TENNESSEE VALLEY AUTHORITY
ENGINEERING LABORATORY

DOE/OR/22001--T/

**IMPACT OF INCREMENTAL CHANGES IN METEOROLOGY ON
THERMAL COMPLIANCE AND POWER SYSTEM OPERATIONS**

Interim Report for

Sensitivity of the TVA Reservoir and Power
Supply Systems To Extreme Meteorology

Report No. WR28-1-680-109

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Norris, Tennessee
February 1992

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EXECUTIVE SUMMARY

The sensitivity of the TVA reservoir and power supply systems to extreme meteorology was evaluated using a series of mathematical models to simulate the relationship between incremental changes in meteorology, associated changes in water temperature, and power plant generation. Single variable analysis techniques were applied at selected TVA facilities for representative average and extreme weather conditions. In the analysis, base case simulations were first conducted for each representative year using observed meteorology (i.e., the no change condition). The impacts of changes in meteorology were subsequently analyzed by uniformly incrementing the variable of interest over a specified range, while holding other variables constant at their respective base case values. Project results are generally presented in terms of deviations from base case conditions for each representative year.

Based on an analysis of natural flow and air temperature patterns at Chickamauga Dam, 1974 was selected to represent extreme cold-wet conditions; 1965 as reflecting average conditions; and 1986 as an example of an extremely hot-dry year. The extreme years (i.e., 1974 and 1986) were used to illustrate sensitivities beyond historical conditions; while the average year provided a basis for comparison. Observed reservoir conditions, such as inflows, dam releases, and reservoir elevations for each representative year, were used in the analysis and were assumed to remain constant in all simulations. Therefore, the Lake Improvement Plan (which was implemented in 1991) and its consequent effects on reservoir operations were not incorporated in the assessment. In the model simulations, computed water temperatures were based on vertically well-mixed conditions in the reservoirs.

As meteorology was incrementally changed, air temperature and solar radiation were found to be the dominant meteorological variables influencing dam release and river system water temperatures. In the Upper Tennessee River above Chickamauga Dam, for each 1 F° increase in air temperature, water temperatures were generally increased by 0.25 to almost 0.5 F° depending on the type of year and location in the reservoir system. Temperature impacts cascaded down the reservoir system, and the mainstem reservoirs were more sensitive to changes in air temperature than the deep tributary reservoirs.

In the model simulations, water temperature and humidity (when cooling towers were required) were the dominant meteorological variables impacting thermal power plant performance. Increased air, and associated water, temperatures reduced simulated annual generation at the three fossil (Bull Run, Kingston, and Paradise) and the three nuclear (Watts Bar, Sequoyah, and Browns Ferry) plants analyzed in this study. Incremental generation losses resulted from plant deratings, cooling tower usage, and/or forced nuclear power plant shutdowns to avoid noncompliance with environmental and safety limits, as well as from reductions in plant efficiency and other operational constraints encountered at higher temperatures. The greatest incremental load reductions occurred in the hot-dry year. Under hot-dry conditions the impacts of increased temperature appeared to become critical between +4 and +6 F° air temperature.

Under simulated worst case conditions (hot-dry year 1986 and an air temperature increase of 8 F°), the six plants combined lost an additional 3,020 GWh or an equivalent of 13 days of

full plant load as compared to base case conditions. This reduced load represents only a small percentage of TVA's annual net system power generation (less than 2 percent). The impacts on the power supply system, however, could still be significant. The timing of load reductions was not explicitly evaluated in this sensitivity analysis. However, given the sequential location of the plants analyzed on the Clinch and Tennessee Rivers, it is likely that the majority of the load reductions would occur in a similar time frame during the hottest part of the summer. Issues related to system reliability could become important and warrant further investigation.

Assuming three operational nuclear power plants, the six plants analyzed represent approximately 30 percent of TVA's power system capacity. Consequently, based on the assumptions of this analysis, it appears that small increases in air temperature (more than +2 F° uniformly incremented over the year) beyond the historically extreme conditions in 1986 could cause 'operational headaches' or inconveniences in meeting system load requirements during peak demand periods. If air temperature increases during the hot-dry year were to approach +6 F°, the thermal power system could be seriously stressed due to environmental constraints, safety limits, and internal plant limitations. During critical summer periods, issues related to system reliability could potentially become important. In this analysis, the TVA power system appeared resilient to temperature increases during the cold-wet and mean years.

While these analyses are useful for identifying critical thresholds and evaluating the resiliency of the reservoir and power supply systems to meteorological extremes, there are limitations to the methodology. Simulated impacts could be moderated or accentuated by factors such as modifications in reservoir operations, changes in the seasonal distribution of the temperature increases, alterations in the flow regime, variance from current thermal regulatory constraints, consideration of the effects of reservoir stratification on power plant cooling water intake temperatures, and/or the inclusion of warming effects on boundary inflow temperatures.

This interim report summarizes major results from the sensitivity analysis phase of a multiphase study to assess the impacts of extreme meteorology on the TVA reservoir and power supply systems. In the scenario analysis phase of the project, the integrated system response to regional climate scenarios will be evaluated. The combined effects of changes in hydrology and air temperature, the influence of reservoir operations on water temperatures, and the time sequence of power plant load reductions will also be addressed in this next project phase.

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IMPACT OF INCREMENTAL CHANGES IN METEOROLOGY ON THERMAL COMPLIANCE AND POWER SYSTEM OPERATIONS

INTRODUCTION

The interdependency of reservoir operations and electric power generation has become increasingly complex in recent years. Electric power systems often depend upon reservoirs to generate hydropower, as well as to provide condenser cooling water and dissipate thermal waste discharges in support of nuclear and fossil power generation. Use of a reservoir system to support power generation, however, must usually be balanced against other multiple, and often conflicting, uses such as flood control, navigation, recreation, water supplies, and maintenance of water quality.

