AN OPERATIONAL PROCEDURE FOR PREDICTING THE MOST ECONOMICAL USE OF CONDENSER COOLING MODES

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ABSTRACT

A technique is presented for estimating the most economical use of the cooling towers at the Tennessee Valley Authority (TVA) Browns Ferry Nuclear Plant while complying with the applicable thermal water quality standards of the State of Alabama. This plant is designed to operate in either of three condenser cooling modes: Open Cycle in which the condenser cooling water is discharged directly into the river through submerged diffusers; Helper Mode in which the cooling water is routed through the cooling towers prior to being discharged into the river through the diffusers; and Closed Cycle in which the cooling tower effluent is returned to the intake for reuse as condenser cooling water. The energy required for pumping and the loss of plant operating efficiency is minimized by computing the least amount of cooling tower operation required for each hour to comply with the Alabama thermal standards for the Tennessee River.

The procedure requires projections for the heat transfer rate from the condenser to the cooling water, the rate of cooling from the cooling towers, and the dispersion of heated effluent in the river. Plant performance curves and projected generating levels are used to estimate the condenser heat disposal rate. Cooling tower performance estimates, projected meteorology, and incoming water temperatures are used for estimating cooling tower effluent temperatures. Projected operation of upstream and downstream hydroelectric plants is used to compute river flows in the vicinity of the diffuser. These flows, along with upstream ambient river temperature, the temperature of the effluent, and results of laboratory and theoretical investigations of diffuser-induced mixing are used to compute the downstream temperature in the river. This program is used daily by the personnel of the Browns Ferry Nuclear Plant to predict the most efficient cooling mode for each hour throughout the following 24 hour period.

INTRODUCTION

TVA's Browns Ferry Nuclear Plant, situated on Wheeler Reservoir of the Tennessee River in north Alabama (Figure 1), was designed to generate 3456 MW. This plant was originally designed to operate in Open Mode for condenser cooling. In this mode, the plant pumps 4410 cubic feet per second (cfs) of water from the river and through the steam condenser where the cooling water is heated approximately 25°F before being discharged through submerged multiport diffusers in the river.

The river flow past the submerged diffuser is primarily determined by the discharges from Wheeler Dam 19 miles downstream and Guntersville Dam 55 miles upstream of the nuclear plant. The mean annual flow rate of the river is 45,000 cfs. Since discharges from these dams are normally used for hydroelectric generation at periods of peak power demand, the flow in Wheeler Reservoir is often unsteady. As a result, flows near the plant site usually change drastically throughout the day and may, for an hour or so, reverse due to a "sloshing" effect of the reservoir. During such periods of low flow, there is an insufficient supply of cool river water available for mixing with the diffuser discharge; consequently, compliance with the thermal water quality standards is not possible when operating in the Open Mode of condenser cooling during low flows. These water quality standards permit a maximum plant-induced mixed temperature rise of 5°F and a maximum downstream temperature of 86°F. TVA maintains three permanent water temperature monitors downstream of the mixing zone of the diffusers to demonstrate compliance with these standards.

After delineation of the possible environmental consequences of this method for disposing of the excess heat from the condensers, and later the enactment of the thermal water quality standards, the nuclear plant was retrofitted with six mechanical draft cooling towers, two per unit. This provides the plant operators with the option of cooling the condenser cooling water when the thermal discharge of the Open Mode can contribute to a violation of the thermal standards. The effluent from the cooling towers can either be routed to the diffusers for discharge into the river (Helper Mode), or routed to the plant intake channel for reuse as condenser cooling water (Closed Mode). These three possible modes of operation of the Browns Ferry Nuclear Plant cooling system are illustrated in Figure 2.

This paper describes a computer model for analyzing the heat rejection rate of the plant and the pertinent meteorological and river conditions for the purpose of advising the plant operators of the most economical method of routing the condenser cooling water while assuring compliance with the thermal water quality standards.

