MODELING THE RESPONSE OF A MULTI-UNIT ELECTRIC POWER PLANT TO A CHANGING ENVIRONMENT

Dudley J. Benton, Ph.D.
TVA Engineering Laboratory
Norris, Tennessee

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ABSTRACT

A multi-unit electric power plant cooling system model is used to compute the response of a fossil plant to a changing environment. This model can be used to compute the response to both historical (past) and hypothetical (future) conditions. In addition to a changing environment, the thermal discharge constraints imposed by the environmental protection agencies have been changed and may be changed in the future. The effect of both environmental conditions and regulations on plant performance and operations is presented. Using the model to perform long-range simulations based on historical data provides a means by which to quantify the impacts changes in the environment and regulations.

INTRODUCTION

A multi-unit electric power plant cooling system computer model was developed in order to determine the effects of changes in the environment and environmental regulatory constraints on plant performance. The model could also be used to provide guidance in operational strategies and evaluate the relative thermal advantages of potential plant modifications. The model approximates the thermal operation of an important class of power plants, namely large steam cycle based electric power generating units. The model can be used with either coal-fired or nuclear units.

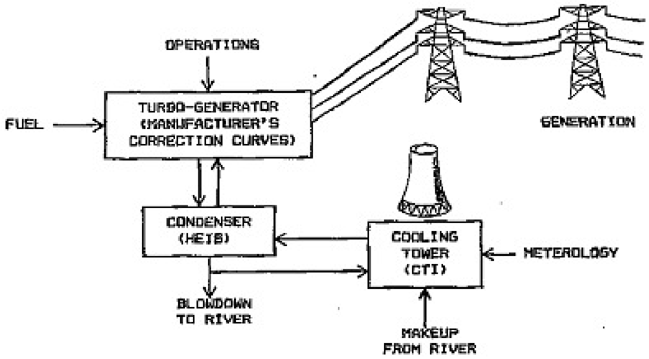

Figure 1. Schematic Representation of a Power Plant

A Multi-Unit Cooling System Model

The primary objective of the model is to accurately quantify the overall response of existing power plants. A large three unit fossil plant operated by the TVA (Tennessee Valley Authority) was selected as the principle test case for the model. This selection was primarily based on the complexity of this particular plant; as it was retrofitted with three large evaporative cooling towers. This particular plant has an unusually complicated cooling system configuration due to the design of the retrofit. In addition to this most complicated case, the model has been applied to ten other coal-fired plants (each having one to ten units) and three nuclear plants (each having two to three units). The model allows for a range of coupling between generating units and cooling towers, from completely isolated to completely mixed cooling water streams.

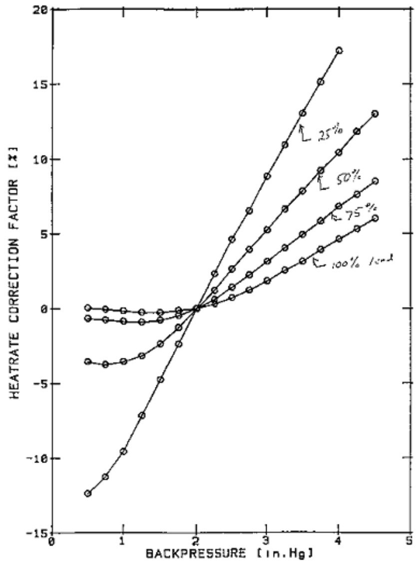

Figure 2. Typical Backpressure Correction CurvesChanging Environment and Regulations

Thirteen years of historical data (daily averages along with brief periods of hourly averages) were collected from TVA, USGS (United States Geological Survey), and NWS (National Weather Service) monitors. These data include river, dry-bulb, and wet-bulb temperatures and river flow. These data are a sample of the historical environment within which the plant must operate. A considerable variation can be seen on a year-to-year basis even in this brief period of historical record. The effect of this year-to-year variation will be quantified later as to its effect on power generation. Considerable variation can be seen even in the current environment, apart from any long-range trends, which may exist globally. Since the plant was built in 1963, the environmental regulations governing thermal discharges have been changed. Modifications to the plant were subsequently made, including the addition of cooling towers in 1969.

Operational Constraints

Because a power plant must operate in a changing environment and must operate within certain constraints, both internal equipment limitations and external regulatory limitations, realistic computer modeling is complex. Determining the most desirable operation (i.e., maximum net power output) is further complicated by the unusual configuration of this particular plant. The plant has one unit that must always operate in a recirculating cooling loop with the towers and two which can operate in variations of once-through without tower cooling, once-through with tower cooling, and recirculating with tower cooling. This operation is further complicated in that the towers are on the opposite side of the condensers to that at most plants (hot water from the condensers is first discharged to a sheltered embayment in the river and then must be drawn back into the plant in order to be pumped to the cooling towers).

