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Project Summary

Executive Summary for Power Plant Cooling System Water Consumption and Nonwater Impact Reports

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This executive summary contains salient features of three studies performed by United Engineers & Constructors Inc. (UE&C) and Versar, Inc. to aid EPA in assessing water consumption and other nonwater quality environmental impacts of cooling systems used by the steam-electric generating industry. After an introduction followed by a summary and major conclusions from the reports, important details and data serving as bases for major conclusions are condensed separately in a section for each report.

The two reports on water consumption agree that the Leung-Moore model satisfactorily predicts evaporation rates of evaporative cooling towers. Versar found that this model predicted evaporation rates at base-load plants within ±15 percent of material balance values based on plant data. UE&C addressed the Harbeck and Brady models for predicting evaporation rates from cooling ponds and (using available data) could not reach a definite conclusion on which model predicted evaporation more closely. Comparing predictions from five models, including the Harbeck and Brady models, Versar concluded that the Harbeck-Koberg-Hughes and Meyer models predicted evaporation rates for five of six cooling ponds studied within ±15 percent of material balance values and appear suited to preliminary studies. UE&C concluded that limited data precluded general conclusions on drift effects from saltwater cooling towers, but that cooling tower drift and deposition apparently do not increase ambient salt loading to an extent that a significant impact has been observed or is expected. Similarly, the effects of wet cooling tower and stack plume interactions on acid rain formation and deposition could not be established from available information.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Three studies were performed by two contractors to assist EPA's Effluent Guidelines Division in addressing the water consumption and nonwater quality environmental impacts of cooling system options available to the steam-electric generating industry. Reports for these studies, listed below, addressed issues which the court (in remanding effluent guidelines for the steam-electric generating industry, point source category) instructed EPA to reconsider.

1. Water Consumption and Costs for Various Steam Electric Power Plant Cooling Systems (EPA-600/7-78-157, NTIS No. PB 285397) by M.C. Hu, G.F. Pavlenco, and G.A. Englesson, United Engineers & Construction Inc. (designated as the first UE&C study).
2. Nonwater Quality Impacts of Closed-Cycle Cooling Systems and the Interaction of Stack Gas and Cooling Tower Plumes (EPA-600/7-79-090, NTIS No. PB 80-102387) by G.A. Englesson and M.C. Hu, United Engineers & Constructors Inc. (designated as the second UE&C study).
3. Comparison of Model Predictions and Consumptive Water Use of Closed-Cycle Cooling Systems (EPA-600/7-78-206, NTIS No. PB 80-148273) by Jerome B. Strauss, Versar, Inc. (designated as the Versar study).

The results of these reports are[1] summarized in this Executive Summary to facilitate easy access to the salient features contained in these reports. The major conclusions are presented in this report, along with a summary which provides an overview of the methodologies, data bases, and conclusions of the three reports. The important details and data which provide the basis of the major conclusions drawn in the three reports are condensed in separate sections, one for each report.

Summary of UE&C Report: Water Consumption and Costs for Various Steam-Electric Power Plant Cooling Systems

General Description

The subject study reviewed and evaluated available information and assessed the state-of-the-art on the following subjects: (a) water consumption rates of various open- and closed-cycle cooling systems used by moderate and large capacity steam-electric generating stations in the U.S.; (b) costs of cooling system alternatives; (c) the estimated availability of water for all uses, and, in particular, for power plant water heat rejection in the various regions of the U.S.; and (d) the impact of regulatory guidelines on consumptive water use in the U.S.

The primary objective of the study was to better understand the water consumption aspects of power plant cooling systems as they may impact water availability for power generation and other uses. The literature search included papers and reports published since 1973.

Water Consumption* Rates of Cooling Systems

The literature review on water consumption revealed that two reports by Espey, Huston and Associates, Inc. (EH&A) and one by Hanford Engineering Development Laboratory (HEDL) contained comprehensive calculations of water consumption requirements of all the major cooling system alternatives for all 18 water resource regions in the conterminous U.S. Only one field study on a closed-cycle cooling pond was found in the literature. Preliminary results from the first phase of the concurrent Versar study, using unpublished field data supplied by utilities, were also reviewed.

The cooling system alternatives considered in the EH&A and HEDL studies included the open-cycle once-through cooling system and the closed-cycle cooling tower and cooling pond/lake systems. These studies emphasized the latter systems. A cooling tower was classified as: (a) a tower with or without a supplemental water reservoir for makeup supply, and (b) a tower with its blowdown retained for on-site disposal or a tower with its blowdown returned to its water resource. A cooling pond was classified as either a single-purpose pond or a multi-purpose pond. The former refers to a man-made pond used primarily for power plant cooling with other uses being incidental to its construction. The latter refers generally to a natural pond used for power plant cooling and other purposes such as recreation and flood control.

The water consumption rate of the cooling systems is calculated by equations which may include some or all of the following water consumption terms as appropriate: (a) forced evaporation loss; (b) natural evaporation loss; (c) blowdown; (d) uncontrolled release such as seepage, overflow, and drift loss; (e) local runoff inflow; (f) makeup water; and (g) precipitation impingement onto the cooling water surface. Forced evaporation loss is specifically attributed to the cooling process; whereas, natural evaporation exists whether the power plant is operating or not. Of these terms, the evaporation loss is the major component for calculating cooling system water consumption rates. It can be calculated with semi-empirical models simulating the operating behavior of various cooling systems.

The major differences between the EH&A studies and HEDL study, which provided the bulk of the calculated water consumption rates reported in this UE&C study, are: (a) the models used to calculate the cooling tower and cooling pond evaporation rates, (b) the assumed cooling tower blowdown rate as a percentage of the tower evaporation rate, and (c) the assumed precipitation which may be credited as local runoff to a pond/lake or impoundment. The details of these differences are summarized in Table 1. The evaporation prediction models used in these studies are briefly described below.

Evaporation Prediction Models

1. Cooling Tower Models

An evaporative or wet cooling tower is a device which cools hot water by heat exchange at the air/water interface. The process is primarily based on evaporation (latent heat of vaporization is absorbed by evaporating some water from the cooling liquid) with a small portion of sensible heat transfer. Because both the air and water flows are channeled through the tower, the physical process involved in the tower operation can be easily modeled to give reasonably accurate predictions of the forced oxidation rate, which dominates the natural evaporation.

*The water consumption of a power plant cooling system is defined as that portion of the water removed from and not returned to the surface water resources of a given area

Table 1. *Assumptions Used for Calculating Water Consumption of Cooling Towers and Cooling Ponds*

	Espey, Huston & Associates, Inc. (Document No 7775, September 1977)		Hanford Engineering Development Laboratory (HEDL-TME 76-82, September 1976)	
	Cooling pond	**Cooling tower**	**Cooling pond**	**Cooling tower**
1. Forced Evaporation Model	Harbeck (heat budget method)	Leung & Moore	Brady, Graves & Geyer (mass transfer analysis)	Merkel Equation
2. Storage Volume	No Change	N/A	No Change	N/A
3. Seepage	Neglected	N/A	Neglected	N/A
4 Precipitation (P)	Included for single purpose pond only but adjusted downward by runoff rainfall ratio	N/A	Included without any correction for runoff	N/A
5 Natural Evaporation (EN)	Included for single purpose pond only; data taken from mean annual lake evaporation	N/A	Included for manmade (single purpose) pond only	N/A
6. Forced Evaporation (EF)	Included	Included	Included	Included
7 Miscellaneous Plant Use Water	Neglected	Neglected	Neglected	Neglected
8 Ambient Conditions	Major city annual averages for dry bulb and wet bulb temperature and relative humidity in the region	Same as for cooling pond	Mean of monthly average temperatures	Same as for cooling pond
9 Wind Speed	Annual average wind speed adjusted to wind speed at 2 meters above water surface	N/A	Annual average	N/A
10. Blowdown (B)	Neglected	Case 1 = Neglected Case 2 = 25% of evaporation	5% of evaporative requirements	Same as for cooling pond
11. Pond Size	1 acre/MWe and 2 acres/MWe	N/A	1 acre/MWt and 3 acres/MWt	N/A
12. Water Surface Temperature	Same as average dry bulb temperature	N/A	Determined by iteration using the equilibrium temperature concept	N/A
13 Water Consumption (C) Equation Used	C = EN + EF - 1 (l-r) P (for single purpose pond) C = EF (for multipurpose pond)	C = EF + B (blowdown retained) C = EF (blowdown returned)	C = EN + EF - P (for single purpose pond) C = EF (for multipurpose pond)	C = EF + B (blowdown retained) C = EF (blowdown returned)
14. Cycles of Concentration/ Percent Blowdown	N/A	5/25% of evaporation loss	N/A	21/5% of evaporation loss
15. Capacity Factor	80% for calculating heat rejected annually by a 1000 MWe fossil fuel plant	Same as for cooling pond	80% for calculating heat rejected annually by a 1000 MWe fossil fuel plant	Same as for cooling pond
16 Effect of Elevation on Water Consumption	Neglected	Considered	Neglected	Considered
17. Cooling Range	Not specified	Not specified	Considered for the slug flow pond model only	Not specified

EH&A used the Leung-Moore model for calculating tower evaporation rates, given the tower heat rejection rate, wet bulb temperature, relative humidity, and elevation. HEDL used the Winiarski model which involves solving Merkel's equation to obtain tower performance and then using the performance data to calculate evaporation rate.

2. Cooling Pond Models

Heat from the pond surface is dissipated through evaporation, convection, conduction, and radiation. It is highly dependent on local meteorological conditions (solar radiation, dry bulb temperature, relative humidity or dew point, wind speed, and cloud cover).

Determining the evaporative loss of a cooling pond is considerably more complex than for a wet cooling tower, because quantitative estimates of evaporation for cooling ponds involve many parameters, making the modeling difficult. There are two basic approaches for estimating the forced evaporation from cooling ponds. The energy budget method, based on the First Law of Thermodynamics, accounts for all incoming, outgoing, and stored energy at the pond surface layer and enables the calculation of the energy available for evaporation. The mass transfer method is based on the Law of Conservation of Matter. Numerous models have been developed based on these approaches. The Harbeck model, based on the energy budget approach, was used by EH&A, while the Brady model, based on the mass transfer approach, was used by HEDL.