FACTORS INFLUENCING CHOICE OF COOLING MODES

The possible environmental consequences of thermal discharges are well documented and the thermal water quality standards were promulgated to prevent adverse effects upon the aquatic ecosystem. The environmental advantages between the Open and Helper Modes are variable; the discharge rates are comparable, 4410 cfs for Open Mode versus 3675 cfs for Helper Mode. However, the discharge temperature for the Helper Mode, which depends upon meteorology, is normally cooler than that of Open Mode.

The discharge rate for Closed Mode is only about 110 cfs; therefore, the discharge during Closed Mode has a negligible effect on the downstream temperature of the river.

The environmental effects of plant intakes are also of concern. Fish may be trapped within intake structures or canals and become impinged against the intake screens. Fish too small to be impinged on the intake structures may be entrained into the cooling system of the plant. Although impingement and entrainment of fish must be evaluated for each plant, the number of fish affected is usually proportional to the flow rate of condenser cooling water pumped from the river. Therefore, the environmental effects at the plant intake are approximately the same for Helper Mode and Open Mode operation. The Closed Mode of operation is superior with respect to intake environmental effects since only a small quantity of water (approximately 220 cfs) is pumped from the river for "makeup."

The cooling tower lift pumps, fans and peripheral equipment require approximately 56 MW for normal operation. This is power which would be included in the net output of the plant in Open Mode, but which must now be obtained from other sources. In Closed Mode, there is an additional loss of net power generated due to the decreased efficiency which results from increased cooling water temperature. The precise loss in efficiency varies as a function of meteorology, but a conservative estimate of this loss, based on a Carnot cycle, is one percent of total generation or 35 MW. This results in a total loss of 91 MW in Closed Mode.

The cost of the power required to recover these losses varies with the source from which the power is obtained. The additional expense of Helper and Closed Mode operation will range from $560 per hour to $3,640 per hour or more, depending upon the source of the replacement power. This does not include depreciation of the cooling tower pumps, fans, etc. It is obvious, therefore, that unnecessary cooling tower operation can result in considerable cost to TVA and its consumers.

The relative environmental and economic advantages and disadvantages of each mode of cooling system operation are summarized in Table 1.

PROGRAM PARAMETERS AND COMPUTATIONS

The mixed temperature in the river downstream of the plant depends upon the performance of several subsystems of the plant cooling system. These will be discussed individually.

Temperature Increase Across Condensers

The condenser rise was determined by calibration tests which equated heat rejection (BTU/sec) with plant generation levels (MW). For a known condenser flow rate, the increase in temperature was easily computed.

Cooling Tower Performance

The cooling tower effluent temperature is primarily a function of the wet bulb temperature of the air and the temperature of the hot water from the condenser. The wet bulb temperature is computed from the dry bulb temperature and the dew point. An example of the tower performance curves is presented in Figure 3.

Multiport Diffuser Mixing

The mixed temperature of the river downstream of the plant depends upon the flow rate and temperature of both the thermal discharge and the river. The discharge conditions depend upon the mode of cooling and the condenser and, if applicable, cooling tower performance.

River flows over the diffuser are computed with a one-dimensional, unsteady finite-difference flow model. Hourly releases from Guntersville and Wheeler Dams are input as boundary conditions. A water temperature monitor [Ref. 1] upstream of the plant provides an ambient river temperature at initiation of a computer run. Subsequent river temperatures are computed by superimposing a statistical diurnal and annual cycle.

The mixing induced by the high velocity (approximately 10 ft/sec) jets of the submerged multiport diffuser is highly dependent upon the flow rate in the river. Model studies of this diffuser [Ref. 2] and theoretical techniques for this general class of diffuser [Ref. 3] were used to generate diffuser mixing curves such as those presented in Figure 4.

OPERATION OF THE COMPUTER MODEL

The computer program is used daily by personnel of the TVA Load Control Center in Chattanooga, Tennessee, to predict the optimum mode of cooling for the following 24 hours at the Browns Ferry Nuclear Plant. As input, the program uses ambient river temperature and projected hourly values of (a) Browns Ferry Nuclear Plant generation (MW); (b) flow releases from Guntersville Dam; (c) flow releases from Wheeler Dam; and (d) air temperature and dew point. The program uses these inputs to compute the mixed temperature in the river downstream of the diffusers for each of the following 24 hours. For each hour, computations are first performed for the most economical mode (Open Cycle), but if the thermal water quality standards cannot be satisfied, the program automatically cycles to Helper Mode and finally to Closed Mode if necessary. A flow chart for this computer program is presented in Figure 5.