BASIC ASSUMPTIONS AND MODEL DESCRIPTION

The model consists of four sub-models: the primary steam cycle and electric power generation, the main steam condenser, the cooling tower or towers (if any), and the circulating water system. These are coupled in such a way as to approximate the actual power plant. A schematic of the model is shown in Figure 1.

Primary Steam Cycle and Electric Power Generation

The primary steam cycle is modeled as behaving according to the various manufacturers performance curves for heat rate as a function of load and backpressure (see Figure 2). These curves are adjusted so as to agree with average observed performance where available (see references TVA 1988, 1989, and 1990). It is assumed that the functional relationship of the manufacturers performance curves is correct other than for this adjustment to the average.

The boiler efficiency is specified as coefficients for a second-order bivariate polynomial in the ambient temperature and load (e.g., Equation 1). The generator efficiency is specified as coefficients for a second-order polynomial in the load (e.g., Equation 2). Station service is divided into two parts: inside plant and cooling tower lift pumps; as the latter are turned on and off by the program while determining the optimum operation. The inside plant service is specified as coefficients for a second-order bivariate polynomial in the ambient temperature and load. The tower lift pump service is specified as coefficients for a second-order polynomial in the flow. The heat rate curves and adjustment for a particular plant are specified in a data file along with the boiler and generator efficiency and service load.

Main Steam Condenser

The main steam condenser is modeled as behaving according to the Heat Exchange Institute's (HEI) Standards for Steam Surface Condensers. The method prescribed by the HEI includes various physical parameters such as the number of tubes, average tube-side velocity, and tube material as well as an adjustment factor (cleanliness) which is applied to each condenser based on design or observed performance where available. This too is specified in the data file.

Evaporative Cooling Towers

For units equipped with evaporative cooling towers, these are modeled as behaving according to the methods detailed by Perry and Chilton (1973). They provide a step-by-step procedure along with the necessary equations. These methods are parallel to, but are more specific and readily adaptable than, those recommended by the Cooling Tower Institute in their various publications.

Circulating Water System

Although the analyses presented here are for a particular plant, the model has the flexibility to handle the variety of circulating water systems at all 15 TVA power plants (68 units in all). These variations include combinations of units with or without cooling towers and once-through or recirculating cooling. Some of the plants are capable of operating in more than one cooling mode or configuration of the circulating water system. The model has been designed so as to be able to handle all of these different configurations. The possible operations are specified in yet another data file. In order to determine the optimum operation, the model checks every operation that is specified in this file.

The effect of positive feedback is a very important consideration when modeling the behavior of a plant with recirculating cooling. The water leaving the cooling towers returns to the condenser. While there is some makeup from a river or other water supply and some blowdown to limit the concentrating effect of evaporation, most of the water remains in the loop. The temperature of the water depends on the performance of the cooling towers, the temperature and humidity of the air, and the temperature of the makeup. Because this constitutes a positive feedback loop, the temperature of the water cannot be computed in a single step, instead this must be computed iteratively.

The temperature of the water affects the pressure in the condenser. The pressure in the condenser in turn affects the performance of and heat rejected by the steam cycle. The performance of and heat rejected by the steam cycle affects the net load, station service, boiler efficiency, etc. These calculations must be done as an integrated whole. Unfortunately, this has often not been the case in the design phase of some plants, especially older ones.

Constraints

The model imposes four types of constraints: mechanical, operational, environmental, and nuclear safety. Mechanical constraints include: maximum load, maximum heat input (reactor power or coal feed, for nuclear and fossil, respectively) and maximum turbine backpressure. Operational constraints include the configuration of the cooling water system and the ability to operate with a variable dependency on cooling towers. The frequency with which operational modes can be changed is also a user-defined input. Many operators prefer not to change the cooling configuration more often than once per shift or once per day. Environmental regulatory constraints include maximum discharge temperature and maximum heat discharge. Nuclear regulatory safety constraints include maximum intake temperature and maximum reactor heat output. The model meets these constraints by turning on and off cooling towers, diverting cooling water, and load reductions.