The Harbeck model is represented by a nomograph which gives the ratio of the heat energy input used for forced evaporation to the total heat energy input to the pond/lake as a function of the pond water surface temperature, with the 2-m wind speed as the only parameter. (Thermal loading of the pond, that is, heat rejection rate per unit pond surface area, need not be specified.) According to Harbeck, the pond water surface temperature required for the application of the nomograph can be considered approximately equal to the air temperature above the pond. Harbeck states that, in areas where ice cover does not occur, the average annual water surface temperature is usually slightly lower than the average annual air temperature because of the cooling effect of natural evaporation. The addition of heat by a power plant may cause the water surface temperature to more nearly equal the air temperature, unless the thermal load is large relative to the size of the lake. Harbeck also states that if large air/water temperature differences exist, the procedure using his nomograph becomes of questionable value* because of probable errors in the conducted energy term of the energy budget equation.

The Brady model and all other models based on the mass transfer approach fit the following general mass transfer equation:

$$E = A \cdot f(u) \cdot e_v \qquad (1)$$

where:

E = total evaporation rate,
A = pond surface area,
$f(u)$ = wind speed function, and
e_v = water vapor pressure potential for mass transfer between the saturated air at the pond water surface and the ambient air above.

*In the two studies reviewed by UE&C, EH&A used air temperatures as pond water surface temperatures when applying the Harbeck nomograph to calculate forced evaporation rates of cooling ponds No analysis was given concerning the validity of this assumption when high thermal loading ponds are considered in which large air/water temperature differences potentially exist. In responding to this question raised in the UE&C report after it was published, EH&A performed an analysis which was documented in an unpublished memorandum EH&A states that its analysis shows that the "Harbeck nomograph is a viable means of estimating forced evaporation for a cooling pond even at load levels in the EH&A report (i e , 1 and 2 ac/MWe)."

The Brady model requires an iterative procedure based on an equilibrium temperature concept for estimating the pond water surface temperature in order to determine e_v, given the heat rejection per unit pond surface area (often called pond thermal loading) and local meterological conditions (dew point, wind speed, and gross solar radiation).

HEDL used the Brady model to determine both the total evaporation rates and natural evaporation rates using estimated pond water surface temperatures and pond equilibrium temperatures, respectively. The forced evaporation rates were obtained by subtracting the calculated natural evaporation rates from the total evaporation rates. The natural evaporation rates used in the EH&A estimates were based on pan evaporation rates obtained from weather stations.

Water Consumption Rates of Cooling Systems

Tables 2 and 3 present a portion of the predicted water consumption rates of cooling towers and cooling ponds compiled in the UE&C study. These results are the basis of the observations and conclusions drawn in the study.

As indicated earlier, the predicted cooling system water consumption rates presented in the UE&C study were taken mainly from the EH&A and HEDL studies. The EH&A results are given as single values for each of the 18 water resources regions; whereas, the HEDL results are given as low and high values resulting from the consideration of a range of design parameters and operating conditions. All the results were adjusted by UE&C to the same plant heat rejection basis and to the same data units. No other adjustments were made. Therefore, the comparison of the EH&A and HEDL results as presented in the UE&C report reflect the differences in the models for calculating evaporation and the assumptions on blowdown for cooling towers, water consumption credit for cooling ponds due to local runoff and precipitation, etc. as shown in Table 1.

The single field study reported in the literature on a closed-cycle cooling pond did not provide measured water consumption rates. This study concluded that the Meyer model predicts pond evaporation rates in excellent agreement with field measurements obtained in the same study.

Observations and Conclusions

Based on the separate comparisons of the EH&A results and the HEDL results on cooling towers versus cooling ponds as given in Tables 2 and 3, UE&C made the following observations with respect to whether the cooling tower or the cooling pond is more water consumptive:

1. The results of the EH&A study (Figures 1 and 2) clearly show that a cooling tower is more water consumptive than a cooling pond. (Figures 1 and 2 are the graphic representations of the EH&A results in Tables 2 and 3.)
2. The results of the HEDL study (Figures 3 and 4) show that in some regions a cooling tower is more water consumptive than a cooling pond, while in other regions the opposite is true. (Figures 3 and 4 are the graphic representations of the HEDL results in Tables 2 and 3.)

The major conclusions drawn by the first UE&C study with respect to water consumption and evaporation rates of cooling systems are:

1. The two cooling tower evaporation prediction models (Leung-Moore used by EH&A and Winiarski used by HEDL) gave comparable results.
2. The two evaporation rate prediction models for cooling ponds/lakes (Harbeck model* used by EH&A and Brady model used by HEDL) gave disparate results; the rates predicted by the Brady model were consistently higher than those given by the Harbeck model.**
3. Because of the disparity between the predicted cooling ponds/lakes evaporation rates and the unavailability of consistent sets of field data, a definitive conclusion cannot be drawn as to which of the models, Harbeck or Brady, gives more accurate results.
4. Without the consideration of the actual cooling pond water surface temperature, the use of the Harbeck model for calculating the forced evaporation losses of cooling ponds may result in an underestimation of these losses. The assumption that the pond water surface temperature is equal to

*Referred to as the "Harbeck nomograph" in the Versar study.

**These models are also compared in the Versar study

Table 2. *Consumptive Water Use for Cooling Towers*

Water resource region	Location (1974)	*Without makeup pond (10^6 gal./day)* Blowdown returned EH&A (1977)	EH&A Low	HEDL High	Blowdown retained EH&A (1977)	EH&A Low	High	HEDL
1. New England	Boston, MA			6.73	7.77		7.07	8.16
	Concord, NH	7.91	8.51	6.77	7.81	10.64	7.10	8.20
	Bangor, ME			6.24	7.58		6.54	7.96
2. Mid-Atlantic	Richmond, VA	8.27	8.87	7.31	8.06	11.09	7.68	8.46
	Philadelphia, PA			7.06	7.94		7.41	8.34
3. South Atlantic-Gulf	Tampa, FL	8.98	9.34	8.08	8.48	11.68	8.49	8.90
	Atlanta, GA			7.85	8.35		8.24	8.77
4. Great Lakes	Detroit, MI	8.03		6.79	7.83		7.13	8.22
	Cleveland, OH			6.90	7.88		7.24	8.28
5. Ohio	Columbus, OH	8.50	8.75	7.01	7.93	10.94	7.36	8.32
	Louisville, KY			7.27	8.06		7.63	8.46
6. Tennessee	Knoxville, TN	8.62		7.40	8.10		7.77	8.50
	Chattanooga, TN			7.49	8.13		7.86	8.54
7. Upper Mississippi	Twin Cities, MN	8.27	8.39	6.44	7.66	10.49	6.76	8.04
	St. Louis, MO		8.87	7.28	8.06	11.09	7.65	8.46
8. Lower Mississippi	Jackson, MS	8.86	9.22	7.81	8.33	11.53	8.20	8.75
	New Orleans, LA			7.92	8.38		8.31	8.80
9. Souris-Red-Rainy	Bismarck, ND	7.79	8.51	6.46	7.67	10.64	6.79	8.05
	Duluth, MN			6.26	7.59		6.57	7.97
10. Missouri Basin	N. Platte, NE	8.39	8.87	7.14	8.01	11.09	7.50	8.41
	Great Falls, MT		8.75	6.74	7.78	10.94	7.07	8.17
11. Arkansas-White-Red	Tulsa, OK	8.74		7.57	8.19		7.95	8.60
	Garden City, KS			7.57	8.19		7.95	8.60
12. Texas-Gulf	Dallas, TX	9.09	9.34	7.85	8.33	11.68	8.24	8.75
	Houston, TX			7.91	8.40		8.31	8.82
13. Rio Grande	Albuquerque, NM	8.98	9.34	7.48	8.10	11.68	7.86	8.51
	El Paso, TX			8.02	8.41		8.42	8.83
14. Upper Colorado	Farmington, NM	8.15		7.53	8.16		7.91	8.57
	Gr. Junction, CO			7.11	7.95		7.47	8.35
15. Lower Colorado	Phoenix, AZ	8.98		8.21	8.58		8.62	9.00
	Yuma, AZ			8.33	8.77		8.75	9.21
16. Great Basin	S. Lake City, UT	8.50	8.99	6.88	7.84	11.24	7.22	8.24
	Reno, NV			7.30	8.01		7.67	8.42
17. Pacific Northwest	Seattle, WA	8.27	8.39	6.64	7.81	10.49	6.97	8.20
	Portland, OR			6.77	7.84		7.11	8.23
18. California	Los Angeles, CA	8.75	8.75	7.69	8.21	10.94	8.07	8.62
	Sacramento, CA	9.10	9.10	7.45	8.08	11.38	7.82	8.49

the average air temperature is not satisfactory for high thermal loading ponds which correspond to 1.0 acre/MWe or less.*

5. The Brady model appears to result in more credible cooling pond forced evaporation losses than does the Harbeck nomograph because it considers the actual thermal loading of the pond in order to estimate the pond surface temperature.
6. A general conclusion cannot be drawn as to whether a cooling tower or a cooling pond is more water consumptive.

Costs of Cooling System Alternatives

Cost information on various cooling system alternatives was compiled for all 18 water resource regions in the conterminous United States for both nuclear and fossil power plants. The cooling system alternatives considered included two wet/dry tower systems designed to conserve water. All costs were adjusted to 1978 dollars.

Two main categories of costs were presented in the UE&C report: (a) the capital cost for equipment (i.e., cooling device, circulating water system including condenser and electric equip-

*For a plant with a thermal efficiency of 38 percent, 1.0 acre/MWe is approximately equivalent to 2.5 MWt/acre.