Predicted mixed downstream river temperature, plant-induced heating and recommended cooling modes for each of the next 24 hours are transmitted to the operators at the Browns Ferry Nuclear Plant. Within practical limits, the nuclear plant operators follow these recommendations. If it is necessary to deviate significantly from any of the projections, the program is rerun to determine if changes in the recommended mode of cooling are required.

Table 2 presents typical results of a computation during a period of low river flows. Releases from Guntersville Dam varied between 0 and 45,000 cfs and releases from Wheeler Dam varied between 0 and 58,000 cfs. The resulting flows near the Browns Ferry Nuclear Plant were quite unsteady, as shown in Table 2. The net generation of the plant was a constant 2900 MW throughout this period. Predicted mixed temperatures (T_M) and plant-induced temperature rises (ΔT_M) in the river immediately downstream of the diffuser correspond to the mode of cooling recommended for that particular hour.

The column showing the approximate cumulative cost incurred by cooling tower operation during this period is not included in routine computations. These costs are based upon purchasing this power from outside utilities at an estimated rate of $40 per MW-hr. At those rates, the total cost of operating the towers for the minimum time suggested was $23,000. Without a sophisticated computation scheme of this type, it is likely that the cooling system of this nuclear plant would be operated in the Closed Mode throughout most of this 24-hour period. The cost of Closed Mode cooling for 24 hours at the maximum estimated rate is $87,000. However by using this predictive technique, TVA could effect a savings of as much as $64,000 while placing no undue thermal stress upon the aquatic ecosystem of the Tennessee River.

CONCLUSIONS

The condenser cooling system of the TVA Browns Ferry Nuclear Plant is designed to operate in three modes: Open, Helper and Closed. Open Mode discharges the cooling water directly to the river; Helper Mode routes the cooling water through cooling towers prior to discharge; and Closed Mode recycles the cooling tower effluent to the intake for reuse in condenser cooling.

Much of the time the plant can operate in the Open Mode without violating the thermal water quality standards and overstressing the aquatic ecosystem. However, because the river flows near the plant are often unsteady as a result of releases from upstream and downstream hydroelectric plants, the Helper and Closed Modes must be used periodically. The power required to operate these towers, and, for the case of Closed Mode, the loss in plant efficiency resulting from warmer temperatures of condenser cooling water, dictate that the cooling towers should be operated no more than necessary to protect the environment.

The factors influencing the choice of cooling mode are complex and include computations of heat rejection rate of the condenser, cooling tower performance, river flow and temperature, and submerged diffuser mixing. A computer program has been developed which analyzes hourly projections of plant generations, river flows, ambient river temperatures, and meteorology for the following 24 hours, and predicts the most efficient mode of cooling which will assure compliance with the thermal water quality standards for each hour. This program is run daily at TVA's Load Control Center in Chattanooga and results are transmitted to the Browns Ferry Nuclear Plant. An example of a typical 24-hour operation demonstrated that using the cooling towers only when necessary could save as much as $64,000 per day when compared with Closed Mode cooling for the same period. This was accomplished without violating the thermal water quality standards.

TABLE 1: RELATIVE ENVIRONMENTAL AND ECONOMIC IMPACT OF THE THREE COOLING MODES

Cooling Mode	Power Loss Due to Cooling Tower Operation	Cost to Replace Lost Power		Relative Aquatic Environmental Impact	
		Within TVA @$10/MW-hr	Outside TVA @$40/MW-hr	Intake	Discharge
Open	0	0	0	xx	xx
Helper	56 MW	$560/hr	$2240/hr	xx	x
Closed	91 MW	$910/hr	$3640/hr	--	--