Model Complexity

The complexity of the model is moderate (i.e., it is neither trivial nor state-of-the-art in detail). While it may be possible to compute the velocity profiles throughout every pipe, fitting, and channel within a power plant, such an effort is not justifiable for the present task, especially when many thousands of operating conditions must be considered in order to characterize the response of a plant to years of environmental record. Figure 2 is a typical manufacturer's set of performance curves and is just one illustration of the nonlinear behavior of these plants. Figure 2 shows the variation of heat rate with load and backpressure. In some regions of operation (viz. 100% load and 1 to 2 inches of Hg) there is very little effect on heat rate (i.e., the curve is nearly flat), whereas in other regions (e.g., all loads and 3 to 4 inches of Hg) there is a significant effect on heat rate (i.e., the curves are nearly straight, upwardly sloping lines). Trivial analyses such as constant or linearly varying heat rate cannot accurately characterize the performance of a real plant.

Model Calibration

In addition to the known condenser cleanliness, cooling tower performance, and station service, the model was calibrated by adjusting the manufacturers heat rate correction curves so as to agree with average observed plant performance. This is not to say that the model performance and observed performance agree at every point; but that the averages agree (i.e., there is no net bias). Further calibration would require more detailed operational data, whereas only average performance indicators are archived at this time.

RESULTS

Due to limited space, all of the results cannot be shown here, even in summary form. A single year was selected: 1986 (particularly hot and dry). The model response of the Plant assuming 100 percent availability (i.e., no outages) is shown in Figures 3 and 4. Figure 3 shows what the response would have been were there no environmental restrictions. Figure 4 shows the model response with the currently enforced thermal discharge regulations.

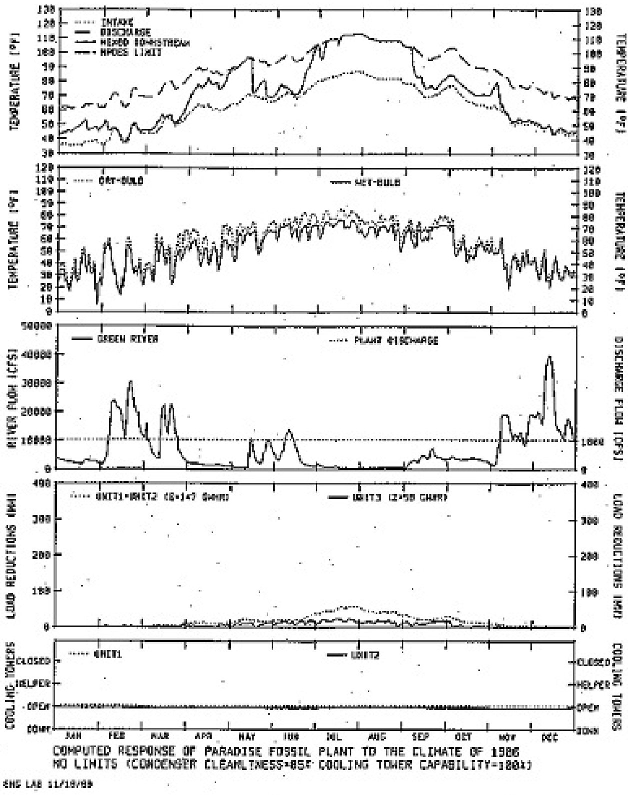

Figure 3. Typical Results without Environmental Regulations

The top graph in each figure shows the upstream, discharge, and mixed downstream river temperature. The NPDES (National Pollution Discharge Elimination System) instream fully-mixed downstream limit is also shown in Figure 4 (this does not apply to Figure 3 where no limit was presumed).

The second graph in each figure shows the dry-bulb and wet-bulb temperature (from the nearest commercial airport and NWS weather station).

The third graph in each figure shows the river flow and plant discharge flow. Note that this is a constant in Figure 3 (as no environmental restrictions were assumed) but varies in Figure 4 (where plant operation was adjusted to meet environmental restrictions).

