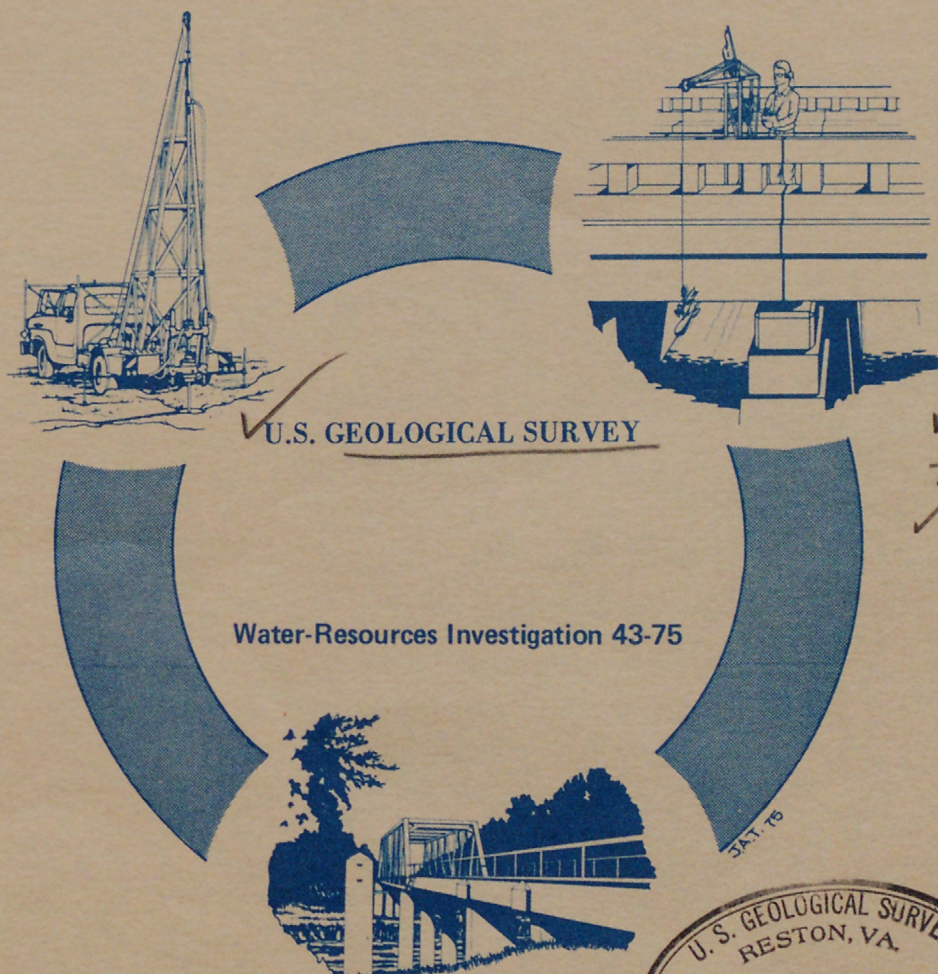
PERSPECTIVE ON USE OF FRESH WATER FOR COOLING SYSTEMS OF THERMOELECTRIC POWERPLANTS IN FLORIDA



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In 1970, cooling systems of power plants in Florida consumed about 106 Mgal/d of water, mostly saline; however, power plants in Florida increasingly are being located inland where saline water is not available for cooling purposes. In Florida, a cooling pond for a 1,000 megawatt nuclear power plant operating at full load in summer consumes about 12.5 Mgal/d of water. A cooling tower for a plant of the same size consumes about 14.8 Mgal/d. Once-through cooling systems require 5 to 10 percent less water than cooling ponds, but the total withdrawal of water for this method is so large that it is practicable in Florida only along the coast where saline water can be used. Water consumption for power production in Florida could increase to 400 Mgal/d by 1990 and 800 Mgal/d by 2000. Demand also will increase greatly for other uses that require fresh water. The continued use of saline water for cooling systems of power plants would help to conserve the fresh-water supply for these other uses.

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PERSPECTIVE ON USE OF FRESH WATER FOR COOLING SYSTEMS OF THERMOELECTRIC POWERPLANTS IN FLORIDA

by

G. H. Hughes

ABSTRACT

Cooling ponds, evaporative cooling towers, and once-through cooling systems of thermoelectric powerplants consume appreciable quantities of water. In Florida a cooling pond for a 1,000 megawatt nuclear powerplant operating at full load in summer consumes about 12.5 million gallons of water per day (0.55 cubic metres per second). A cooling tower for a plant of the same size consumes about 14.8 million gallons per day (0.65 cubic metres per second). Because the natural water loss to evaporation is greater for a water body than for a land area of comparable size in the same general environment, the total water consumption attributable to powerplant cooling may be greater for a cooling pond than for a cooling tower in instances where, for lack of a suitable natural water body, a cooling pond is created out of a dryland area. Additional water is required to maintain the chemical quality of the recycled cooling water, the quantity varying with the chemical quality of the makeup water and the concentration of chemical constituents that can be tolerated in the cooling water. Once-through cooling systems require 5 to 10 percent less water than cooling ponds, but the total withdrawal of water for this method is so large that it is practicable in Florida only along the coast where saline water can be used.

In 1970 cooling systems of powerplants in Florida consumed about 106 million gallons per day (4.6 cubic metres per second), mostly saline water. Water consumption for power production in Florida could increase to 400 million gallons per day (17.5 cubic metres per second) by 1990 and to 800 million gallons per day (35.0 cubic metres per second) by 2000. Demand also will increase greatly for other uses that require fresh water. The continued use of saline water for cooling systems of powerplants would help to conserve the fresh-water supply for these uses.

INTRODUCTION

Because of the growing concern about the environmental impact of heated water from cooling systems of thermoelectric powerplants on the saline waters of bays and estuaries, powerplants in Florida increasingly are being located inland where fresh water rather than saline water is used for cooling steam condensers. This increase in fresh-water use adds to the stress already imposed on the fresh-water resource by other types of uses, such as public supply, irrigation, and industrial uses, which have no alternative but to use fresh water. Concern is now expressed by water-management agencies as to the ability of the fresh-water resource to meet in the future the large and growing demand of all uses. The purpose of this report is to provide some useful information on the magnitude of cooling-water requirements for different types of cooling systems of thermoelectric powerplants in Florida.

Thermoelectric power production in Florida requires a large quantity of water for condensing the spent steam from turbine-driven generators. In 1970, for example, withdrawals of water for power production totaled 11,100 Mgal/d (486 m^3/s) (Pride, 1973, p. 20-22). About 84 percent of this amount was saline surface water; 15 percent was fresh surface water, and the remaining 1 percent was ground water. Water withdrawals for electric power production far exceeded those for other water uses in Florida, as indicated in table 1. Almost all the water withdrawn for power production is used for cooling steam condensers; only a small quantity is used for boiler feed, domestic use at the plants, and irrigation of the plant grounds.

Power production in Florida almost tripled from 1960 to 1970 (Florida Statistical Abstract, 1974, p. 376). Power generation in the United States is expected to increase about 7 times from 1970 to 2000 (Hauser, 1971, p. 124), and Florida's future growth rate probably will be at least as great as the national average. Thus, the production of thermoelectric power in Florida can be expected to increase greatly in the next 2 to 3 decades and the cooling-water requirements will increase proportionately.

In 1970 an estimated 106 Mgal/d (4.6 m^3/s) of water was consumed in the production of thermoelectric power in Florida (table 1). The effect on the fresh-water resource was small because, as indicated in figure 1, most of the large powerplants were near the coast, and saline water was used for cooling. If power production doubles in each successive decade, the quantity of water consumed could exceed 400 Mgal/d (17.5 m^3/s) by the year 1990 and 800 Mgal/d (35.0 m^3/s) by the year 2000. If the large powerplants of the future are located inland where fresh water rather than saline water would be consumed, the stress on the fresh-water resource could be locally severe.

Table 1.--Estimated water use in Florida in 1970, million gallons per day (adapted from Pride, 1973).

TYPE USE	WATER WITHDRAWN				WATER CONSUMED	
	GROUND WATER		SURFACE WATER			
	FRESH	SALINE	FRESH	SALINE	FRESH	SALINE
Thermoelectric power production	12	50	1,700	9,300	20	86
Public supplies	760		120		230	
Rural domestic	160		12		130	
Livestock	18		12		30	
Irrigation	1,200		900		1,300	
Industrial[1/] (self supplied)	740	87	190	46	160	

1/ Other than thermoelectric power production.