TABLE 2: PREDICTED RESULTS FOR TYPICAL
24-HOUR OPERATION OF THE BROWNS
FERRY COOLING SYSTEM

Hour	River Flows (cfs)	Tm (°F)	ΔTm (°F)	Cooling Mode	Cumulative Estimated Cost (Dollars)
1200	33,650	38.8	2.6	Open	0
1300	28,899	39.3	3.0	Open	0
1400	19,543	40.8	4.5	Open	0
1500	17,221	39.8	3.4	Helper	0
1600	15,147	40.5	4.1	Helper	$ 2,240
1700	25,034	40.0	3.5	Open	4,480
1800	29,313	39.5	3.0	Open	4,480
1900	35,668	39.0	2.5	Open	4,480
2000	30,422	39.4	2.9	Open	4,480
2100	30,028	39.4	3.0	Open	4,480
2200	26,825	39.7	3.3	Open	4,480
2300	24,204	40.0	3.7	Open	4,480
2400	17,315	39.1	2.9	Helper	6,720
0100	12,361	40.2	4.0	Helper	8,960
0200	10,121	36.3	0.2	Closed	12,600
0300	8,571	36.4	0.4	Closed	16,240
0400	12,591	40.0	4.2	Helper	18,480
0500	18,098	38.7	2.9	Helper	20,720
0600	18,384	38.9	3.1	Helper	22,960
0700	34,005	38.5	2.7	Open	22,960
0800	41,125	38.1	2.2	Open	22,960
0900	43,226	38.0	2.0	Open	22,960
1000	39,272	38.3	2.2	Open	22,960
1100	39,981	38.4	2.2	Open	22,960
1200	40,728	38.4	2.2	Open	22,960

REFERENCES

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3. Jirka, G. and D.R.F. Harleman, "The Mechanics of Submerged Multiport Diffusers for Buoyant Discharges in Shallow Water," MIT. Report No. 169, Cambridge, MA. March 1973.