During the 1980's record drought in the Southeast, multiple use pressures in the Tennessee Valley Authority (TVA) reservoir system intensified. Dependence of power generation on reservoir operations also became readily apparent, as the TVA power system had to compete for available flows to support hydro and thermal power production. As a consequence of this experience, as well as to address potential climatic change issues, a multi-phase study was initiated to assess the impacts of extreme meteorology on the TVA reservoir and power supply systems (Miller et al., 1992). The project objective was to gain an improved understanding of the interactions between hydrometeorology, reservoir operations, and power generation. Major phases of the project included (1) sensitivity analysis of individual system components to changes in hydrometeorology, and (2) scenario analysis of the integrated system response to regional climate change scenarios. This interim report summarizes results from the sensitivity analysis phase.

THE TVA SYSTEM

The TVA Reservoir and Power Systems

The Tennessee River Basin drains a 40,910 square mile (105,960 square kilometer) area from seven states in the southeastern United States. Within the river basin, TVA is responsible for a range of programs including power production, water resource management, economic development, and resource conservation.

The TVA Reservoir System, which includes 42 major dams and reservoirs, is a large, comprehensively managed, multipurpose system (see Figure 1). Major objectives of the reservoir system are to provide for navigation, flood control, hydropower generation, recreation, and minimum flows for the maintenance of water quality and aquatic habitat. The reservoir system also supports fossil and nuclear power production by providing condenser cooling water and dissipating thermal waste loads generated from energy conversion.

The TVA power system, one of the largest in the United States, has an installed capacity in service of approximately 29,497 MW, provided by a combination of coal-fired (60 percent), hydroelectric (14 percent), nuclear (12 percent), combustion turbine (9 percent), and pumped-storage (5 percent) facilities (1991 statistics). The system includes 11 fossil plants and 29 TVA-owned hydropower generating facilities. In 1991, Units 1 and 2 at Sequoyah Nuclear Plant (SQN) and Unit 2 at Browns Ferry Nuclear Plant (BFN) were operational; additional units at Browns Ferry and Watts Bar Nuclear Plants (WBN) are scheduled for future operations. The 1991 net generation from TVA's own facilities totaled 116.4 million MWh, producing total operating revenues of more than \$5.1 billion. Total operating expenses for the same year were \$3.0 billion.

The Significance of Thermal Issues to Power Production

Air and water temperatures influence environmental and safety compliance at thermal (fossil and nuclear) power plants, as well as the efficiency of power plant operations. TVA thermal plants utilize the river system for cooling water to remove waste heat from the condensers. Unless operating in closed-mode with cooling towers, the heated effluent is discharged back into the river system. Environmental regulatory constraints determine the maximum temperature of the discharged water based on discharge temperatures and/or instream temperatures (such as a maximum downstream limit). Additionally, the Nuclear Regulatory Commission (NRC) sets safety limits at the nuclear plants on the maximum temperature of intake water to essential auxiliary and emergency cooling systems. Among other functions, these systems provide backup cooling for support equipment and remove reactor heat during emergencies.

When cooling water intake temperatures are high, power plants curtail power production (derate) from full power output or use cooling towers (if available) to reduce the temperature of the discharged water and avoid non-compliance with thermal limits. If nuclear safety intake

Figure 1. The TVA Reservoir System and Overview of Major Project Components

temperatures reach their limits, the plants are required to shut down in accordance with NRC regulations. Consequently, during hot periods, elevated water temperatures can influence power generation by causing forced deratings, additional use of cooling towers, and/or nuclear plant shutdowns. Reservoir operations and other multipurpose reservoir uses can also be impacted if additional flow releases are required to enhance mixing of the thermal discharge or to help moderate intake water temperatures for compliance purposes.

Increased air and water temperatures can also influence the efficient operation of electric power plants, particularly those with cooling towers. Increased condenser cooling water temperatures reduce the efficiency of the power production cycle. Reductions in power output can also result from internal mechanical and/or operational constraints encountered at higher ambient temperatures, such as maximum turbine backpressure or the maximum coal feed rate at fossil plants. At higher temperatures, the reduced density of hot air can also cause efficiency losses in air draft systems, adversely impacting the combustion process at coal-fired plants.

At power plants operating in a recirculating cooling loop (i.e., closed-mode), cooling tower performance determines the temperature of the water entering the condenser. In the "wet" type cooling towers used at TVA plants, evaporative cooling is facilitated by bringing hot water in direct contact with cooler, dryer air. Hotter, more humid air is less receptive to evaporation. Consequently, increases in air temperature and/or humidity reduce the efficiency of cooling tower performance, which can result in higher condenser inlet water temperatures and reduced power output.

The overall effect of changes in temperature on plant performance is generalized in Figure 2. Reductions in power output are typically small over a wide range of intake temperatures.

Figure 2. Typical Effect of Water Temperature on Power Output

To maintain constant power output, however, fuel consumption must increase to offset reductions in efficiency. Temperature impacts become more apparent at higher temperatures (in the 70 to 90°F range for TVA plants) as equipment and operating constraints become limiting and/or environmental constraints are reached. The slope of the curve can change abruptly - or reach a "knee" - at these critical points. The exact shape of the curve and location of the knee varies with plant design and the stringency of environmental and safety constraints.

In the TVA system, plant performance issues can become critical in the summer when peak power demands coincide with high air and water temperatures. During the warmest summer month (July), mean daily air temperatures generally range from 76°F in the Upper Tennessee Valley to 80°F in the Lower Valley below Chattanooga. Similarly, daily average summer water temperatures (well-mixed) in the mainstem of the Tennessee River above Chickamauga Dam are on the order of 75°F; while water temperatures in the lower mainstem are approximately 80°F.

During an extremely hot-dry year such as 1986, daily average summer air temperatures can reach 90°F. Well-mixed water temperatures can exceed 85°F, while surface water temperatures can exceed 90°F. As illustrated in Figure 3, during such extremely hot years, cooling water intake temperatures can approach or exceed environmental limit action levels at certain TVA plants. The action level is the intake temperature at which plants will utilize cooling towers (if available), request special river flow, or derate to avoid non-compliance with discharge or downstream environmental limits. A more comprehensive list of historic intake temperatures in relationship to environmental and safety limit action levels at TVA plants is provided in the full project report (Miller et al., 1992). This project quantifies the effects of historic temperatures, as well as incrementally increased temperatures, on power generation at representative TVA power plants.