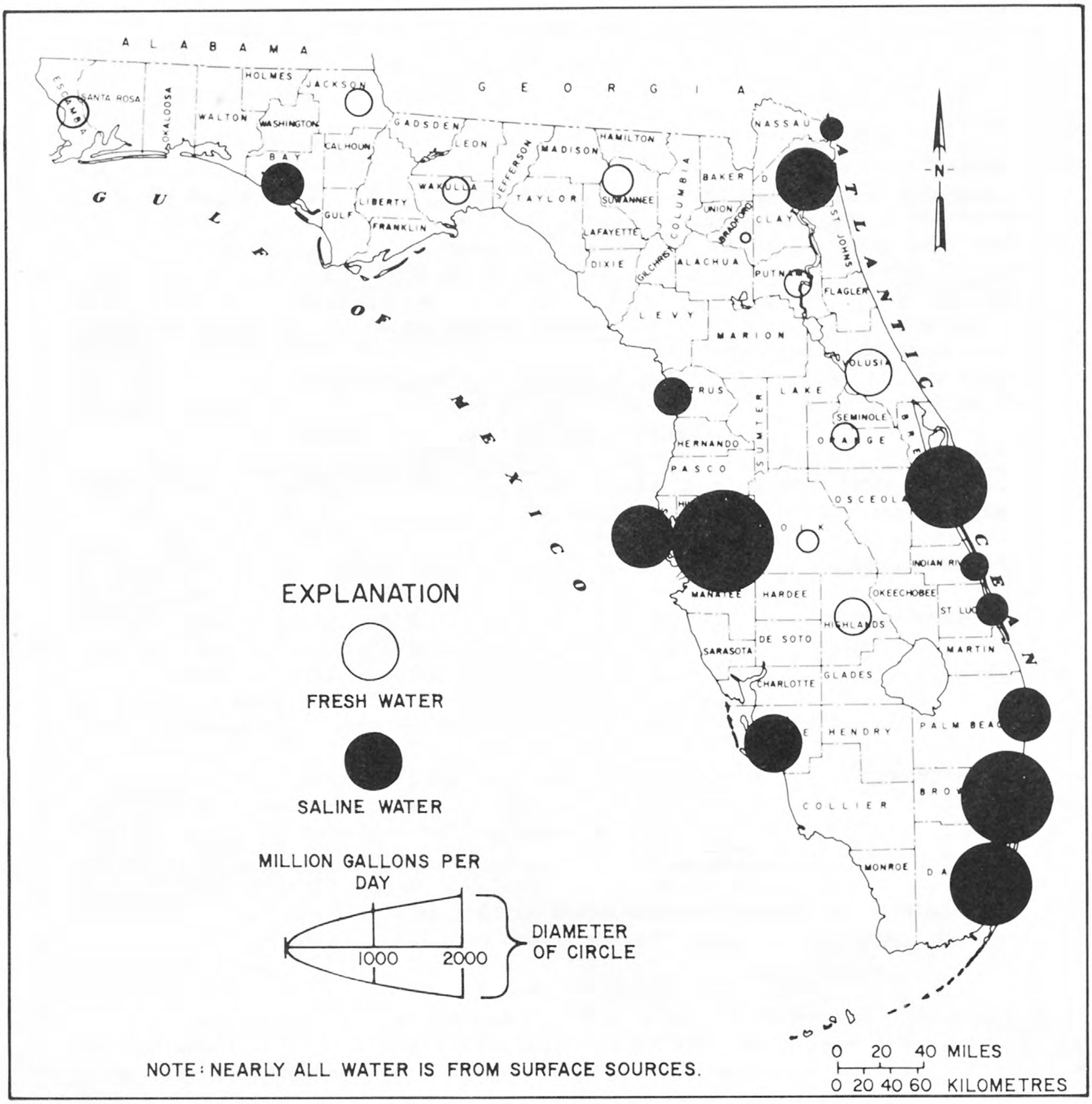

Figure 1.--Water withdrawn for thermoelectric power by counties in Florida, 1970 (adopted from Pride, 1973).

The quantity of cooling water required for thermoelectric power production varies with the type of cooling system used. This report considers the cooling-water requirement for 3 types of cooling systems generally used in Florida: cooling ponds, evaporative cooling towers, and once-through cooling. A distinction is made between the quantity of water withdrawn from a water supply for cooling purposes and the quantity of water that is consumed as a result of the cooling process.

Powerplants require some additional water for the boiler feed-water make-up, sanitary systems, and miscellaneous uses. However, the quantity of water required for such uses is small in relation to the quantity used by the cooling system and is not discussed herein.

YARDSTICK FOR EVALUATING COOLING-WATER REQUIREMENT

The cooling-water requirement of a thermoelectric powerplant varies with the quantity of power generated. In this paper the cooling-water requirement is appraised in terms of the need for a 1,000 MW nuclear powerplant operating at rated capacity with a thermal efficiency of 32 percent. The thermal efficiency of a powerplant represents the percentage of the energy input to the plant that is converted to electrical power. The thermal efficiency varies with the type of plant and with the back pressure on the steam turbine which in turn varies with the temperature of the condenser cooling water.

Most of the energy input to the plant that is not converted to electrical power is transferred to the cooling water circulated through the stream condenser, but some is dissipated directly to the atmosphere by radiation and conduction from the heated parts of the plant or, in the case of fossil-fuel plants, is carried off by chimney gases or by other minor waste products of combustion. The direct loss to the atmosphere is only about 5 percent for present nuclear plants compared to about 15 percent for fossil-fuel plants (Young and Thompson, 1973, p. 801). Thus, for a given thermal efficiency of 32 percent, a nuclear plant transfers about 63 percent of the energy input to the condenser-cooling water compared to 53 percent for a fossil-fuel plant. Contemporary fossil-fuel plants are also significantly more efficient thermally than nuclear plants. Consequently, the cooling-water requirement is substantially greater for a nuclear plan than for a fossil-fuel plant. The distribution of energy input to a nuclear plant is shown in figure 2.

A 1,000 MW powerplant is larger than some of the powerplants in Florida and smaller than others. For example, one of the larger plants in Florida is at Turkey Point in south Florida where generating capacity recently was increased to 2,320 MW. Present plans are to increase the capacity of a plant at Tallahassee in north Florida to 550 MW. Construction of a 1,700 MW powerplant is underway near Tampa in central