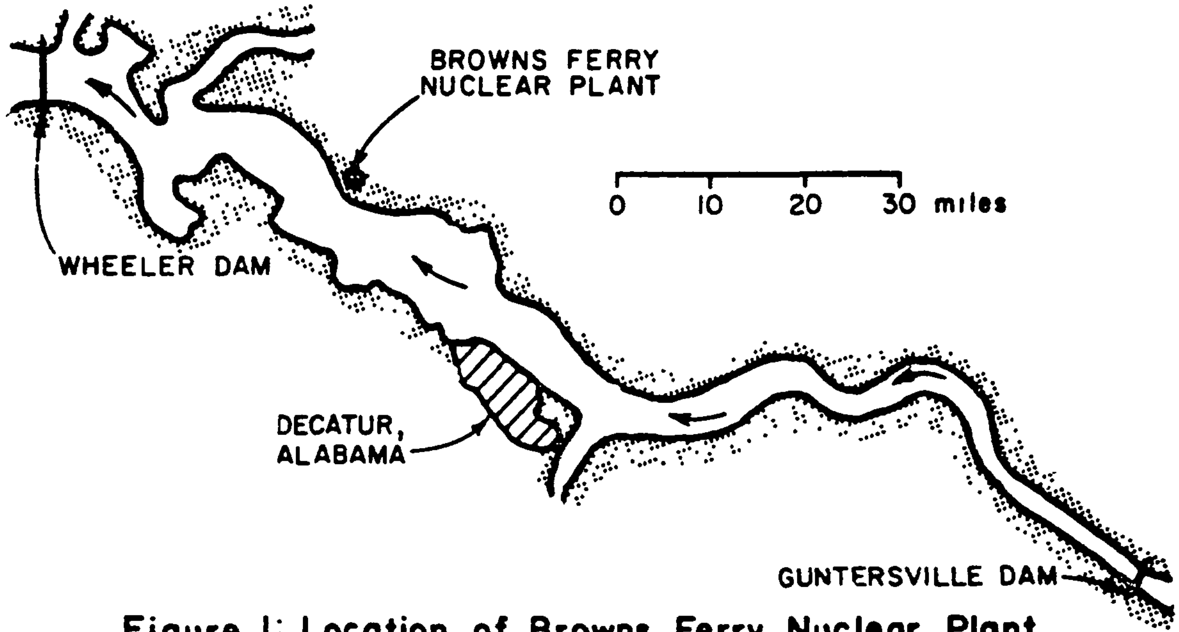

Figure 1: Location of Browns Ferry Nuclear Plant

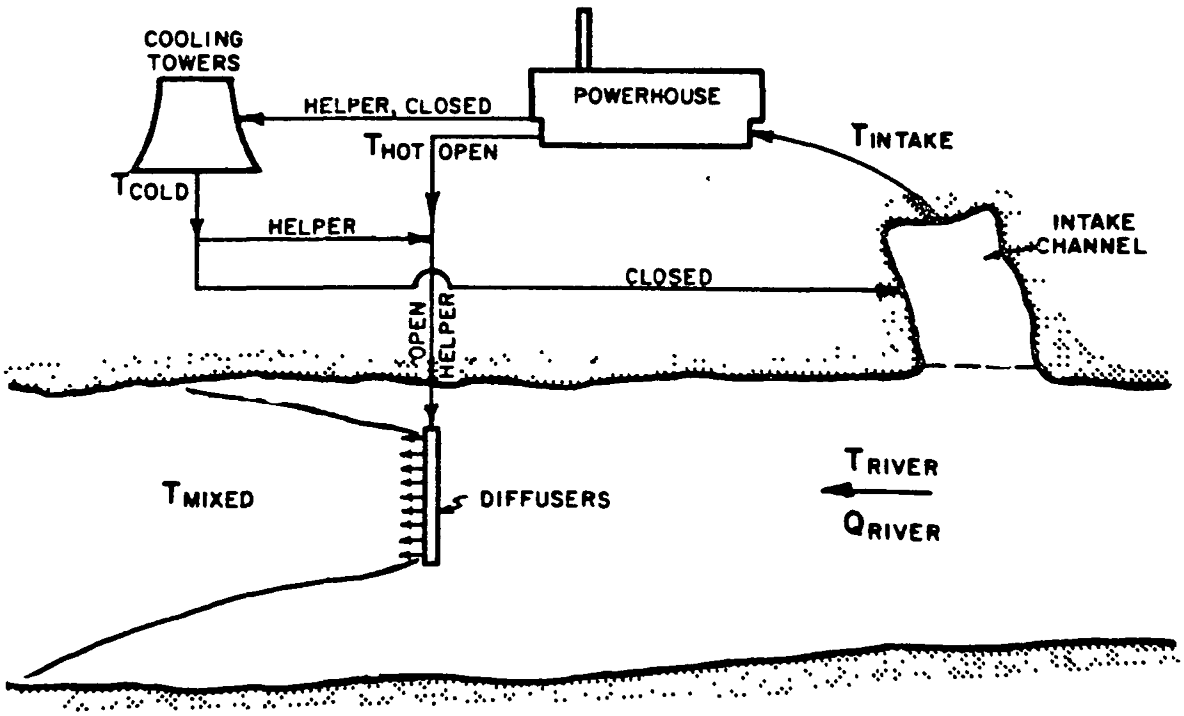

Figure 2: Schematic of Three Condenser Cooling Modes of Browns Ferry Nuclear Plant

