	74±110
70	95	10888±34	297±18	1± 1	1275±1	1168±47	77±6	31±41	30± 63
80	70	10837±37	342±20	6± 8	1276±2	1112±47	86±6	79±41	254±203
80	75	10868±35	315±19	2± 4	1276±1	1141±48	81±6	53±42	96±124
80	80	10893±34	292±18	0± 1	1276±1	1168±47	78±6	30±41	30± 62
80	85	10914±34	271±18	0± 1	1276±0	1188±38	74±6	14±33	8± 27
80	90	10931±33	254±17	0± 0	1276±0	1200±27	71±6	5±23	2± 10
80	95	10946±33	239±17	0± 0	1275±0	1205±19	69±6	2±15	1± 4
90	70	10895±35	290±19	1± 2	1277±1	1161±48	79±6	36±42	42± 77
90	75	10919±34	266±18	0± 1	1276±0	1187±39	75±6	14±34	9± 28
90	80	10941±33	245±17	0± 0	1276±0	1201±26	71±6	4±21	2± 9
90	85	10959±33	227±17	0± 0	1276±0	1207±17	68±6	1±13	0± 2
90	90	10974±32	212±16	0± 0	1276±0	1210±11	65±6	1± 7	0± 1
90	95	10987±32	199±16	0± 0	1276±0	1213± 6	63±6	0± 1	0± 0
100	70	10933±34	253±18	0± 0	1277±0	1191±36	74±6	11±31	6± 23
100	75	10955±33	231±17	0± 0	1277±0	1203±23	70±6	3±18	1± 7
100	80	10974±33	212±17	0± 0	1277±0	1208±14	67±6	1±10	0± 2
100	85	10990±32	196±16	0± 0	1276±0	1212± 8	63±6	0± 3	0± 0
100	90	11003±32	182±15	0± 0	1276±0	1215± 6	61±6	0± 0	0± 0
100	95	11014±31	171±15	0± 0	1276±0	1218± 6	58±6	0± 0	0± 0
110	70	10960±34	226±18	0± 0	1277±0	1202±24	71±6	3±19	1± 7
110	75	10980±33	205±17	0± 0	1277±0	1208±14	67±6	1±10	0± 2
110	80	10997±32	188±16	0± 0	1277±0	1212± 7	63±6	0± 2	0± 0
110	85	11011±32	174±15	0± 0	1276±0	1216± 6	60±6	0± 0	0± 0
110	90	11023±31	162±15	0± 0	1276±0	1218± 6	58±6	0± 0	0± 0
110	95	11033±31	152±14	0± 0	1276±0	1221± 6	55±6	0± 0	0± 0
120	70	10981±33	205±17	0± 0	1278±1	1206±17	68±6	1±13	0± 2
120	75	10999±33	187±16	0± 0	1277±1	1211± 9	64±6	0± 4	0± 1
120	80	11014±32	171±16	0± 0	1277±1	1215± 6	61±6	0± 0	0± 0
120	85	11027±31	158±15	0± 0	1277±1	1218± 6	58±6	0± 0	0± 0
120	90	11038±31	147±14	0± 0	1277±0	1221± 6	55±6	0± 0	0± 0
120	95	11047±30	139±13	0± 0	1276±0	1223± 6	53±6	0± 0	0± 0

Note: See Table 1 for Legend

Figure 9 shows contours ranging from an average loss of 250 GWHR (in the lower-left corner) to a gain of 35 GWHR/yr (shown as a minus loss in the upper-right corner) as compared to the design base case. The contours are more steep than a downward 45 degree angle, indicating that percentage points in capability are always worth more than percentage points in cleanliness. The contours are closer together toward the bottom-left (low capability, low cleanliness), and farther apart toward the upper-right (high capability, high cleanliness). This illustrates the diminishing return for greater and greater performance. That is, a tower which performs twice as well is not worth twice as much. This does not mean that there is no value in better performance, but that the economics become less and less attractive as the performance increases. In order to apply the predictions of the FACTS model, this figure should be entered with a capability of 84 percent as indicated by the dotted line and arrow (the same applies to Figures 10 and 11).