HISTORIC INTAKE TEMPERATURE PATTERNS

SEQUOYAH NUCLEAR PLANT

(1976 - 1990)

WIDOWS CREEK FOSSIL PLANT

(1986 - 1990)

NOTES:

1. Daily mean values were used. Mean = average value over the record for each day of the year.
Range = maximum and minimum values in the record for each day of the year.
2. Intake Temperatures were measured on an hourly interval & missing data were ignored in the analysis.
3. Intake Temperature Environmental Limit Action Level above which cooling towers (if available), special river flow schedules, or derating needed to avoid violation of environmental limits.
4. Sequoyah Nuclear Plant is located at Tennessee River Mile (TRM) 484.5.
5. Widows Creek Fossil Plant is located at Tennessee River Mile (TRM) 406.

Figure 3. Historic Cooling Water Intake Temperatures at Sequoyah Nuclear Plant and Widows Creek Fossil Plant

SYSTEM SENSITIVITY TO INCREMENTAL CHANGES IN METEOROLOGY

A series of analyses were conducted to determine the sensitivity of the TVA reservoir and power supply systems to incremental changes in meteorology. As illustrated in Figure 1, the studies focused on six major factors which influence reservoir thermal response and/or impact power generation. These are: (1) dam release temperatures; (2) river system temperatures; (3) environmental compliance and safety issues; (4) power plant performance; (5) hydropower generation and reservoir operations; and, (6) transmission. Results from components 1 through 4 are summarized in this interim report.

General Methodology and Assumptions

The objectives of the analyses were to determine for each component: (1) the dominant meteorological variables which control thermal response; (2) the impacts of incremental changes in meteorology; and/or (3) critical response thresholds. The sensitivity studies were conducted using single variable analysis techniques on representative average and extreme weather conditions at representative sites. In the analyses, base case simulations were first conducted for each representative year using observed meteorology (i.e., no change condition). The impacts of changes in meteorology were subsequently evaluated by uniformly incrementing the variable of interest for the entire year over a specified range, while holding other variables constant at their respective base case values. For example, in the T+2 F° temperature analysis, 2 F° were added to each dry-bulb temperature value in the given data set (hourly or daily depending on the component), for the particular year being analyzed. Project results are generally presented in terms of deviations from base case conditions for each representative year.

Based on an analysis of the combined effects of natural flow and air temperature deviations from long-term mean conditions at Chickamauga Dam for the April-October period, 1974 was selected as the extreme cold-wet year; 1965 as representing average conditions; and 1986 as an example of an extreme hot-dry year. April through October represents the summer warming period when the TVA reservoir system experiences thermal stress. As illustrated in Figure 4, the 1974 average air temperatures were 3°F cooler and flows 25 percent wetter than the mean, while conditions in 1986 were about 2°F warmer and 60 percent drier than normal. Average air temperature and flow in 1965 approximate the long-term mean values of 70°F and 24,200 cfs, respectively. The extreme years (1974 and 1986) were used to illustrate sensitivities beyond historical conditions, while the average year provided a basis for comparison.

Actual reservoir conditions, including inflows, dam release patterns, and reservoir elevations, associated with each of the selected years were used in the analyses. These conditions were assumed to remain constant in all simulations and to reflect operations typical for the given hydrologic patterns. In 1991, TVA implemented a Lake Improvement Plan. The effects of this plan on reservoir operations were not considered in this phase of the project, as the selected representative years occur prior to 1991. Current environmental and safety regulatory constraints at the power plants were used, and it was assumed that four nuclear units were operational at three nuclear plants (Unit 1 at WBN, Units 1 and 2 at SQN, and Unit 1 at

Figure 4. Characterization of Historic Natural Flow and Air Temperatures at Chickamauga Dam (April - October)

BFN). In this report, the term nuclear "plant" refers to an entire nuclear facility or site, while the term "unit" is used to specify a distinct generating unit.

Estimated water temperatures were based on historic dam release temperatures at the inflow boundaries and on well-mixed conditions in the river system. Due to the one-dimensional nature of the version of the river system temperature model used in this analysis, the effects of stratification on power plant intake temperatures were not explicitly considered. Under stratified conditions, water temperatures are warmest near the water surface and coldest below the thermocline toward the bottom of the reservoir. This variation in water temperature with depth can significantly impact intake temperatures at certain TVA plants, depending on the intake location and degree of reservoir stratification. For the purposes of this analysis, however, well-mixed temperatures still provide a good indicator of the relative response of water temperature and plant performance to changes in air temperature.

Limitations of the Methodology

While these analyses are useful for identifying critical thresholds and evaluating the resiliency of the reservoir and power supply systems to meteorological variation, there are

limitations to the methodology. Single variable analysis on individual components ignores inter-relationships among meteorological variables, as well as between reservoir and power operations. By uniformly incrementing variables, the seasonal distribution of meteorological conditions is assumed to remain constant. Use of representative years and sites may mask unique phenomenon and precludes a probabilistic analysis of results. Variance of current thermal regulatory constraints and/or changes in reservoir operations could mitigate the simulated impacts. Consideration of the effect of stratification on power plant intake temperatures and/or the inclusion of warming effects on boundary inflow temperatures could also influence study results.

DAM RELEASE TEMPERATURES

Component Overview

The effect of incremental changes in meteorology and inflow temperatures on dam release temperatures was evaluated in this component for three typical reservoirs: a deep tributary (Norris); a transition tributary (Cherokee), and a mainstem reservoir (Chickamauga). Variables considered included: dry-bulb temperature, dew point temperature, wind speed, cloud cover, solar radiation, and inflow water temperature. A one-dimensional thermal model was used to model Norris Reservoir, while two-dimensional water quality models were applied on Cherokee and Chickamauga Reservoirs (TVA, 1973; Hauser et al., 1987; Butkus et al., 1990). Model results are summarized as the average (April-October) deviation in dam release temperatures from base case conditions.