Table 3. *Consumptive Water Use for Cooling Ponds and Once-Through Cooling*

Water resource region	Location	Multipurpose (natural) pond (10^6 gal/day) EH&A (1977)	HEDL Low	HEDL High	Single-purpose (manmade) pond (10^6 gal/day) EH&A 1 ac/MWe	EH&A 2 ac/MWe	HEDL Low	HEDL High
1. New England	Boston, MA		5.73	7.21			1.81*	5.91*
	Concord, NH	3.66	5.84	7.34	5.10	4.38	2.84*	6.34*
	Bangor, ME		5.35	6.88			2.39*	5.89*
2. Mid-Atlantic	Richmond, VA	4.49	6.58	8.45	5.73	5.11	5.47*	8.07*
	Philadelphia, PA		6.24	8.00			3.82*	7.19*
3. South Atlantic-Gulf	Tampa, FL	5.53	7.76	9.42	7.57	6.50	10.28	13.28
	Atlanta, GA		7.07	7.83			8.62	9.54
4. Great Lakes	Detroit, MI		5.83	7.46			6.35	7.62
	Cleveland, OH		5.92	7.47			5.22*	7.23*
5. Ohio	Columbus, OH	4.01	6.13	7.93	5.17	4.59	5.72*	7.78*
	Louisville, KY		6.46	8.24			5.73*	8.00*
6. Tennessee	Knoxville, TN		6.61	8.61			4.38*	7.85*
	Chattanooga, TN		6.70	8.62			5.24*	8.12*
7. Upper Mississippi	Twin Cities, MN	4.01	5.42	6.90	5.41	4.71	7.38	9.02
	St. Louis, MO	4.61	6.48	8.19	6.11	5.36	8.04	8.88
8. Lower Mississippi	Jackson, MS	5.08	7.18	8.93	6.56	5.82	7.16*	8.90*
	New Orleans, LA		7.31	9.07			2.30*	7.40*
9. Souris-Red-Rainy	Bismarck, ND	4.13	5.25	6.69	6.89	5.51	8.10	11.59
	Duluth, MN		5.13	6.52			5.42	6.62
10. Missouri Basin	N. Platte, NE	4.37	6.05	7.66	8.55	6.46	9.48	13.90
	Great Falls, MT	4.25	5.43	7.00	7.19	5.72	8.59	12.31
11. Arkansas-White-Red	Tulsa, OK		6.82	8.44			8.78	10.50
	Garden City, KS		6.48	7.89			10.71	17.85
12. Texas-Gulf	Dallas, TX	5.55	7.14	8.65	9.89	7.72	10.65	16.16
	Houston, TX		7.42	9.04			9.78	12.51
13. Rio Grande	Albuquerque, NM	4.84	6.26	8.07	12.90	8.87	11.30	18.27
	El Paso, TX		6.94	8.58			13.65	24.92
14. Upper Colorado	Farmington, NM		6.25	8.06			11.44	18.68
	Gr. Junction, CO		6.00	7.82			9.80	14.17
15. Lower Colorado	Phoenix, AZ		7.41	9.37			14.77	26.11
	Yuma, AZ		7.32	9.10			14.90	27.43
16. Great Basin	S. Lake City, UT	4.72	5.55	7.35	7.52	6.12	8.80	11.92
	Reno, NV		6.07	8.12			11.11	17.11
17. Pacific Northwest	Seattle, WA	4.61	5.85	7.79	4.81	4.71	1.20*	6.23*
	Portland, OR		6.07	7.99			-7.55*	3.45*
18. California	Los Angeles, CA	4.01	6.96	8.90	8.91	6.46	11.28	16.47
	Sacramento, CA	4.61	6.69	8.45	10.29	7.45	10.05	13.98

*Average precipitation exceeds natural evaporation.

ment) and (b) the total evaluated cost, including both the capital cost and the capitalized penalty cost.

While the capital costs can be easily identified, the penalty costs are less definitive and can vary considerably, depending on the economic factors, analysis methods, and penalty items included. Because most cost data sources reviewed lacked much of the design, performance, and cost information needed to calculate these penalty costs, only the capital cost estimates were reported for most of the 18 water resource regions. The total evaluated costs were available for less than half of the water resource regions and were extracted from references where the basic information needed for proper adjustment were available.

Conclusions

1. There is no discernible trend of capital costs either by water resource regions or by the types of cooling systems (see Table 4).

2. With respect to total evaluated costs (sum of capital and capitalized operating costs), the observed cost trend for a specific plant generally remains as expected: a dry cooling system has the highest cost, a once-through cooling system has the lowest cost, and conventional closed-cycle cooling systems, including wet/dry tower systems, lie between the two extremes.

3. The economic impact of using dry tower cooling systems to conserve water may be significantly reduced by the use of wet/dry tower cooling systems. When water is available, however, wet tower cooling systems will continue to be the economic choice under most circumstances.

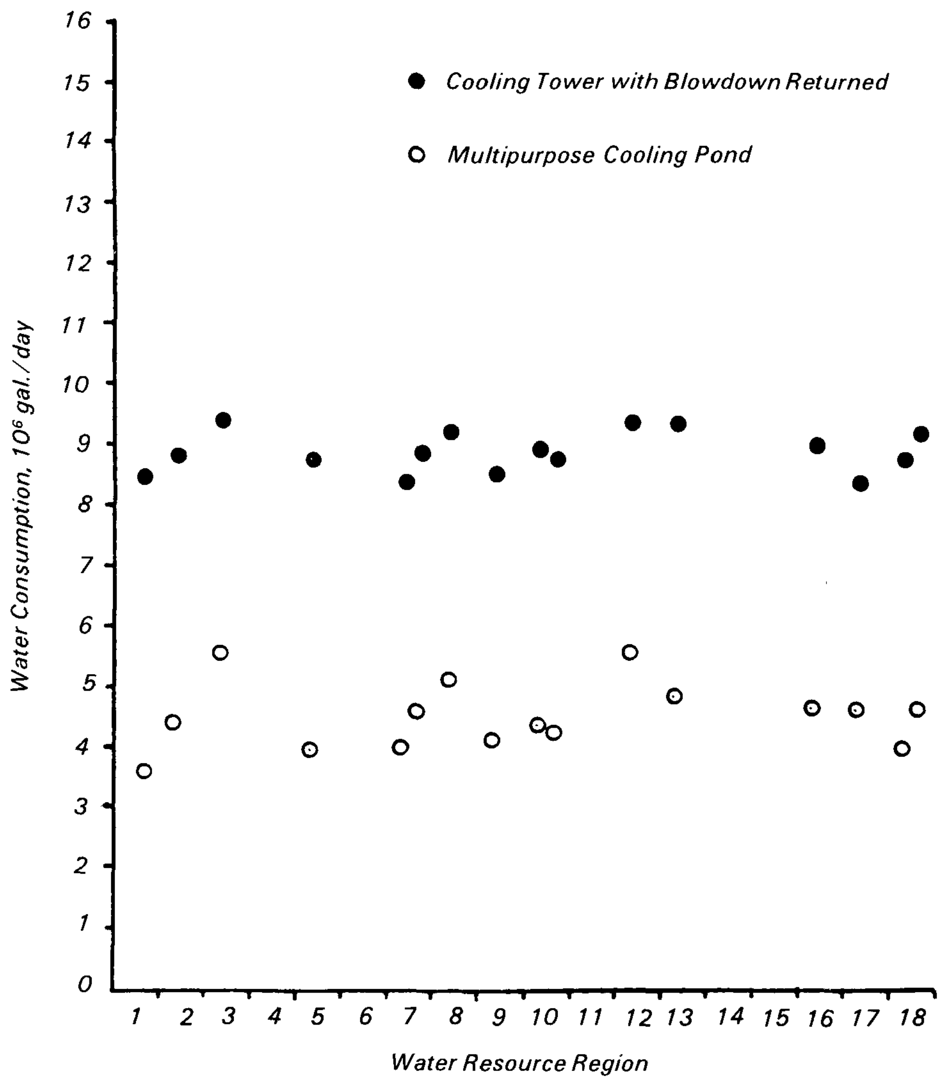

Figure 1. *Comparison of water consumption rates obtained by EH&A study for multipurpose cooling ponds and cooling towers with blowdown returned.*

Water Availability for Steam-Electric Generation and Other Uses

At present, the availability of environmentally acceptable sites for electric power generating plants, whether fossil or nuclear, is strongly influenced by the availability of cooling water. The water availability presented in the UE&C report was based on the then-unpublished results of a comprehensive 4-year study completed in 1978 by the U.S. Water Resources Council (WRC). In the study, the conterminous U.S. is divided into 18 water resource regions (see Table 2 for listing) and further subdivided into 99 subregions. The results of the study included actual water consumption and availability data for 1975 and estimated values for 1985 and 2000.

Conclusions

The major conclusions on water availability are:

1. Under dry-year conditions, there is insufficient water in most of the 18 water resource regions to satisfy all users at current and projected rates of use. This water shortage situation is particularly critical in the Southwest.

2. Relative to total water consumption, the percentage consumption for steam-electric generation was 1.23 percent in 1975 and is estimated to be 2.1 percent in 1985 and 7 22 percent in the year 2000.

3. The greatest potential for consumptive water savings lies in the agricultural sector. Since this sector is the largest consumptive water user in most regions, substantial water savings can be obtained with only small percentage reductions in this user category.

Legal Constraints and Their Impact on Consumptive Water Use

To determine the availability of water from a certain water body for consumptive use by power systems, it is first necessary to examine the laws and regulations that govern water allocation and use. The legal right to use water from a water body is the first determinant of water availability for a particular use, even though water may be physically available.

The review study compiled the major features of the institutional framework within which water for energy conversion uses will be sought and developed. The features include the constitutional basis for water laws, important Federal statutes, international treaties, and interstate compacts. Also addressed are the potential impacts of Federal water rights, Indian water rights, and State water laws and policies.

Conclusions

The major conclusions are:

1. There is no simple way to classify all the differing laws and accompanying rules and regulations, since they vary from state to state and depend on court decisions. Constraints on the legal availability of water form a complex web which involves Federal rights, Indian rights, State rights, riparian rights, appropriation rights, beneficial uses, international treaties, and others. Disregard of or any attempt to abrogate these rights (or arrangements) is certain to raise serious objections and entail lengthy litigation.