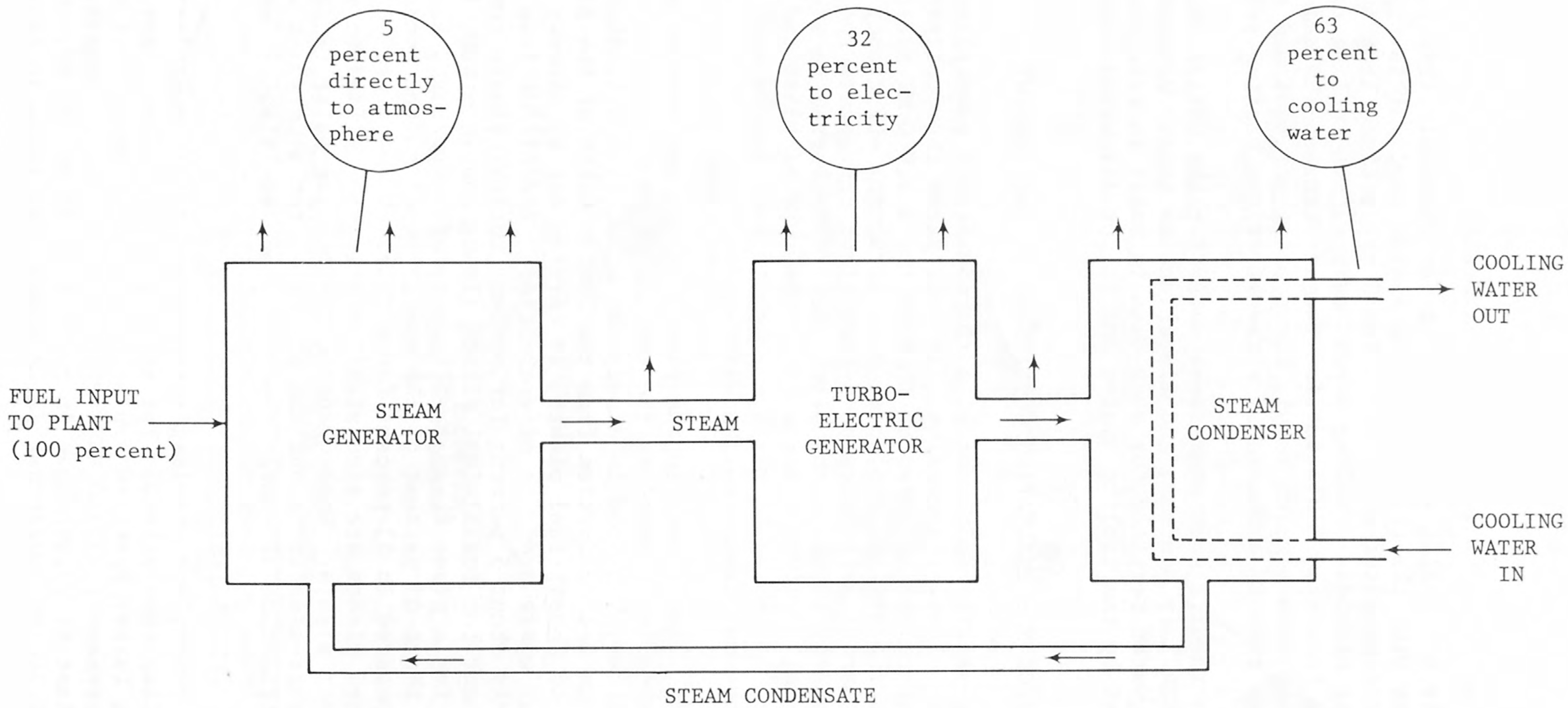

Figure 2.--Approximate distribution of total energy used in production of electricity by nuclear powerplant with a thermal efficiency of 32 percent.

Florida. Plants having generating capacities of several thousand megawatts are envisioned for the future.

WATER REQUIREMENT OF COOLING POND

In a cooling pond, heated water from the steam condenser passes through the pond and loses heat to the atmosphere by evaporation, conduction, and long-wave radiation and then returns to the powerplant for another round of cooling. The rate of heat transfer varies with the water-surface temperature. The temperature distribution of the pond water depends on the pattern of flow through the pond and the extent to which mixing occurs. These factors are in turn influenced by the configuration of the pond. In general, the temperature of the water returned to the plant intake varies inversely with the surface area of the pond. A relatively large area is required to provide cooling water at a temperature low enough to maintain the thermal efficiency of the plant at an acceptable level. For example, the surface area of the cooling pond of the 1,700 MW powerplant being built near Tampa ranges from 2,500 to 4,000 acres (1,000 to 1,600 hectares), depending on the stage of the pond.

A 1,000 MW nuclear powerplant transfers to the condenser-cooling water about 6.75×10^{9} BTU of heat per hour (4.7×10^{8} cal/s). During summer, cooling ponds in Florida transfer about 67 percent of the heat added by the cooling water to the atmosphere by evaporation, about 14 percent by conduction, and about 19 percent by long-wave radiation (Appendix A). For an assumed temperature of 91°F (33°C) the latent heat of vaporization of the cooling-pond water is about 1,040 BTU per pound (578 cal/g) of water. Thus, the added heat of the cooling water evaporates about 4.33×10^{6} pounds of water per hour (5.5×10^{5} g/s) or 104×10^{6} pounds of water per day (5.5×10^{5} g/s). If the density of water is taken as 8.35 pounds per gallon (1×10^{6} g/m^{3}), this converts to 12.5 Mgal/d (0.55 m^{3}/s). This is the quantity of water required to make up for the cooling water that evaporates, and which, for convenience herein, is called the "evaporation requirement" of the cooling system.

Figure 3 shows the evaporation requirements of cooling ponds in Florida for nuclear and fossil-fuel powerplants operating in summer. For a given thermal efficiency, the evaporation requirement varies directly with the generating capacity of the plant. Thus, although figure 3 represents the evaporation requirement for a 1,000 MW powerplant operating at rated capacity, it can be used to estimate the evaporation requirement for a plant of any size simply by multiplying the indicated evaporation requirement by the ratio of the generating capacity of the plant to 1,000 MW (assuming that the ratio of plant capacity to cooling-pond area is about the same for both powerplants).

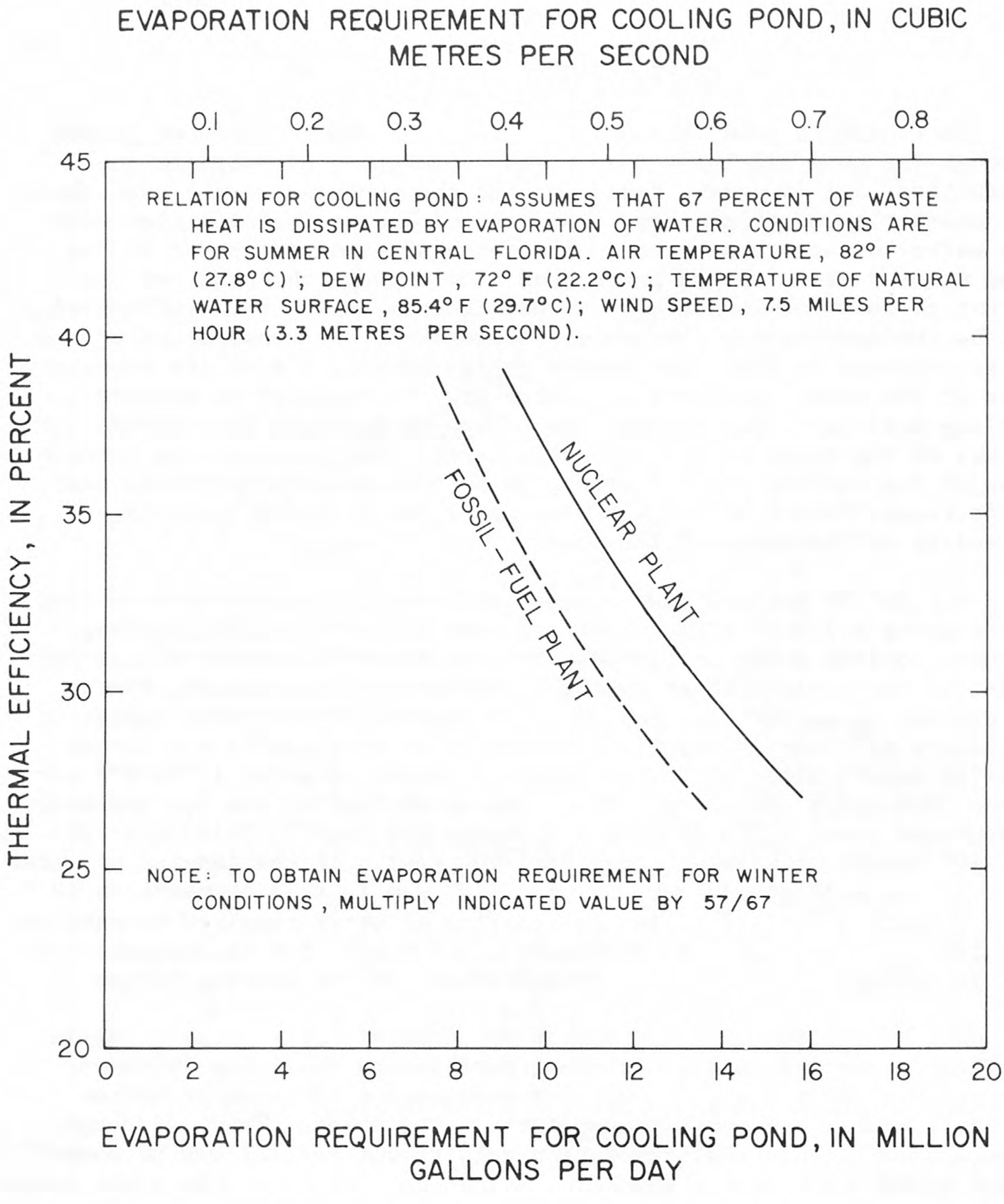

Figure 3.--Relation between thermal efficiency and quantity of water evaporated from cooling pond owing to heat added by condenser-cooling water from 1,000 megawatt powerplant operating at full load in summer in central Florida.

In winter a slightly smaller percentage (about 57 percent) of the waste heat added to a cooling pond is transferred by evaporation and a slightly greater percentage is transferred by conduction and radiation. The evaporation requirement decreases accordingly. The winter evaporation requirement of a cooling pond also can be estimated from figure 3, simply by multiplying the summertime evaporation requirement by the ratio of 57 percent to 67 percent (assuming that adjustments for possible differences in thermal efficiency and generating capacity already have been taken into account).

