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Eugene Eno

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ACCELERATOR COOLING SYSTEMS

Eugene Eno

Lawrence Radiation Laboratory
University of California
Berkeley, California

April 4, 1969

ABSTRACT

The behaviour of accelerator cooling systems is discussed, and an attempt is made to explain the wide variation in the reported costs of cooling systems at various accelerator laboratories.

First, alternate methods of cooling are analyzed as to concept, relative functional suitability, and relative cost. Second, a brief explanation is given of the theory of cooling towers. This explanation includes illustrations of the effects of atmospheric and operating conditions on the efficiency and, hence, the cost of cooling. Third, the economic and functional effects of cooling on other accelerator components are analyzed. Fourth, equipment associated with accelerator cooling systems is briefly discussed and evaluated. This equipment includes such things as heat exchangers, piping materials, and ion-exchange systems. Fifth, tables and charts are included which list the costs of cooling-system components. These prices are intended chiefly to illustrate the relative economic significance of the components and should be used for rough estimating only. Sixth, the cooling systems at existing accelerator laboratories are compared.

The ultimate criterion for evaluation of cooling systems is their actual operating record. Records at this laboratory show that some of our

accelerators have maintained operating beam for more than 95% of the elapsed time, an enviable record.

1. CONCLUSIONS

For the convenience of those who are reluctant to labor through the entire report, the conclusions are presented here.

1. The following are conclusions regarding the capital outlay (expressed as $/kW) for cooling equipment:

a. The cost of similar pieces of cooling equipment is nearly the same throughout the United States.

b. Alternate methods of cooling such as the use of cooling ponds or spray ponds are neither economically nor functionally as desirable as conventional cooling-tower methods.

c. Evaporative coolers are cheaper than cooling towers for small cooling loads. Cooling-towers are cheaper for large loads.

d. A single large-capacity cooling tower is generally cheaper than several small towers of the same aggregate capacity.

e. Cooling equipment is cheaper if designed to operate with a larger approach of the cold-water temperature to the wet-bulb temperature.

f. Cooling equipment is cheaper if designed to operate with a larger water temperature range.

g. When maintaining the same cold-water temperature, cooling equipment is cheaper if designed to operate in that section of the country where the design wet-bulb temperature is lower.

h. When maintaining the same approach (i.e., higher cold-water temperature with higher wet-bulb temperature), cooling equipment is cheaper if designed to operate in that section of the country where the design wet-bulb temperature is higher.

i. The cost of heat exchangers increases with a decrease in the logarithmic-mean temperature difference between the tower water and the closed-circuit water.

j. Larger heat exchangers are cheaper on a dollars-per-square-foot basis than smaller ones.

k. Where applicable, air-cooled heat exchangers, used alone or in combination with cooling towers, are competitive economically with the use of cooling-towers alone. Their use offers a great savings in water consumption.

l. For each laboratory, there is an optimum economic degree of cooling-system centralization.

2. At accelerator laboratories, most of the cooling load generally consists of dissipating the heat developed by magnets. The following are conclusions regarding the effect of cooling systems on the operational cost of magnets:

a. Magnet electric power costs are significantly less at lower magnet temperatures.

b. Magnet insulation life is extended at lower temperatures. This life extension does not appear significant for the temperatures normally encountered.

c. Magnet temperature affects the control of the magnetic field. This effect does not appear significant.

d. Magnet power supplies (particularly solid-state rectifiers and regulating equipment) may require lower operating temperatures than can be obtained from cooling towers. This may necessitate the use of chilling equipment. Such use increases the cost of cooling considerably.

e. With lower magnet temperatures, the cooling system may be operated at lower hydraulic pressure without risking cavitation at high water flow through the magnets. A cooling system operating at a lower hydraulic pressure is cheaper than one operating at a higher pressure.

3. The capital outlay for cooling equipment (expressed as $/kW) is generally higher at the Lawrence Radiation Laboratory (LRL) than at other accelerator laboratories. Factors contributing to this higher capital outlay are:

a. The closed-circuit cooling-water supply temperature is generally maintained at a lower temperature than at other laboratories.

b. The tower-water temperature range is generally less than at other laboratories.

c. A number of rather small capacity cooling-towers are used as contrasted to the use of a few large capacity towers by other laboratories. This is due primarily to the fact that funds for cooling equipment have been made available in steps corresponding to the approval and funding of new installations.

4. The total cost of cooling (expressed as $/kW and defined as the capital outlay plus ten years operational cost including the economic effect on other facilities) is generally less at the Lawrence Radiation Laboratory than at other accelerator laboratories. Factors contributing to this lower total cooling cost are:

a. The savings in magnet electric power cost brought about by lower water temperature outweigh the added costs of maintaining these lower temperatures.

b. The cooling-water temperature is maintained sufficiently low to eliminate the need for chillers in cooling the magnet power supplies.

c. The cooling-water systems are operated at lower hydraulic pressures than are employed by many accelerator laboratories.

5. The cost of maintaining low-temperature water is generally less at the Lawrence Radiation Laboratory than at other accelerator laboratories since, geographically and atmospherically, this section of the country is better suited to accelerator cooling.

6. The choice of heat-exchange equipment should depend upon consideration of the cost, the functional and safety requirements, the ease of maintenance, and the climatic conditions at the site.

7. Many materials are available for use in low-conductivity water systems. All have limitations.

a. Polymetallic low-conductivity water systems should be avoided.

b. The effects of radiation, magnetic field, and impressed current on materials must be considered.

8. The degree of water purity required for low-conductivity water systems depends on the electrical resistance requirements of the accelerator components being cooled.

a. Water obtained from mixed-bed demineralizers is purer than that from two-bed or multi-bed units.

b. Sulfuric acid is cheaper than hydrochloric acid for regenerating cations resins and requires less storage volume.

c. If calcium constitutes more than 20% of the cations in the makeup water to the demineralizer when sulfuric acid is used as the regenerant, the demineralizer should be preceded by a sodium-cycle water softener.

d. The savings in labor cost obtained by using "automatic" or "semi-automatic" demineralizers will pay for the added cost of the automatic features in from one to two years.

e. Recycling 1 or 2% of the low-conductivity water system flow through the demineralizer will usually maintain the system conductivity within satisfactory limits.

9. Low-pressure low-conductivity water systems are cheaper and less subject to trouble than high-pressure systems. Usually magnets and other equipment can be designed to function satisfactorily with a low-pressure cooling system.

10. The cost of accelerator cooling ($/kW) averages approximately the same throughout the United States. In some cases, site conditions and operating requirements peculiar to particular installations cause the cooling cost to vary from the average.

II. ALTERNATE METHODS OF COOLING

A. General Discussion

Once-Through Cooling

This method consists of circulating water from a river or other similar source through a heat exchanger and back to the river. It is a primitive but very effective method of cooling and has been used by many industries.

An advantage to this method is that there is not extensive evaporation and, accordingly, very little concentration of dissolved solids. The water usually does not require chemical treatment.

One disadvantage is that the temperature of the river is raised by the process. This thermal pollution has a detrimental effect on the flora and fauna along and within the stream. Another disadvantage is the fact that rivers often contain considerable debris along with various forms of life. This can lead to rapid fouling of heat-exchange equipment if adequate preventive measures are not taken. Sea water, if used, is very corrosive, and piping and heat exchangers must be constructed of expensive corrosion resistant materials.

Cooling Ponds

Cooling ponds* and once-through cooling were probably the first methods of liquid cooling.

Under given atmospheric conditions, a body of water will eventually come to a temperature where the heat loss is exactly equal to the heat gain. This temperature is called the equilibrium temperature. If a pond has a holdup of 24 hours or more, the equilibrium temperature may be taken as the average

*H. L. Langhaar, Chem. Eng. 80, 194 (1953).

mean monthly water temperature. A list of average mean monthly water and air temperatures for the State of Illinois is listed in Appendices A and B.

The equilibrium temperature is greatly effected by the amount of solar radiation. Table I lists the maximum expected solar radiation in Btu/h-ft^2 at various north latitudes.

In order to cool a pond with a given cooling load to the equilibrium temperature, an infinite pond area would be required for warm water. An approach of 3 or 4°F is the lowest practicable in a pond of reasonable size.

The area of a pond required for a given cooling load is almost independent of the pond depth. For a pond having a 24-h holdup, the leaving water temperature will vary from the average by ±2°F for a 5-ft depth and by 3° for a 3-ft depth. A 5-ft depth is usually chosen to avoid excessive channeling of flow and large night-to-day changes in outlet temperature,

The factors affecting cooling-pond performance are (1) air temperature, (2) relative humidity, (3) wind speed, and (4) solar radiation. Such things as the heat transfer between the earth and the pond, changing temperatures and humidity of the air, and rain have very minor effects on the cooling-pond performance.

Figure 1 is a nomograph providing a rapid method of determining the pond area required for a given cooling duty. Here E_1 is the equilibrium temperature, D_1 is the approach of the return-water temperature to the equilibrium temperature, D_2 is the approach of the leaving-water temperature to the equilibrium temperature, V_w is the wind velocity in miles per hour (mph) and P is a liquid-to-air heat-transfer factor which assumes a pond of uniform flow, without turbulence, and with the water warmer than the air. The product,

Table I. Maximum expected solar radiation in Btu/h-ft^2 at various degrees north latitude. This table was derived from the analysis of Weather Bureau records for a number of stations throughout the United States. These are clear-day values, rarely exceeded even in the high arid regions. The normal or actual average monthly values are only 50 to 60 percent of the tabulated figures for most of the Eastern United States and 80 to 90 percent in the arid Southwest. Also the solar radiation should be multiplied by the absorption coefficient for the pond which appears to exceed 95 percent.*

Day		24-h average at degrees north latitude				Noon value at degrees north latitude			
		30°	35°	40°	45°	30°	35°	40°	45°
Jan.	1	65	50	40	30	240	205	170	135
Feb.	1	75	65	55	45	270	240	210	175
March	1	90	80	75	65	305	285	255	230
April	1	110	105	95	90	340	320	300	280
May	1	120	120	120	115	360	350	335	320
June	1	130	130	130	130	365	360	345	335
July	1	130	130	130	130	365	360	350	340
Aug.	1	125	125	125	120	360	350	340	325
Sep.	1	115	110	105	100	350	335	315	300
Oct.	1	100	90	80	75	315	295	270	245
Nov.	1	80	70	60	50	270	245	215	185
Dec.	1	65	55	45	35	240	210	175	140

*H. L. Langhaar, Chem. Eng. 80, 194 (1953).

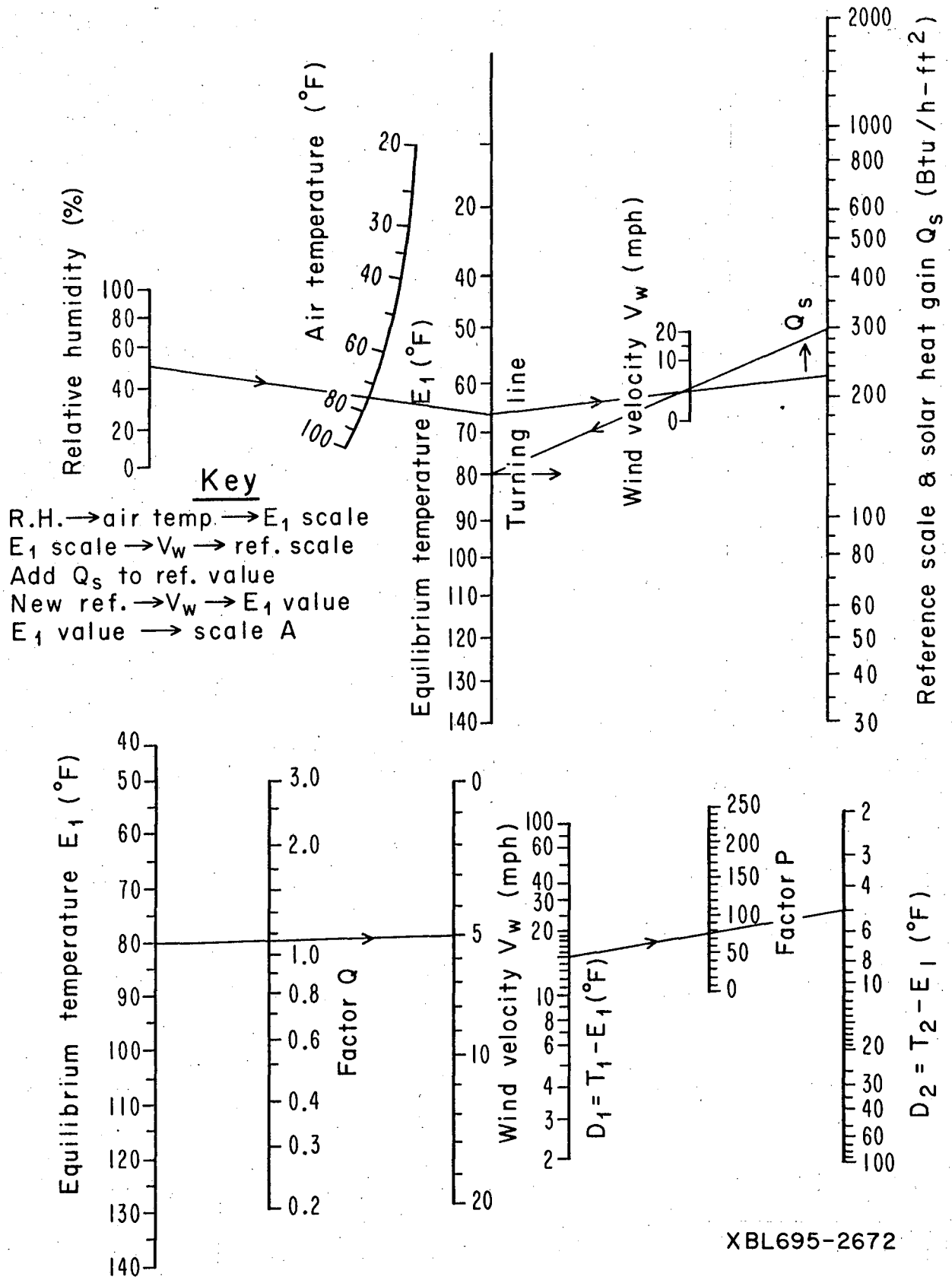


Fig. 1. Cooling-pond nomograph.