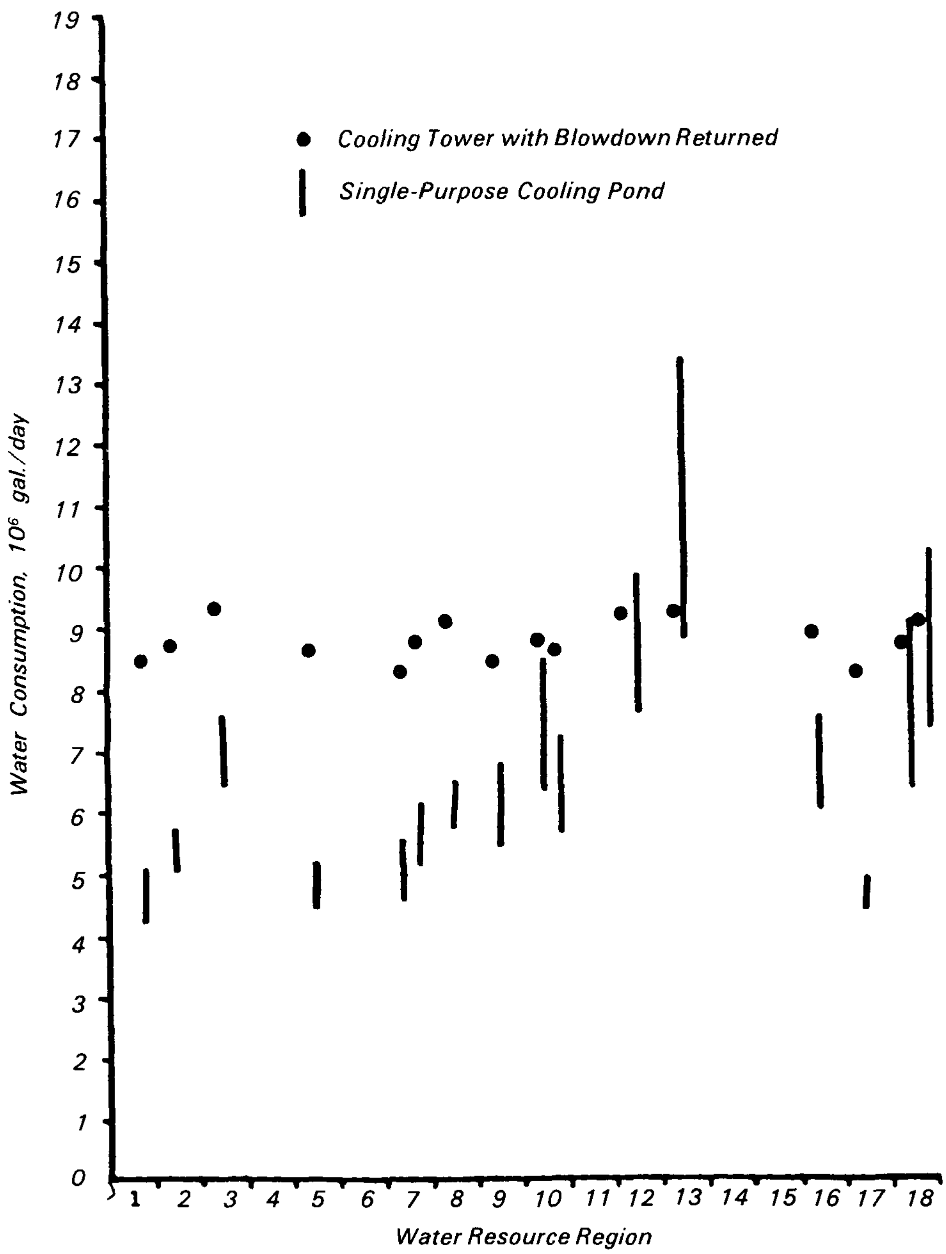

Figure 2. *Comparison of water consumption rates obtained by EH&A study for single-purpose cooling ponds and cooling towers with blowdown returned.*

2. No comprehensive body of law exists, either on the Federal or State level, on the regulation and consumptive use of water. Present Federal and State laws and regulations need codification and, in some cases, rewriting to enhance understanding and to meet societal needs.

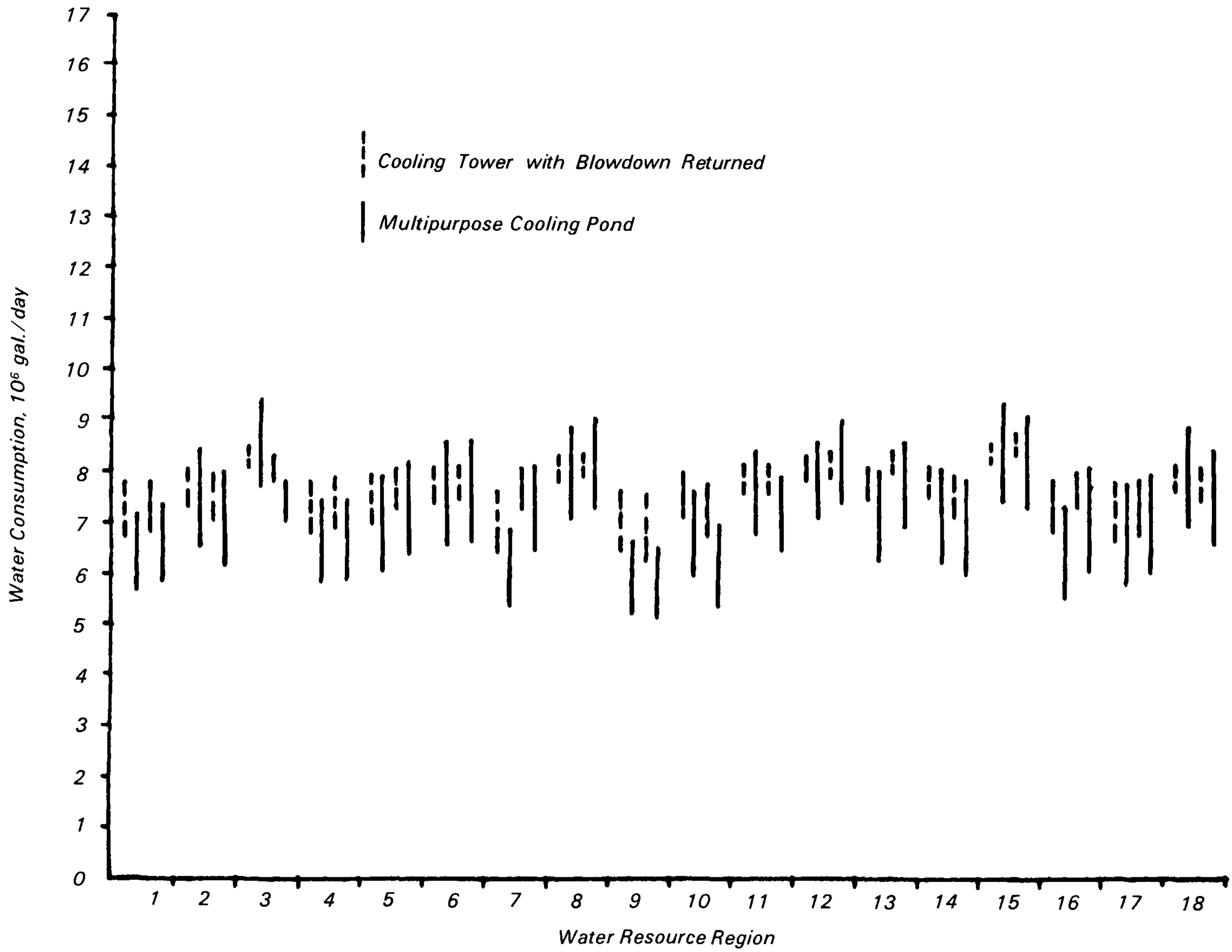

Figure 3. *Comparison of water consumption rates obtained by HEDL study for multipurpose cooling ponds and cooling towers with blowdown returned.*