The relation curves of figure 3 are based on climatological data for central Florida. For summer evaporation requirements, the curves apply reasonably well to the entire State because the summer climate is about the same throughout the State. The winter climate is appreciably warmer in south Florida than in north Florida. Thus, the winter evaporation requirements determinable from figure 3 apply only to central Florida.

As determined herein, the evaporation requirement of a cooling pond does not include makeup water for natural evaporation; that is, it does not include water to make up for evaporation that would have occurred in the absence of heat added by the condenser-cooling water. Over the long term, rainfall in most of Florida averages from a few to serveral inches more than natural lake evaporation (Visher and Hughes, 1969). Thus, in most areas of Florida, rainfall on the cooling pond would be more than ample to sustain natural lake evaporation during years of near-normal or greater-than-normal rainfall. If the storage capacity of the cooling pond is sufficient, the rainfall excess of relatively wet years can be carried over to sustain natural evaporation during relatively dry years when evaporation may exceed rainfall for several successive months.

Evaporation tends to increase the concentration of the chemical constituents of the cooling-pond water. Thus, in addition to the water required to make up for the evaporated water, an appreciable quantiy of water is required to dilute the cooling-pond water and maintain the quality of the cooling-pond water at an acceptable level for ecologic, operational, or other controlling factors. The quantity of water required for this purpose, herein called the "blowdown requirement" varies with the evaporation requirement, with the quality of the makeup water, and with the quality that can be tolerated for the cooling-pond water.

The blowdown-water requirement can be determined from figure 4 as a percentage of the evaporation requirement. For example, if the concentration of dissolved solids in the makeup water is 200 mg/l (milligrams per litre) and it is essential or desirable to maintain the dissolved solids in the pond water at 1,000 mg/l, then as defined in figure 4, the concentration ratio is 5 and the corresponding blowdown

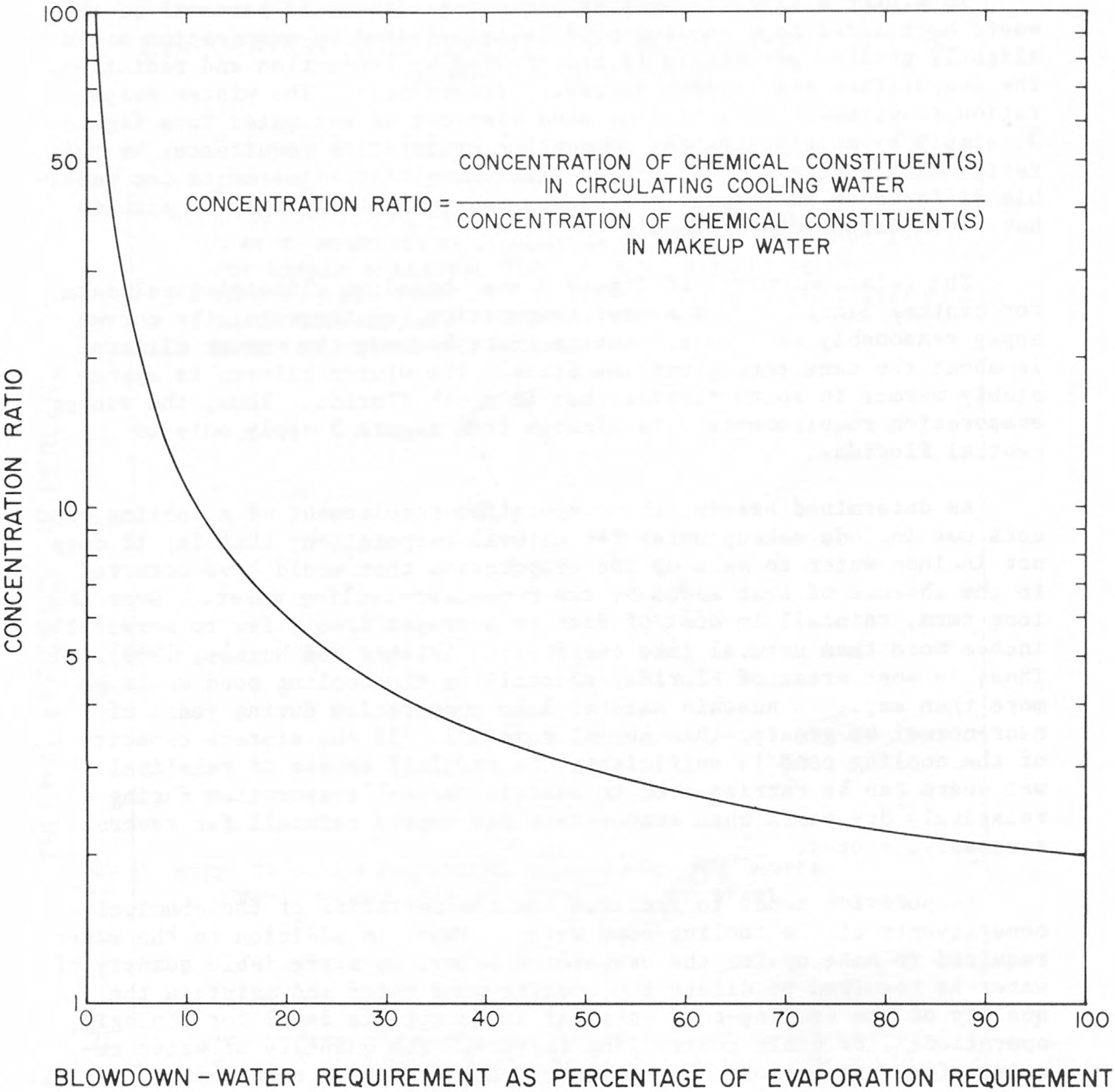

Figure 4.--Relation between blowdown-water requirement and degree of concentration of chemical constituents in makeup water for cooling ponds and evaporative cooling towers in Florida.

requirement is 25 percent of the evaporation requirement. Thus, given the 12.5 Mgal/d (0.55 m^3/s) of water as the evaporation requirement of the cooling pond for the 1,000 MW nuclear powerplant, and makeup water having a dissolved-solids concentration of 200 mg/l, an additional 3.1 Mgal/d (0.14 m^3/s) of water would be required to maintain the concentration of dissolved solids in the pond water at 1,000 mg/l. A like quantity of water would have to be discharged from the pond, of course, to maintain the water balance of the pond and to remove some of the dissolved solids from the cooling system. The blowdown requirement does not represent a reduction in the quantity of the local water resource, but it does represent a reduction in the quality of the local water resource and it might also represent a reduction in the opportunity for the timely withdrawal of water for other beneficial uses.

Without regard to the evaporation requirement of a cooling pond, the impoundment of water causes some reduction of the local water resource, because the natural evaporation from the pond usually is substantially greater than the evapotranspiration that would have occurred from the same area had the pond not been built. For example, in Florida the average annual lake evaporation ranges from about 46 inches (1,170 mm) in the northern part of the state to about 54 inches (1,370 mm) in the southern part (Kohler, Nordenson, and Baker, 1959, plate 2). Although evapotranspiration from land areas varies appreciably with the type of terrain, and is greater in densely vegetated wetland areas than in relatively sandy and barren upland areas, annual evapotranspiration averages about 12 inches (305 mm) less than lake evaporation. Thus, unless a cooling pond is created out of a swampy area, the resultant reduction of the local water resource easily might be as great as 12 inches (305 mm) of water over the pond area. For a cooling pond having a surface area of 3,000 acres (1,200 hectares), therefore, the loss of 12 inches (305 mm) of water owing to the difference between natural lake evaporation and evapotranspiration would equal 2.7 Mgal/d (0.12 m^3/s). This quantity of water would not have to be added to the pond, of course, but it does represent a reduction of the local water resource that is identifiable and chargeable to operation of the powerplant cooling system. Thus, depending on whether an existing water body might be available for use as a cooling pond, or whether a cooling pond would have to be created out of a dry-land area, the cooling pond of a 1,000 MW plant could cause a reduction in the local water resource ranging from about 12.5 to 15.2 Mgal/d (0.55 to 0.67 m^3/s).