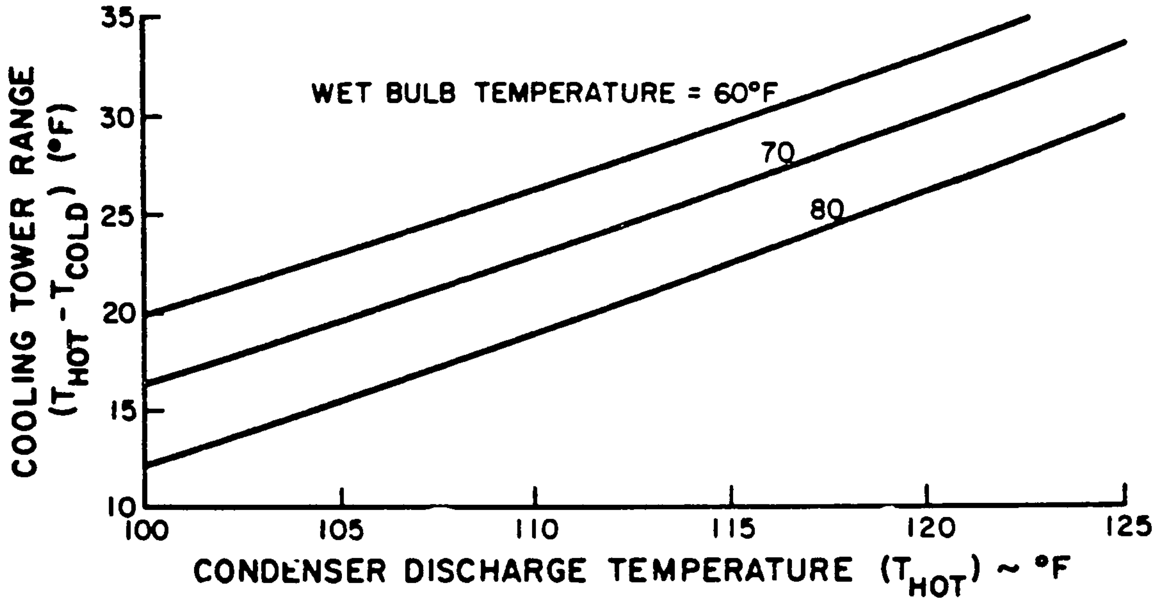

Figure 3: Cooling Tower Performance at Design Flow Rate

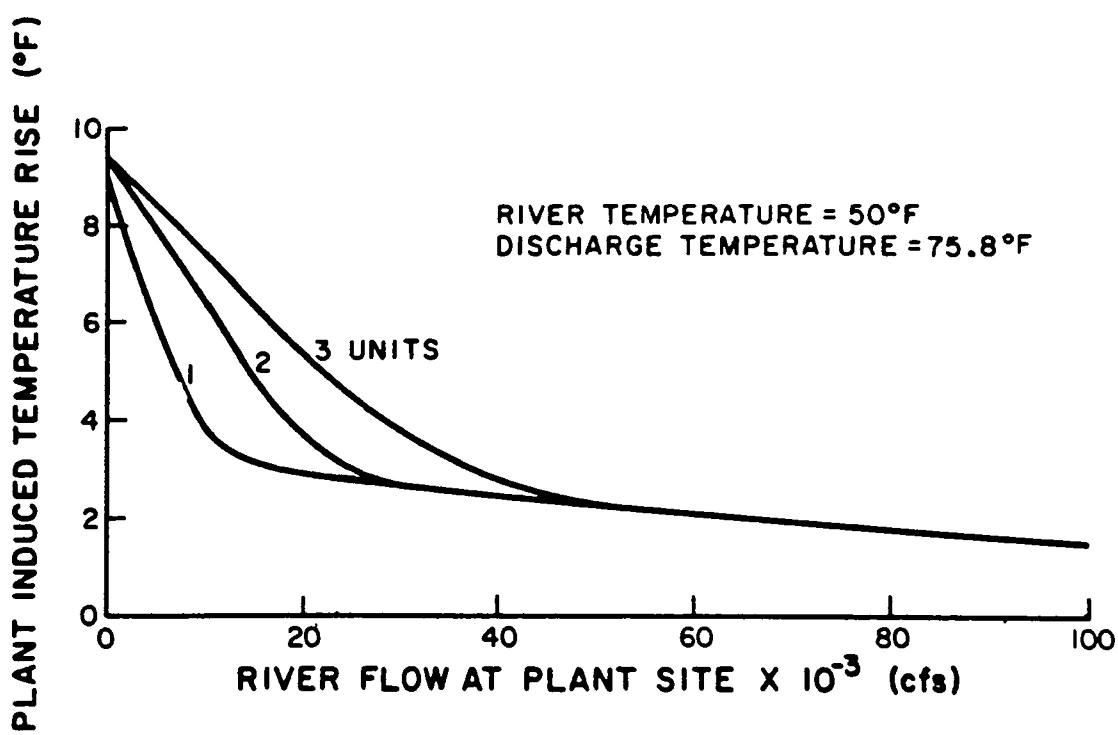