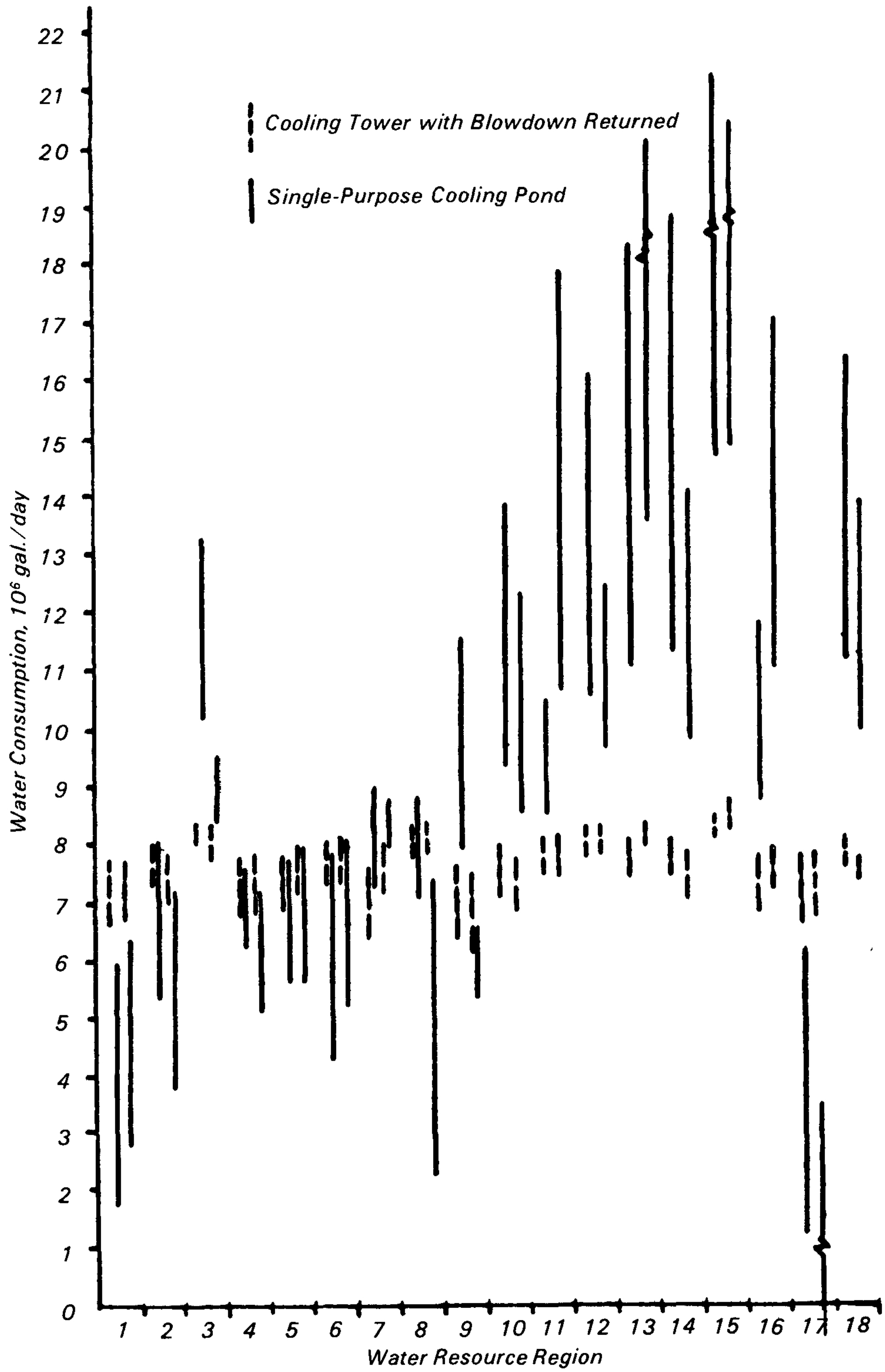

Figure 4. *Comparison of water consumption rates obtained by HEDL study for single-purpose cooling ponds and cooling towers with blowdown returned.*

Table 4. *Capital Costs of Cooling System Alternatives - Fossil Plants ($/kW, 1978 dollars)*

Water Resource Region	Once Through	Wet Tower	Cooling Pond	40% Wet/Dry*	10% Wet/Dry*	Dry Tower: High Back Pressure Turbine	Dry Tower: Low Back Pressure Turbine
1. New England	15	22-28	39			34-38	
2. Middle Atlantic		26-27		43	56	45	85
3. Atlantic-Gulf	19	24-26, 28, 22-37	63	53			
4. Great Lakes		25, 21-23, 44-57	22, 44	27		62	
5. Ohio		25, 19-25				39-45	
6. Tennessee							
7. Upper Mississippi		19				30	
8. Lower Mississippi							
9. Souris-Red-Rainy							
10. Missouri Basin		23		38-43	47-52	47	101-103
11. Arkansas-White-Red							
12. Texas-Gulf	36		62				
13. Rio Grande							
14. Upper Colorado		21-26, 22-24		39-44 52-67	49-57	46-49 73-87	88-108
15. Lower Colorado							
16. Great Basin							
17. Pacific Northwest		25,25-27	69			59	
18. California							

**40% (10 %) wet-dry has 40% (10%) of the water consumption of a wet system designed to reject the same quantity of heat.*

Summary of UE&C Report: Nonwater Quality Impacts of Closed-Cycle Cooling Systems And the Interaction of Stack Gas and Cooling Tower Plumes

General Description

The objective of this study was to collect, analyze, and correlate the information available since 1973 on the following topics: (a) the environmental impacts on biota of drift from evaporative saltwater or brackish water cooling towers, (b) the impacts of cooling tower plumes on weather, and (c) the environmental impacts of the interaction of cooling tower plumes with the combustion gases emitted from power plant stacks.

The air emitted from a wet cooling tower is characterized by a water vapor plume exiting the top of the tower. This thermally buoyant plume typically contains 1 to 3 percent of the water circulating through the cooling tower. In general, it is a visible plume which can rise to several times the height of the cooling tower, depending on the prevailing meteorological conditions. When appropriate meteorological conditions exist, the plume may cause an increase in the frequency of ground level fogging.

The direct contact process of heat transfer in a wet cooling tower allows macroscopic droplets of condenser cooling water to become entrained in the air flowing out of the tower. These droplets, commonly referred to as drift, begin to fall to the ground once the plume leaves the tower. During winter, these droplets can freeze on the surfaces of nearby structures and transportation corridors. Since the drift droplets contain the same chemical constituents as the water circulating through the tower, their presence in the atmosphere may also have significant environmental consequences.

The presence of wet cooling towers, especially large hyperbolic natural draft cooling towers, at fossil-fuel-fired steam-electric generating stations raises the possibility that the cooling tower plumes will interact with the combustion gases emitted from the station's smoke stacks. The commingling of a cooling tower plume with a stack plume, which contains high concentrations of sulfur oxides, nitrogen oxides, and fly ash in addition to carbon dioxide and water vapor, can potentially enhance the formation of acid mist in the atmosphere, causing adverse environmental impacts.

Cooling Tower Drift and Its Environmental Impacts

A major concern of using saltwater and brackish water cooling towers is that the drift from these towers will produce significant adverse environmental impacts, especially to the biota in the vicinity of the towers. An assessment of the potential environmental impacts on biota should include a determination of:

1. The naturally occurring salt deposition rates and the atmospheric salt concentrations in the vicinity of the cooling tower.
2. The total salt deposition rates and the atmospheric salt concentrations that result when the cooling tower is in operation.
3. The salt concentration levels in vegetation before and after the cooling tower is in operation.
4. The salt tolerance of each indigenous species of the biota.
5. The cumulative effects of salt load on biota.

While the UE&C study reviewed all available information, it emphasized available field studies. These field studies are summarized below.

Cooling Tower Drift and Deposition Rate Measurements

Available field studies include: (a) the B.L. England Station of the Atlantic City Electric Company, (b) the Chalk Point Station of the Potomac Electric Power Company, and (c) the Turkey Point Station of the Florida Power and Light Company

B.L. England Station, Unit 3—

The B.L. England Station is located near Marmora, New Jersey, on Great Egg Harbor Bay and about 4.5 miles from the Atlantic Ocean. The station has two coal-fired units and one oil-fired unit with a generating capacity of 476 MWe. The oil-fired Unit 3 is cooled by a closed-cycle cooling tower system which employs a hyperbolic counterflow natural-draft cooling tower designed and built by Research-Cottrell. The tower has a base diameter of 180 feet and a height of 208 feet. The design circulating water flow rate is 200,000 gpm, and the concentration of total dissolved solids in the circulating water ranges from 24,000 to 32,000 ppm.

Field measurements of drift rate were conducted by the tower manufacturer. The mean drift rate from 15 measurements was 0.000424 percent of the circulating water flow rate with a standard deviation of 0.000123 percent.

Field measurements of atmospheric salt concentration and drift deposition rate were conducted by Environmental Systems Corporation. Two studies were undertaken during two consecutive years. The first study performed measurements during the year when the tower was not in operation, and the second study performed measurements during the year when the tower was in operation.

Although the field data collected at the B.L. England Station indicate that the saltwater cooling tower increases the atmospheric salt concentration and deposition rate, anomalies exist, indicating uncertainties with regard to the effects of the cooling tower. For instance, during the periods when the cooling tower was in operation, the annual average salt deposition rates measured at every sampling location increased relative to those measured during the pre- and operational periods. However, the annual average salt concentrations at these sampling locations did not show a similar increase when the cooling tower was in operation. Possible explanations of this apparent anomaly include: (a) the differences in meteorological condition between the periods (1973-1974 and 1974-1975) when the pre-operational and operational measurements were conducted, (b) the difference in sampling times for the deposition rate measurements (approximately 24 hours) and the salt concentration measurements (approximately several hours), and (c) "blow-through" occurred when high winds swept through the cooling tower basin carrying with them droplets of the circulating water.

Chalk Point Station, Unit 3—

The Potomac Electric Power Company's Chalk Point Station is located at the confluence of the Patuxent River and Swanson Creek, about 40 miles southeast of Washington, D.C. The station has three operational units with a total generating capacity of 1329 MWe. Units 1 and 2 are coal-fired base-load units with once-through cooling. Unit 3, on which the Chalk Point Cooling Tower Project (CPCTP) has been conducted, is an oil-fired cycling unit. The unit is cooled by a closed-cycle system using a crossflow natural-draft cooling tower designed by the Marley Company. The cooling water for this system is taken from the discharge of the once-through cooling for Units 1 and 2 and the flow rate is 260,000 gpm. The salinity of the circulating water ranges from 14,000 ppm to 21,000 ppm during the summer. The tower has a base diameter of 374 feet and a height of 400 feet. The CPCTP is an on-going and the most comprehensive study to date of cooling tower drift and its environmental effects. Summarized are the tests and results obtained so far.

Two independent groups (Johns Hopkins University and Environmental Systems Corporation) measured the cooling tower drift at ground level. The two sets of deposition rate measurements differed by factors of 5 to 10 for the same distances from the cooling tower. Droplets less than 100 μm were not necessarily recorded, although they were observed. The explanation of this difference in deposition rates may be that one of the studies was performed under slightly stable conditions. Argonne National Laboratory has attempted to use these data to validate mathematical salt deposition models.

Turkey Point Station—

Florida Power and Light Company's Turkey Point Station is located about 30 miles south of Miami, on Biscayne Bay. It consists of two 430 MWe fossil-fueled units and two 730 MWe nuclear units. Condenser cooling of all four units is provided by a closed-cycle salt water cooling canal system. The salinity of the circulating water ranges from 3,000 ppm to 30,000 ppm.

A single-cell mechanical-draft crossflow tower with improved drift eliminator design was also installed at the station to evaluate the effects of drift from a mechanical-draft cooling tower. The tests indicated that the increase in ambient salt concentrations resulting from the tower operation was less than the instrument accuracy of 3 to 5 $\mu g/m^3$.