WATER REQUIREMENT FOR EVAPORATIVE COOLING TOWER

For powerplants of the same size, the evaporation requirement is appreciably greater for an evaporative cooling tower than for a cooling pond. In a cooling tower almost all the heat load of the condenser cooling water is transferred to the atmosphere by evaporation and conduction, and virtually none is transferred by radiation. During summer in Florida about 80 percent of the heat load is transferred by evaporation (Appendix B). Thus, for a 1,000 MW nuclear powerplant, which discharges about 6.75×10^9 BTU per hour (4.7×10^8 cal/s) to the cooling water, an evaporative cooling tower would evaporate 5.19×10^6 pounds of water per hour (6.5×10^5 g/s) or 124×10^6 pounds of water per day (6.5×10^5 g/s), assuming that the latent heat of vaporization is 1,040 BTU per pound (578 cal/g). At a density of 8.35 pounds per gallon (1×10^6 g/m^3) of water, this quantity converts to 14.8 Mgal/d (0.65 m^3/s) compared to 12.5 Mgal/d (0.55 m^3/s) for a cooling pond.

Although the evaporation requirement is greater for a cooling tower than for a cooling pond, the reduction of the local water resource that is attributable to the operation of a powerplant might not differ significantly for the two unless an existing water body could be used for the cooling pond or unless the cooling pond could be created in a relatively swampy area.

Figure 5 shows the summer evaporation requirement of cooling towers for nuclear and fossil-fuel powerplants operating through a range of thermal efficiencies. For the same heat load, the evaporation requirement of evaporative cooling towers during winter in Florida is about 10 percent smaller than the summer requirement.

Because the evaporation requirement is greater for a cooling tower than for a cooling pond, the blowdown requirement also is greater for a cooling tower, given the same water-quality limitations. For example, if the concentration of dissolved solids in the makeup water is 200 mg/l, then from figure 4 an additional 3.7 Mgal/d (0.16 m^3/s) of water--equal to 25 percent of the 14.8 Mgal/d (0.65 m^3/s) evaporation requirement--is required to maintain the concentration of the dissolved solids in the water circulating through the cooling tower at 1,000 mg/l. Of course, a like quantity of water would have to be released to maintain the water balance and remove some dissolved solids from the cooling system. For a 1,000 MW nuclear powerplant, therefore, the water requirement of a cooling system using an evaporative cooling tower during summer in Florida would total 18.5 Mgal/d (0.81 m^3/s), of which 80 percent would be consumed.

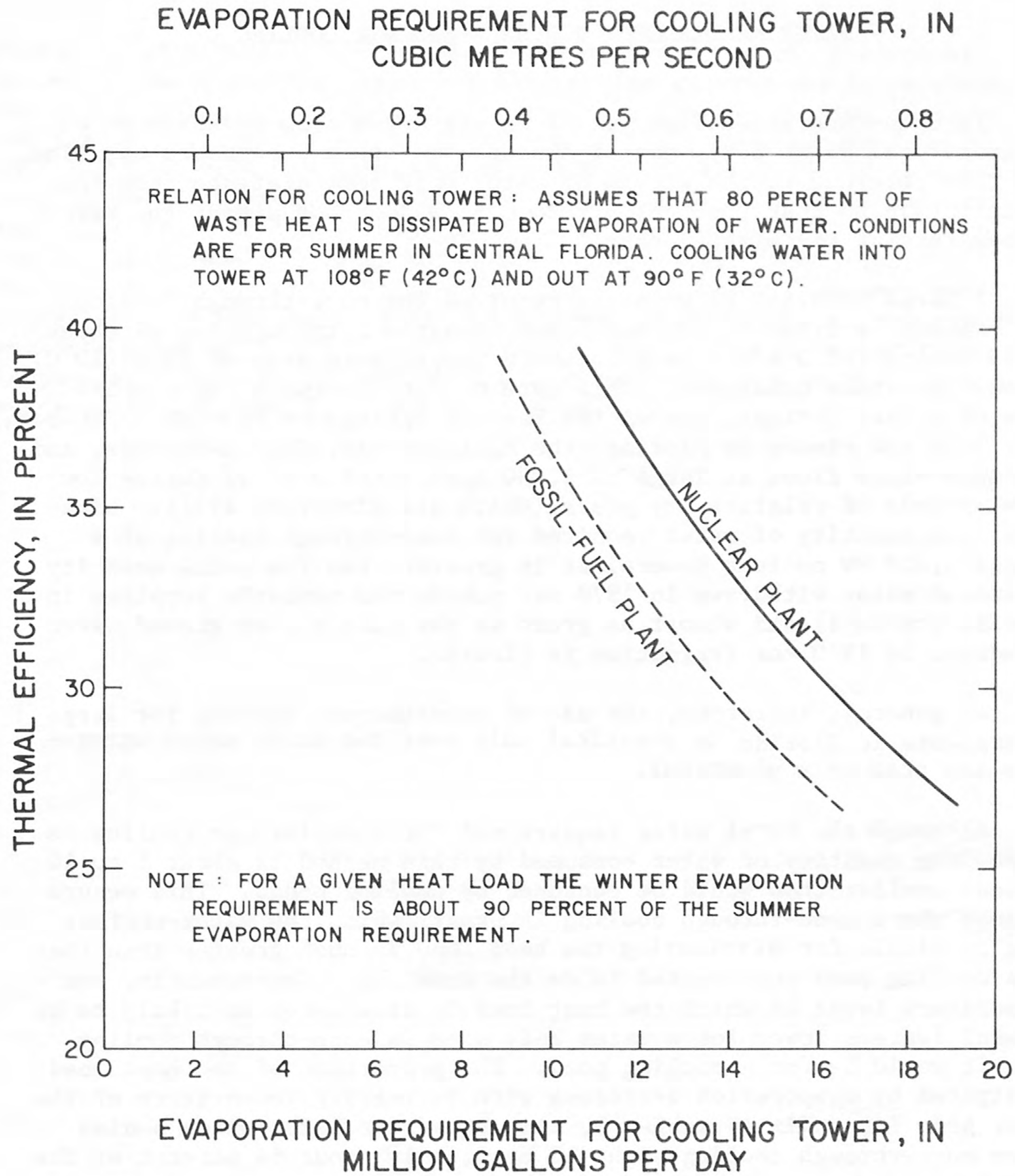

Figure 5.--Relation between thermal efficiency and quantity of water evaporated from cooling tower for 1,000 megawatt powerplant operating at full load during summer in central Florida.

WATER REQUIREMENT FOR ONCE-THROUGH COOLING

In once-through cooling, water is withdrawn from a stream or a large natural water body, passed through the steam condensers one time, and then returned to the stream or water body some distance from the plant intake so that the heated return flow does not affect the water temperature at the plant intake.

A large quantity of water is required for once-through cooling. For example, a 1,000 MW nuclear plant requires a throughflow of about 1,080 Mgal/d (47.3 m^3/s) to maintain a temperature drop of 18°F (10°C) across the steam condenser. This rate of flow is twice the average flow of Silver Springs, one of the largest springs in Florida. Further, only 3 of the rivers in Florida--the Apalachicola, Choctawhatchee, and Suwannee--have flows as large as 1,080 Mgal/d (47.3 m^3/s) during low flow periods of relative dry years (Heath and Wimberly, 1971). Likewise, the quantity of water required for once-through cooling of a single 1,000 MW nuclear powerplant is greater than the total quantity of ground water withdrawn in 1970 for public and domestic supplies in Florida (table 1) and almost as great as the quantity of ground water withdrawn in 1970 for irrigation in Florida.

In general, therefore, the use of once-through cooling for large powerplants in Florida is practical only near the coast where water--from the ocean--is plentiful.

Although the total water requirement for once-through cooling is large, the quantity of water consumed by this method is about 5 to 10 percent smaller than would be consumed by cooling ponds. This occurs because where once-through cooling is practicable, the water-surface area available for dissipating the heat load is much greater than that of a cooling pond constructed to do the same job. Consequently, the temperature level at which the heat load is dissipated is likely to be several degrees lower for a water body used in once-through cooling than it would be for a cooling pond. The proportion of the heat load dissipated by evaporation decreases with decreasing temperature of the water body (Appendix A, tables 3, 4). Thus, for large water bodies where once-through cooling might be used, only about 64 percent of the heat load of the cooling water is dissipated by evaporation in summer, compared to about 67 percent for conventionally sized cooling ponds. In winter, only about 52 percent is dissipated by evaporation compared to about 57 percent for cooling ponds.