Results

At Norris, Cherokee, and Chickamauga Reservoirs changes in air temperature and solar radiation had a more significant effect on dam release temperatures than other modeled variables. Based on results from Norris Reservoir, wind and cloud cover also influenced average release temperatures; while changes in dew point temperature had an insignificant impact.

Water inflow temperatures also significantly impacted dam release temperatures. Coupled changes in air and inflow temperatures almost doubled the effect of changes in air temperature alone. While these results bear further investigation, they highlight the potential importance of the boundary inflow water temperature conditions.

In general, as illustrated in Figure 5, on the tributary reservoirs, Norris and Cherokee, approximately one-fourth, or 25 percent, of the air temperature deviation was reflected in the release temperature (e.g., a 2 F° increase in air temperature resulted in a 0.5 F° increase in release temperature). The impact on the mainstem reservoir Chickamauga was slightly greater, where on the average almost 40 percent of the air temperature deviation was translated into changes in release temperature. Wind effects were also greater on Chickamauga Reservoir than on the other modeled reservoirs.

Differences in the thermal response of the three reservoirs can be attributed to differences in reservoir type and operation. Chickamauga has the largest surface area of the three reservoirs. It also experiences more convective mixing and less stratification due to a larger throughflow; consequently, it appears more sensitive to meteorological influences. Norris and Cherokee are tributary reservoirs that remain more strongly stratified through the summer; water temperatures below the thermocline appear to be less sensitive to meteorological influences.

A comparison of base case condition release temperatures also illustrates the importance of hydrology and reservoir operations on release temperatures at the tributary dams (see Figure 6). At Norris and Cherokee, the warmest release temperatures occurred in the cold-wet

SIMULATED IMPACT OF INCREMENTAL CHANGES IN AIR TEMPERATURE ON DAM RELEASE TEMPERATURES

Figure 5. Impact of Changes in Air Temperature on Dam Release Temperature

Figure 6. Simulated Norris Dam Release Temperatures for Base Case Conditions

year 1974; while the coolest occurred during the hot-dry year 1986. Under wet conditions, high flow releases typically flush out the cool hypolimnetic water early in the year, producing higher summer release temperatures. Conversely, in a dry year, flow releases are minimized, and the cooler water below the thermocline is conserved later into the year.

No critical response thresholds were identified. Changes in release temperature were directly related to changes in air temperature, air+inflow water temperature, solar radiation, and dewpoint temperature; and inversely related to changes in wind speed and cloud cover.

RIVER SYSTEM TEMPERATURES

Component Overview

The impacts of incremental changes in selected meteorological variables on river water temperatures were evaluated in this component. SYSTEMP, a one-dimensional mathematical model capable of simulating flow dynamics and thermal processes, was used to compute longitudinal temperature distributions in the Upper Tennessee and Clinch Rivers (Alavian and Ostrowski, 1992). Meteorological variables considered included: air temperature, wind speed, and solar radiation. Inflow conditions at the model boundaries (i.e., flow releases and temperatures at major tributary dams) were assumed to remain at historic levels. SYSTEMP model results were analyzed at those reservoir/riverine reaches which supply cooling water at four selected TVA power plants: Bull Run Fossil Plant (BRF), Kingston Fossil Plant (KIF), Watts Bar Nuclear Plant (WBN), and Sequoyah Nuclear Plant (SQN). Simulation results are summarized as the average deviation of well-mixed water temperature from base conditions for the April through October period.

Results

The dominant variables which influenced the thermal response of river system water temperatures were found to be air temperature and solar radiation. As illustrated in Figure 7, incremental changes in air temperature were directly related to changes in water temperature and no critical thresholds were apparent.

The cascading influence of reservoir operations and meteorology on water temperature down the reservoir system is also apparent in Figure 7. Moving downstream from Norris Dam, in an average year (1965), for each 1 F° increase in air temperature, water temperatures increased by approximately 0.1, 0.3, 0.3, and 0.4 F° for the April through October period at Bull Run, Kingston, Watts Bar and Sequoyah Power Plants, respectively. Water temperatures at Bull Run are largely influenced by the temperature of Norris Dam releases, which are relatively cool. Further downstream on the Clinch River and mainstem of the Tennessee River, meteorological effects became pronounced, with the greatest impact apparent in Chickamauga Reservoir.

The variation in thermal response during different types of years is shown in Figure 8. The impact of increased air temperatures appeared to be greatest in the hot-dry year and less evident in the cold-wet year; thermal response in the mean year fell between the two extremes. In Chickamauga Reservoir near Sequoyah Nuclear Plant, under the most extreme conditions simulated (1986 and an 8 F° increase in air temperature ($T_{air} + 8 \text{ F}^\circ$)), almost 50 percent of the change in air temperature was reflected in water temperature deviations (i.e., 0.5 F° increase in water temperature per 1 F° increase in air temperature). This represents as much as a 1 F° greater incremental impact in the hot-dry year 1986 as in the cold-wet year 1974.

SIMULATED IMPACT OF INCREMENTAL CHANGES IN AIR TEMPERATURE ON RIVER SYSTEM WATER TEMPERATURE

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Figure 7. Impact of Changes in Air Temperature on Water Temperature in the Upper Tennessee River

SIMULATED IMPACT OF CHANGES IN AIR TEMPERATURE ON RIVER SYSTEM WATER TEMPERATURE

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Figure 8. Impact of Changes in Air Temperature on Water Temperature at Sequoyah Nuclear Plant Intake for Three Representative Years

ENVIRONMENTAL COMPLIANCE AND SAFETY ISSUES

Component Overview

The impact of incremental changes in water temperature on the ability of fossil and nuclear power plants to meet environmental and safety limits was evaluated in this component. As illustrated in Figure 9, simplified thermal environmental compliance and safety water intake models were applied to 5 representative fossil plants and 3 nuclear plants in the Tennessee and Cumberland River Basins (Ostrowski et al., 1988; TVA, 1989; TVA, 1983). Model results are presented in terms of days exceeding discharge/instream limits, days of required cooling tower use or plant shutdown, and/or days of equivalent load reductions for each representative year.