Field Studies of Biological Impacts of Cooling Tower Drift

At Chalk Point and Turkey Point Stations, studies have also been conducted to assess the vegetative impacts of salt drift from the cooling towers. The UE&C study found no field study investigating the impacts of salt drift on animal species. The available field studies on vegetative impacts are summarized below.

Chalk Point Station—

Studies have been conducted at the station to investigate the cumulative short-term effects of salt loading on native vegetation. Four tree species native to the Chalk Point area were studied: Virginia pine, black locust, sassafras, and dogwood. The test data indicate that the naturally occurring salt loading (Na^+ and Cl^-) on the four tree species does not approach the threshold concentrations of these ions when marginal necrosis occurs. The threshold concentrations of Na^+ and Cl^- for many woody species are 2000 ppm and 5000 ppm, respectively. Operational test data obtained in 1975 for the four tree species did not show significant increases of Na^+ and Cl^- concentrations. Similar results were obtained for soybeans, tobacco, and corn with regard to the naturally occurring salt loading and the increase in salt concentration resulting from tower operation.

Turkey Point Station—

At Turkey Point, cultivated plants (bush beans) were introduced to the area near the station's saltwater cooling tower. Using glass slide collectors, different salt deposition rates were observed on the windward and leeward sides of the plants. The excessive accumulation of Na^+ and Cl^- in the tissue on one side of a plant's foilage can result in "molding;" i.e., stunted growth on the windward side of the plant.

UE&C found an abundance of information on the effect of salt aerosol deposition on vegetation. But, the results generally cannot be directly applied to power plant cooling towers because the experimental conditions do not necessarily correspond to power plant environments.

Conclusions

Based on the information compiled, the following major conclusions were drawn concerning the measurements and the biological impacts of drift from saltwater and brackish water cooling towers.

1. Cooling tower drift and salt deposition apparently do not increase ambient salt loading to the extent that a significant impact has been observed or is expected. Field data from the operational Chalk Point and B.L. England Stations indicated that, although drift and its deposition from cooling towers may be significant within the immediate region of the station, contributions from cooling towers beyond 1 km may be inseparable from the natural salt loading of the local region.
2. The degree of salt injury to biota from cooling tower drift and salt deposition cannot be firmly determined using presently available data.

Weather Modifications by Evaporative Cooling Towers

The atmospheric effects of evaporative cooling towers operating at steam-electric generating stations include the potential modification of the weather locally with respect to: (a) the frequency and intensity of fogging and icing conditions, (b) the enhancement of cloud formation, and (c) the enhancement of precipitation.

Fogging and Icing

Fogging and icing, as phenomena resulting from visible, wet cooling tower plumes travelling near ground level, have been observed during cooling tower operation. Meteorologists have derived various mathematical models to predict the frequency of occurrence of fogging and icing from wet cooling tower operation, and these models have been summarized in a model validification effort by Argonne National Laboratory. Although the model predictions differ, they indicate that fogging and icing are not likely to occur beyond a 10-km radius of the cooling tower.

Field observations of fogging and icing near wet cooling towers have been reported. However, no ground fog from the operation of a natural draft cooling tower at the Paradise Station of the Tennessee Valley Authority was observed during a 5-year study. Similarly, no evidence was found of induced ground fogging from the natural draft cooling towers at the John E. Amos Power Station of the American Electric Power Service Corporation.

The occurrence of icing rather than fogging is due to the presence of temperatures below the freezing points of the water vapor and drift droplets in the cooling tower plume. Meteorological conditions conducive to fogging include wind speeds greater than 2 m/sec, stable temperature lapse rates, relative humidity greater than 95 percent, and low dry bulb temperatures. These conditions create downwash, low dispersion, low evaporation, and condensation.

Field studies determined that icing from the natural draft cooling towers at the Paradise Station was insignificant. At the Chalk Point Station, the natural draft cooling tower caused no more than a few millimeters of ice on structures located on the plant site. Only in rare instances could icing be observed at distances more than 5 km from the natural draft cooling towers at Amos Station.

Cloud Enhancement

The meteorological conditions which are conducive to the formation of additional clouds include a stable stratification of the vertical temperature profile, high relative humidity, cool temperatures, and low insolation. Under these conditions the clouds will be typically of the stratus variety.

Theoretical considerations indicate that wet cooling towers can modify these natural cloud formations. However, there have been no field studies to establish the extent of any cloud enhancement.

Precipitation Enhancement

A maximum of 2.5 cm of snowfall from natural draft cooling towers at the John E. Amos Station was measured when no other precipitation existed in the area. Snow accumulations were found as much as 43 km from the cooling tower, and visibility was restricted to less than 1600 m in the area where the cooling tower plumes approached ground level. However, no statistically meaningful change in rainfall was found near a 2000 MW electric generating station with eight natural draft cooling towers in England. Convective precipitation enhancement by wet cooling towers has been observed only once.

Conclusions

The following conclusions were drawn concerning weather modification by evaporative cooling towers.

1. Field observations on the fogging and icing from natural draft cooling towers suggest that these effects are not significant environmental problems. At most, only a few millimeters of ice have been observed to accumulate on surrounding structures, while fogging from natural draft towers has not been observed under a variety of meteorological conditions. Fogging and icing from mechanical draft towers have been observed, but the tower design significantly

affects the probability that the plume will intersect the ground.

2. Precipitation and cloud enhancement by cooling towers have been insignificant although they have been observed in a few cases. Previous studies indicate that precipitation and cloud enhancement for any sector downwind from a tower are increased by only a few percent.

Cooling Tower Plume and Stack Gas Interaction

The presence of wet cooling towers, especially large hyperbolic natural draft cooling towers, at fossil-fuel-fired steam electric generating stations raises the possibility that the cooling tower plumes will interact with the combustion gases emitted from the stations' stacks. The commingling of a cooling tower plume with a stack plume containing high concentrations of sulfur oxides, nitrogen oxides, and fly ash in addition to carbon dioxide and water vapor, can enhance the formation of acid mist in the atmosphere. The presence of acid mist may be evident as increased concentrations of aerosols and fine particulates containing sulfates and nitrates in the commingled plume, acid rainfall, and a reduction in atmospheric visibility.

A complete description of the interaction of a cooling tower plume with a stack plume requires an understanding of : (a) the physical, chemical, and geometrical characteristics of each plume as it leaves the source; (b) the meteorological conditions which affect the rise of each plume in the atmosphere and the spatial extent of the interaction of the plume and the ambient atmosphere; and (c) the complex physico-chemical reactions that can take place when the plumes commingle. At present, there are insufficient data to give a comprehensive description and quantitative assessment of cooling-tower-plume/stack-plume interactions.

Meteorological conditions conducive to the merging of a visible cooling tower plume with a stack plume have been established reasonably well in the literature. The longer than usual visible cooling tower plumes occur during light winds, high relative humidity (greater than 80 to 85 percent), low ambient temperatures, and stable lapse rates. The light winds and stable lapse rates ensure low atmospheric dispersion of the plume. The high relative humidity reduces the rate of evaporation of the water droplets in the cooling tower plume, thereby enhancing the visible plume length. Finally, the low temperature may also help to keep the water in the cooling tower plume in a condensed state.

Quantitative data concerning acid precipitation enhancement resulting from plume/stack gas interaction are scarce. Existing literature generally provides unsophisticated explanations and non-quantitative descriptions. Three field studies, one at the Chalk Point Station and two at the Keystone Station, obtained limited quantitative data, but these data are site-specific and cannot reliably be extrapolated to general circumstances.

Conclusions

The major conclusions concerning cooling tower plume and stack gas interaction are:

1. There is no mathematical model for predicting acid precipitation or deposition due to cooling-tower-plume/stack gas interaction.

2. Neither the enhancement of acid precipitation due to cooling-tower-plume/stack-gas interaction nor the quantification of resulting environmental impacts has been demonstrated in the field.

Summary of Versar Report: Comparison of Model Predictions and Consumptive Water Use of Closed-Cycle Cooling Systems

The primary objectives of this study conducted by Versar, Inc. were: (a) to survey and identify simple generic models for predicting evaporation rates from power plant closed-cycle cooling systems using wet towers and ponds/lakes, (b) to verify and calibrate these generic evaporation models with field data from operating power plants, and (c) to determine which of the two types of cooling systems is more water consumptive in terms of evaporation.

To achieve these objectives the available technical literature was reviewed, and available field data were solicited and acquired for a number of operating power plants. Evaporation prediction models satisfying certain criteria were selected and evaluated using available field data provided by utilities and data estimated by Versar when the field data were insufficient for the intended analyses. Tower and pond evaporation rates were then compared on a regional basis, to determine which (the tower or the pond) is more water consumptive.

Selection of Evaporation Models for Evaluations

The evaporation prediction models selected by Versar for validation, one for cooling towers and five for cooling ponds/lakes, were selected because they are simple, non-iterative, and generic (i.e., not intended for site- or plant-specific applications). For cooling towers, the model selected was the mechanical-draft cooling tower model developed from studies performed for the Navajo Station in northern Arizona. The model, called the Leung-Moore model, is represented by a set of four nomographs.

Five evaporation prediction models were selected for cooling ponds/lakes. The models are identified in the Versar report as: (a) Marciano-Harbeck (Lake Hefner); (b) Harbeck-Koberg-Hughes (Lake Colorado City); (c) Meyer; (d) Brady et al.; and (e) Harbeck nomograph.

Models (a) through (d) are based on mass transfer concepts and fit a general mass transfer equation of the form noted earlier; see Equation (1). Each has a different empirically developed wind speed function. They were selected as they had been evaluated in an earlier study for EPA.

The Brady model for cooling ponds was also used in the HEDL study, while the Leung-Moore model for cooling tower and the Harbeck nomograph for cooling ponds were used in the EH&A studies. The HEDL and EH&A studies were summarized earlier in this summary.