In instances where streamflow might be large enough to serve as a supply for a once-through cooling system of a relatively small power plant, the rise in temperature of the streamflow downstream from the plant outlet is appreciable--unless the diversion to the powerplant is only a small part of the total flow of the stream--and it persists for a great distance downstream. For example, a throughflow of about 108 Mgal/d (4.73 m^3/s) is required to maintain a temperature drop of 18°F (10°C) across the condenser of a 100 MW powerplant. If this quantity of cooling water represents one-third the total flow of the stream, the temperature of the streamflow after mixing downstream from the plant outlet would be 6°F (3.3°C) above the natural water temperature. If the stream was 300 feet (91 m) wide, the heated water in summer would travel about 2.5 miles (4.0 km) downstream before the water temperature would be lowered to 5°F (2.8°C) above the natural water temperature (Appendix C) and the distance would be progressively greater for each successive increment (1°F or 0.6°C) of cooling.

SUMMARY

Appreciable quantities of water are consumed by cooling systems of thermoelectric powerplants in Florida. In summer the cooling systems of a 1,000 MW nuclear powerplant operating at full load consumes about 12.5 Mgal/d (0.55 m^3/s) of water if a cooling pond is used and 14.8 Mgal/d (0.65 m^3/s) if a cooling tower is used. Because the natural water loss to evaporation is greater for a water body than for a land area of comparable size in the same general environment, the total water consumption attributable to powerplant cooling may be greater for a cooling pond than for a cooling tower in instances where, for lack of a suitable natural water body, a cooling pond is created out of a dry-land area. Additional water is required to maintain the chemical quality of the cooling water at an acceptable level. Once-through cooling consumes 5 to 10 percent less water than a cooling-pond, but the total withdrawal of water for this method is so large that it is practicable only along the coast where the supply of saline water is virtually unlimited.

In 1970 about 106 Mgal/d (4.6 m^3/s) of water was consumed in producing electrical power in Florida. Most of this was saline water. With the anticipated increase in power production, consumption could increase to 400 Mgal/d (17.5 m^3/s) by 1990 and 800 Mgal/d (35.0 m^3/s) by 2000. Continued use of saline water--rather than fresh water--would contribute importantly to conservation of the fresh-water resource.

SELECTED REFERENCES

Anderson, E. R., 1954, Energy-budget studies, in Water-loss investigations--Lake Hefner studies, technical report: U.S. Geol. Survey Prof. Paper 269, p. 71-119.

Bowen, I. S. , 1926, The ratio of heat losses by conduction and evaporation from any water surface: Phys. Rev. v. 27, p. 779-787.

Edinger, John E., and Geyer, John C., 1965, Heat exchange in the environment: Edison Electric Inst., New York, N. Y., Pub. 65-902, 259 p.

Florida Statistical Abstract, 1974: Bur. Econ. Business Research, Univ. Florida, 8th ann. ed., 621 p.

Harbeck, G. Earl, Jr., 1953, The use of reservoirs and lakes for dissipation of heat: U.S. Geol. Survey Circ. 282, 6 p.

Hauser, L. G., 1971, Cooling water for power generation: Am. Soc. Civil Engineers, Jour. Power Div., v. 97, no. PO1, p. 123-133.

Heath, R. C. and Wimberly, E. T., 1971, Selected flow characteristics of Florida streams and canals: Florida Dept. Nat. Resources, Bur. Geology, Inf. Circ. 69, 595 p.

Kohler, M. A., Nordenson, T. J., and Baker, D. R., 1959, Evaporation maps for the United States: U.S. Weather Bur. Tech. Paper 37, 13 p., 5 pl.

Marciano, J. J., and Harbeck, G. E., Jr., 1954 Mass-transfer studies in Water-loss investigations--Lake Hefner studies, technical report: U. S. Geol. Survey Prof. Paper 269, p. 46-70.

Marks, Lionel S., (Ed.), 1951, Mechanical Engineers' Handbook, 5th edition: McGraw-Hill Book Company, Inc., N. Y.

Nelson, Guy R., 1974, Water recycle/reuse possibilities--Power plant boiler and cooling systems: National Environmental Research Center, U.S. Environmental Protection Agency, EPA-660/2-74-089, 51 p.

Pride, R. W., 1973, Estimated use of water in Florida, 1970: Florida Dept. Natural Resources, Bur. Geology Inf. Circ. 83, 31 p.

Ryan, P. J., Harleman, D. R. F., Stolzenbach, K. D., 1974, Surface heat loss from cooling ponds: Water Resources Research, v. 10, no. 5, p. 930-938.

SELECTED REFERENCES (Continued)

Visher, F. N., and Hughes, G. H., 1969, The difference between rainfall and potential evaporation in Florida: Florida Dept. Nat. Resources, Bur. Geology, Map Ser. 32, 1 sheet.

Young, P. H., and Thompson, R. G., 1973, Forecasting water use for electric power generation: Water Resources Research, v. 9, no. 4, p. 800-807.

APPENDIX A

HEAT TRANSFER BY COOLING POND

Waste heat to cooling pond = $\Delta Qe + \Delta Qh + \Delta Qbs$ (1)

wherein ΔQe = part of waste heat used by evaporation,
ΔQh = part of waste heat transferred from pond as sensible heat, and
ΔQbs = part of waste heat transferred by long-wave radiation, all in calories per square centimeter per day.

The magnitude of ΔQe, ΔQh, and ΔQbs are determined as the difference between the energy transferred from the pond by the respective processes with heat added by the condenser cooling water and the energy that would have been transferred from the pond in the absence of the heat added by the cooling water; that is, the conditions of a natural water body are used as a reference.

Evaporation presumably can be estimated satisfactorily by use of a simplified mass-transfer equation such as that proposed by Marciano and Harbeck (1954, p. 65):

$$E = n\,u\,(e_o - e_a) \tag{2}$$

in which E = evaporation, in inches per day;
n = an empirical coefficient (See equation 12;)
u = wind speed at some level over the water surface, in miles per hour;
e_o = vapor pressure of air saturated at the temperature of the water surface, in millibars; and,
e_a = vapor pressure of the air, in millibars.

The energy required for the evaporation of E inches of water is

$$Q_e = 2.54\rho LE \tag{3}$$

in which Q_e = the energy used for evaporation, in calories per square centimeter per day

ρ = density of water, in grams per cubic centimeter,
L = latent heat of vaporization, in calories per gram.

Thus, if symbols without prime remarks represent conditions of a natural water body and symbols with prime marks represent conditions of the same water body but with heat added by the condenser cooling water:

$$\Delta Q_e = Q_e' - Q_e \tag{4}$$

$$\simeq \rho L\, n\, u\, (e_o' - e_o) \tag{5}$$

The approximation of equation 5 results from the presumption that the density and latent heat of vaporization of water are the same for the heated and unheated water, which is not true, of course; however, for the purpose of this report the resulting error is inconsequential for temperature differences as much as 15°C.

Similarly, for energy transferred as sensible heat (Q_h),

$$\Delta Q_h = Q_h' - Q_h \tag{6}$$

By use of Bowen's (1926) ratio (R),

$$Q_h = RQ_e \tag{7}$$

$$= \frac{0.61P\,(T_o - T_a)}{1{,}000\,(e_o - e_a)}\, Q_e \tag{8}$$

where P = atmospheric pressure, in millibars;
T_o = temperature of water surface, in °C; and
T_a = temperature of the ambient air, in °C.

Combining equations 2, 3, 6, and 8,

$$\Delta Q_h \simeq \frac{1.55\ P}{1{,}000}\, \rho L\, n\, u\, (T_o' - T_o) \tag{9}$$

The energy transferred by long-wave radiation from a water body to the atmosphere (Q_{bs}) can be computed by use of the Stefan-Boltzman law for black body radiation:

$$Q_{bs} = \varepsilon\sigma(T_o+273)^4 \tag{10}$$

where ε = emissivity of water (0.97; Anderson, 1954),

σ = the Stefan-Boltzman constant for black-body radiation [1.171×10^{-7} calories per square centimeter per day per (degree Kelvin)^4].

Thus, the part of the added heat transferred by long-wave radiation from the cooling pond is

$$\Delta Q_{bs} = \varepsilon\sigma[(T_o' + 273)^4 - (T_o+273)^4] \tag{11}$$

The coefficient (n) of the mass-transfer equation (equation 2) was determined as follows:

$$n = \frac{E_a}{365} \times \frac{1}{\frac{\Sigma u\ (e_o - e_a)}{12}} \qquad (12)$$

where E_a = average annual lake evaporation, taken as 51 inches on basis of the estimate for the general area of Tampa, Florida, by Kohler, Nordenson, and Baker (1959, pl. 2)

and $\Sigma u\ (e_o - e_a)$ = sum of the products of monthly wind speed and vapor-pressure difference for each month of year, based on data in table 2.