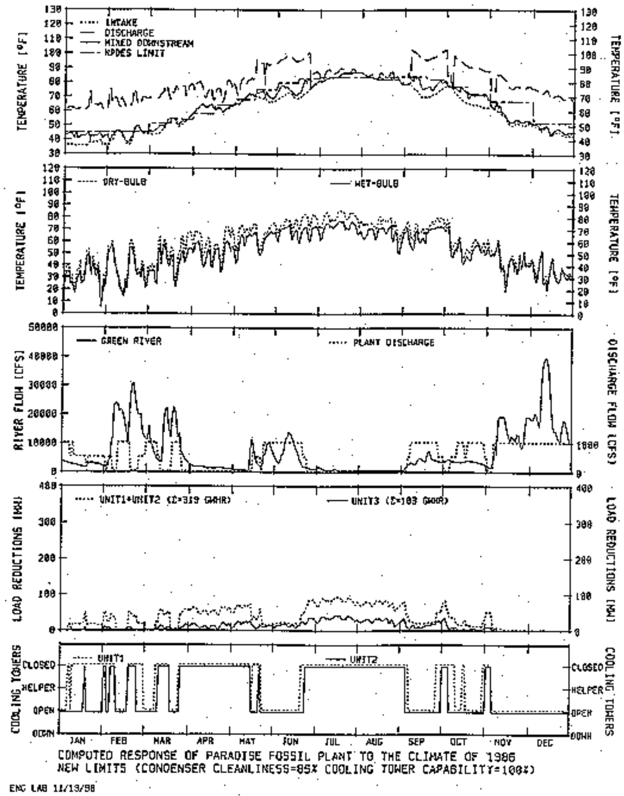

Figure 4. Typical Results with Environmental Regulations

The fourth graph in each figure shows the difference between maximum base load and actual load (i.e., lost load). The lost load in Figure 3 is due entirely to the mechanical limitations of the system (147 gigawatt-hours (GWHR) for Units 1 and 2 and 58 GWHR for Unit 3). The lost load in Figure 4 contains this as well as additional service and forced load reductions in order to meet environmental restrictions (319 GWHR for Units 1 and 2 and 103 GWHR for Unit 3). Conditions in the environment (viz. air and water temperature and river flow being something other than the ideal point at which the plant was designed) in 1986 would have been responsible for 205 GWHR of lost load and environmental regulatory constraints would have added an additional 217 GWHR were the units not subject to outages.

The fifth graph in each figure shows the mode of operation of for Units 1 and 2 (Unit 3 must always operate in recirculating cooling mode). In Figure 3, Units 1 and 2 were operated in once-through cooling without towers, as there were no environmental constraints assumed in this case. In Figure 4, Units 1 and 2 were switched on and off cooling towers as required to meet the environmental regulatory constraints.

These results as well as results for additional years and a summary can be found in Table 1.

Table 1. Computed Lost Load in Gigawatt-Hours

	No Environmental Limits		With Environmental Limits	
Year	Units 1 & 2	Unit 3	Units 1 & 2	Unit 3
1976	112	47	243	76
1977	123	61	262	97
1978	121	53	237	86
1979	89	50	113	54
1980	118	56	255	94
1981	103	52	220	71
1982	107	49	188	67
1983	106	52	215	75
1984	107	49	208	75
1985	130	56	319	102
1986	147	58	319	103
1987	166	69	373	122
1988	151	53	349	108
Maximum	166	69	373	122
Average	122	54	254	87

DISCUSSION

The difference between base load and actual load (or the ***lost load***) is due to both mechanical limitations of the system as well as environmental regulatory limitations. Although a severe year was selected for the figures, moderate years show similar, though less dramatic, results. The results for 1979 (a moderate year) were 89, 50, 113, and 54 GWHR for Units 1 and 2 and Unit 3 with and without environmental regulatory limitations.

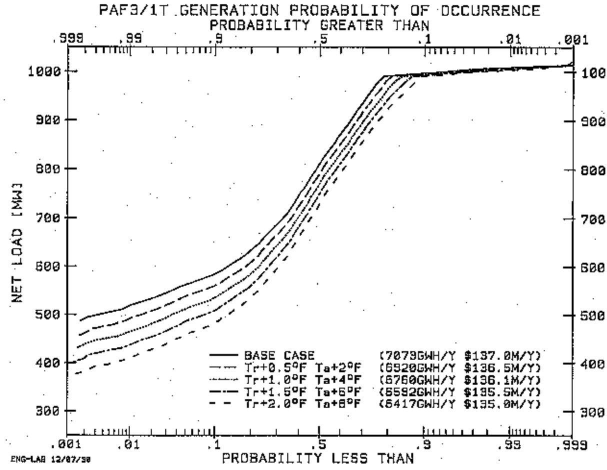

Figure 5. Generation Probability of Occurrence without Environmental Regulations

The value of the model for computing the vulnerability of a plant to changes in the environment and environmental regulations can be seen from Figures 3 and 4. Even without environmental regulations, the mechanical limitations of the Plant in a moderate year limit the production by as much as 139 GWHR below the base, which is worth approximately $4.2M at $30/MWHR (a typical summer replacement power cost). In an extreme year, like 1986, this would be more like $6.2M. When environmental restrictions are added, these figures increase by $0.8M and $6.5M for 1979 and 1986, respectively.