Acquisition of Field Data and Verification of Evaporation Prediction Models

To verify the evaporation prediction models, using available field data of cooling towers and cooling ponds, Versar obtained data from 12 utilities in time to be included in the study. The data supplied by the utilities include 15 wet cooling tower systems, 7 cooling ponds, and 1 cooling canal system. These data are summarized in Tables 5 and 6 for cooling towers and cooling ponds/lakes, respectively.

The data in Tables 5 and 6 are not entirely field data. They include some design data provided by utilities and also some estimates by Versar. Since in most cases the data provided were incomplete for the intended evaluations, Versar made approximations or estimations to make up for the missing data. However, the estimations were done on a consistent basis with the best available information. The data were then used as inputs for both the models and the water budget equations to determine evaporation rates.

When using the material balance method, the evaporation rate was determined from the difference between the inflow to, and the outflow from, the system. The inflow for towers is the makeup water; inflow for ponds/lakes may include stream flow into the lake (makeup), local runoff, and direct precipitation. The outflow for towers may include blowdown and drift, and that for ponds/lakes may include blowdown (outflow) and seepage. The tower drift and pond seepage, being usually small compared to the other terms, were neglected in Versar's evaluation. Local runoff was determined from direct precipitation by multiplying it by an estimated runoff coefficient based on local U.S. Geological Survey information.

The comparisons of the evaporation results obtained in the Versar study for cooling towers and cooling ponds are shown in Tables 7 and 8, respectively. Table 7 illustrates the accuracy of the Leung-Moore model relative to material balance values. On the average, the Leung-Moore model predicted evaporation rates to within ± 15 percent of the material balance results when the power plants with capacity factors over 50 percent were considered. Cooling tower evaporation rates for peaking and cycling units (capacity factor below 50 percent) are not well simulated by the model. Table 8 compares the accuracy of the five cooling pond/lake models with material balance values. The power plants associated with the cooling ponds/lakes were mostly large base-load units. The comparison shows that the Harbeck-Koberg-Hughes and Meyer models give better predictions than the other three models. Further, the Brady model gave closer predictions than the Marciano-Harbeck model in all cases and than the Harbeck nomograph in most cases. The latter three models underpredicted material balance values of evaporation rate in all cases considered.

Regional Comparison of Cooling System Evaporation Rates

A primary objective of the study was to compare water consumption rates of cooling towers and cooling ponds/lakes on a regional basis. In actual analysis, Versar compared the evaporation rates of the two types of cooling systems and considered that this also represented the comparison of water consumption rates of these cooling systems.*

A total of 20 cooling systems for 16 plants investigated in the Versar study provided comparisons for 7 water resource regions as shown in Table 9. The predicted evaporation rates for towers are the values calculated by the Leung-Moore model, and those for the cooling ponds are the values calculated by the model which gives the closest prediction to the material balance value. The results in Table 9 show that cooling ponds in these cases evaporate more water than cooling towers. The relationship is most dominant in the southern regions (Lower Colorado, Rio Grande, Texas Gulf) where natural evaporation rates are high.

Conclusions

The major conclusions drawn from the Versar study concerning water evaporation and consumption of cooling towers and cooling ponds/lakes are:

1. For cooling towers at base-load plants (blowdown returned and no makeup impoundments), the predicted evaporation rates by the Leung-Moore model are in good agreement with those determined from material balances (within ± 15 percent).
2. For cooling ponds/lakes, the Harbeck-Koberg-Hughes model (Lake Colorado City) and Meyer model generally give predictions within ± 15 percent of the material balance results; the Brady model, Harbeck nomograph, and Marciano-Harbeck model (Lake Hefner) give consistently lower evaporation rates than the material balance values. Generally, the Brady model predictions approximated the material balance values more closely than the Harbeck nomograph and Marciano-Harbeck model.
3. Cooling ponds/lakes generally evaporate more water than cooling towers.
4. The satisfactory comparison of the cooling tower evaporation rates (predicted by the Leung-Moore model with material balance values developed using field data supplemented with estimations where needed to complete the evaluation) suggest that this model can be used adequately for estimating cooling tower evaporation rates.
5. Comparisons of the evaporation rates (predicted with the five cooling pond/lake models and the results determined from material balances developed using field data supplemented with estimations where needed to complete the evaluation) indicate that predictions from the Harbeck-Koberg-Hughes model and the Meyer model are preferable over the other models for estimating cooling pond/lake evaporation rates.

*In the UE&C study, the water consumption of a power plant cooling system is defined as that portion of the water removed from and not returned to the surface water resources of a given area. In the Versar study, the water consumption is implicitly defined as evaporation only. Both definitions have been used in previous water consumption studies

Table 5. Cooling Tower Data

Station Name / Unit No	Huntington Unit 1	NAVJO		North Main - Unit 1 Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Permian
Utility Name	Utah Power & Light	Arizona Public Service		Texas Electric Service Company						Texas Electric
Test Period	1976 Annual Average	Test 1-A (1 hr) August 6, 1977	Test 2-A (2 hrs) August 20, 1977	1 Week Performance Test January 21-26, 1960						6 hours November 5, 1958
Plant Capacity, MWe	400	750	750	85 85	85 85	85 85	85 85	85 85	85 85	100
Capacity Factor, %	80	107	100	48	63	35	76	82 5	100	Not Known
Unit Heat Rejection, Btu/kWh	5100	4480	4480	6018	5979	6315	5948	6063	6119	4788
Circulating Water Flow, GPM	185,800	145,326	147,306	66,244	63,116	64,092	63,429	64,189	63,765	69,550
Makeup Water Flow, GPM	4,000	3,482	3,432	508	535	553	509	644	710	704
Blowdown Rate, GPM	320	0	0	201	250	250	141	141	148	0
Range, °F	23 9	28 1	27 7	7 8	10 0	6 0	12 0	14 0	16 4	13 8
Approach, °F	17 5	20.3	22 7	15 9	21 9	13 7	22 2	22 1	23 3	17 2
Air Flow Rate, SCFM	18 x 10^6	2 8 x 10^7	2 9 x 10^7	3 5 x 10^6	3 5 x 10^6	3 5 x 10^6	3 5 x 10^6	3 5 x 10^6	3 5 x 10^6	3 3 x 10^6
Outlet Air Temperature, °F	82~97	94 8	92 0	66	71 5	64	78	84	91 5	92
Approximate Drift Loss, GPM	372	293	295							12

Station Name / Unit No	Newman/Rio Grande Stations Unit 1	Unit 2	Unit 3	Unit 6	Unit 7	Unit 8	Moses Units 1 and 2	Couch Units 1 and 2	Lynch Units 1, 2 and 3
Utility Name	El Paso Electric Company						Arkansas Power and Light	Arkansas Power and Light	Arkansas Power and Light
Location (Water Resource Region)									
Test Period	August, 1977			July, 1977			1976 Annual Data	1976 Annual Data	1976 Annual Data
Plant Capacity, MWe	86	90	110	50	50	165	126	161	239
Capacity Factor, %	59 3	85 5	98 2	30 5	58 5	48	11	29	12
Unit Heat Rejection, Btu/kWh	5680	5715	5310	6545	5615	5150	7600(1) 7575(2)	7370(1) 6650(2)	9500(1) 8090(2) 7950(3)
Circulating Water Flow, GPM	43,000	42,000	42,500	36,800	28,350	56,300	79,650	116,500	164,500
Makeup Water Flow, GPM	1580	1484	1672	500	608	1627	1030	622	1186
Blowdown Rate, GPM	375	350	397	145	175	407	221	160	0 1
Range, °F	25	25	28	10	15	22	8 4	12	9 8
Approach, °F	24	20	18	12	16	17	14	14	14
Air Flow Rate, SCFM	2 3 x 10^6	3 x 10^6	4 1 x 10^6	3 5 x 10^6	3 0 x 10^6	8 7 x 10^6	8 9 x 10^6	11 3 x 10^6	12 5 x 10^6
Outlet Air Temperature, °F	104	97	97	86	91	94	66	83	68
Approximate Drift Loss, GPM	87	84	85	74	57	113	160	46 6	66

Table 5. (continued)

Station Name Unit No	Homer City Plant			Clay Boswell Plant Unit 3			Koshkonong Plant* Unit 1
Utility Name	Pennsylvania Electric Company (Natural Draft Tower)			Minnesota Power & Light Company			Wisconsin Electric Power Company
Location (Water Resource Region)							
		1977 Average		1977 Average			
Test Period	January	April	July	January	August	Annual	
Plant Capacity, MWe	1328	1328	1328	350	350		900
Capacity Factor, %	49 41	34 94	57 35	86	93		100
Unit Heat Rejection, Btu/kWh	5238	5576	5685	5130	4965		7383
Circulating Water Flow, GPM	205,500	205,500	205,500	130,800	130,781		524,100
Makeup Water Flow, GPM	9186	8889	14,150	—	—	2616	12,500
Blowdown Rate, GPM	2595	2660	2838	—	—	500	1850
Range, °F	34 9	28 1	28 3	20	15 6		26
Approach, °F	48	24	18	32 9	21 8		18
Air Flow Rate, SCFM	$12\ 38 \times 10^6$	$8\ 25 \times 10^6$	$14\ 44 \times 10^6$	12×10^6	12×10^6		$40\ 2 \times 10^6$
Outlet Air Temperature, °F	93	92	105	64 3	89 5		82
Approximate Drift Loss, GPM	20 6	20 6	20 6	13	13		26

