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Large quantities of heat to be rejected by future generating stations must be discharged in such a way that the ecology of the receiving waters is not unduly disturbed. Although the logic of this objective is unquestionable, the expense involved in meeting the stated criteria is considerable. Considering the magnitude of the investment involved, extensive analyses of all possible solutions for each project is imperative. Plant location and water quality standards for a particular location make the heat rejection problem associated with each large steam plant unique. Water temperatures and flows at a site may have a significant effect on the possible solutions. Overall economics are almost always overwhelmingly against cooling towers but, if there is inadequate cooling water flow available, if the maximum temperature of the inlet cooling water is extremely high, or if the water quality standard is restrictive, cooling towers of some sort may be the only solution. If no special considerations other than water quality are predominant, however, the system with the lowest total present worth evaluated at the date of initial operation should be selected. If the most economic solution which meets all requirements is to design the condenser for a limited rise, the condenser geometry will be dictated to a great degree by the maximum inlet circulating water temperature and the water quality standards.

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W. W. AVRIL **C. F. BOWMAN**

INTRODUCTION

Economic justification of large single or multiunit fossil generating stations and nuclear units with their lower efficiencies has produced a heat-rejection problem, sometimes termed thermal pollution, which results when the heat rejected from a generating station is sufficiently large to upset the ecology of the receiving waters. The ecology or biological relationship between the organisms in the river, reservoir, or bay which may serve as the heat sink, and their environment is affected by excessive water surface temperatures, an excessive rise in the average temperature after reasonable mixing, or extremely sudden localized changes in temperature. In the interest of conservation and to conform to the requirements of the state or other agencies in which the generating station is located, the electric utility industry must employ some solution to the heat-rejection problem. The State of Tennessee has submitted the following water quality standards to the Federal Water Pollution Control Administration for receiving waters outside the mixing zone:

1 A maximum temperature of 93 F
2 Not more than 10 F rise at any time
3 A maximum temperature change rate of 3 F/hr (not considered to be pertinent to the system design)

To comply with these standards in designing the two coal-fired, 1300-mw, 3500 psig, 1000/1000 F TVA Cumberland Steam Plant units now under construction at Cumberland City, Tennessee, the following solutions were considered:

Scheme 1

Natural Draft Cooling Towers—Closed loop wet-type cooling towers.

Scheme 2

Mechanical Draft "Helper" Cooling Towers—To cool a part of the discharge as required to hold mixed river temperature to an acceptable limit.

Scheme 3

Discharge Diffuser System—Design condenser for high temperature rise and provide diffuser pipes laid on the river bottom to thoroughly mix the station discharge water with the receiving waters.

Scheme 4

Variable Condenser Flow—Design condenser for the lower limit of tube velocity and a fairly high temperature rise through the condenser during normal operation and provide additional circulating water pumps which may be operated to increase the flow through the condenser and reduce the rise as required to keep from exceeding the maximum discharge temperature during the time of abnormally high inlet water temperatures.

Scheme 5

Bypass Dilution System—Design condenser for approximately same temperature rise as scheme 4 normal operation but provide an additional bypass pumping system to circulate water around the condensers to mix with the hot water before discharge to the river as required to hold the outlet temperature to an acceptable limit.

Scheme 6

Large Flow Limited Rise System—Size the condenser such that the rise through the condenser will not cause the discharge temperature to exceed the maximum acceptable, and river flow past the plant will dilute and hold overall rise to acceptable limit.

MOST ECONOMIC SOLUTION

In the absence of other limitations, the system with the lowest total evaluated present worth should be selected based on proper evaluation of all factors. Considerations such as labor costs, auxiliary power requirements, interest rate, capacity factor, heat rate and capability, and

Table 1

Scheme 1	$7,771,000
Scheme 2	5,700,000
Scheme 3	Not Evaluated
Scheme 4	418,000
Scheme 5	Base
Scheme 6	258,000

site location have a significant effect on the cost of factors considered and make each study unique. Four factors must be considered in each of the proposed solutions in varying magnitude, in addition to other factors which apply only to a particular solution. These factors are:

1 Initial installed cost of the unit condenser
2 Present worth of circulating water pumping power
3 Present worth of unit heat rate and capacity correction as a function of condenser back pressure
4 Initial installed cost of circulating water pumping system including pumps, pumping station, valves, and intake and discharge tunnel.

The two cooling tower schemes (1 and 2) must include, of course, in addition to the four basic factors, the first cost of the cooling towers and maintenance. The evaluation of scheme 3 with the discharge diffusing system must include the cost of the diffusing conduit. The cost of the additional circulating water pumps, valves, and pump stations must be included in the variable condenser flow scheme 4, and the additional cost of the circulating water tunnel bypass around the condenser, together with the additional pumps, valves, and pump stations, must be considered in the evaluation of scheme 5. No factors, in addition to the basic four, need to be considered with the limited rise scheme 6.