P × Q, is the area of pond surface required in square feet for each gallon per minute (gpm) of water flow through the heat exchangers.

Spray Ponds

One disadvantage of the cooling pond is the fact that as one increases the area of the pond to accomodate an increase in the given cooling load, the pond simultaneously receives a greater solar load. In order to reduce this solar load, another method was sought to obtain the required area. This study resulted in the development of the spray pond.

The water in a spray pond is sprayed into the air so that the prevailing wind passes through the sprays at right angles to the length of the spray area. The effective air area of the spray is taken to be the length of the pond times the sum of the height of the spray nozzles plus the water pressure at the spray nozzles in pounds per square inch. As the air passes through the sprays, it picks up moisture, and its enthalpy increases. The change in air enthalpy divided by the change in the temperature of the water is equal to the liquid-to-gas (L/G) ratio. This L/G ratio is defined as the pounds per hour of liquid in the sprays divided by the pounds per hour of air passing through the sprays.

The performance of a spray pond is affected by (1) the cooling range of the water, (2) the wet-bulb temperature, (3) the wind speed, and (4) the construction parameters of the pond. Tables II and III give engineering parameters and degree adjustments. Figure 2 is a performance curve relating the approach to the wet-bulb temperature vs the temperature range. It will be noticed that with a wet-bulb temperature of 70°F, a 5-mph wind, and a 10°F cooling range; the approach of the water temperature to the wet-bulb temperature is about 11°F. This means that with a 70°F wet-bulb temperature, the water can be cooled to only 81°F.

Table II. Spray-pond engineering data and design parameters*

Recommendations	Usual	Minimum	Maximum
Nozzle capacity (gal/min each)	35-50	10	60
Nozzles per 12-ft length of pipe	5-6	4	8
Height of nozzles above sides of basin (ft)	7-8	2	10
Nozzle pressure (psi)	5-7	4	10
Size of nozzles and nozzle arms (in.)	2	$1\frac{1}{4}$	$2\frac{1}{2}$
Distance between spray lateral piping (ft)	25	13	38
Distance of nozzles from side of unfenced pond (ft)	25-35	20	50
Distance of nozzles from side of fenced pond (ft)	12-18	10	25
Height of louver fence (ft)	12	6	18
Depth of pond basin (ft)	4-5	2	7
Friction loss per 100 ft of pipe (in. H_2O)	1-3		6
Design wind velocity (mph)	5	3	10

*From Spray Pond Bull. No. 8P-51, P. 3, Marley Co., Kansas City, Mo.

Table III. Degree adjustments to be applied to leaving-air wet-bulb temperature to find cooled-water temperature* of spray-ponds**

Cooling Range (°F)	Entering Wet-bulb Temp.† (°F)	Adjustments (°F) Length of air travel (ft)‡ 100	50	25
10	80	-3	+2	+4
	70	-2	+3	+5
	60	-1.5	+3.5	+5.5
15	80	-5.0	+1	+5
	70	-4.0	+2	+5.5
	60	-3.5	+2.5	+6
20	80	-7	0	+6
	70	-6	+1	+7
	60	-5.5	+1.5	+7.5

*Cooled-water temperature = wet-bulb temperature of leaving air plus values shown.

**From Heating, Ventilating, Air-Conditioning Guide, 38th ed., (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, N. Y., 1960), p. 598.

†Wet-bulb temperature of air entering spray-filled volume. Spray-filled volume = (height of nozzles above pond + 1 ft per psi of nozzle pressure) × (plan area extending 10 ft beyond outer nozzles).

‡Length of air travel through spray-filled volume.

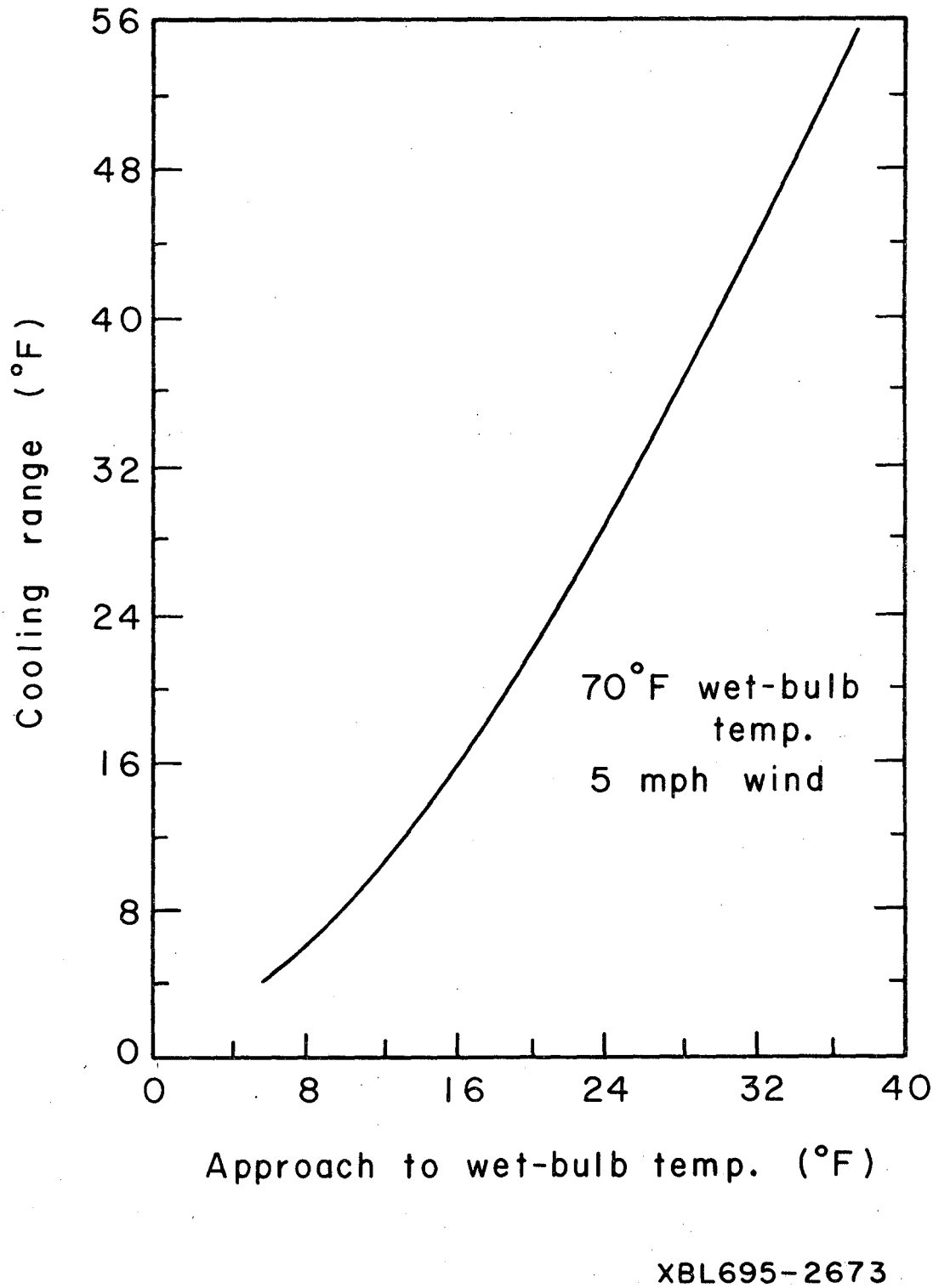


Fig. 2. Spray-pond performance curve.

Cooling Towers

Two disadvantages of the spray pond are (1) excessive drift loss of water during periods of high wind velocity and (2) inability to adjust the wind velocity to correspond to the impressed cooling load and(or) the atmospheric conditions. Studies to eliminate these disadvantages have resulted in the development of the modern induced-draft cooling tower. The forced-draft tower causes too much recycling of the effluent air and presents a problem where dust, weed seeds, and other debris may be sucked into the tower fan. Natural-draft cooling towers (hyperbolic towers) are generally intended for use where the heat-dissipating capacity required is much greater than that normally encountered at accelerator laboratories. The operating costs of natural-draft towers is less than that of induced-draft towers, but the capital cost is over twice as high.

Cooling-tower performance and theory are covered elsewhere in this report.

Tower-water drift loss is limited by the Cooling Tower Institute to 0.2% of the circulation rate.

Evaporative Coolers (Closed-Circuit)

In evaporative-coolers, tower water is sprayed onto the surface of built-in exchanger tubes containing the closed-circuit water. Evaporation of this tower-water on the surface of these tubes cools the closed-circuit water. The approach referred to with evaporative coolers is that of the closed-circuit water temperature to the wet-bulb temperature.

Air-Cooled Heat Exchangers

In this method of cooling, the closed-circuit water is cooled in an atmospheric heat exchanger by air passing across the outside of the heat-exchanger tubes. The air is moved by either induced or forced draft.

The water within the tubes may be cooled to about 20°F above the dry-bulb temperature of the ambient air. It is not economical to maintain a closer approach of the water temperature to the air dry-bulb temperature, because of the large additional heat-exchange area required.

B. Economic and Functional Evaluation

Once-Through Cooling

1. This method is the simplest and has the lowest capital cost of all cooling methods.

2. There is not extensive evaporation and, accordingly, very little concentration of dissolved solids. The water usually does not require chemical treatment.

3. The temperature of the source water is raised by the cooling process. This thermal pollution has a detrimental effect on the flora and fauna within and along the sides of the source water.

4. The source water often contains debris along with various forms of life. This can lead to rapid fouling of heat exchangers and other equipment if preventive measures are not taken.

5. Sea water, if used, presents a severe corrosion problem.

6. No fire protection is required.

7. Temperature control is poor.

Cooling Ponds

1. Cooling ponds have the highest capital cost of any of the cooling methods if the pond, itself, must be constructed.

2. The shallow depth of the pond and the large surface area exposed to sunlight are extremely conducive to algae growth. Measures can be taken to control this growth, but it is doubtful that the spring and fall "bloom" can be effectively eliminated over the large surface area required.

3. Animal droppings, wind-blown seeds, dust, and other debris are prone to collect in the pond.

4. A cooling pond cannot be certified by contract as to performance. No responsibility for performance can be ascribed to the contractor or vendor.

5. A large expensive land area is required to accomodate the pond.

6. No fire protection is required.

7. Temperature control is poor.

Spray Ponds

1. Spray ponds are economically competitive with cooling towers.

2. The algae problem is less than with cooling ponds, but greater than that with cooling towers.

3. Fire protection is not usually required.

4. When there are high winds, water from the sprays will be blown over a large area, creating a nuisance in addition to a considerable drift loss of industrial water.

5. The wind velocity cannot be adjusted to correspond to the impressed cooling load and(or) the atmospheric conditions.

Evaporative Coolers (Closed-Circuit Water)

1. Evaporative-coolers are cheaper than cooling-towers for small loads. They are more expensive for large loads. In general, evaporative-coolers are designed for small cooling loads. Multiple units are used to cool large loads so that load consolidation does not yield the economic gain that exists with cooling-towers.

2. Heat exchangers are built in as a part of the unit.

3. Evaporative coolers have small size and weight. They can be rendered portable if so desired.

4. No fire protection is required.

5. Scaling is greater than with cooling towers.

Air-Cooled Heat Exchangers

1. The capital cost is competitive with cooling-towers.

2. No tower water is required.

3. No fire protection is required.

4. The closed-circuit, cold-water temperature is limited economically to a minimum temperature about 20°F higher than the ambient air dry-bulb temperature.

Piggy-Back Cooling

Air-cooled heat exchangers may be used in combination with cooling towers to lower the closed-circuit cold-water temperature to some desired minimum. This is a two-step process in which the closed-circuit hot water is precooled by the air-cooled heat exchangers to a temperature about 20°F above the ambient-air dry-bulb temperature. The water is then further cooled

by conventional cooling-tower methods to the desired cold-water temperature. The cost of this system is competitive with the cost of using a cooling tower for all cooling. There is a savings in makeup tower water. If the air-cooled heat exchanger is sized large enough, it can cool the entire load for about 85% of the year. Figure 3 illustrates a typical piggy-back cooling system.