The interaction of the units can also be seen from these figures. While Units 1 and 2 can be operated in more than one cooling mode, Unit 3 can only operate in one (recirculating with tower cooling). If neither Unit 1 nor 2 requires the cooling towers, then all three towers can be devoted to Unit 3 (unless the weather is too cold, where freezing would be a problem and additional cooling is unnecessary). If either Unit 1 or 2 requires the cooling towers, they must be shared with Unit 3. This is why the lost load for

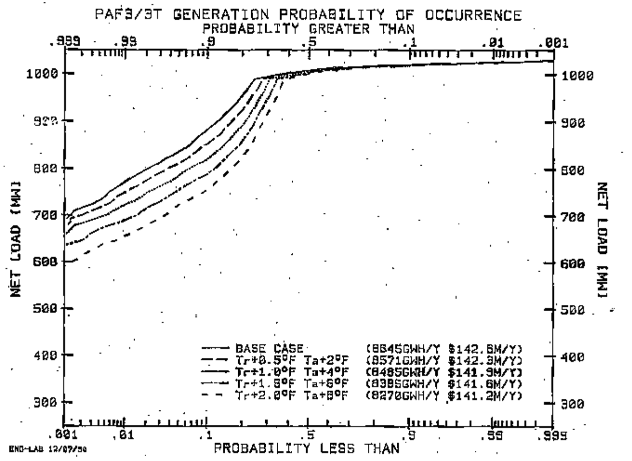

Figure 6. Generation Probability of Occurrence with Environmental Regulations

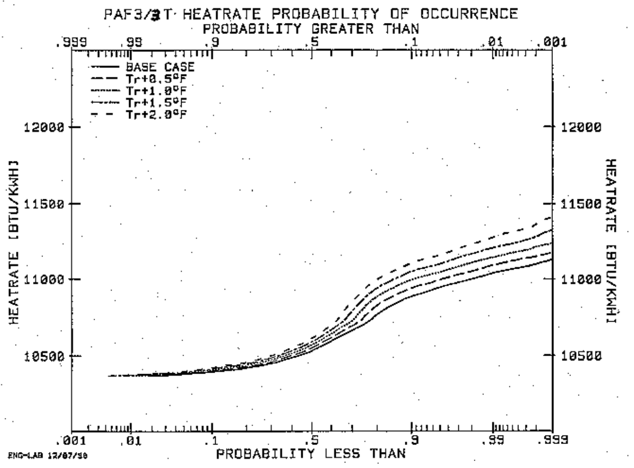

Figure 7. Heat Rate Probability of Occurrence without Environmental Regulations

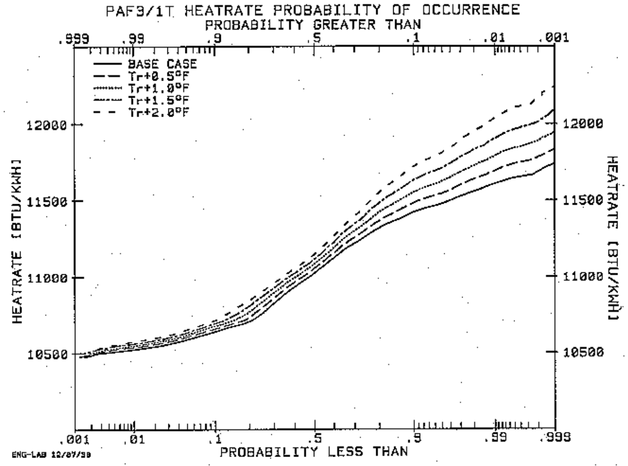

Figure 8. Heat Rate Probability of Occurrence wit Environmental Regulations

Unit 3 increases from 50 to 54 GWHR in 1979 and 58 to 103 GWHR in 1986 when the environmental regulatory constraints are added to Units 1 and 2.

CONCLUSIONS

Due to the nonlinear behavior of power plants, a linear and/or non-iterative analysis cannot accurately model the response of a plant to changes in the environment. Furthermore, a model which neglects the constraints, such as mechanical and environmental regulatory, cannot be expected to reveal the vulnerability of a plant to changes in the environment and environmental regulations. A model has been developed which includes these considerations and is practical in its complexity. The model is capable of handling complex circulating water systems, multiple units, and multiple cooling modes. The vulnerability of the selected plant in terms of lost load to changes in the historical environment has been computed to be on the order of 4 to 6 million dollars per year. The cost of meeting environmental regulatory constraints on thermal discharges has been computed to be on the order of 1 to 6 million dollars per year.

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