Figure 10 shows the number of hours of backpressure-limited operation per year in an average year (this is not the average number of hours in a hot year). While the contours are spaced in 24-hour increments, this does not mean that such periods are continuous. For example, the most adverse conditions of the year might occur over a 3-hour interval for

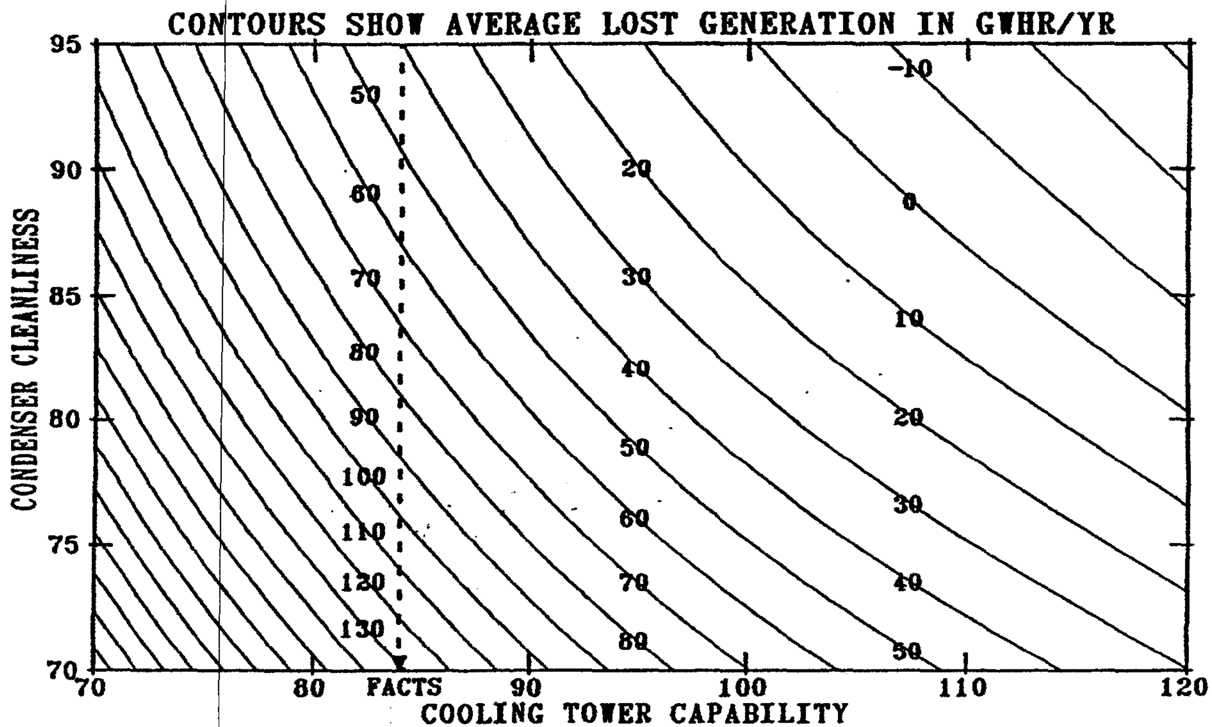

Figure 9. Impact of Tower Capability and Cond. Cleanliness on Generation

eight days running, equalling a total of 24 hours. It can be seen from the figure that backpressure-limited operation at BLN should not be expected in an average year even with a tower capability of 84 percent unless the condenser cleanliness falls to 80 percent (this is near where the dotted line intersects the 0 contour). However, Table 2 shows that backpressure-limited operation can be expected in hotter than average years for any combination of capability and cleanliness which has a non-zero average or 95 percent confidence interval in the column labeled "nhrs". Table 2 shows that 1 hour of backpressure-limited operation can be expected in a hot year even with a capability of 90 percent and a cleanliness of 90 percent. Table 2 shows that 1+4=5 hours of backpressure-limited operation can be expected in a hot year with a capability of 80 percent and a cleanliness of 95 percent.