Combination of a Cooling Pond with a Spray Pond

The cost of such a combination is always cheaper than that of the cooling pond alone and always more than that of the spray pond alone.

Combination of a Cooling Pond with a Cooling Tower

The cost of such a combination is always cheaper than that of the cooling pond alone and always more than that of the cooling tower alone.

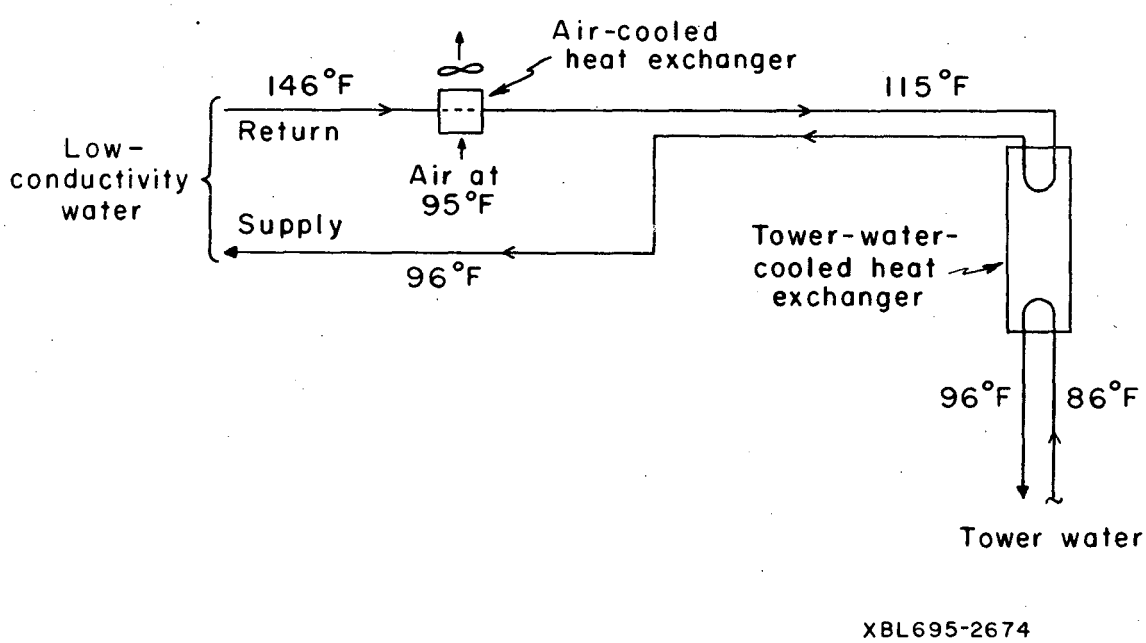


Fig. 3. Example of "piggy-back" cooling.

III. COOLING-TOWER THEORY

A. Synopsis of General Theory

Definitions of Normally Used Cooling-Tower Terms

The wet-bulb is the wet-bulb temperature of the entering air.

The range is the difference between the hot water temperature and the cold water temperature.

The approach is the difference between the cold water temperature and the wet-bulb temperature of the entering air.

The L/G ratio is the ratio of the rate of water flow to the rate of air flow, both expressed as pounds per hour per square foot (lb/h-ft^2) of tower ground area.

General

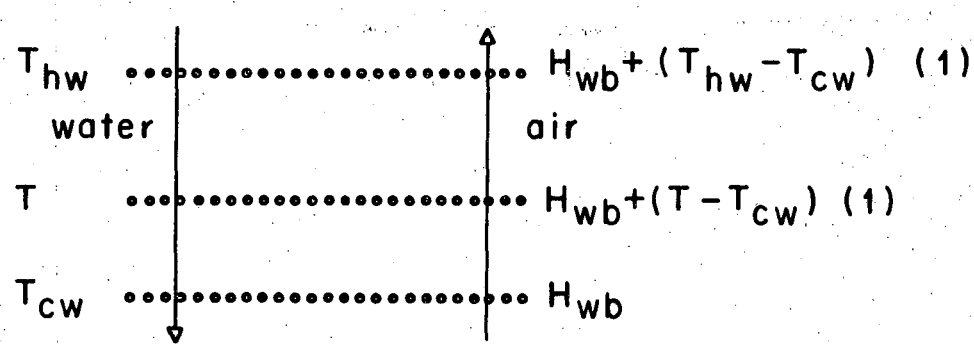
Basically, the water falling through a cooling tower is cooled by air passing up through the tower. The following is a general discussion of the mechanism of this cooling.

To simplify this discussion, we shall assume that in a particular cooling tower, the gravimetric rate of water flow is equal to the rate of air flow, i.e., the liquid-to-gas ratio is 1 (or L/G = 1.) If the enthalpy (total heat) of the air entering the tower is designated as H_{wb}, then the enthalpy of the air leaving the tower is H_{wb} plus the heat removed from the water. We shall not concern ourselves with the latent heat or sensible heat of the air, but only with the total heat. Since the specific heat of water is unity and in this case we have defined L/G = 1, the heat removed from the water is simply the difference in water temperatures.

The enthalpy of the air leaving the tower can now be expressed as $H_{wb} + (T_{hw} - T_{cw})(1)$, where T_{hw} is the hot-water temperature, T_{cw} is the cold-water temperature, H_{wb} is the enthalpy of the entering air, and the liquid/gas ratio L/G is 1. Similarly, the enthalpy of the air passing any point in the tower is H_{wb} plus the water temperature at that point less the temperature of the water entering the tower or generally, the enthalpy of the passing air is $H_{wb} + (T - T_{cw})(1)$. Here T is the temperature of the passing water. The system is shown in Fig. 4.

We may assume that at each particular temperature, a part of the passing air contacts the water and becomes saturated at that temperature. No additional heat can be transferred from the water to this part of the air at this temperature. It is apparent now that the driving force bringing about the transfer of heat from the water to the air at any particular temperature is the difference of the enthalpy of the saturated air and the enthalpy of the passing air at this temperature.

Both the enthalpy of the saturated air and the enthalpy of the passing air are functions of the water temperature. The total driving force for the



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4. Temperature-enthalpy diagram for air-cooled water tower.

overall heat-transfer process is then the integral of the differences in enthalpies with respect to temperature over the range of the water temperature.

In Fig. 5, the enthalpy of the saturated air is represented by H', and the enthalpy of the passing air by H. Accordingly, the driving force for heat transfer at any water temperature is H' - H at that temperature. The total driving force for the overall heat-transfer process is represented by the area ABCD.

Specific

Water at any particular temperature has a certain vapor pressure. This vapor pressure increases as the water temperature increases. Saturated air

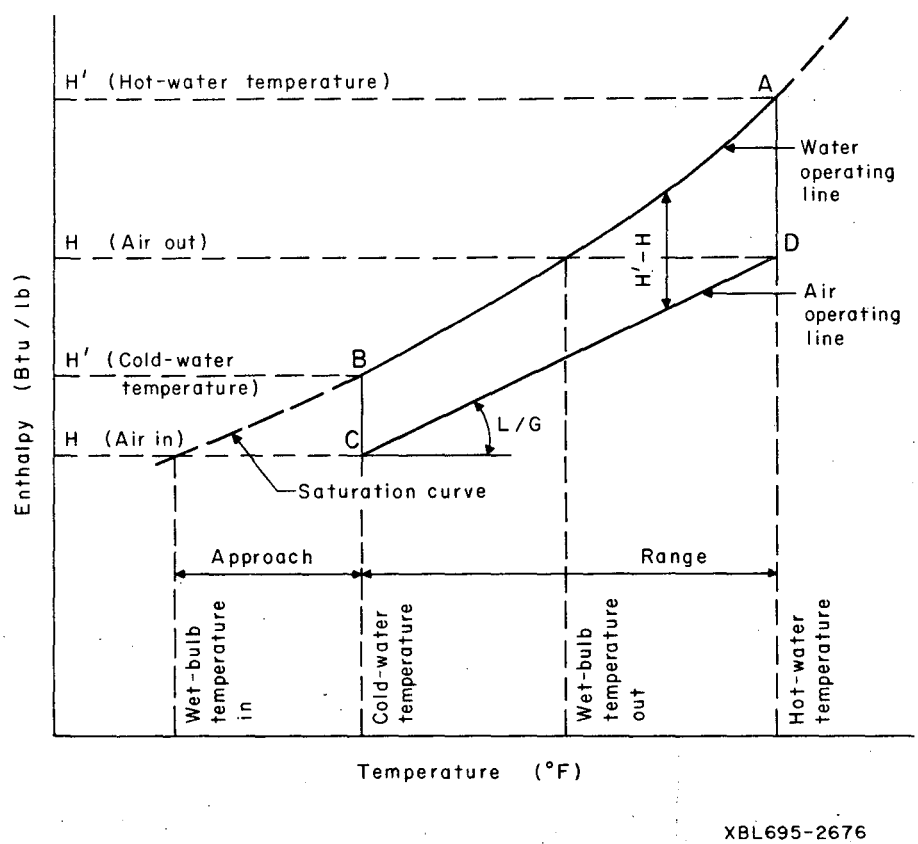


Fig. 5. Cooling-tower process heat balance.

at any particular temperature contains a certain amount of water vapor (usually expressed as either pounds or grains of water per pound of dry air) which is a function of the vapor pressure of water at that temperature.

The enthalpy of saturated air at any temperature is the sum of the enthalpy of the dry air plus the enthalpy of the water vapor contained in the air. (See Table IV.) At temperature T, enthalpies are as follows:

Enthalpy, dry air at T	= 0.24 T
Enthalpy, vapor at T	= (lb H_2O/lb air) (T)
Enthalpy, latent heat of vapor at T	= (lb H_2O/lb air) (H_{vs} at T).

The enthalpies in Table IV are computed using the method given in the following example. At 75°F the saturation partial pressure of water is 0.4298 psia. The humidity is

$$X' = \frac{p_w}{p_t - p_w} \frac{M_w}{M_a} = \frac{0.4298}{14.696 - 0.4298} \times \frac{18}{29} = 0.0187 \text{ lb water/lb air.}$$

The enthalpy above 0°F is

$$H' = 0.0187 \times 75 + 0.0187 \times 105.5 + 0.24 \times 75$$
$$= 39.1 \text{ Btu/lb dry air.}$$

As stated previously, the enthalpy H of the passing air is the sum of the enthalpy of the entering air plus the heat taken from the water:

$$H = H_{wb} + (L/G)(T - T_{cw}).$$

The enthalpy of the entering air is generally assumed to be the enthalpy of saturated air at the wet-bulb temperature of the entering air. This is not strictly correct, but the error is small and is on the safe side for design purposes. The heat taken from the water is the difference in water temperature times L/G. In the L/G ratio L is defined as the ratio of water flow through the tower when expressed as pounds per square foot of tower ground

Table IV. Enthalpies and humidities of air-water mixtures at 14.7 psia

Temp. °F	Vapor pressure (psia)	Humidity (lb H_2O/lb air)	Enthalpy (Btu/lb air)	v_3 air (ft^3/lb)	v air + H_2O (ft^3/lb)^2
40	0.1217	0.005	15.15	12.59	12.70
45	0.1475	0.0063	17.8	12.72	12.85
50	0.1781	0.0076	20.5	12.84	13.00
55	0.2141	0.0098	23.8	12.97	13.16
60	0.2563	0.0110	26.7	13.10	13.33
65	0.3056	0.0130	30.4	13.23	13.51
70	0.3631	0.0160	34.5	13.35	13.69
75	0.4298	0.0187	39.1	13.48	13.88
80	0.5069	0.0222	44.1	13.60	14.09
85	0.5959	0.0262	50.0	13.73	14.31
90	0.6982	0.0310	56.7	13.86	14.55
95	0.8153	0.0365	64.2	13.99	14.81
100	0.9492	0.0430	72.7	14.11	15.08
105	1.1016	0.0503	82.5	14.24	15.39
110	1.2748	0.0590	93.8	14.36	15.73
115	1.4709	0.0691	106.7	14.49	16.10
120	1.6924	0.0810	121.5	14.62	16.52
125	1.9420	0.0948	138.8	14.75	16.99
130	2.2225	0.1108	158.5	14.88	17.53
135	2.5370	0.1300	181.9	15.00	18.13
140	2.8886	0.1520	208.6	15.13	18.84
145	3.2810	0.1810	243.8	15.26	19.64
150	3.7180	0.2160	286.0	15.39	20.60

area. For example, in a cooling tower with a 24-ft square base and a water flow rate of 1500 gal/min, we have L = (1500)(8.3)(60)/526 = 1302. G is defined as the rate of air flow through the tower expressed as pounds per hour per square foot of tower ground area. For example, in a cooling tower with a 24-ft square base and an air flow rate of 152,151 ft^3/min, we have G = (152,151)(60)/(13.33)(526) = 1302. L/G may be defined as the ratio of lb/h of water flow to lb/h of air flow through the tower. It is represented in Fig. 5 by the slope of the air operating line CD.

Modern cooling-towers are generally induced-draft towers with the air flowing in a counterflow or crossflow direction to the flow of the tower water.

The stream of water falling through a cooling tower is broken up by the tower "fill" or packing. This fill creates sufficient water surface area to allow the required heat transfer between the water and the air passing through the tower. The fill may consist of wood slats, plastic grid, ceramic berls, or other materials or shapes.