*All of the data given are design values

Table 6. Cooling Pond/Lake Data

Station Name Unit No	Cholla	Morgan Creek	Kincaid	Powerton No 5	Powerton No 6	H B Robinson	Belews Creek	Mt Storm	
Utility Name	Arizona Public Service Company	Texas Electric Service	Commonwealth Edison Company	Commonwealth Edison Company		Carolina Power and Light Company	Duke Power Company	Virginia Electric and Power Company	
Test Period	1974-1976 Annual Average	1959-1960	1977 Annual Average	1973 Annual	1977 Annual	1975-1976 Average	1977 Annual Average	January 1977	July 1977
Plant Capacity, MWe	120	102	1319	840	945	885	2286	1662	1662
Capacity Factor, %	70	—	34	51 7	47 1	67	66	69 (No. 1),	61 (No 2), 35 4 (No 3)
Unit Heat Rejection, Btu/kWh	4820		5200	4540	4540	4900	4225	4280	4280
Circulating Water Flow, GPM	27,800	493,714	479,981	690,562	690,562	500,923	1,050,332	889,020	889,020
Flow Rate into Pond, GPM	1696	6,075	28,800	19,666	19,666	131,202	26,222	182,743	142,378
Flow Rate Out of Pond, GPM	313	860	19,300	14,772	14,772	125,232	11,381	7,676	3,124
Cooling Range, °F	Not Given		13 8	18 8	19 3	14 1	18 40	33 3	33.3
Condenser Makeup Water Temperature, °F	56 9	68	62 0	61 5	60 6	71 6	67 9	42 2	83 1
Effective Pond Surface Area for Cooling Acres	340	1100	2400	1426	1426	2250	3553	1130	1130
Water Volume of Pond, Acre-feet	Not Given	31,000	33,500	15,600	15,600	41,000	176,000	49,000	49,000
Drainage Area, sq mi	Not Given	326	76.6	—	—	173	70 9	30	30

Table 7. Comparison of All Cooling Tower Evaporation Rates, as Calculated and Normalized

Plant/Unit Size (MW)	Time Period	Material Balance (cu m/min)	Model Prediction (cu m/min)	Ratio Model/Material Balance	Normalized Evaporation cu m/min-MW: Material Balance	Normalized Evaporation cu m/min-MW: Model	Normalized Evaporation cu m/10⁶ kcal: Material Balance	Normalized Evaporation cu m/10⁶ kcal: Model
Huntington/400	annual	12 5[b]	12 8	1 02	0 039	0 040	1 84[b]	1 88
Navajo/750	hourly-summer	12 6	13 8	1 10	0 016	0 018	0 85	0 96
		(12 2)[c]					0 88[c]	
N Main/85	hourly-summer	1 46	1 96	1 34	0 025	0 034	0 99	1 32
Permian/100	hourly-summer	3 0	3 1	1 03	0 030	0 031	1 49	1 54
Newman-1/86	August	4 2	3 7	0 88	0 082	0 072	3 44	3 02
-2/90	August	4 0	3 9	0 98	0 052	0 051	2 17	2 15
-3/110	August	4 5	4 5	1 00	0 042	0 042	1 86	1 86
Rio Grande-6/50[a]	July	1 1	2 4	2 18	0 072	0 157	2 62	5 73
-7/50	July	1 4	2 1	1 50	0 050	0 075	2 11	3 17
-8/165[a]	July	4 2	6 5	1 55	0 053	0 082	2 45	3 79
Moses/126[a]	annual	2 45	7 2	3 0	0 177	0 531	5 54	16 5
			(0 85)[e]	(0 34)[e]		(0 061)[e]		(1 92)[e]
Lynch/239[a]	annual	4 16	14 4	3 5	0 145	0 508	4 93	17 3
			(1 7)[e]	(0 41)[e]		(0 047)[e]		(1 60)[e]
Couch/161[a]	annual	1 62	7 6	4 7	0 035	0 163	1 02	4 77
			(2 2)[e]	(1 35)[e]		(0 059)[e]		(1 73)[e]
Homer City/1328	January	16 9	14 7	0 87	0 030	0 026	1 19	1 04
	July	40 5	26 0	0 67	0 054	0 036	2 62	1 68
		(18 6)[d]		(1 44)[d]	(0 026)[d]		(1 20)[d]	
Clay Boswell/350	January		5 61			0 019		0 86
	August		8 41			0 026		1 24
	annual	7 95		0 88	0 031		1 50	
Koshkonong Nuclear/900	annual	40	42	1 05	0 044	0 046	1 43	1 50
				range 1 50-0 67 (baseload plants)				

[a] Units with capacity factors less than 50 percent
[b] Based on constant outlet air temperature
[c] Marley test results
[d] Gilbert Assoc curves
[e] Results X capacity factor

Table 8. Summary of Cooling Pond/Lake Material Balance and Computer Model Evaporation Values on as-is and Normalized Bases

Plant/Unit or Station Size (MW)	Time Period	Material Balance (cu m/min)	Model Predicted (cu m/min)					Evaporation Rate Ratio Model/Material Balance					Area/Power (acres/MW)	Normalized Evaporation Rate for Model Giving Closest Prediction to the Material Balance Value: (cu m/min-MW)	(cu m/min-ha)	cu m/10⁶ kcal
			QH	QC	QM	QB	HN	QH	QC	QM	QB	HN	ha/MW			
Cholla/120	July	—	6 8	9 9	8 7	7 6							(2 83)	0 103	0 073	5 81
	annual	6 9	4 3	6 3	6 0	5 3	5 0	0 62	0 91	0 87	0 77	0 72	1 15	0 075	0 046	3 70
Morgan Creek/102	August	29 8	22 6	33 3	30 0	25 6		0 76	1 12	1 01	0 86		(4)	0 294	0 067	11 1
(equivalent)	annual	21 0	12 2	17 9	15 0	13 9	14 7	0 58	0 85	0 71	0 66	0 70	1 62	0 201	0 043	7 60
H B Robinson/885	August	76 5	38 1	56 0	62 9			0 50	0 73	0 82			(2 54)	0 089	0 069	4 37
	annual	44 6	26 0	38 3	40 2	34 0	26 8	0 58	0 86	0 90	0 76	0 65	1 03	0 068	0 046	3 31
Belews Creek/	August	99 1	68 5	101	109	83 5		0 69	1 02	1 09	0 86		(1 64)	0 062	0 070	3 45
2,286	annual	90 9	37 8	55 5	58 7	46 5	48 8	0 42	0 61	0 65	0 51	0 54	0 66	0 039(0 060)[a]	(0.041) (0 063[a]	2 19
Mt Storm/1,662	January		7 7	11 2	10 6	10 0							(0 68)	(0 012-0 026)	(0 019-0 024)	0 45-0 68
	July		10 9	16 2	24 3	19 2							0 275		(0 024-0 053)	0 66-1 5
Kincaid/1,319	August		44 7	65 8	63 1	51 5							(1 64)			
	annual	36 2	26 4	39 0	34 4	30 1	19 8	0 73	1 08	0 95	0 83	0 55	0 664	0 077	0 035	3 51
Powerton/840	August		18 8	27 6	26 1	21 5							(1 70)			
	annual (1973)	18.5	12 6	18 0	15 7	14 0	14 0	0 68	0 97	0 85	0 76	0 76	0 689	0 046		2 40

[a]Based on material balance evaporation

QH - Marciano and Harbeck model (Lake Hefner)
QC - Harbeck et al model (Lake Colorado City)
QM - Meyer model
QB - Brady et al model
HN - Harbeck nomograph plus pan evaporation

Table 9. *Regional Comparison of Cooling System Evaporation Rate*

Water Resource Region	Plant	Cooling System[a]	Plant Size (MW)	Capacity Factor	Model Predicted/ Material Balance Evaporation[b,c] (m^3/min)	Summer Normalized Evap. Rate (m^3/min-MW)	Summer Normalized Evap. Rate ($m^3/10^6$ Kcal)	Annual Normalized Evap Rate (m^3/min-MW)	Annual Normalized Evap Rate ($m^3/10^6$ Kcal)
Lower Colorado	Huntington	T	400	80	12.8/12 5	—	—	0 04	1 88
	Navajo	T	750	100	13.8/12 6	0 018	1 68	—	—
	Cholla	P	120	0 7	6 3/6.9[e]	0 103	5.81	0.075	3.70
Texas Gulf & Rio Grande	Newman-Unit 1	T	86	59	3 7/4 2	0.072	2.88	—	—
	Newman-Unit 2	T	90	86	3 9/4 0	0.024	2 00	—	—
	Newman-Unit 3	T	110	98	4.5/4 5	0 025	1 86	—	—
	Rio Grande-Unit 6	T	50	30	2.4/1 1	0.292	5 73	—	—
	Rio Grande-Unit 7	T	50	58	2 1/1 4	0.075	3 17	—	—
	Rio Grande-Unit 8	T	165	48	6 5/4 2	0 101	3.96	—	—
	North Main	T	85	100	2 9/2.5	0.034	1 89	—	—
	Permian	T	100	—	3 1/3 0	0 031	1 54	—	—
	Morgan Creek	L	102	12	20 5/20 9[e]	0.29	11 1	0 201	7.60
South Atlantic	H.B. Robinson	L	885	67	40.2/44 6	0 089	4.4	0 068	3 31
Gulf	Lake Bellews	L	2,286	66	58 7/90 2[f]	0.062	3 5	0.039	2 19
Upper Mississippi	Clay-Boswell	T	350	93	8.4/7 95[d]	0 026	1 35	—	—
	Koshkonong	T	900	100	42/40	—	—	0 04	1 50
	Kincaid	L	1,319	34	34 4/36 2[f]	—	—	0 077	3 51
	Powerton-Unit 5	P	840	47	8.0/18 5[e]	—	—	0 046	2 40
Ohio	Homer City	T	664	57	25.9/39 5[d]	0.036	1 68	0 03	1 40
Mid-Atlantic	Mt. Storm	L	1,662	55	—	0.012-0.026	0.66-1 5	—	—

[a]Cooling Tower (T); Cooling Pond (P); and Cooling Lake (L)
[b]For cooling towers the Leung and Moore model was used. For cooling ponds, the Harbeck-Koberg-Hughes, or Meyer model, or the Harbeck nomograph was used dependent upon which model more closely approximates material-balance values
[c]Annual values are shown, except for performance test results on cooling towers which are based on full capacity test.
[d]Summer value
[e]Harbeck-Koberg-Hughes model
[f]Meyer model

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The complete report, entitled "Executive Summary for Power Plant Cooling System Water Consumption and Nonwater Impact Reports," (Order No PB 81-231 474; Cost: $8.00, subject to change) will be available only from.

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