Figure 11 shows the capacity for the hottest hour of the average year. This figure indicates that even with a capability of 100 percent and a cleanliness of 95 percent, the generator output can be expected to drop to as low as 1218 MW at least once in the average year (this is specifically listed in Tables 1 and 2 and lies just above the 1215 contour in Figure 11). Table 1 shows that 1207 can be expected in the worst year (1966) and 1224 can be expected in the most favorable (1974). Table 1 gives the 95 percent confidence interval for this parameter as ±6 MW. This means that 95 years out of 100, the worst-hour capacity each year should lie between 1212 and 1224 MW. For this 32-year sample size, 1974 lies within the worst 5 of the statically extrapolated 100 year period; while all the rest in the table lie within the 95 percentile.

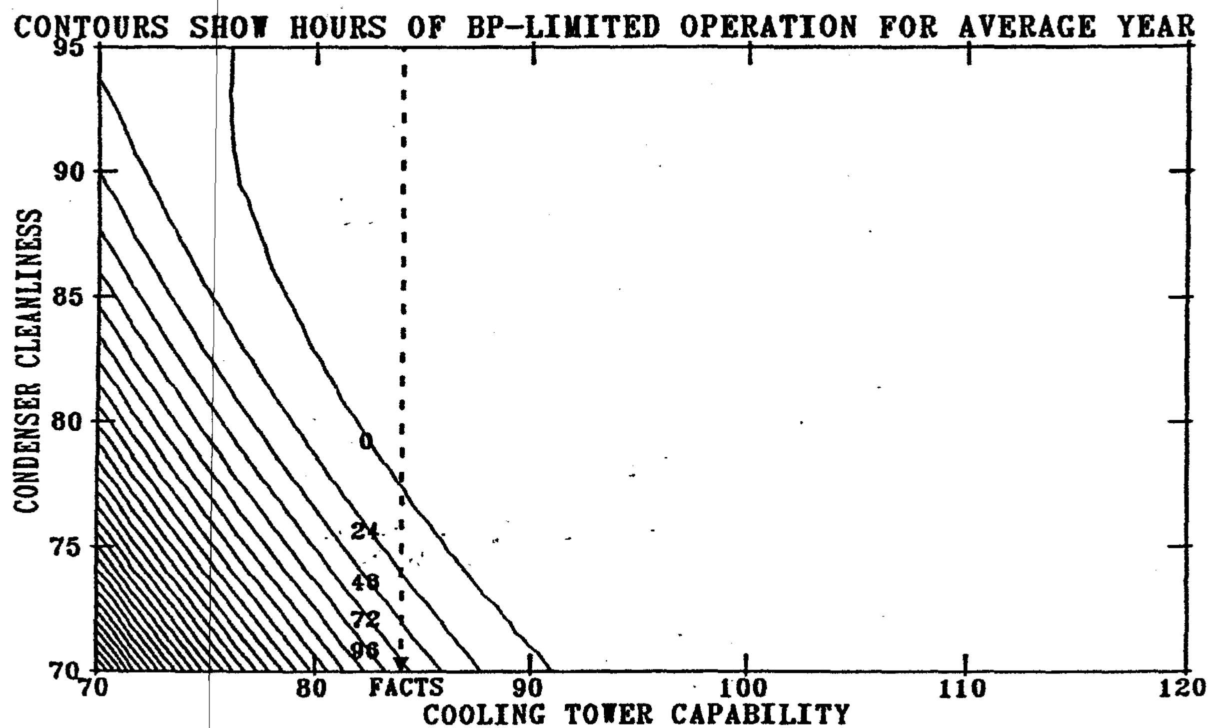

Figure 10. Impact of Tower Capability and Cond. Clean. on BP-Limited Operation

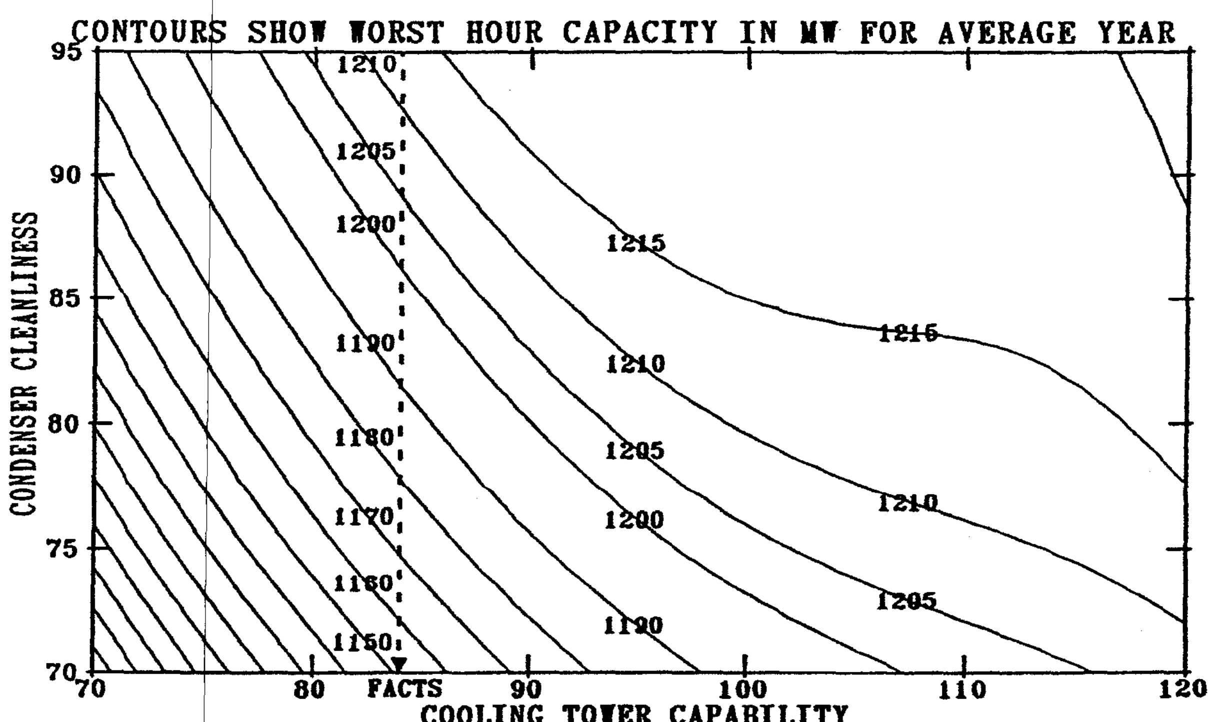

Figure 11. Impact of Tower Capability and Cond. Cleanliness on Capacity

The contours in Figure 11 are closer together in the lower-left corner and farther apart in the upper-right corner--again the principle of diminishing return. In the lower-left corner (low capability, low cleanliness), each percentage point in capability or cleanliness translates to a significant impact in worst-hour capacity. In the upper-right corner (high capability, high cleanliness), there is essentially no impact on worst-hour capacity. Specifically, for both capability and cleanliness above 90 percent, there is less than a 5 MW impact until the capability exceeds 115 percent. Note that the contour lines in the upper-right corner of Figure 9 are not so widely spaced. This means that the impact on generation for high capability