The following formula illustrates the relationships of the various factors involved in the cooling:

$$N_d = KaV/L = \int_{T_{cw}}^{T_{hw}} dT/(H' - H).$$

Here N_d is the number of diffusion units required to accomplish the desired cooling under the specified conditions and parameters. K is a heat-transfer factor comparable to the U_c factor employed in heat-exchanger calculations. It is expressed as lb/h sq ft lb/lb. a represents the water surface area created by the fill expressed as sq ft of area per cu ft of unit volume. V is the unit volume of a diffusion unit in cu ft. T_{hw} is the temperature of the hot water

(°F). T_{cw} is the temperature of the cold water (°F). H' is the enthalpy of saturated air at temperature T (Btu/lb). H is the enthalpy of passing air at temperature $T = H_{wb} + (L/G)(T)$ (Btu/lb). H_{wb} is the enthalpy of saturated air at the entering wet-bulb temperature (Btu/lb). L is the lbs/hr of water per sq ft of tower cross-sectional area. G is the lbs/hr of air per sq ft of tower cross-sectional area. The height of the tower fill in feet is $Z = N_d L/Ka$; the height of a diffusion unit is then Z/N_d feet.

Since in the differential equation, we have $\int dT/(H' - H) = N_d$, neither H' nor H are given as functions of T; the equation cannot be directly integrated. An approximation is usually made using temperature increments of 5°F and the average values of (H' - H) for each temperature increment. (See Table V.)

The performance of a cooling tower with a specific KaV/L is affected by the wet-bulb temperature, the approach, the range, and the L/G ratio. (Altering the L/G will alter the KaV/L.) The effect of each of these factors on the KaV/L is illustrated later.

Table V. Computation of KaV/L for 65°F wet-bulb temperature, L/G = 1, and 10°F approach and range.

T (°F)	H'	H	ΔH*	ΔH_a*	$\Delta T/\Delta H_a$
75	39.1	30.4	8.7		
80	44.1	35.4	8.7	8.7	0.575
85	50.0	40.4	9.6	9.15	0.550
				KaV/L	1.125

*$\Delta H = H' - H$

Figure 6 is a nomograph which may be used to predict cooling-tower performance under various operating and atmospheric conditions. When the wet-bulb temperature, the range, and the cold-water temperature are known, a straight line may be drawn through these points. If the L/G is known, a line drawn through the L/G and parallel to the first line will give the KaV/L. For other operating conditions, a straight line drawn through the point representing the new parameter and parallel to the first line will give the expected corresponding performance factors.

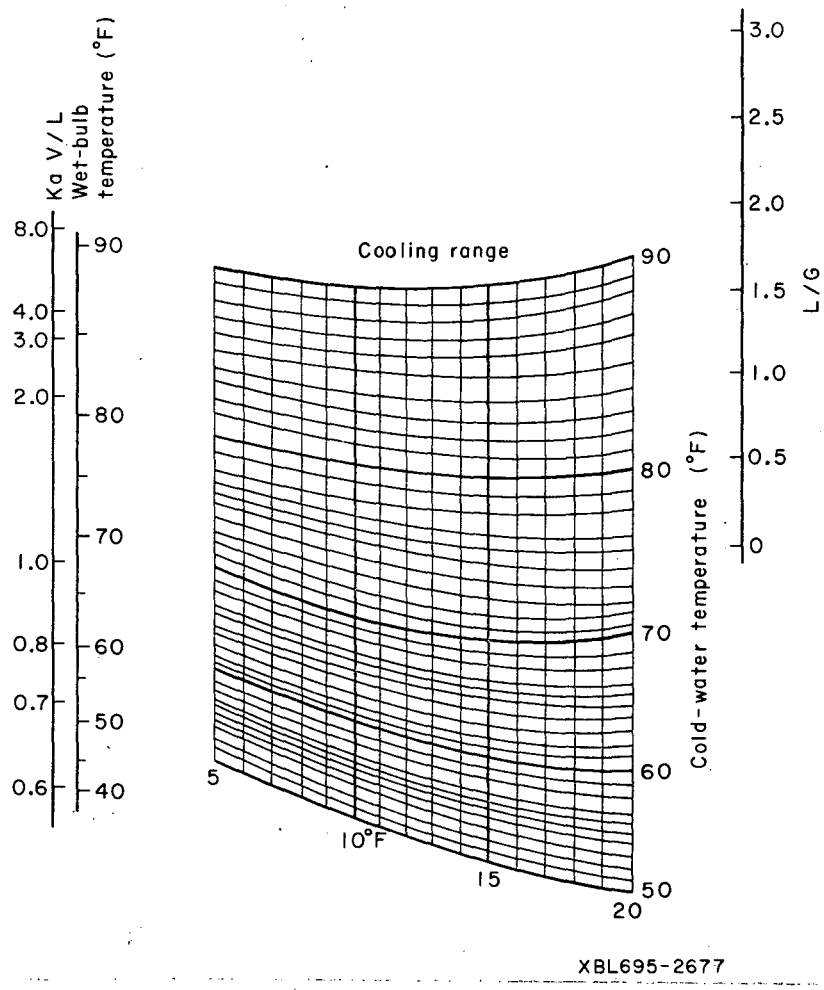


Fig. 6. Nomograph of cooling-tower characteristics [From Wood and Betts, Engineer 189 (4912), 337 (1950)].

B. Effect of Wet-Bulb Temperature of Entering Air

In the example below, both towers have the same 10°F approach, 10°F range, Ka, cross-sectional area, and L/G = 1.

In order to dissipate the same amount of heat, the fill height of a cooling-tower operating at a 65°F design wet-bulb temperature must be 1.125/0.793 = 1.44 times that of a tower operating at a 75°F design wet-bulb temperature.

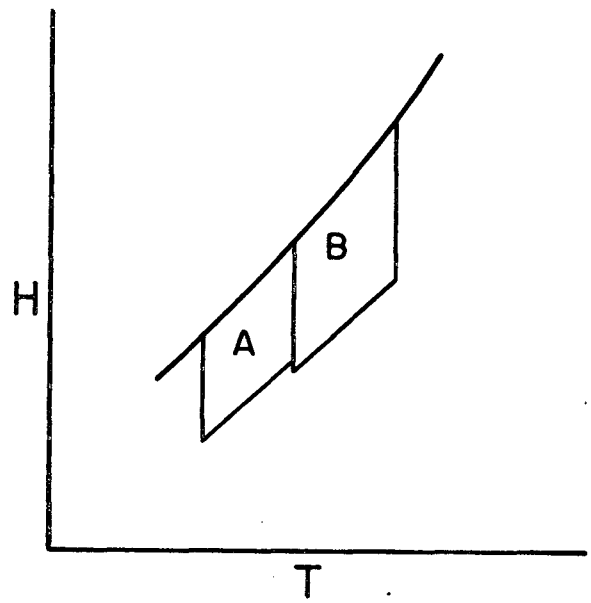


Fig. 7. Enthalpy vs temperature for (A) 65°F and (B) 75°F wet-bulb entering air.

Table VI. Computation of KaV/L for the above towers.

A = 65°F wet-bulb entering air						B = 75°F wet-bulb entering air					
T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$	T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
75	39.1	30.4	8.7			85	50.0	39.1	10.9		
80	44.1	35.4	8.7	8.7	0.575	90	56.7	44.1	12.6	11.75	0.425
85	50.0	40.4	9.6	9.15	0.550	95	64.2	49.1	15.1	13.85	0.368
			KaV/L =		1.125				KaV/L =		0.793

C. Effect of Approach to Wet-Bulb Temperature

In the example in Fig. 8, both towers have the same 10°F range, 65°F wet-bulb temperature, Ka, tower cross-sectional area, and L/G = 1.

When dissipating the same amount of heat, a cooling tower maintaining a 5°F approach must have a tower fill height 2.633/1.121 = 2.35 times that of a cooling tower maintaining a 10°F approach.

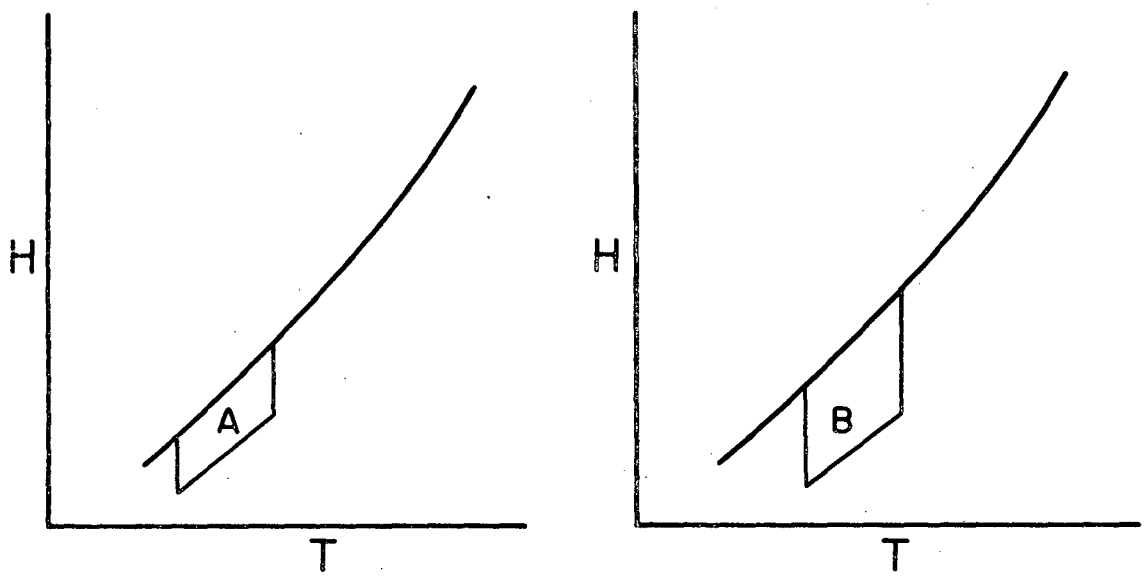


Fig. 8. Enthalpy vs temperature for (A) 5°F and (B) 10°F approaches.

Table VII. Computation of KaV/L for the above towers.

A = 5°F approach						B = 10°F approach					
T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$	T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
70	34.5	30.4	4.1			75	39.1	30.4	8.7		
75	39.1	35.4	3.7	3.9	1.282	80	44.1	35.4	8.7	8.7	0.575
80	44.1	40.4	3.7	3.7	1.351	85	50.0	40.4	9.6	9.15	0.546
			KaV/L =		2.633				KaV/L =		1.121

D. Effect of Extending the Approach

In the example in Fig. 9, both towers have the same 65°F wet-bulb temperature, 10°F range, Ka, tower cross-sectional area, and L/G = 1.

When dissipating the same amount of heat, a cooling tower maintaining a 85°F cold-water temperature (20°F approach) will require a tower fill height of only 0.466/1.121 = 41.6% of that required by a cooling tower maintaining a 75°F cold-water temperature (10°F approach).

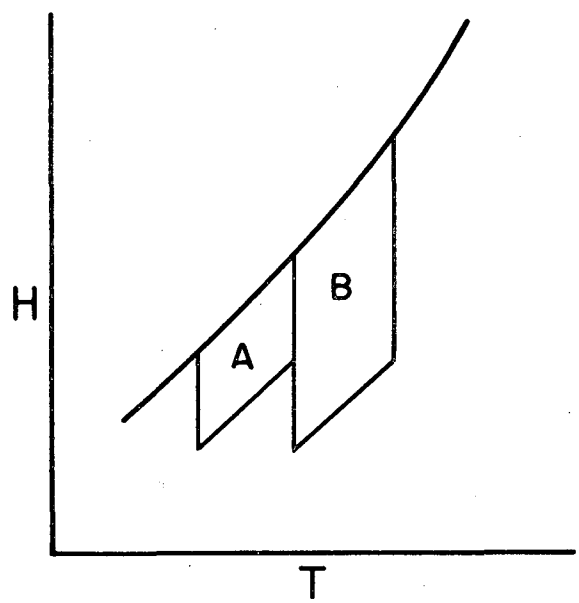


Fig. 9. Enthalpy vs temperature for (A) 75°F and (B) 85°F cold tower water.

Table VIII. Computation of KaV/L for the above towers.

A = 75°F cold tower water						B = 85°F cold tower water					
T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$	T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
75	39.1	30.4	8.7			85	50.0	30.4	19.6		
80	44.1	35.4	8.7	8.7	0.575	90	56.7	35.4	21.3	20.45	0.244
85	50.0	40.4	9.6	9.15	0.546	95	64.2	40.4	23.8	22.51	0.222
				KaV/L =	1.121					KaV/L =	0.466

E. Effect of Tower-Water Temperature Range

In the example below, both towers have the same 10°F approach, 65°F wet-bulb temperature, Ka, tower cross-sectional area, and L/G = 1.