At the four plants in the Upper Tennessee River (Bull Run, Kingston, Watts Bar, and Sequoyah), expected water temperature deviations resulting from incremental increases in air temperature were based on the SYSTEMP model runs. These water temperatures were based on the assumption of well-mixed conditions; therefore, the effect of the variation of water temperature with depth on intake temperatures was not considered. The version of the SYSTEMP model used in this study was also incapable of simulating complex flow patterns, such as the recirculation of heated discharge into the intake channel at Bull Run due to unsteady reservoir conditions and/or extended low releases from Norris Dam. Consequently, compliance problems resulting from this situation could not be evaluated.

At the remaining plants in the Lower Tennessee River and Cumberland River (Browns Ferry, Widows Creek, Colbert, and Cumberland), SYSTEMP simulated model results were not available for this study. Increases of +2 and +4 F° were directly applied to historical cooling water intake temperatures to approximate the impact of +4 and +8 F° increases in air temperature.

Results

Increased air, and associated water, temperatures can increase the incidences of exceeding environmental and safety intake limits at thermal power plants in the TVA system. The impacts, however, are plant specific, depending on the location of the plant, the stringency of the thermal limits, and the type of year.

In this analysis, warmer temperatures did not influence environmental compliance at Kingston Fossil Plant or safety compliance at Watts Bar Nuclear Plant. Thermal limits at Kingston under base case and increased temperature conditions were not exceeded due to the relatively high discharge limit at the plant, coupled with cool water releases from Norris Reservoir. Similarly, the safety intake limit at Watts Bar Nuclear was not exceeded under base case or elevated temperature conditions.

Under current climatic conditions (represented by the base case simulations), Sequoyah Nuclear, Widows Creek Fossil and Cumberland Fossil Plants did not exceed thermal and/or

SUMMARY OF SIMULATED IMPACT OF INCREASED AIR & WATER TEMPERATURE ON ENVIRONMENTAL & SAFETY COMPLIANCE AT SELECTED THERMAL POWER PLANTS

Hot-Dry Year (1986)

Figure 9. Impact of Increased Air and Water Temperature on Environmental and Safety Compliance at Selected Thermal Power Plants

safety limits. Thermal limits in the base years, however, were exceeded at Bull Run Fossil, Browns Ferry Nuclear, and Colbert Fossil Plants. Bull Run thermal compliance was largely influenced by Norris Dam release temperatures. Assuming full plant operation, discharge limits were exceeded from 4 to 7 days in the cold-wet and mean years (1974 and 1965), respectively. During these years, flow releases were relatively high and the cold water was flushed from the reservoir early in the year; consequently, relatively high release temperatures occurred in the late summer.

At Browns Ferry Nuclear and Colbert Fossil Plants, environmental compliance in the base case simulations was problematic only during the hot-dry year 1986. In 1986, plant load had to be reduced an equivalent of 3 days at Browns Ferry. (The Browns Ferry evaluation assumed a cooling tower return channel limit of 94°F. In actual operations, this constraint has recently been removed.) Assuming full power operations, Colbert exceeded discharge limits for almost one month under 1986 base case conditions.

During the hot-dry year 1986, the number of plants impacted and the incidences of thermal violations increased with increasing air and water temperature. As illustrated in Figure 9, tower usage was required at Sequoyah Nuclear Plant for a 2 F° increase in air temperature ($T_{air} + 2\text{ F}^\circ$) and became significant (30 days) at $T_{air} + 4\text{ F}^\circ$. At the extreme ($T_{air} + 8\text{ F}^\circ$), SQN would have to be shut down for over one month due to its safety limit. Browns Ferry Nuclear Plant experienced an additional one to three weeks of reduced load for the elevated temperature increments considered. Plants on the Lower Tennessee and Cumberland Rivers (Widows Creek, Colbert, and Cumberland Fossil Plants) exceeded thermal limits an additional one week to over one month as compared to base conditions for the $T_{air} + 4\text{ F}^\circ$ and $T_{air} + 8\text{ F}^\circ$ simulations, respectively.

At all plants analyzed, except Bull Run, thermal limits were not exceeded during the cold-wet and mean years, even when temperatures were incrementally increased.

POWER PLANT PERFORMANCE

Component Overview

The impacts of incremental increases in air, and associated water, temperatures on power plant performance were evaluated in this component. MUPIT, a model which approximates the thermal operation of steam cycle electric power plants, was used to conduct the analysis (TVA, 1991). Impacts were evaluated at six thermal power plants representing a range of TVA plant types and configurations (see Table 1).

Model results are summarized in terms of equivalent "lost days" of generation per year, based on the difference between annual maximum and simulated generation for each model run. Maximum generation, which is based on peak net capacity, is rarely achieved continuously through a year due to plant equipment limitations and/or environmental constraints. As MUPIT was calibrated to reflect historic operations, base case simulations reflect the load reductions that could occur in each of the representative years at each plant. In the elevated temperature simulations, incremental generation losses above base case conditions can be attributed to additional plant deratings, cooling tower use, and/or plant shutdowns to avoid non-compliance with environmental and safety limits, as well as from losses in efficiency and other operational constraints encountered at high temperatures. Estimated costs to replace the lost load were based on the cost to generate this power with alternative resources during critical summer periods (TVA Research and Development, 1990; TVA Power Supply, 1992).

At the four plants in the Upper Tennessee River (Bull Run, Kingston, Watts Bar, and Sequoyah incremental change in air temperature were provided by the SYSTEMP model runs. At the remaining plants (Browns Ferry Nuclear and Paradise Fossil), where simulated water temperatures were not available, it was assumed that each 1 F° increase in air temperature would result in a 0.5 F° increase in water temperature deviation. Changes in wet-bulb temperature were computed assuming constant air moisture content (or humidity).