Inasmuch as the values of wind speed used herein were not adjusted for differences in the height of wind instruments used in this and other studies, the resulting value of the mass-transfer coefficient is not directly comparable with values obtained in other studies.

The heat-transfer rates determined by the use of the preceding equations, in conjunction with the climatic data listed in table 2, are summarized in tables 3 and 4, and also in figure 6. The percentage of the total heat load that is transferred by the evaporation of water increases slightly with increasing temperature of the cooling-pond water. Presumably the surface temperature of a cooling pond would vary appreciably between the inlet to and outlet from the powerplant. The values of 67 and 57 percent used to determine summer and winter evaporation requirements of cooling ponds in Florida were presumed to be representative average values.

Figure 6 shows that for the same rate of heat transfer, the temperature increase (heated water body over natural water body) is greater in winter than in summer. Thus, for a given heat load and cooling pond area, the increase in water temperature would be greater in winter than in summer.

For a given water-surface temperature, the rate of heat transfer might be appreciably greater than indicated by tables 3 and 4 because of convection currents owing to the change in density of air that is warmed in passing over a heated water surface (Ryan, Harleman, and Stolzenbach, 1974). This effect would require an adjustment to the mass-tranfer coefficient which is beyond the scope of this report. Any adjustment to the mass-transfer coefficient would affect ΔQ_e and ΔQ_h to

Table 2.--Monthly wind speeds, air and water temperatures that are generally representative of central Florida.

	Air temperature 1/ (T_a)		Dew-point 2/		Vapor pressure 3/ of air (e_a)	Natural water-surface temperature 4/ (T_o)		Saturation vapor pressure at water-surface temperature 5/ (e_o)	Wind-speed 6/ (u)
	°F	°C	°F	°C	millibars	°F	°C	millibars	miles per hour
January	61.2	16.2	50.5	10.3	12.5	61.5	16.4	18.6	9.1
February	62.7	17.0	48.6	9.2	11.6	63.8	17.6	20.1	9.7
March	66.0	18.9	52.8	11.6	13.7	69.2	20.6	24.3	10.0
April	71.4	21.9	59.6	15.4	17.5	74.3	23.5	28.9	9.7
May	76.8	24.9	62.8	17.1	19.3	79.6	26.4	34.4	9.2
June	80.6	27.0	69.3	20.7	24.4	84.8	29.4	41.0	8.4
July	81.6	27.6	71.5	22.0	26.4	85.6	29.8	41.9	7.6
August	82.0	27.8	72.0	22.2	26.8	85.3	29.6	41.5	7.4
September	80.5	27.0	70.1	21.2	25.2	82.7	28.2	38.2	8.6
October	74.7	23.7	64.4	18.0	20.6	76.6	24.8	31.3	9.1
November	66.8	19.4	54.1	12.3	14.3	68.9	20.5	24.1	8.9
December	62.3	16.8	51.6	10.9	13.0	63.6	17.6	20.1	8.9

1/ Long-term monthly average for Tampa, Fla. (National Weather Service).
2/ Monthly average for Tampa, Fla., 1965-72 (National Weather Service).
3/ Vapor pressures correspond to monthly average dew-point temperatures.
4/ Monthly average based on 3 years USGS unpublished data for Lake Helene in central Florida.
5/ Saturation pressures correspond to monthly water-surface temperatures.
6/ Long-term monthly average for Tampa, Fla. (National Weather Service); wind instruments 22 to 56 feet above ground level.

Table 3.--Summer distribution of heat load transferred to the atmosphere by evaporation, conduction, and long-wave radiation from hypothetical cooling pond in central Florida.

Temperature rise 1/		Evaporation (ΔQ_e)	Conduction (ΔQ_h)	Long-wave radiation (ΔQ_{bs})	Total ($\Delta Q_e + \Delta Q_h + \Delta Q_{bs}$)	$\frac{\Delta Q_e}{\text{Total}}$
°C	°F	BTU per square foot per day				
1	1.8	140	33	44	217	0.64
2	3.6	280	68	92	440	.64
4	7.2	594	136	188	918	.65
6	10.8	929	206	284	1,419	.65
8	14.4	1,316	273	383	1,972	.67
10	18.0	1,733	343	487	2,562	.68
12	21.6	2,186	413	600	3,189	.69
14	25.2	2,684	479	697	3,860	.70

1/ Temperature rise above natural water-surface temperature owing to added heat.

Note.--Summer rates are based on the average of climatic conditions given in table 2 for July and August.

Table 4.--Winter distribution of heat load transferred to the atmosphere by evaporation, conduction, and long-wave radiation from hypothetical cooling pond in central Florida.

Temperature rise 1/		Evaporation (ΔQ_e)	Conduction (ΔQ_h)	Long-wave radiation (ΔQ_{bs})	Total ($\Delta Q_e + \Delta Q_h + \Delta Q_{bs}$)	$\frac{\Delta Q_e}{\text{Total}}$
°C	°F	BTU per square foot per day				
1	1.8	85	44	41	170	0.52
2	3.6	181	85	85	351	.52
4	7.2	387	170	170	727	.53
6	10.8	608	254	254	1,116	.54
8	14.4	863	343	343	1,549	.56
10	18.0	1,135	428	428	1,993	.57
12	21.6	1,449	512	523	2,484	.58
14	25.2	1,784	597	616	2,997	.60

1/ Temperature rise above natural water-surface temperature owing to the added heat.

Note.--Winter rates are based on the average of climatic conditions given in table 2 for January and February.

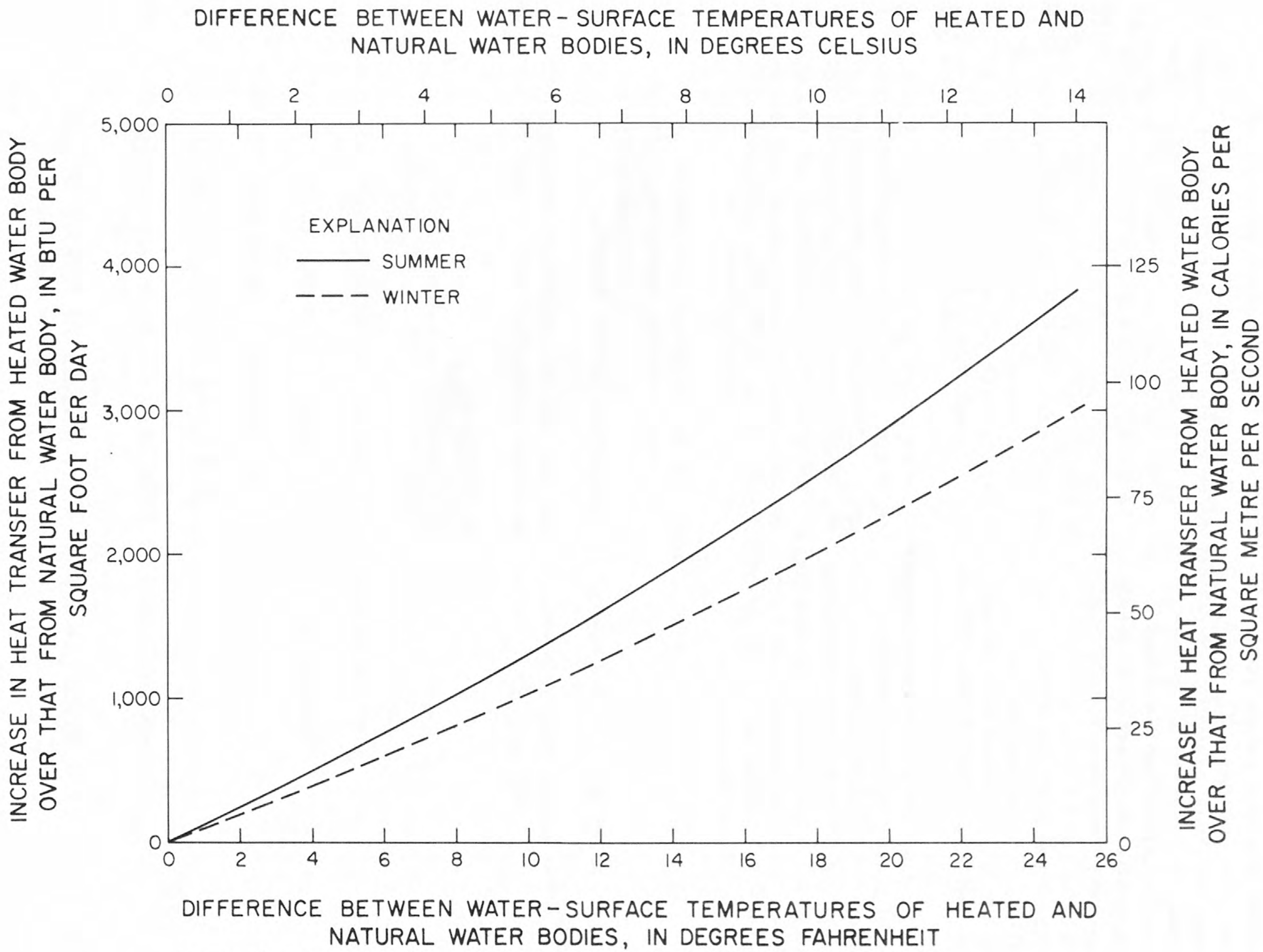

Figure 6.--Relation between water-surface temperature and rate of heat transfer from hypothetical heated water body in central Florida.