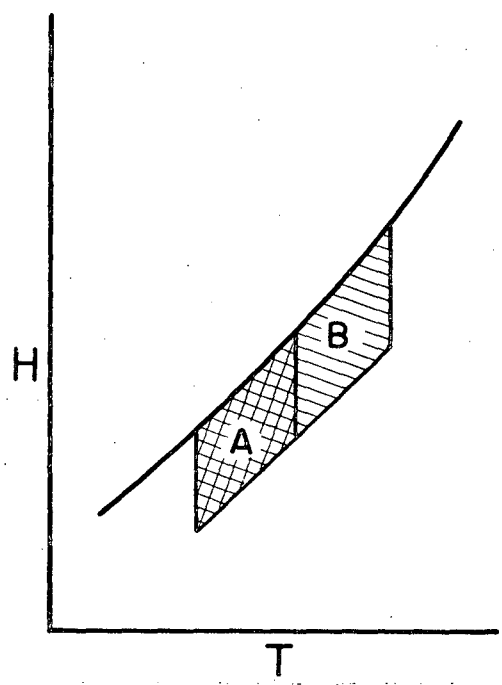


Fig. 10. Enthalpy vs temperature for (A) 10°F and (B) 20°F ranges.

Table IX. Computation of KaV/L for the above towers.

A = 10°F range						B = 20°F range					
T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$	T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
75	39.1	30.4	8.7			75	39.1	30.4	8.7		
80	44.1	35.4	8.7	8.7	0.575	80	44.1	35.4	8.7	8.7	0.575
85	50.0	40.4	9.6	9.15	0.546	85	50.0	40.4	9.6	9.15	0.546
			KaV/L =		1.121	90	56.7	45.4	11.3	10.45	0.478
						95	64.2	50.4	13.8	12.55	0.398
									KaV/L =		1.997

To increase the water temperature range from 10°F to 20°F (twice the cooling load), the tower fill height must be increased 1.997/1.121 = 178%. The efficiency of the cooling tower in terms of heat dissipated per unit of tower fill height at the 20°F range is 1.121/(1.997/2) = 112% of that at the 10°F range. The increase in tower efficiency with increase in range is greater at higher design wet-bulb temperature (e.g., it is 119% at 75°F wet-bulb temperature).

F. Effect of Liquid/Gas Ratio

In the example below, all towers have the same 10°F approach, 10°F range, 65°F wet-bulb temperature, Ka, and tower cross-sectional area.

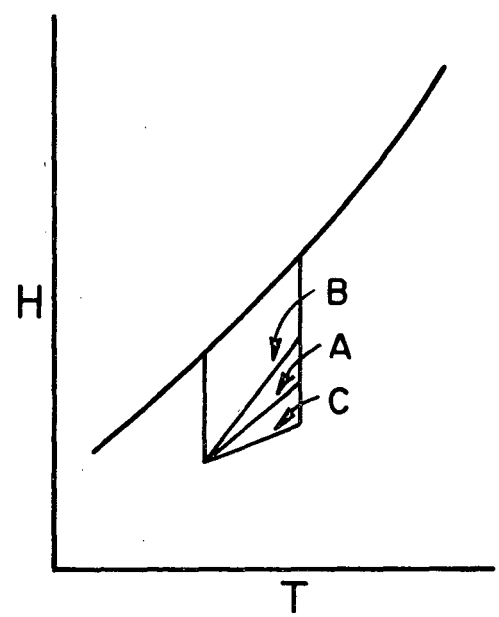


Fig. 11. Enthalpy vs temperature for (A) L/G = 1, KaV/L = 1.21, (B) L/G = 1.5, and (C) L/G = 0.5.

Table X. Computation of KaV/L for the preceding tower.

(B) L/G = 1.5						(C) L/G = 0.5					
T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$	T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
75	39.1	30.4	8.7			75	39.1	30.4	8.7		
80	44.1	37.9	6.2	7.45	0.671	80	44.1	32.9	11.2	9.95	0.503
85	50.0	45.4	4.6	5.4	0.926	85	50.0	35.1	14.9	13.05	0.383
			KaV/L =		1.597				KaV/L =		0.886

For a tower with a L/G ratio of 1 as a base and a constant water flow (L), doubling the air flow (L/G = 0.5) will decrease the tower fill height required by (1.121-0.886)/1.121 = 26.5%. Decreasing the air flow by one-third (L/G = 1.5) will increase the fill height required by (1.597 - 1.121)/1.121 = 42.5 %.

G. Effect of Operating Control

In order to vividly illustrate the economic effect brought about by poor control of cooling-water temperature and cooling-water flow through equipment, the following analysis is made of actual operating conditions.

Table XI. Comparison of actual and design parameters for a cooling system.

	Design	Actual
Entering air temperature (° F)	65° F wet bulb 95° F dry bulb	67° F wet bulb 95° F dry bulb
Cold tower-water temperature (° F)	75	70
Hot tower-water temperature (° F)	85	72
Approach (° F)	10	3
Range (° F)	10	2
Cold LCW temperature (° F)	85	72
Hot LCW temperature (° F)	97.35	75
Cost - tower and fans only ($/kW)	12.96	64.80
Cost - heat exchangers ($/kW)	11.42	57.11
Total tower and fan cost ($/4 MW)	51 840	259 200
Total heat-exchanger cost ($/4 MW)	45 691	228 455

Basis of figures:

Design heat dissipation is 4 MW = 4000 kW.

Actual heat dissipation is (72 - 70) (4)/(85 - 75) = 0.8 MW = 800 kW.

Cost of tower and fans is $51 840.

Cost/kW tower and fans under design conditions is $51 840/4000 = $12.96/kW.

Cost/kW tower and fans actually is $51 840/800 = $64.80/kW.

Cost for 4 MW tower and fans under actual conditions is (64.80) (4000) = $259 200.

$Q = UA\Delta T_m$, $A = Q/U\Delta T_m$

$U = 150$

$Q = (4\ MW)(3\,413\,000) = 13\,652\,000$ Btu/h

Design $\Delta T_m = ((97.35-85) - (85-75))/Ln(97.35-85)/(85-75) = 12.35°F$

$A = 13\,652\,000/(150)(12.35) = 7369.5$ sq ft

Cost of heat exchangers at \$6.20/sq ft is (6.20)(7369.5) = \$ 45 691

Design cost/kW of exchangers is \$45 691/4000 = \$11.42/kW

Cost/kW of exchangers actually is \$45 691/800 = \$57.11/kW

Cost of 4 MW of exchangers under actual conditions is (\$57.11) (4000) = \$228 455.

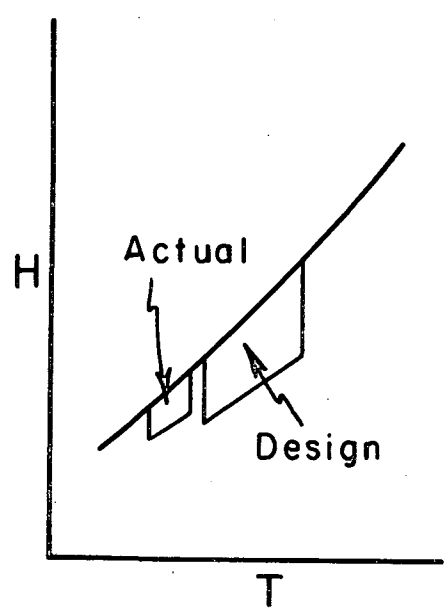


Fig. 12. Enthalpy vs temperature under design and actual conditions.

H. Effect of Relocation on the Performance of an Existing Tower

The following are design parameters for a 12-MW cooling tower used for cooling experimental magnets at the Brookhaven National Laboratory.

Hot water temperature	=	131°F
Cold water temperature	=	85°F
Wet-bulb temperature	=	78°F
Approach = 85 - 78	=	7°F
Range = 131 - 85	=	46°F
L	=	1565 lbs/hr of water per sq ft
G	=	2450 lbs/hr of air per sq ft
L/G = 1565/2450	=	0.639
Fan motor horsepower	=	35

Table XII. Calculation of KaV/L for tower under Brookhaven design parameters.

T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
85	50.0	42.000	8.000		
90	56.7	45.195	11.505	9.260	0.5399
95	64.2	48.350	15.820	13.665	0.3658
100	72.7	51.585	21.115	18.468	0.2707
105	82.5	54.780	27.720	24.418	0.2147
110	93.8	57.975	35.825	31.773	0.1573
115	106.7	61.170	45.530	40.678	0.1229
120	121.5	64.365	53.935	50.233	0.0995
125	138.8	67.560	71.240	62.588	0.0798
131	162.5	70.755	91.745	81.745	0.0674
				KaV/L =	1.908

Relocating this tower to operate under Berkeley design parameters (65°F design wet-bulb temperature and 10°F approach) would give the values shown in Table XIII.

Table XIII. Calculation of KaV/L for tower under Berkeley design parameters

T (°F)	H'	H	ΔH	ΔH_a	$\Delta T/\Delta H_a$
75	39.1	30.400	8.700		
80	44.1	33.595	10.505	9.605	0.5206
85	50.0	36.790	13.210	11.858	0.4216
90	56.7	39.985	16.715	14.963	0.3341
95	64.2	43.180	21.020	18.888	0.2649
100	72.7	46.375	26.325	23.673	0.2112
105	82.5	49.570	32.930	29.628	0.1687
				KaV/L =	1.9211

The range is now approximately (105 - 75) = 30°F. The heat dissipated is 30/46 ≈ 65.2% of that dissipated at Brookhaven. The cost in $/kW is ≈ 1/0.652 ≈ 153% of the cost at Brookhaven.

If this tower were relocated to operate under conditions of 65°F design wet-bulb temperature and a 20°F approach (same 85°F cold-water temperature as at Brookhaven), KaV/L would need to be only 1.20 to yield the same 46°F range. Therefore the tower fill required need be only 1.20/1.908 = 62.9% of that at Brookhaven. If this tower were relocated to operate under conditions of 65°F design wet-bulb temperature and a 15°F approach (80°F cold-water temperature), the range would be extended to 100°F for the same KaV/L. The heat dissipated would then be 100/46 = 217% of that at Brookhaven. The cost ($/kW) is 1/2.17 = 46% of the cost ($/kW) at Brookhaven.

I. Effect of Cooling-Load Consolidation on Cost

The following prices (1967) are based on 79°F wet-bulb temperature and a 12°F range:

Table XIV. 4-MW cooling tower

	9°F approach	7°F approach	5°F approach
Circulation tw (gpm)	2260	2260	2260
Fan HP	2 × 20	2 × 25	2 × 25
Size (sq. ft.)	384	960	960 (more fill)
Cost (no basin)	$11 500	$14 000	$15 500

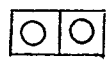
Table XV. 12-MW cooling tower

	9°F approach	7°F approach	5°F approach
Fan hp	70	96	124
Size (sq. ft.)	1300	1700	2200
Cost (no basin)	$28 500	$37 000	$48 000

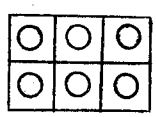
Table XVI. Effect of consolidation

	3 × 4 MW	12 MW	Difference
9°F approach	$34 500	$28 500	+ $6 000
7°F approach	$42 000	$37 000	+ $5 000
5°F approach	$46 500	$48 000	- $1 500

Larger size cooling towers are derated at lower approach temperatures because of (1) the increased air requirements at lower approaches as evidenced in the tables by the higher fan horsepower requirements, and (2) by the decreased air intake area, viz.



4-NW tower (2 2-NW cells)
Each cell can receive air from three sides.



12-MW tower (six 2-MW cells)
Four cells have 2 sides.
Two cells have one side.

Because of the additional costs of long lengths of large piping, etc., we have found that in each case there is an optimum degree of cooling system centralization which is economically feasible.

IV. EFFECT OF TEMPERATURE ON MAGNET OPERATING COSTS

Electric Power Costs

Magnet electric power cost is significantly less at lower magnet temperatures. The field created by an electromagnet is proportional to the current in the coils. The electric power required for this field is proportional to the coil resistance. The resistance of the coils increases as their temperature increases in accordance with $R_2/R_1 = (T + t_2)/(T + t_1)$, where R_1 is the coil resistance at temperature t_1 (°C), R_2 is the coil resistance at temperature t_2 (°C), and T = 234.5 for copper.

For example, in a system using copper magnet coils with a 85°F cooling-water supply temperature and a 10°F temperature range, t_1 is 85 + 10/2 = 90°F = 32.22°C (average). Using this same system with a 95°F cooling-water supply temperature and a 10°F temperature range, t_2 is 95 + 10/2 = 100°F = 37.78°C (average). R_2 is then R_1 (234.5 + 37.78)/(234.5 + 32.22) = 1.02 R_1

Let the power cost at temperature t_1 be \$0.009/kWh = \$78.84/kW-year; i.e., 1 kW at temperature t_1 costs \$78.84 per year. The power cost for the same current at temperature t_2 is (1.02) (\$78.84) = \$80.42 per year. The increase in power cost at temperature t_2 is \$80.42 - \$78.84 = \$1.58 per year = \$15.80 for ten years.

Magnet Insulation Life

The life of electric motor insulation is doubled for each 10°C lowering of the temperature. We can assume magnet insulation life is similarly extended. New inorganic insulation and rapid magnet obsolescence may render this extension of life insignificant.

Magnet Power Supplies

Magnet power supplies (particularly solid-state rectifiers and regulating equipment) may require lower operating temperatures than can be obtained from cooling towers. This may necessitate the use of chilling equipment. Such use increases the cost of cooling considerably. The cooling-water temperature is maintained sufficiently low at the Lawrence Radiation Laboratory so as to eliminate the need for chillers.