Table 1 shows the relative evaluated differential costs per unit of the six schemes considered.

The high first cost of the cooling towers, greater pumping power due to the high head requirements, and the associated higher condenser back pressure remove both cooling tower schemes from consideration. The evaluated present worth of the remaining four schemes were of the same order of magnitude. The discharge diffusing system (scheme 3) was rejected and therefore not evaluated because the physical characteristics of the river channel at this site was not suitable for installation of diffuser pipes. The economic evaluation favored scheme 5 slightly over scheme 6, but the difference was not large enough to dictate the final decision. Schemes 4 and 5 were not selected because, during a large part of the year, circulating water heated considerably above the inlet water temperature, would be returned to the river, and would, due to the narrow river at the site, require a mixing zone of considerable length which could cover the entire width of the river. The last solution, designing the system for a low rise through the condenser, was selected as a reasonable compromise between economic evaluation and prudent design to satisfy the proposed water quality requirements of the State of Tennessee.

Table 2

	BFPT Condenser	FDFT Condenser
Circulating water booster pumps	No	Yes
Passes	One	Two
Circulating water flow rate, gpm	49,000	4000
Surface area, sq ft	12,700	3850
Tube diameter, in.	1	3/4
Tube length, ft	13.0	18.0
Tube velocity, fps	6.6	7.0

AUXILIARY TURBINE CONDENSER DESIGNS

Analysis of the six schemes proposed was based on the assumption that each unit's entire heat rejection would be removed by one condenser. The unit has two boiler feed pump turbines and three forced-draft fan turbines, each of which discharges into a separate condenser. Having determined the amount of flow required to maintain a given temperature rise through the entire unit, the flow split between the main and auxiliary condensers must then be determined.

Need for supplementary circulating water pumps was determined by the physical proximity of the auxiliary condensers to the main condenser. A simple analysis, comparing the installed cost of piping to the cost of pumps and pumping power, was performed which indicated that the circulating water to the fan turbine condensers would be pumped; however, the boiler feed pump turbine condensers would not require booster pumps but be in parallel with the main condenser. Once the pumping question was settled, the optimum auxiliary condenser arrangement was determined by considering the following factors:

Table 3

Circulating water flow rate, gpm	808,000
Surface area, sq ft	404,000
Tube diameter, in.	$1^1/4$
Tube length, ft	35
Tube velocity, fps	7.0

1 The auxiliary condenser cost
2 The auxiliary turbine back pressure effect on the main unit heat rate and capability
3 The cost of the circulating water conduit to and from the auxiliary condensers
4 The effect of the auxiliary condenser size on both the cost of the main condenser and the back pressure in the main condenser. (Since, for a given rise, the total flow through the unit is fixed, circulating water to the auxiliary condensers is, therefore, flow unavailable to the main condenser.)
5 The cost of circulating water booster pumps and motors
6 The value of pumping power

Preliminary analyses of condenser configurations confirmed that the fan turbine condensers, which are in parallel with the main condensers and require booster pumps, should be of the two-pass design. The boiler feed pump turbine condensers, which are also in parallel with the main condensers but with no booster pumps, were required to be of the single-pass design. It was also shown that the back pressure in the auxiliary condensers is a predominant factor which has a constant optimum value for all condenser geometries; therefore, the back pressure was fixed at its optimum value. An array of tube diameters, velocities, and length combinations were selected from which the rise through the condenser, surface area required to produce the optimum back pressure, and corresponding evaluated present worth were calculated. The circulating water conduit to the boiler feed pump turbine condenser was sized so that the total pressure drop in the conduit and the condenser from the point where it exits from the main circulating water tunnel to the point where it reenters the water tunnel is equal to the pressure drop through the main condenser and piping. The final configurations for each auxiliary condenser, Table 2, were selected based on the lowest evaluated present worth.

Flow to the main condenser is equal to the total required flow less the flow to the auxiliary condensers and other station cooling requirements. With the flow to the main condenser established

Table 4

Paradise Steam Plant 1 and 2	River flow and cooling tower
Paradise 3	Cooling tower (closed circuit)
Browns Ferry Nuclear Plant 1-3	Diffuser
Sequoyah Nuclear Plant Units 1 and 2	Diffuser

for a given rise, the optimum condenser geometry may be determined.