the same extent as long as Bowen's ratio is presumed to apply; long-wave radiation from the pond would not be affected. If for a given water-surface temperature the effect of the change in density of air were to increase ΔQ_e and ΔQ_h by as much as 10 percent (and the total rate of heat transfer increased accordingly), the percentage of waste heat transferred by evaporation would be about 1 percent greater than indicated in tables 3 and 4. Thus, for a given water surface temperature the evaporation requirement of a cooling pond would be 1 percent greater than previously indicated in this paper. On the other hand, if the rate of heat transfer were greater than indicated, the temperature rise for a pond of given size and heat load would be decreased. Thus, insofar as the percentage of heat transferred by evaporation of water is involved the effect of a higher rate of heat transfer would be partly offset by the effect of the lower resulting water temperature.

Similarly, the heat transfer rates given in tables 3 and 4 for ΔQ_e and ΔQ_h are dependent on the estimate of an average annual lake evaporation (51 inches or 1,300 mm). If annual lake evaporation is greater or less than estimated, the heat transfer rates would be increased or decreased accordingly. However, the percentage of the waste heat that is transferred by the evaporation of water would not be appreciably affected by an error of 10 percent or so in the estimate of annual lake evaporation.

APPENDIX B

HEAT TRANSFER BY EVAPORATIVE COOLING TOWER

The percentage of waste heat transferred to the atmosphere by the evaporation of water in a cooling tower can be determined by solving a water-balance equation and an enthalpy-balance equation simultaneously, using as two unknowns the quantity of water to be evaporated and the quantity of air to be passed through the cooling tower (Marks, 1951, p. 363).

The water-balance equation of a cooling tower (per pound of cooling water) may be written:

$$1 + W_a s_1 = 1 - x + W_a s_2 \tag{13}$$

in which W_a = quantity of air passing through tower, pounds of air per pound of cooling water,

s_1 = specific humidity of air entering tower, pounds of water per pound of air,

s_2 = specific humidity of air leaving tower, pounds of water per pound of air, and

x = pounds of water evaporated per pound of cooling water.

The specific humidity of air (s) may be computed with ample accuracy by use of the following equation (Marks, 1951, p. 355):

$$s = \frac{p_v}{1.61\ (P - p_v)} \tag{14}$$

in which p_v = vapor pressure of air, in inches of mercuty, and

P = atmospheric pressure, in inches of mercury.

The enthalpy-balance equation is:

$$h_{w1} + W_a h_{a1} = (a - x)h_{w2} + W_a h_{a2} \tag{15}$$

in which h_{w1} = enthalpy of cooling water on entering tower, BTU per pound,

h_{w2} = enthalpy of cooling water on leaving tower, BTU per pound,

h_{a1} = enthalpy of air entering tower, BTU per pound,

h_{a2} = enthalpy of air leaving tower, BTU per pound,

W_a and x are as previously defined for the water-balance equation.

The enthalpy of the cooling water (h_w) can be determined with ample accuracy by subtracting 32 from the temperature of the water in ^{o}F. The enthalpy of air (h_a) may be computed by the following equation: (Marks, 1951, p. 356):

$$h_a = 0.24\ T_a + s\ (1062 + 0.44\ T_a) \qquad (16)$$

in which T_a = dry-bulb temperature of air, in ^{o}F, and

s = specific humidity of air, in pounds of water per pound of air.

For summer calculations, the cooling water was assumed to enter the cooling tower at $108^{o}F$ ($42^{o}C$) and leave it at $90^{o}F$ ($32^{o}C$). The ambient air was assumed to have a temperature of $82^{o}F$ ($27.5^{o}C$) and a dew point of $72^{o}F$ ($22^{o}C$). Air was assumed to leave the cooling tower saturated at a temperature of $104^{o}F$ ($40^{o}C$). Results were essentially unchanged by assuming the air to leave the tower saturated at $108^{o}F$ ($42^{o}C$). Atmospheric pressure was taken as 30 inches (760 mm) of mercury.

For winter calculations, the cooling water was assumed to enter the cooling tower at a temperature of $88^{o}F$ ($31^{o}C$) and leave it at a temperature of $70^{o}F$ ($21^{o}C$). The air was assumed to enter the cooling tower at a temperature of $62^{o}F$ ($16.5^{o}C$) and a dew point of $50^{o}F$ ($10^{o}C$); air was assumed to leave the tower saturated at a temperature of $84^{o}F$ ($29^{o}C$).

Once the quantity of evaporated water (x) is known, the quantity of heat transferred by evaporation is readily determinable by taking into account the latent heat of vaporization; the quantity of heat transferred by evaporation then can be expressed as a percentage of the total heat transferred to the air.

APPENDIX C

DISSIPATION OF HEAT ADDED TO A STREAM

The downstream distance required for lowering the temperature of streamflow heated by waste heat from a powerplant was determined from the area required to dissipate a given heat load under steady-state conditions. If the total heat load raises the temperature of the streamflow 6°F (3.3°C) above the natural water temperature, then one-sixth of the total heat load is dissipated for each 1°F (0.6°C) that the water temperature is lowered as the water cools. For the example cited in the text, the total heat load was 6.75×10^8 BTU per hour (4.7×10^7 cal/s), or one-tenth of that given for a 1,000 MW nuclear powerplant. From the relation in figure 6, the rate of heat transfer from a heated water body in summer is about 760 BTU per square foot per day [24 (cal/m^2)/s] at 6°F (3.3°C) above the natural water temperature and about 620 BTU per square foot per day [19 (cal/m^2)/s] at 5°F (2.8°C) above the natural water temperature. The approximate area required to lower the temperature of the streamflow 1°F (0.6°C) is obtained by dividing one-sixth the total heat load by the average rate of cooling for the reach in which the cooling takes place. In this instance the average rate of heat transfer would be about 690 BTU per square foot per day [22 (cal/min^2)/s]. Once the area is known, the downstream distance is automatically determined for any assumed width of stream. Because of the non-linear relations involved, the computation of area should be done for relatively small increments of cooling. Inasmuch as the rate of heat transfer for a given temperature rise is larger in summer than in winter (fig. 6), the downstream distance required to dissipate a given heat load would be appreciably greater in winter than in summer.

Although the relation of figure 6 does not allow for a possible increase in the rate of heat transfer owing to convection currents set up by the change in density of air passing over a heated water surface, the resulting error in computed area would be small in instances where the water is heated only a few degrees above the natural water temperature.

APPENDIX D

CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	Multiply by	Metric
inches (in)	25.4	millimetres (mm)
	.0254	metres (m)
feet (ft)	.3048	metres (m)
miles (mi)	1.609	kilometres
acres	.4047	hectares (ha)
million gallons per day (Mgal/d)	.04381	cubic metres per second (m^3/s)
gallon (gal)	3.785×10^{-3}	cubic metres (m^3)
pounds (lb)	454	grams (g)
British thermal units (BTU)	252	calories (cal)
British thermal units per hour (BTU/hr)	.0700	calories per second (cal/s)
millibars (mb)	.7501	millimeters of mercury (mm Hg)
watt (W)	.2388	calories per second (cal/s)
megawatts (MW)	2.388×10^5	calories per second (cal/s)
British thermal units per square foot per day ($(BTU/ft^2)/d$)	.03140	calories per square metre per second ($(cal/m^2)/s$)
British thermal units per pound (BTU/lb)	.5551	calories per gram (cal/g)