Magnetic-Field Control

As the temperature varies, there must be voltage regulation to maintain a steady current and thus a steady magnetic field.

V. HEAT EXCHANGERS

The heat-transfer area required and, hence, the cost of heat exchangers is determined by (1) the cooling load, (2) the overall heat-transfer coefficient, and (3) the driving force bringing about the heat transfer (i.e. the mean logarithmic temperature difference between the cooling water and the water being cooled.) Appendix H lists heat-exchanger costs ($/kW) versus cooling loads (MW) for various mean logarithmic temperature differences. An overall heat-transfer coefficient of 150 is assumed.

For cooling low-conductivity water with tower water, we prefer atmospheric heat exchangers installed in a coil-shed cooling-tower. This type of installation requires no ground area beyond that required for the cooling tower. The exchanger tubes can be examined for scale at any time, and they can be cleaned easily and effectively without the expense of disassembly of the equipment. There is some evidence that this type of heat exchanger has a little greater overall heat-transfer coefficient than the tube-and-shell heat exchangers. In some parts of the country, freezing weather may render this type of heat-exchange equipment less desirable.

U-tube type shell-and-tube heat exchangers are cheaper than other types since only one tube-sheet is required. We do not recommend them. They are very difficult to clean, and there have been many reports of tube failures in the region of the tube bends.

If fixed-tube-sheet type shell-and-tube heat exchangers are to be used in cooling low-conductivity water with tower water, the low-conductivity water should be circulated through the shell side and the tower-water through the tube side of the exchanger. This arrangement permits cleaning of the

tower-water side of the heat exchanger where most of the fouling will occur. Since the low-conductivity water cannot contain corrosion inhibiting chemicals because of conductivity requirements, the heat exchanger shell must be made of corrosion resistant material such as copper or stainless steel.

Floating-head type shell-and-tube heat exchangers permit reasonably simple disassembly and cleaning. They also allow for the expansion and contraction brought about by variations in temperature. With this type of heat exchanger, it is preferable to circulate the low-conductivity water through the tube side and the tower water through the shell side of the exchanger. This eliminates the necessity of using expensive corrosion-resistant materials for the shell.

Square-pitch tube bundles are easier to clean than triangular pitch bundles. They are slightly more expensive.

The materials to be used in a heat exchanger depend to a large extent upon the materials used in the remainder of the closed-circuit system. Where low-conductivity water passes through the tube side, we have found that admiralty metal or stainless steel tubes and steel shells, tube sheets, and headers are satisfactory provided those parts which contact the low-conductivity water are effectively coated. Effective coatings include polyvinyl chloride and some of the phenolic-based resins. Their use is much cheaper than the use of all stainless steel or all copper heat exchangers, and they are just as effective.

Ethylene glycol-water solutions are often used in chilled water systems. They should not be used where the chilled water is used to cool domestic water. Ethylene glycol is extremely poisonous (vide U. S. Food and Drug Administration, elixir of sulfanilimide incident - 114 deaths from ethylene

glycol*). Any leakage in heat-exchange equipment could be very hazardous. (In an actual incident, the head of a heat exchanger used for this identical purpose cracked from freezing.) The general practice of the food, drug, and cosmetic industry is to use the nontoxic propylene glycol-water solutions to cool domestic water.

*Administrative Report of the Food Law Institute, 1907-1949, (Commerce Clearing House Institute, Inc., New York, N. Y., 1951), pp. 904, 910, 946, and 1057.

VI. LOW-CONDUCTIVITY WATER SYSTEM

A. Piping Materials

The following conclusions are based on the results of materials testing and on some twenty years of experience at accelerator laboratories.

Aluminum

Pure aluminum forms a protective coating of aluminum oxide. It has been used successfully for years as the piping material in low-conductivity-water and distilled-water systems.

For strength, larger sizes of aluminum pipe must be alloyed. Aluminum alloys contain both anodic and cathodic areas. Because of this, the aircraft industry formerly experienced considerable trouble with aluminum-alloy corrosion. This was alleviated by the use of "alclad" material (aluminum alloy with a surface coating of pure aluminum). At this time, we have no knowledge of the pure aluminum surface coating of large pipe.

Aluminum-alloy piping is used with certain degrees of success in accelerator low-conductivity water systems consisting of no other metals than aluminum, stainless steel, and(or) nickel. The aluminum alloy of choice is 6061-T6. Alloy 6063 is not as satisfactory, and alloy 3003 is much less satisfactory. These conclusions are based on the results of ASTM coupon tests made on a number of different aluminum alloys. These tests were conducted simultaneously in independent low-conductivity water systems. The results were identical.

The welding of aluminum pipe must be done by the inert-gas-heliarc process which requires experienced welders and special equipment.

Buried aluminum pipe should be adequately coated or wrapped to prevent corrosion. Any pinhole in this coating will lead to rapid deterioration of the pipe at the point of the pinhole. Aluminum structures should not be buried in concrete.

Copper

In general, copper is probably the metal of choice for use with accelerator low-conductivity water systems.

There have been reports that copper is unsuitable for use where the conductivity of the water must be maintained below 5 μmho/cm. Past experience does not bear this out. Copper low-conductivity water systems have operated trouble-free for many years where the conductivity of the water was maintained well below 1 μmho/cm.

The expense and limited availability will probably rule out any extensive use of copper piping larger than about 4 in. nominal size.

Care should be taken in the selection of the solder to be used. Generally, 95-5 silver solder or brazing have proved the most successful. Zinc-brass fittings should be avoided. Copper will deteriorate rapidly in the presence of ammonia.

Iron, Steel, Galvanized Steel, and Cast Iron

Iron, steel, or cast iron, as such, are not suitable for use in low-conductivity water systems. They deteriorate rapidly, the conductivity of the water is raised, and the corrosion products plug small lines, orifices, and equipment.

Galvanized steel has no place in low-conductivity water systems. The zinc, being a sacrificial metal, passes into solution rapidly and raises the

conductivity of the water. The remaining steel will act as described above.

Some laboratories have coated the inside of steel pipe with various inert materials. We await further reports as to the functional and economic suitability of such a procedure.

We have found that steel tanks coated with polyvinyl chloride are very satisfactory for use in low-conductivity water systems. In regard to coating, probably the most important part is the surface preparation. If the coating is to be successful, it is absolutely mandatory that the manufacturer's instructions be rigidly adhered to.

Phospho-nickel nonelectrolytic coating of cast-iron pumps and valves has proven reasonably successful in low-conductivity water systems.

Stainless Steels

The 400 series (martensitic or cutlery series) stainless steels sacrifice corrosion resistance for the ability to be tempered and are not applicable for use in low-conductivity water piping systems. The 300 series (austenitic or so-called nonmagnetic series) have been used successfully in many accelerator applications. The basic pipe material is 304 (18-8) stainless steel. One difficulty with this material is the tendency of the carbon which is present to combine with the chronium, thus removing it from the alloy as chronium carbide. This destroys much of the alloy's corrosion resistance. This problem can be alleviated by using the expensive ELC (extra low carbon) stainless steels or by adding something to the alloy which will preferentially combine with the carbon, thus stopping the chromium carbide formation. Two of these substances are molybdenum and niobium (columbium), and the corresponding alloys are 18-8 Mo (316) and 18-8 Nb (347). Probably the alloy of choice as

far as corrosion resistance is concerned is 316, which is quite a bit more expensive than 304. Other 300 series alloys such as 302 are used because of machinability, etc. They do not have as much corrosion resistance.

The corrosion resistance of stainless steel arises from an oxide film a few molecules thick which forms on the surface of the alloy. If this film is removed (e.g. with hydrochloric acid) and the alloy is immediately placed in water, it will rust like ordinary steel. However, if the alloy is rinsed and allowed to stand in air for a short time, the protective coating will reform.

There is little problem of potential-difference corrosion when stainless steel is used with other metals.

Welding of stainless steel can present a number of problems. Between 800 and 1500°F, the components of the alloy (particularly the carbon) drop out of solution. This leads to intragranular corrosion adjacent to the weld. These components will redissolve at a higher temperature, and small pieces of stainless steel which have been welded are passivated by heating them to 2000°F and then rapidly cooling them. Obviously, such a procedure is not practical with long lengths of large pipe. The welding should be carried out in an inert atmosphere. The problem of the separation of components can be alleviated by the use of the expensive ELC alloys and by rapid welding. (The separation is time-dependent.) Care should be taken to assure that the weld on the inside of the pipe is smooth and continuous or, otherwise, crevice corrosion may occur.

In low-pressure, low-conductivity water systems where radiation is no problem, stainless steel piping can be joined easily and effectively through the use of clamp-on neoprene or rubber couplings.

Glass, Polyvinyl Chloride, Polyethylene, and Polypropylene

These substances are inert and are unaffected by other materials in the system. Most of them have a limited pressure rating, and in some cases, as with polyvinyl chloride, a limited temperature rating. Where pressure, radiation, temperature, and size limitations are not factors, these materials have proven quite satisfactory and very economical.

Epoxy-Lined Cement-Asbestos

Epoxy-lined cement-asbestos pipe, installed within the pressure rating and in accordance with the manufacturer's recommendations, gives satisfactory results when used in low-conductivity water systems.

Buried pipe should stop about five feet from the excavations for foundations with a transition piece continuing from that point. This transition piece is needed to absorb the sheer stresses that may develop near the foundations.

This pipe is more brittle than metallic pipe and will rupture if, for example, it is struck by a fork-lift truck or subjected to severe water hammer.

Epoxy-Impregnated Fiberglass

This piping can be obtained with a pressure rating of 300 psi pulse pressure and 450 psi steady pressure. There is no problem of corrosion arising from potential difference. The material is inert and the cheapest of the materials considered. Work needs to be undertaken to see how this material withstands radiation. If it is not adversely affected by radiation, it appears to be an excellent material for use in low-conductivity water systems.

Rubber, Neoprene and Elastoids

Exercise care in using rubber-lined valves or similar equipment in low-conductivity water systems. Some of these materials are slightly porous and

contain entrapped salts. Osmotic pressure will force water into the interior of the material causing it to swell and(or) rupture. Also some of the rubbers will harden under radiation.

Polymetallic Systems

In general, it is poor policy to circulate low-conductivity water through polymetallic systems. It is particularly poor to use a system consisting of aluminum and copper where there is a potential difference between the metals of over two volts.

Where the low-conductivity water is used to cool accelerator magnets, the problem of potential difference cannot be solved by simply adding insulators to separate the different metals. The IR drop through each hydraulic circuit in the magnet coil renders one end of the circuit considerably more positive in potential than the other. This positive potential forces copper ions into solution in the low-conductivity water. (This is evidenced by the eating away of the connections to the copper coil. See Fig. 13.) These copper ions will plate out when contacting a metal such as aluminum. The aluminum, in turn

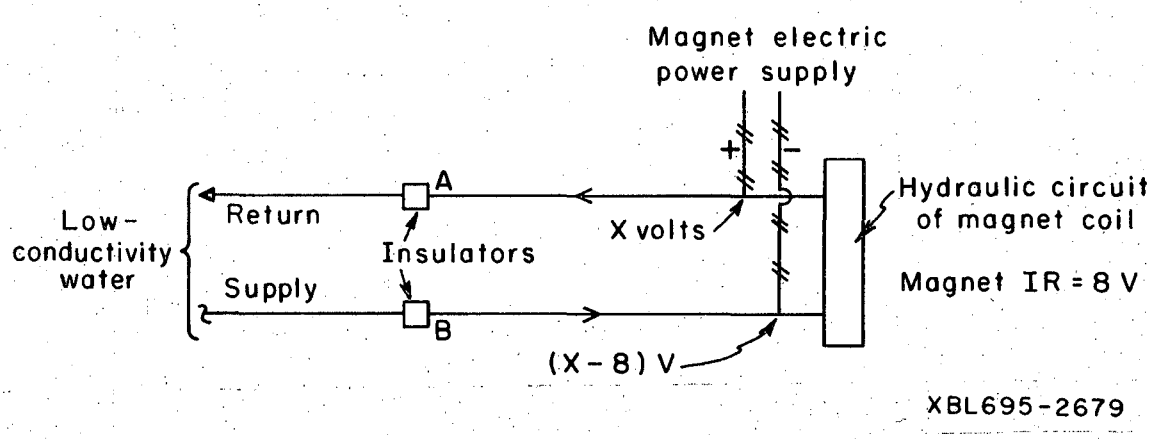


Fig. 13. Electrolytic corrosion. A potential across the magnet will cause deterioration of the copper pipe at point A.

is oxidized to aluminum ions which combine with water to form gelatinous aluminum compounds. This gelatinous material has caused much trouble at some accelerator installations by plugging orifices, regulating equipment, small lines, etc.

B. Factors Influencing Pipe Deterioration

Effect of Radiation on Piping Materials

In general, the effect of radiation on metals resembles that of cold rolling the metals. Radiation affects organic materials about a thousand fold more than metals. Synthetic organic products are affected more than natural products. The ionization of organic material by radiation generally results in the cross-linking of the long polymer chains. This results in both a toughening and an increase in the brittleness of the material. Sometimes the material is destroyed. Positive information concerning the effect of radiation on a particular material should be obtained through empirical testing.