and cleanliness is not accumulated in the hot time of the year when the worst-hour capacity will occur. For high capability and cleanliness, the impact accumulates a few MWHR at a time throughout most of the year. This spread-out accumulation of impact also occurs for low capability and/or cleanliness; but the accumulation is small compared to that which accumulates in the hot time of the year when the impact on capacity is much larger (i.e., where the contours are close together in the lower-left corner of Figure 11).

The impact of thermal inversions is applied as indicated in Figure 7 as an adjustment to tower capability. This adjustment was applied for each of the 280,512 hourly values in the meteorological data base. These adjustments ranged from a 19 percent reduction in performance to a 6 percent enhancement. The average was found to be a 7 percent reduction. The bottom of the 95 percent confidence interval was found to be a 13 percent reduction. The average impact on generation and worst-hour capacity of thermal inversions at the design capability and cleanliness was 10 GWHR/yr and 1 MW, respectively. This slight impact on capacity is a consequence of the inversions not occurring during the hottest time of the year (c.f. Figure 8).

Differences between Bellefonte, Watts Bar, and Sequoyah

The maximum backpressure indicated in any of the performance drawings and curves for SQN is 3.5 inches Hga. Although the LP turbines are identical at SQN and WBN, the WBN performance curves extend to 5.0 inches Hga. The BLN performance curves also stop at 5.0 inches Hga. Higher backpressures are mentioned in the contractual documents, but not the performance ones. This inconsistency--or perhaps incompleteness--is found at all three plants even though SQN and WBN are Westinghouse designs and BLN is BBC.