Results

Results from the base case analysis shown in Figure 10 indicate that some level of load reduction from maximum generation (at net peak capacity) occurred in the simulations for the three years representing current climatic conditions. The magnitude of the load reductions varied with the plant type and configuration, plant location, and the type of year. The smallest base case load reductions (<2 days per year) occurred at Bull Run and Kingston Fossil Plants, which receive relatively cool water from Norris Dam. The largest load reductions (12 to 14 days) were experienced by Watts Bar, a closed-cycle nuclear power plant. Base case load reductions at Sequoyah Nuclear, Browns Ferry Nuclear, and Paradise Fossil Plants were more moderate, ranging from 4 to 11 days per year. In general, the largest base case load reductions occurred in the hot-dry year 1986. Base case load reductions were as much as twice as high in the hot-dry year than in the cold-wet year. Generation losses during the average and cold-wet year reflect the inability of the plant to operate at peak capacity at all times (i.e., internal

Table 1. Characteristics of Six Representative TVA Thermal Power Plants

CHARACTERISTICS OF SIX REPRESENTATIVE TVA THERMAL POWER PLANTS

PLANT	CATEGORY	COOLING TOWERS		LOCATION ²	CHARACTERISTICS			ANALYSES ASSUMPTIONS			
		Type	Mode of Operation ¹		No. Units	Rated Capacity (MW/unit)	Total Capacity (MW)	No. Units	Peak Net Capacity (MW)	Maximum Generation ³	
										(GWh/yr)	(GWh/day)
Bull Run (BRF)	Fossil (Large)	-	-	CRM 48 Melton Hill Res.	1	950	950	1	894	7,632	21
Kingston (KIF)	Fossil (Small)	-	-	CRM 3 Watts Bar Res.	9	175 (U1-4) 200 (U5-9)	1700	9	1569	13,744	38
Watts Bar ⁴ (WBN)	Nuclear (PWR) ⁵	Natural Draft Counter Flow	Closed	TRM 528 Chickamauga Res.	2	1270	2540	1	1186	10,389	28
Sequoyah ⁴ (SQN)	Nuclear (PWR) ⁵	Natural Draft Cross Flow	Mixed	TRM 484.5 Chickamauga Res.	2	1220	2440	2	2344	20,568	56
Browns Ferry ⁴ (BFN)	Nuclear (BWR) ⁵	Mechanical Cross Flow	Mixed	TRM 294 Wheeler Res.	3	1152	3456	1	1083	9,487	26
Paradise (PAF)	Fossil (Large)	Natural Draft Counter Flow	Mixed (U1-2) Closed (U3)	GRM 100	3	704 (U1-2) 1150 (U3)	2558	3	2342	20,507	56

Totals 13,644 9,418 82,527 225

NOTES:

1. Mode of Operation:

Closed = Recirculating cooling

Mixed = Once-through, Once-through with cooling, or Recirculating cooling

2. Location:

CRM = Clinch River Mile

TRM = Tennessee River Mile

GRM = Green River Mile

3. Maximum generation assumes continuous operation at peak capacity

4. Major dates of operation:

WBN - Never operated

SQN - 11/80 to 8/85; 5/88 to Current

BFN - 8/74 to 3/75; 9/76 to 3/85; 7/91 to Current

5. PWR = Pressurized Water Reactor

BWR = Boiling Water Reactor

SIMULATED PLANT PERFORMANCE UNDER BASE CONDITIONS

NOTES:

1. Load reduction based on difference between maximum generation & simulated generation for each year.
2. BFN & PAF reference years are:
 Cold-Wet (1979)
 Average (1982)
 Hot-Dry (1986)

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Figure 10. Simulated Performance at Selected Thermal Power Plants Under Base Case Conditions for Representative Years

equipment and plant limitations), while environmental and safety constraints contribute to the additional losses apparent in the hot-dry year.

The impacts of incremental changes in air and water temperature on plant performance and replacement costs are provided in Figures 11 and 12. Results are presented in terms of deviations from the base case simulation for each selected year, and represent the incremental load reductions that could result from environmental, safety, and operational constraints, as well as from additional efficiency losses encountered at higher temperatures. Impacts were plant specific, depending on plant design, the stringency of environmental and safety constraints, plant location, and the type of year. Overall, incremental impacts were more severe at the nuclear plants than the fossil plants evaluated in this study; and the greatest load reductions generally occurred in the hot-dry year 1986. Plant performance impacts during this critical year are summarized in Figure 13. The frequency of load reductions also increased with increasing temperatures.

Bull Run and Kingston Fossil Plants appeared the most resilient to increased temperatures. Over the range of temperatures evaluated, incremental load reductions and replacement costs at BRF and KIF were minimal (less than .4 days lost load under worst case conditions). BRF and KIF, which are located on the Clinch River, received relatively cool

SIMULATED IMPACT OF INCREASED TEMPERATURES ON PLANT PERFORMANCE

Bull Run Fossil Plant (1 unit) &
Kingston Fossil Plant (Units 1-3)

MINIMAL IMPACT

AIR TEMPERATURE DEVIATION (F°)

NOTES:

1. DEVIATIONS FROM BASE CASE
2. Browns Ferry & Paradise Representative Years:
Cold-Wet (1979)
Average (1982)
Hot-Dry (1986)

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Figure 11. Impact of Changes in Air and Water Temperature on Annual Plant Performance at Selected TVA Thermal Power Plants

SIMULATED IMPACT OF INCREASED TEMPERATURES ON REPLACEMENT COST

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Figure 12. Impact of Changes in Air and Water Temperature on Annual Power Replacement Costs

SUMMARY OF SIMULATED IMPACT OF INCREASED AIR & WATER TEMPERATURE ON ANNUAL PLANT PERFORMANCE AT SELECTED THERMAL POWER PLANTS

Hot-Dry Year (1986)

Bull Run Fossil	Kingston Fossil
(1 unit)	(Units 1 - 9)
MINIMAL IMPACT	

Watts Bar Nuclear	T _{AIR} (F°)			
(Unit 1)	+2	+4	+6	+8
LOAD REDUCTION (days/yr)	1	2	3	4

Sequoyah Nuclear	T _{AIR} (F°)			
(Units 1 & 2)	+2	+4	+6	+8
LOAD REDUCTION (days/yr)	2	4	19	40
TOWER USE (days/yr)	19	37	35	19
SHUTDOWN (days/yr)	-	-	15	38

Browns Ferry Nuclear	T _{AIR} (F°)			
(1 unit)	+2	+4	+6	+8
LOAD REDUCTION (days/yr)	5	16	18	22
TOWER USE (days/yr)	18	38	43	47

Paradise Fossil	T _{AIR} (F°)			
(Units 1 -3)	+2	+4	+6	+8
LOAD REDUCTION (days/yr)	-	1	1	1

NOTES:

1. Corresponding period average intake water temperature deviations are approx. +1, +2, +3, & +4 F° for air temperature increments shown.
2. DEVIATION FROM BASE CASE

Figure 13. Summary of the Impact of Increased Air and Water Temperature on Annual Plant Performance (Hot-Dry Year)

releases from Norris Dam and operated fairly efficiently in this range of inlet water temperatures.