Effect of a Magnetic Field on Piping

The effect of a magnetic field on metal pipe is shown in Fig. 14. Care must be taken to insure that the metallic pipe installed within the magnetic field of an accelerator is well grounded. This is particularly true where the low-conductivity water piping runs a circular path parallel to the path of the accelerator magnets. The rising and collapsing magnetic field of the accelerator magnets will induce a current in the piping if steps are not taken to ground the piping at frequent intervals. For example, at one proton accelerator, the main loop of the low-conductivity water system was made up of two different metals (aluminum and copper). These metals were isolated from

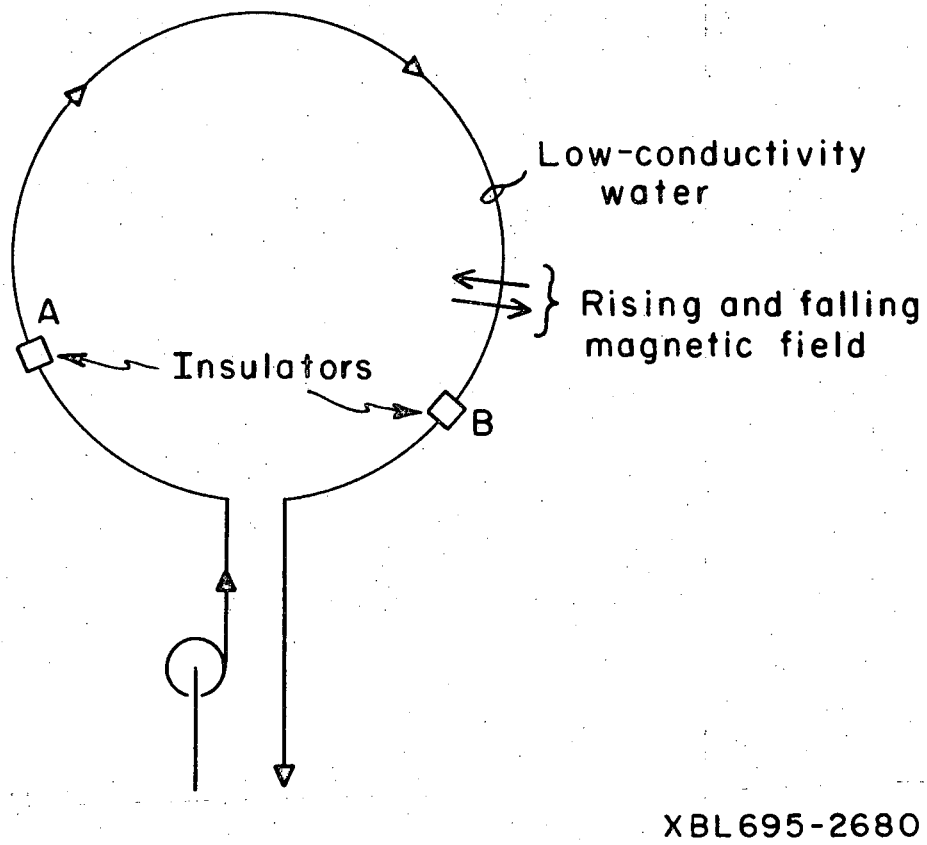


Fig. 14. Effect of magnetic field on piping. An accidental ground at A can induce a dangerous current at B.

each other by insulating materials. As a result, a portion of the piping containing one of these metals was "floating" electrically. When one end of this portion of piping was grounded accidentally, a current amounting to 5 to 7 V and 1 kA was observed. It was necessary to ground this portion of piping at frequent intervals to prevent this dangerous current buildup.

Effect of Electrical Potential on Metal Oxidation

Figure 15 illustrates how metallic components are oxidized by electrical potential. It represents a portion of the equipment used in a physics experiment performed at Cory Hall, University of California, Berkeley.

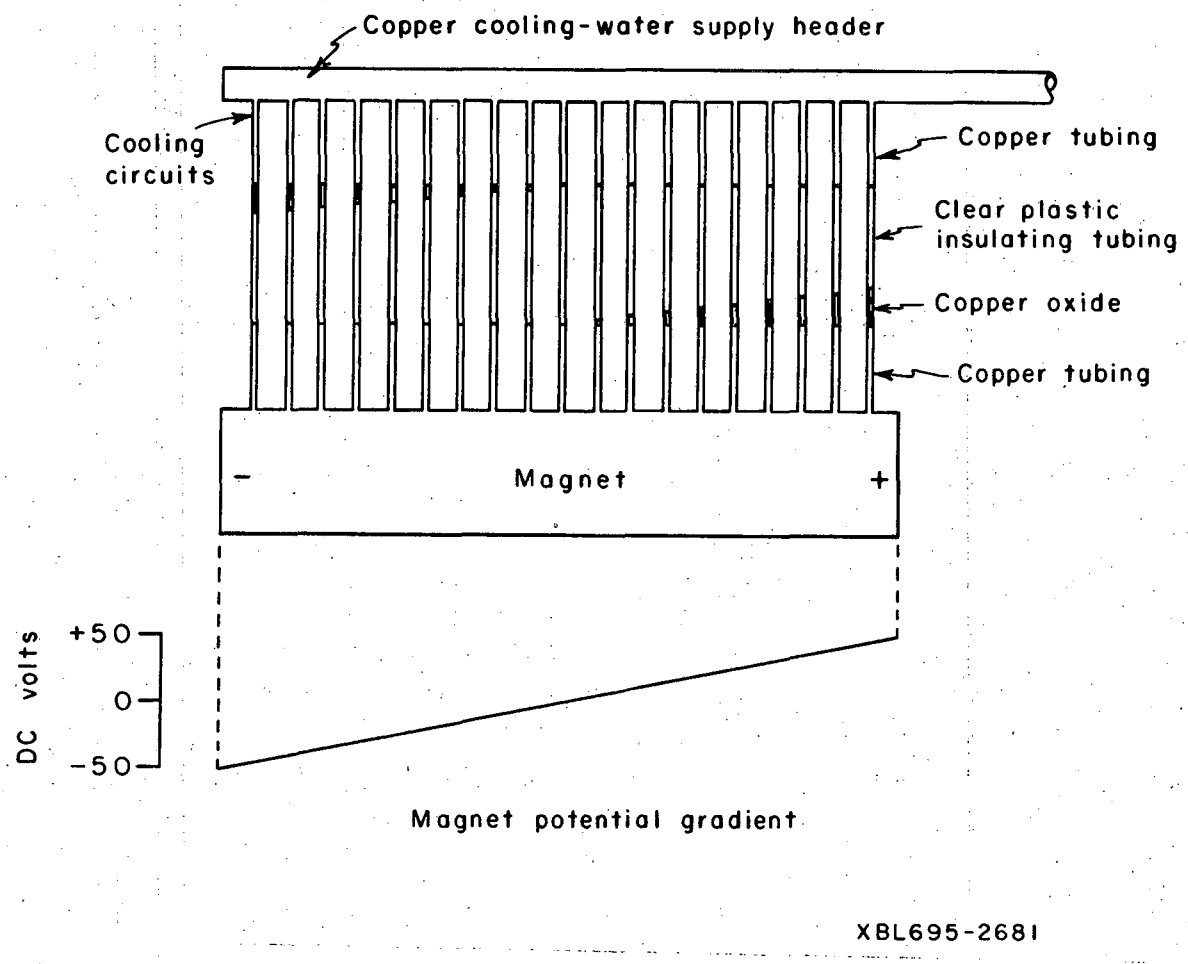


Fig. 15. Magnet potential gradient.

The magnet has an even dc potential gradient from + 50 V at one end to - 50 V at the other. It is cooled by evenly spaced parallel copper water circuits. Each circuit is insulated from the cooling-water supply header by a length of clear plastic tubing. The amount of copper oxide deposited at the junctions of the plastic and copper tubing appears to be directly proportional to the positive potential impressed on the particular piece of copper tubing.

VII. DEMINERALIZED WATER

Description

The term "low-conductivity water" (LCW) is used to designate water which has been "demineralized" or "deionized". This water is most generally used at accelerator laboratories for cooling electrical or electronic equipment where it is necessary to keep the electrical resistance of the cooling media at about 1MΩ-cm. This water is also used for purposes where a very low chemical content is required (e.g., photographic development processes and plating processes).

"Deionized water" and "demineralized water" are synonymous terms used to designate water from which all ions other than those created by the dissociation of water have been removed. Theoretically, deionized water will contain dissolved substances which are not ionized (e.g., sugar and other organic compounds). Practically, deionized water is usually quite free of these nonionized materials, since the water supply to the demineralizer does not usually contain nonionized material in any significant amount.

The purity of demineralized water is expressed in many ways including: (1) parts per million in terms of pounds of sodium chloride expressed as calcium carbonate per pound of water, (2) resistivity in terms of megohms-centimeter, and (3) conductivity in terms of micromhos/centimeter. The degree of water purity when expressed in terms of megohms-centimeter or micromhos/centimeter is the resistance or the conductance, respectively, of that amount of water contained between two 1-cm^2 plates 1 cm apart.

The resistance or conductance of the water is determined by the current flow and, hence, the movement of ions through the water. Accordingly,

the values of the resistance or conductance are determined by (1) the concentration of the ions; (2) the mobility of these ions (determined by the transport number, mass, charge, and types of ions); and (3) the viscosity of the media (determined by the temperature of the water). Although the relationship between the conductance and the concentration is modified by the types of ions present and by the temperature of the water, many people use the conversion formula, "2.5 × ppm (in terms of NaCl expressed as $CaCO_3$) = micromhos/cm" as an approximation for quick field estimating.

Preparation

Water is deionized by a process designated as "ion exchange". In this process, certain chemical substances (ion-exchange resins) remove those ions present in the water and substitute in their place another kind of ion.

The ion-exchange resins which exchange positive ions are called cation resins. Cations are those ions which migrate to the cathode. During the regeneration cycle, the cation resins may be charged with either sodium ions or hydrogen ions. The corresponding ion-exchange processes are referred to as the "sodium cycle" process or the "hydrogen cycle" process, respectively. Domestic water softeners contain cation resins charged with sodium ions. During the water softening process, these resins remove calcium and magnesium ions from the water and substitute sodium ions in their place. (Calcium and magnesium ions are the principal source of hardness in water.)

Cation resins charged with hydrogen ions remove all positive ions from the water and substitute hydrogen ions in their place. They are most generally used in conjunction with anion resins in the deionization process.

The ion-exchange resins which exchange negative ions are called anion resins. Anions are those ions which migrate to the anode. Strong-base anion resins are usually charged with hydroxyl ions during the regeneration process. The resins so regenerated remove all negative ions from the water and substitute hydroxyl ions in their place.

"Weak base" resins are usually regenerated with chemicals other than the strong acids or sodium hydroxide. They are generally used either in an intermediate step in the demineralization process or in applications where complete removal of all ions from the water is not required. They are more economical than the strong base resins for these certain applications. Generally, they are not too applicable for use in the low-conductivity water systems for accelerators.

Water is deionized in units usually designated as deionizers, demineralizers, ion-exchange units, etc. These units contain both cation and anion resins. These two types of resins may be mixed together in a single bed (mixed-bed unit) or be used separately and consecutively in separate beds (two-bed or multi-bed units).

In the mixed-bed unit, the two types of resins are thoroughly and intimately mixed together except during the regeneration process. The water passing through the unit sees a multiplicity of cation- and anion-exchange processes as though the water were passing through many small demineralizers. Because of this, the effluent water from a mixed-bed unit has a much higher purity than that obtained from a two-bed or multi-bed unit. There is, accordingly, a shorter period between regenerations. After separation, the resins in a mixed-bed unit may be regenerated either consecutively or simultaneously. A better regeneration is obtained by the consecutive method, but this method

requires more time to carry out the regeneration. With automatic and semi-automatic units, this added time may not be significant in terms of the man-hours of labor expended. The conductivity of the effluent water from a mixed-bed unit should be in the range of 0.1 to 0.5 μmho/cm.

In the two-bed and multi-bed units, the water generally passes through the cation bed first, then through the anion bed. As a result, the water between the cation bed and the anion bed is quite acid. Sometimes a degassifier is placed between the beds to remove carbon dioxide from the water, thus easing the load on the anion bed. The effluent water from a two-bed or multi-bed unit will be from 1 or less to 5 μmho/cm.

The capacity of the resins is ion capacity. Accordingly, the amount of water that an ion exchange unit can demineralize between regenerations depends on both the quantity of water processed and the concentration of ions in this water. When the resins have reached their exchange capacity, they must be regenerated.

Normally, the resins hold the larger ions and the multivalent ions more securely than the hydrogen (or hydroxyl) ions. This fact makes the ion-exchange process possible. The larger ions in the water replaced the loosely held hydrogen (or hydroxyl) ions in the resins. The hydrogen ions from the cation resins and the hydroxyl ions from the anion resins pass into the water and combine to form more water. Regeneration of the resins is accomplished by the application of the mass law. By applying an overwhelming concentration of hydrogen (or hydroxyl) ions, the normal process is caused to proceed in the reverse direction, so that these ions replace the other ions now held by the resins. These other ions are passed to waste.