OPTIMUM CONDENSER GEOMETRY

An analysis of the available reservoir temperature data was performed to determine the average and maximum inlet water temperatures for design purposes, and from the turbine manufacturer's maximum expected heat balance, the expected heat rejection was calculated. With this information available, a computer program was written to determine the total evaluated present worth of an array of possible condensing arrangements including tube velocities from 6 to 8 fps, tube diameters from 3/4 to $1^1/2$ in., tube lengths from 35 to 45 ft, and condenser back pressures from 1.2 to 2.2 in. Hg for both stainless-steel and admiralty metal tubes. For a given combination of these parameters, the rise through the condenser, the required circulating water flow rate through the unit, and the required surface area of the condenser was calculated. With these values and price information on condenser shells and tubes, a heat rate and capacity correction curve from the turbine manufacturer, an evaluation cost for auxiliary power, and an estimate of the cost of the circulating water pumping system as a function of flow, the total evaluated present worth of each combination of parameters was determined by the computer calculation. The evaluated present worth for each combination of tube velocity, diameter, and length was plotted as a function of circulating water flow (which is a direct function of back pressure). Figs.1 and 2 show plots of evaluated present worth versus circulating water flow for a sample of possible combinations for admiralty metal and stainless-steel tubes, respectively. Smaller diameter, longer tubes at lower velocities were found, in general, to be more attractive at lower flows; while at high flows, large, short tubes at higher velocities were found more attractive. For a given flow, the optimum tube diameter is smaller for stainless steel than for admiralty metal. Dis-