Incremental impacts at Paradise Fossil (Units 1 - 3) were greater than at BRF and KIF, but less severe than at the other modeled plants. PAF is located on the Green River, where water temperatures are typically higher than on the Clinch River. Cooling towers are also present at Paradise (Units 1 and 2 operate in mixed mode; Unit 3 in closed mode). Under worst case conditions (1986 and an 8 F° increase in air temperature ($T_{\text{air}} + 8 \text{ F}^\circ$)), Paradise lost almost 1.4 additional days of generation at an incremental replacement cost of \$2.5 million. Lost load at Paradise, when expressed as a percentage increase from the base simulation, ranged from 4 percent to 16 percent for $T_{\text{air}} + 2 \text{ F}^\circ$ and $T_{\text{air}} + 8 \text{ F}^\circ$, respectively.

At Watts Bar Nuclear (Unit 1), annual load reductions under base case conditions were slightly higher than at other plants analyzed, but the impact of incremental changes was less severe and consistent for all types of years. Under the worst case condition (1986, $T_{\text{air}} + 8 \text{ F}^\circ$), WBN experienced an additional 4 days of lost load at an incremental replacement cost of \$4 million. Forced shutdowns were not required at WBN due to NRC safety limitations, however intake temperatures were within a few degrees of the 85°F safety limit. The percentage increase in equivalent days of lost load for 1986 ranged from 6 to 29 percent over the range of temperature increases evaluated.

At Sequoyah Nuclear Plant (Units 1 and 2), the incremental impacts of increased temperatures were minimal under normal to cool conditions, but significant in the hot-dry year 1986. At Browns Ferry Nuclear (Unit 1), incremental impacts were apparent during all years; the most dramatic impacts, however, also occurred in 1986. During this hot-dry year, the impacts of increased temperatures appeared to become critical between +4 and +6 F° air temperature.

At +4 F° during the hot-dry year, substantial incremental tower usage (> 1 month) was required at SQN and BFN. Although, the safety intake limit was not exceeded at +4 F° at either plant, there were 9 days at Sequoyah when intake temperatures were within 0.5°F of the 85.4°F limit. At +6 F°, the safety intake limit was exceeded at Sequoyah, resulting in more than 2 weeks of plant shutdown.

Under the worst case conditions (1986, $T_{\text{air}} + 8 \text{ F}^\circ$), SQN experienced an additional 40 days of equivalent lost load for the year at an incremental replacement cost of about \$75 million. Most significantly, the majority of these load reductions (38 days) resulted from forced shutdowns. Worst case conditions at BFN resulted in an additional 22 days of lost power and a 47 day increase in tower usage, valued at \$19 million. SQN and BFN experienced the greatest percentage increase in lost load. Sequoyah, due to its safety limit, was particularly sensitive to increased temperatures in the hot-dry year, realizing an almost 500 percent increase in equivalent lost days of load under worst case conditions.

The combined effect of increased air temperature, and associated water temperature, on plant performance and replacement costs for all 6 plants for the worst case condition (1986) is summarized in Table 2. In the hot-dry year, under base case conditions, the difference between

Table 2. The Combined Impact of Increased Temperature on Plant Performance at Six Thermal Plants for a Hot-Dry year (1986)

SUMMARY OF SIMULATED POWER PLANT PERFORMANCE & REPLACEMENT COST IMPACTS

Six Plant Total

(Hot, Dry Year 1986)

AIR TEMP. (F°)	MAX WATER TEMP. (F°)	LOST GENERATION (GWh/yr)	EQUIVALENT ¹ LOST DAYS (full plant days/yr)	REPLACEMENT COSTS (\$ millions/yr)	% TOTAL SYSTEM	
					LOST GENERATION ² (%)	OPERATING COSTS ³ (%)
BASE		1,751	8	59	1	2
DEVIATION FROM BASE CASE						
+2	+1	287	1	10	-	-
+4	+2	741	3	25	1	1
+6	+3	1,676	7	56	1	2
+8	+4	3,020	13	101	2	3

6 plant capacity (BRF, KIF, WBN, SQN, BFN, PAF).....	9,418	MW
6 plant maximum generation.....	82,527	GWh/yr

TOTAL SYSTEM CAPACITY ⁴	30,787	MW
NET SYSTEM GENERATION ⁵	132,953	GWh
SYSTEM OPERATING COSTS (1991)	\$3.1	BILLION
SYSTEM OPERATING REVENUES (1991)	\$5.1	BILLION

NOTES:

1. Based on 6 plant total maximum generation of 225 GWh/day.
2. Lost generation compared to net system generation.
3. Replacement cost compared to system operating cost.
4. 1991 system capacity (including SQN units 1 & 2; BFN unit 2) adjusted to also include WBN (1 unit).
5. 1991 system generation (including SQN units 1 & 2; BFN unit 2, partial year) adjusted to also include BFN unit 2 for a full year & WBN (1 unit).

annual maximum generation at peak net capacity and simulated generation was 1,751 GWh, representing a loss of full load from these six plants for 8 days. A 2 F° increase in air temperature resulted in approximately one additional full plant day of equivalent lost load (287 GWh), representing a 13 percent increase over base case conditions. At $T_{\text{air}} + 6 \text{ F}^\circ$, incremental days of lost load increased by as much as 87 percent. Under the most extreme condition (1986, $T_{\text{air}} + 8 \text{ F}^\circ$), the six plants lost an additional 3,020 GWh or 13 days of load for the year, representing as much as a 163 percent increase over base case conditions.