The ability to operate at high backpressure has a pronounced effect on the capacity during hot weather. The chief concern with high backpressure operation is vibration. The most attractive way of dealing with high backpressure operation appears to be that of installing the best available vibration monitoring instrumentation and then limiting operations based on these measurements. The actual onset of damage-cumulative vibration may or may not be accurately reflected in the turbine manufacturer's original contractual documents. Instrumentation technology has improved significantly since any of the TVA turbo-generator contracts were negotiated.

The cooling towers at SQN have a design approach (exit water temperature minus wet-bulb) of 26 °F. The towers at WBN and BLN have design approaches of 21 and 20 respectively. The design thermal effectiveness (range over range plus approach) for the three plants is 53, 64, and 64 percent, respectively. This means that the design performance of the BLN towers are somewhat better than the WBN towers (same effectiveness, 1 degree closer approach), both of which are considerably better than the SQN towers. SQN was designed to be operated in closed mode occasionally; whereas WBN and BLN were designed to operate only in closed mode.

CONCLUSIONS AND RECOMMENDATIONS

Various analyses by the Engineering Laboratory dating back to 1984 indicate that the performance of the towers may be approximately 16 percent less than design. The presence of thermal inversions (which was not considered in the design and specification of cooling towers in the U.S. until the late 1980s) can be expected to further reduce the performance of the towers by as much as 19 percent under adverse conditions. These adverse conditions have been observed at BLN and are quantified in the FSAR. The average impact of thermal inversions can be expected to be an equivalent to a 7 percent decrease in tower capability over and above any shortfall in the tower design. This shortfall in tower performance can be expected to result in a reduction in capacity and generation.

The thermal design of BLN is significantly more robust than any other surviving TVA nuclear plant. The most significant difference being the massive BBC LP turbines which can operate at high backpressure. Even if the cooling towers perform at 84 percent of design--including the impact of thermal inversions--and provided that the condensers are maintained at a cleanliness of 95 percent, backpressure-limited operation should not occur during the average year, but can be expected during a hot year. Should the towers perform worse than this, or the condenser cleanliness not be maintained at this level, or some other deficiency arise such as CCW flow being less than expected, the impact on generation and capacity can be expected to rise sharply.

Considering the principle of diminishing return, it is in TVA's best interest to first insure the best possible performance of the existing system. This includes proper maintenance of the condenser cleaning system, CCW pumps, and cooling towers--as well as the associated support systems. The best available vibration monitoring instrumentation should be installed and high backpressure operations based on actual measurements--with the goal of avoiding load curtailment unless absolutely necessary. The performance of the towers should be measured as soon as possible after full heat load can be applied. The urgency and cost-effectiveness of any action will depend on the actual performance of the system.

APPENDIX

The following analyses were also performed as part of the present study, though they do not directly impact the numerical results, discussion, or conclusions.

Computed Backpressure Resulting in Unit Trip with Loss of a CCW Pump

One operational concern has been that the backpressure alarm point be set sufficiently below the trip point such that the loss of a single CCW pump would not implicitly result in a unit trip. If all of the before-stated assumptions are made, along with and a 3-pump CCW flow of 361,000 gal/min, calculations using the code modules developed as part of this study show that the alarm should be no higher than 7.96 inches Hga. There is, of course, no additional margin in this calculation; but it is already significantly above the current alarm point.

Estimated Performance of Cooling Towers with Additional PVC Fill

The FACTS cooling tower model was used to estimate the potential increase in tower performance which could be expected by adding PVC film fill above the existing ACB fill. It was found that between a 5 and 9 percent increase in performance could be expected depending on whether the PVC fill were added around the periphery on Tier 6 or the filling in of Tier 5 up to the level of Tier 6. Some problems do exist with this type of installation including potential plugging of the PVC fill and degradation of spray coverage due to a reduced spray zone. Neither of these effects have been considered in these calculations.

Estimated Performance of Cooling Towers with Added Spray Trees

Analysis of WBN heat rejection system [DJB, 1992] found that the performance of those towers could be increased by approximately 7 percent (and possibly as much as 11 percent) through the addition of spray trees. The BLN and WBN towers are quite similar and were purchased from the same contractor.