Figure 4: Mixed Temperature Increase Downstream of Diffuser

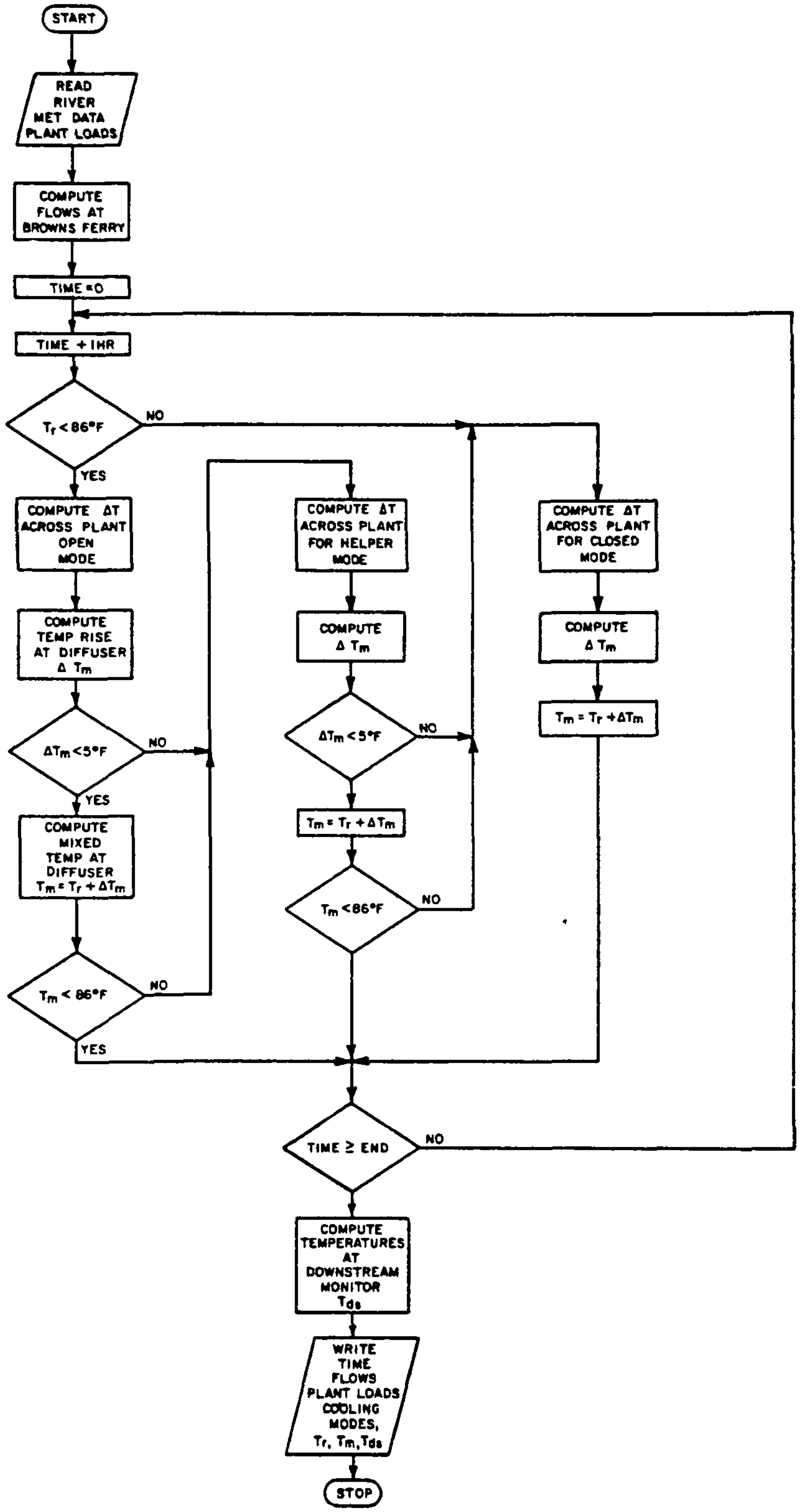

Figure 5: Flow Chart of Browns Ferry River Temperature Rise Prediction Program