The computed incremental losses in load and increases in replacement costs represent only a small percentage of net system annual generation and operating costs (approximately 2-3 percent under worst case conditions). During an extremely hot-dry year, however, increased temperatures could still significantly impact the thermal power production system. The timing of load reductions was not evaluated in this sensitivity analyses; however, given the sequential location of these plants on the Clinch and Tennessee Rivers, it is likely that most of the load reductions would occur in a similar time frame during the hottest part of the summer. Issues related to system reliability could become important and warrant further investigation.

Assuming that the three nuclear plants considered are operational, these six plants represent more than 30 percent of TVA's total power system capacity. Consequently, it appears that due to environmental constraints and internal plant limitations, small increases in air temperature (more than +2 F° uniformly incremental over the year) beyond the historically extreme conditions in 1986 could cause 'operational headaches' or inconveniences in meeting system load requirements during periods of peak demand. If hot-dry year temperature increases were to approach +6 F°, the power system could be seriously stressed during critically hot periods due to environmental constraints and NRC safety limits. In this analysis, the TVA power system appeared resilient to temperature increases during the cold-wet and mean years.

SUMMARY AND CONCLUSIONS

A series of mathematical models were used to simulate and quantify the relationship between changes in air temperature, associated changes in water temperature, and power plant performance. Based on single variable sensitivity analysis and the assumptions used in the study, the following major conclusions can be made concerning the sensitivity of the TVA reservoir and power supply systems to extreme meteorology.

1. Water Temperature: The dominant variables which influence the thermal response of dam release and river system water temperatures are air temperature and solar radiation. For each 1 F° increase in air temperature, water temperatures are generally increased by 0.25 to almost 0.50 F° depending on the type of year and location in the reservoir system. Mainstem reservoirs are more sensitive to changes in meteorology than deep tributary reservoirs.

2. Environmental Compliance and Safety Limitations: Increased air, and associated water, temperatures can cause plant deratings, additional cooling tower usage, and/or forced shutdowns due to environmental constraints and/or safety water intake limits. Incremental impacts are most severe in a hot-dry year. Vulnerability is plant specific, depending on plant design, the location of the plant, and the stringency of the regulatory constraints.

For the projects analyzed, the sensitivity of power plant environmental and safety compliance to increased air temperature during a hot-dry year can be comparatively rated as follows:

Bull Run Fossil	Low
Kingston Fossil	Low
Watts Bar Nuclear (safety)	Low
Widows Creek Fossil	Moderate to High
Cumberland Fossil	Moderate to High
Sequoyah Nuclear	High
Browns Ferry Nuclear	High
Colbert Fossil	High

3. Power Plant Performance: The dominant meteorological variables impacting thermal power plant performance are water temperature and wet-bulb temperature (if cooling towers are operational). Due to internal plant limitations and environmental constraints, some level of load reduction from maximum generation (based on peak net capacity) is apparent under current climate conditions for all types of years. The largest base case load reductions, however, generally occur in the hot-dry year.

The impact of incremental changes in air and water temperatures on plant performance is plant specific, depending on plant design, the stringency of environmental and safety constraints, plant location, and the type of year. The greatest incremental load reductions generally occur in the hot-dry year. Incremental load reductions can be attributed to plant deratings, additional cooling tower usage, and/or plant shutdowns to avoid non-compliance with environmental and safety constraints, as well as from losses in efficiency and other operational constraints encountered at higher temperatures. Under hot-dry conditions, increased air temperature impacts appear to become critical between +4 and +6 F° air temperatures.

For the projects analyzed, plant performance vulnerability to increased temperatures under hot-dry conditions can be comparatively rated as follows:

Bull Run Fossil	Low
Kingston Fossil	Low
Watts Bar Nuclear	Moderate
Paradise Fossil	Moderate
Browns Ferry Nuclear	High
Sequoyah Nuclear	High

Incremental load reductions due to increased temperatures represent a small percentage of annual net system generation. However, during an extremely hot-dry year, temperature-induced load reductions could significantly impact the power supply system and could raise system reliability issues during critically hot periods. Small increases in temperature (+2 F° air temperature) beyond historically extreme conditions could cause 'operational headaches' in meeting system load requirements during peak demand periods. If hot-dry year air temperature increases were to approach +6 F°, the power system could be seriously stressed due to environmental constraints, NRC safety limits, and internal plant limitations. The TVA power system appears resilient to temperature increases in the cold-wet and mean years.

While these analyses are useful for identifying critical thresholds and evaluating the resiliency of the reservoir and power supply systems to meteorological extremes, there are limitations to the methodology. Simulated impacts could be moderated or accentuated by factors such as modifications in reservoir operations, changes in the seasonal distribution of the temperature increases, alterations in the flow regime, variance of current thermal regulatory constraints, consideration of stratification effects on power plant intake temperatures, and/or inclusion of warming effects on boundary inflow temperatures.

WORK IN PROGRESS

This interim report summarizes major findings from the sensitivity analysis phase of a multi-phase study to assess the impacts of extreme meteorology on the TVA reservoir and power supply systems. The relationship between changes in meteorology, water temperature, and thermal power plant performance is the primary focus of this report. The impacts of changes in hydrology, or runoff, on hydropower generation and multi-purpose reservoir uses was also addressed in the sensitivity analysis phase of the project. Results from the latter study will be summarized in the final project report (Miller et al., 1992).

The integrated system response to regional climate change scenarios will be evaluated in the scenario analysis phase of the project. The combined effects of changes in hydrology and air temperature, the influence of reservoir operations on water temperatures, and the time sequence of power plant load reductions will also be addressed in this next project phase.

Acknowledgments: This project was funded by TVA, with additional support from the Electric Power Research Institute, the U.S. Environmental Protection Agency, and the Bureau of Reclamation. The assistance of engineering aides Laura Cole and William Proctor is greatly appreciated. Special thanks to word processor Teresa McBee and to Cynthia Webb, the editorial clerk.

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