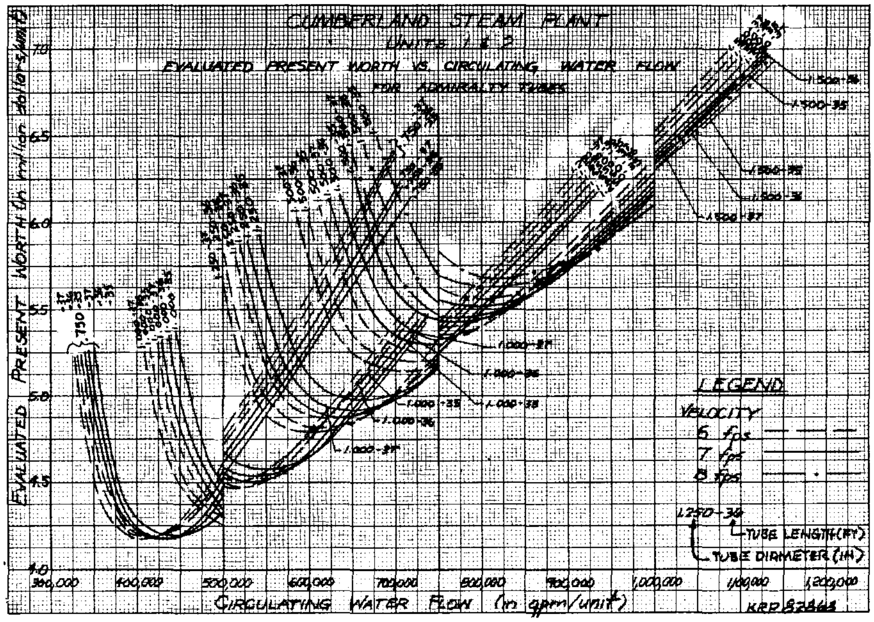

Fig.1

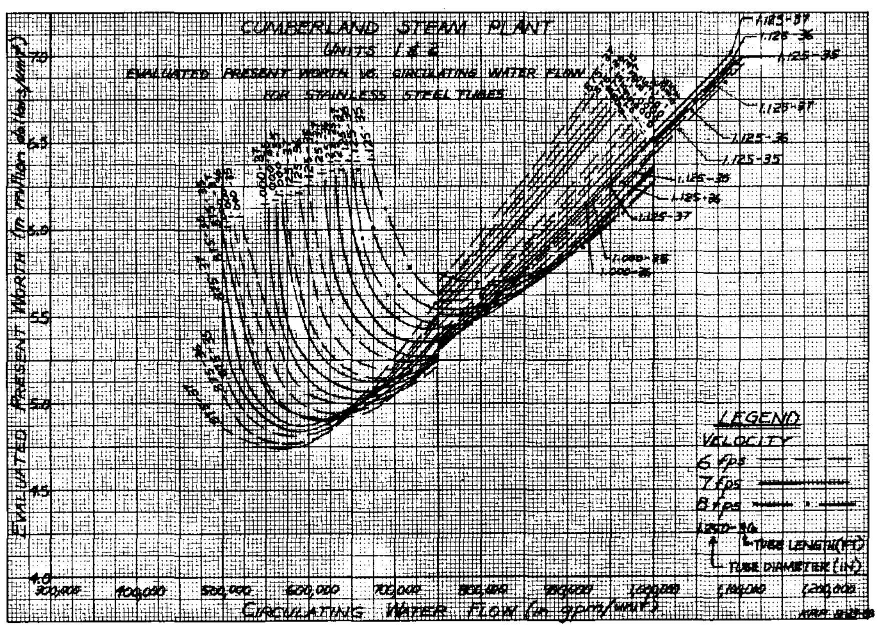

Fig.2

continuities result from increasing the number of circulating water pumps. Fig.3 shows the locus of lowest evaluated present worth of the various combinations as a function of flow for both admiralty and stainless-steel tubes. Admiralty tubes were selected not only because the evaluation is slightly lower for all flows, but also because TVA has had generally very satisfactory service experience with admiralty tubes in similar water conditions and has experienced poor results with stainless-steel tubes in some trial installations. Since for a given circulating water temperature rise the flow to the main condenser is known, one can immediately select the combination of parameters which requires the lowest evaluated present worth from Fig.1.

The final configuration for the main condenser is given in Table 3.

CONCLUSIONS

Large quantities of heat to be rejected by future generating stations must be discharged in

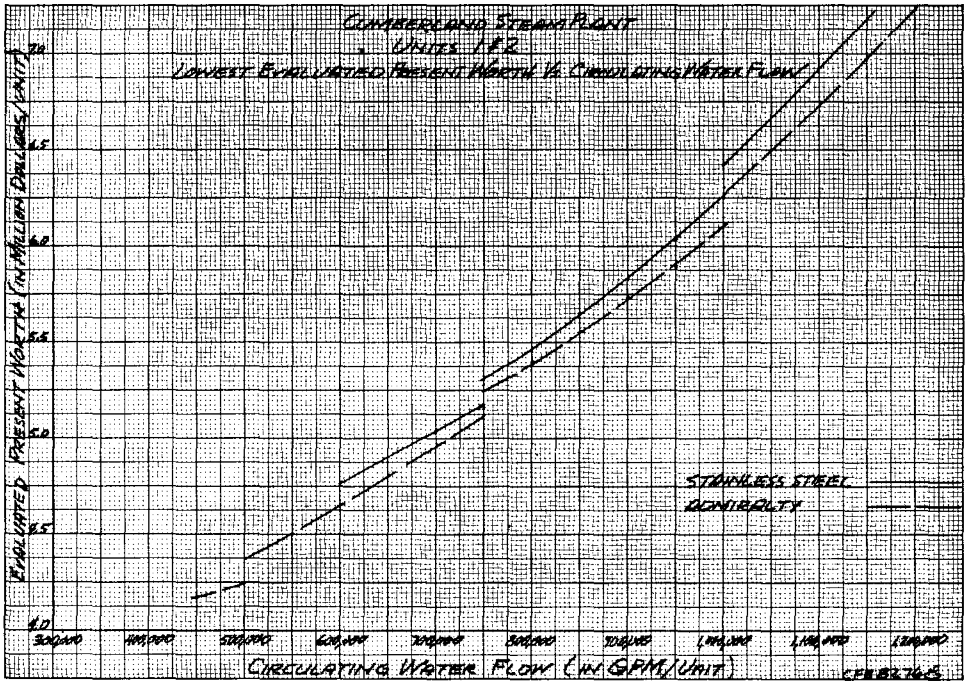

Fig.3

a way such that the ecology of the receiving waters is not unduly disturbed. Although the logic of this objective is unquestionable, the expense involved in meeting the stated criteria is considerable. An estimated additional $4,000,000 in capital costs and evaluated operating costs will be spent by TVA for the two units at Cumberland City to ensure that the ecology of the Cumberland River will not be disturbed. Considering the magnitude of the investment involved, extensive analyses of all possible solutions for each project is imperative.

Plant location and water quality standards for a particular location make the heat-rejection problem associated with each large steam plant unique. Water quality standards may preclude the use of one or more of the solutions considered for Cumberland, may create special considerations which will make one solution more attractive than another without regard to the economics, or may permit some solution not here considered. For example, other large units on the TVA system, Table 4, have been designed.

Water temperatures and flows at a site may have a significant effect on the possible solutions. Overall economics are almost always overwhelmingly against cooling towers; but if there is inadequate cooling water flow available, if the maximum temperature of the inlet cooling water is extremely high, or if the water quality standard is restrictive, cooling towers of some sort may be the only solution. If no special considerations other than water quality are predominant, however, the system with the lowest total present worth evaluated at the date of initial operation should be selected.

If the most economic solution, which meets all requirements, is to design the condenser for a limited rise, the condenser geometry will be dictated to a great degree by the maximum inlet circulating water temperature and the water quality standards.