Regeneration of the anion-exchange resins is a straightforward process involving (1) backwashing of the resins to remove sediment and(or) other extraneous material, (2) passing a concentrated solution of sodium hydroxide through the resin bed, and (3) and (4) a slow and a fast rinse to remove the chemicals not taken up by the resin bed.

Cation resins are regenerated in several ways. When the resins are employed in the "hydrogen cycle" process, the resins are regenerated with either hydrochloric acid or sulphuric acid. The actual regeneration procedure consists of (1) backwashing, (2) passing a concentrated solution of acid through the resins, and (3) and (4) a slow and a fast rinse. Hydrochloric acid may be used for regeneration in an effective concentration (~ 10%) without the danger of clogging the resin bed which is present when sulphuric acid is used. The higher cost of hydrochloric acid coupled with the handling of the large volume of this acid needed for regeneration, however, predisposes toward the use of sulphuric acid. When the positive ions in the water supply to the demineralizer is composed of 20% or more of calcium ions, the concentration of the regenerant sulphuric acid must be kept down in the range of 2%. Above this concentration, there is a precipitation of the sparingly soluble calcium sulphate. It is this calcium sulphate which clogs the resin bed, coats the resins, and thus reduces the exchange capacity of the unit. A "sodium cycle" water softener placed ahead of the demineralizer will replace the calcium ions in the water supply with sodium ions. This will remove the problem of calcium sulphate formation and allow a higher, more effective concentration of sulphuric acid to be used.

We advise continuously recycling some of the recirculated water from the main system loop in order to remove those ions introduced into the system by electrolysis or mechanical contamination. The amount of recycle is a matter

of judgment depending upon the degree of water purity desired and the amount of contamination expected to be introduced by the low-conductivity water system components. We have found that a recycle rate amounting to 1 to 2% of the total recirculation rate of the main system loop will maintain a satisfactory water purity.

Problems may arise due to the character of the water supply or to the particular conditions of use of the low-conductivity water system. These problems include (1) water hardness and bed fouling due to high content of iron in the water supply, (2) fouling of the beds and "silica break-through" due to a high silica content in the water supply, (3) difficulty in removing unusually high quantities of carbon dioxide, (4) bed fouling due to silt in the water supply, and (5) bed fouling due to particular ions forced into the low-conductivity water by electrical potential. High-efficiency filters, degassifiers, etc. are available to deal with many of these problems.

VIII. WATER-PRESSURE LOSS THROUGH MAGNET COOLING COILS

Generally, the loss of water pressure through magnet cooling coils at LRL does not exceed 50 to 75 psi at design water flow. Most magnets (except for a few used for special purposes) can, through proper sizing of coil water passages and paralleling of water circuits, be designed to meet these pressure loss limitations.

We believe these pressure-loss limitations should be maintained if possible for the following reasons:

1. Comparatively low-head pumps and standard-weight pipe and fittings can be used in the low-conductivity water system. The capital cost is, accordingly, less than that of a system where high-pressure pumps, pipe, and fittings are required.
2. The operating cost of a system using low-pressure pumps is less than that of a system requiring high-pressure pumps.
3. Water leaks are both more prevalent and more serious in high-pressure systems than in low-pressure systems.
4. There are more limitations on materials and equipment with high-pressure systems than with low-pressure systems.

Often the hydraulic resistance of certain magnets is considerably less than that of others. If the water flow through the magnets is not controlled, those magnets with low resistance will receive an excess of water flow while those with high resistance will receive insufficient flow and will possibly overheat. Increasing the quantity of overall water flow will do little to help this situation in that most of the additional flow will pass through the magnets with low resistance and very little of it through those with high resistance. In these

instances, local control of the water flow through the magnets appears to be the most feasible solution.

Where a number of similar magnets are cooled by parallel water circuits (e.g., in the case of accelerator magnets), it is desirable to use a reverse water-return system to assure a comparable water flow through each of the magnets. Figure 16 illustrates a standard water-return system. Figure 17 illustrates reverse return systems.

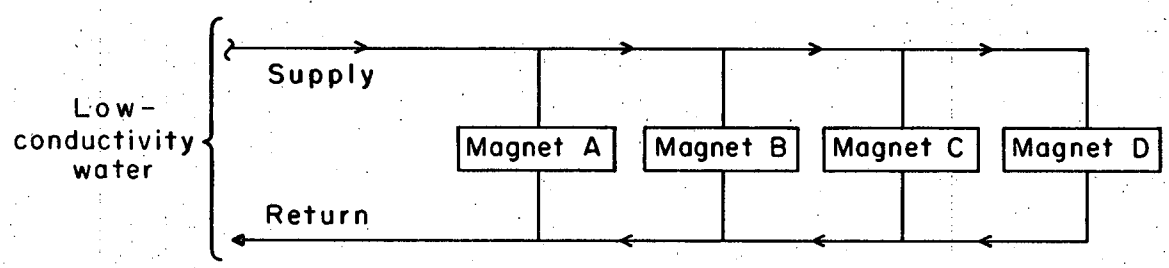


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Fig. 16. Standard water return system. The water header resistance for the magnets is uneven, the greatest amount flowing through Magnet A, the least through Magnet D.

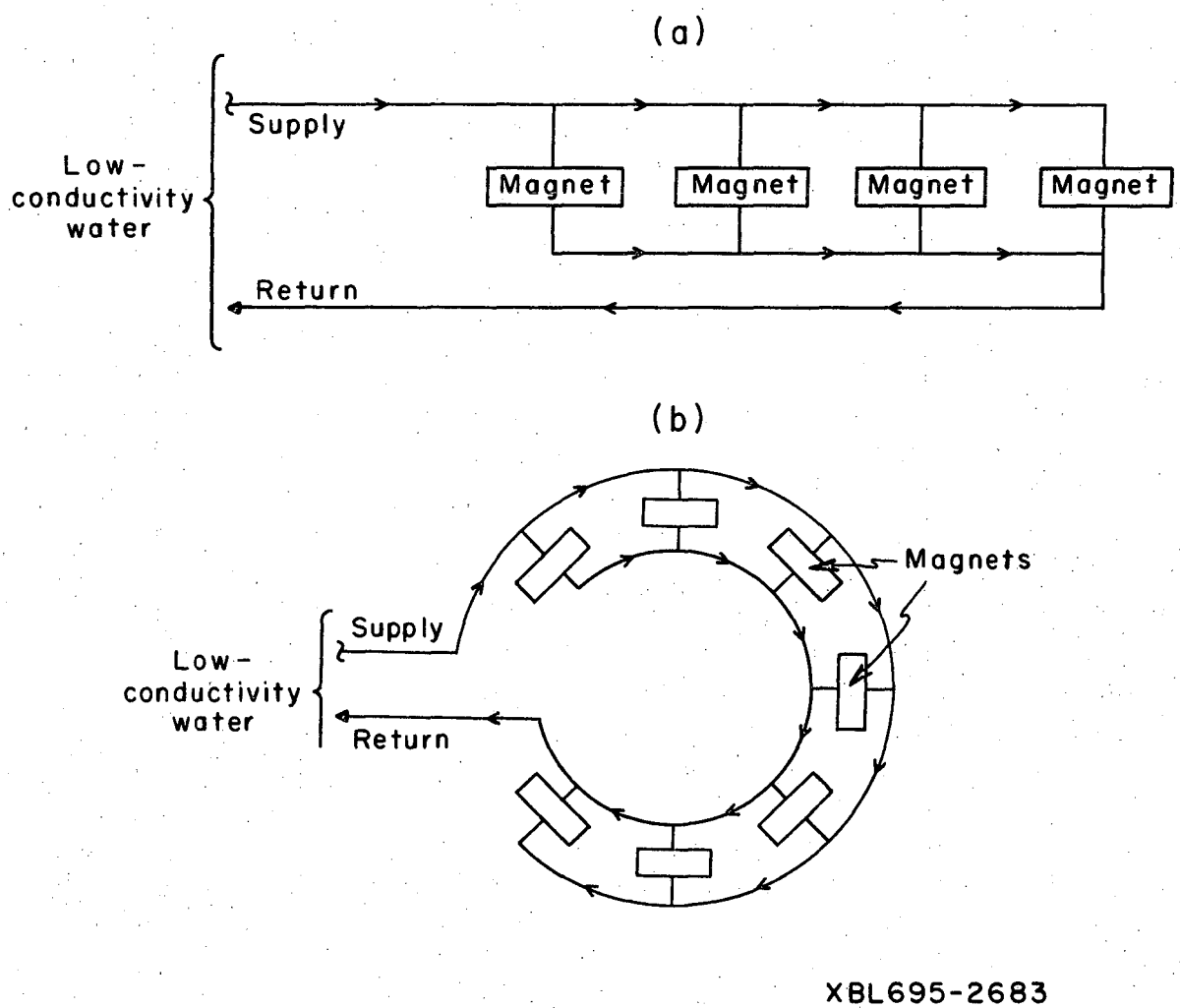

Fig. 17. (a) Linear and (b) loop reverse water return systems. The sum of the supply and return water header resistance is the same for each magnet. Approximately the same amount of water will flow through each magnet.

IX. COOLING WATER SYSTEMS

We believe the highest priority in an accelerator laboratory should be assigned to the production of research. Accordingly, our systems are so designed as to permit routine maintenance and repair without interrupting accelerator operations. For example, for circulating low-conductivity water, three pumps may be installed, any two of which can supply the required flow. The pumps are used alternately to permit maintenance and repair without shutting down the accelerator.

The nature of experimentation creates considerable variation from time to time in the demand for cooling water. Accordingly, the low-conductivity cooling-water is best moved by "flat-curve" pumps, so as to accomodate this variable demand while maintaining a nearly constant cooling-water system pressure.

In the selection of low-conductivity water pumps care should be taken in regard to the pump cutoff. If clearances are too small, vibrations may be set up which will be transmitted to the accelerator equipment.

Figures 18 and 19 illustrate typical accelerator cooling-water systems.

ACKNOWLEDGEMENT

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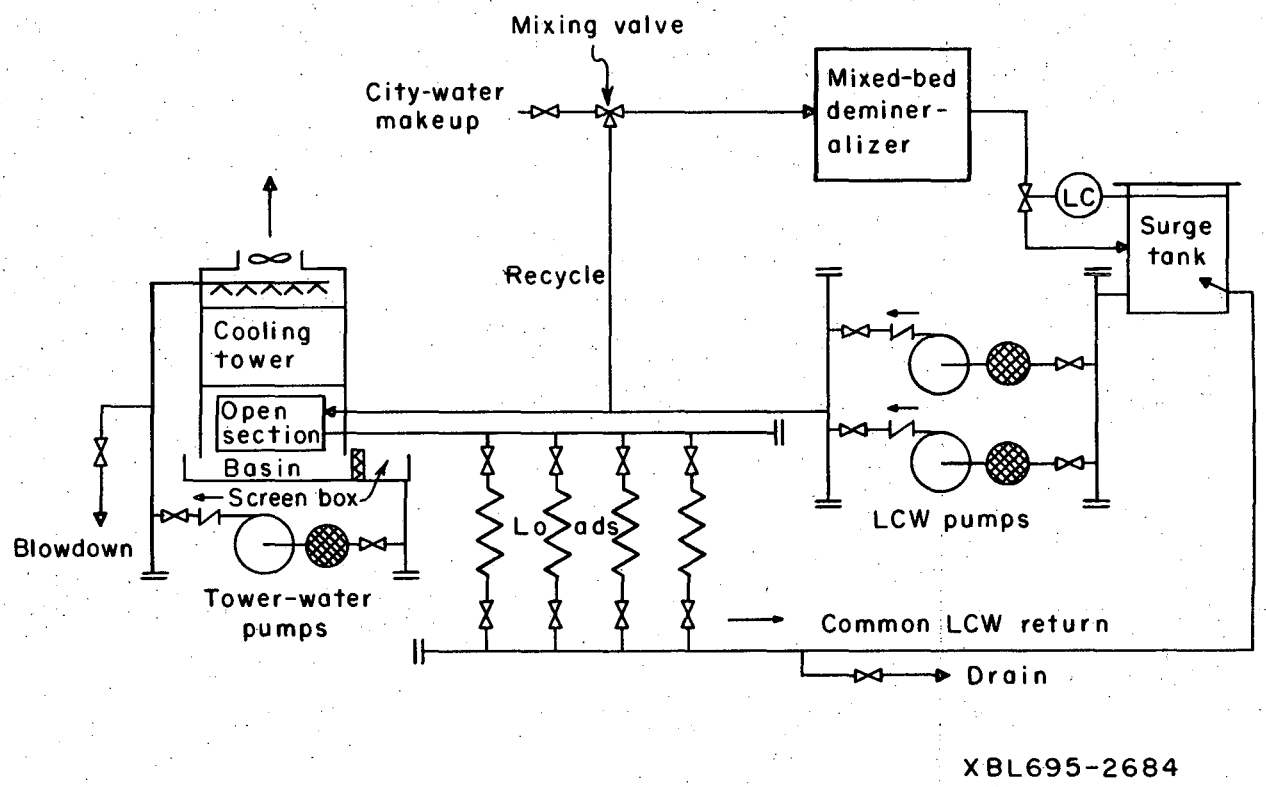


Fig. 18. Typical closed-circuit LCW cooling system. This is the best all-around system for uniform pressure distribution. More pumps and circuits can be added as needed.

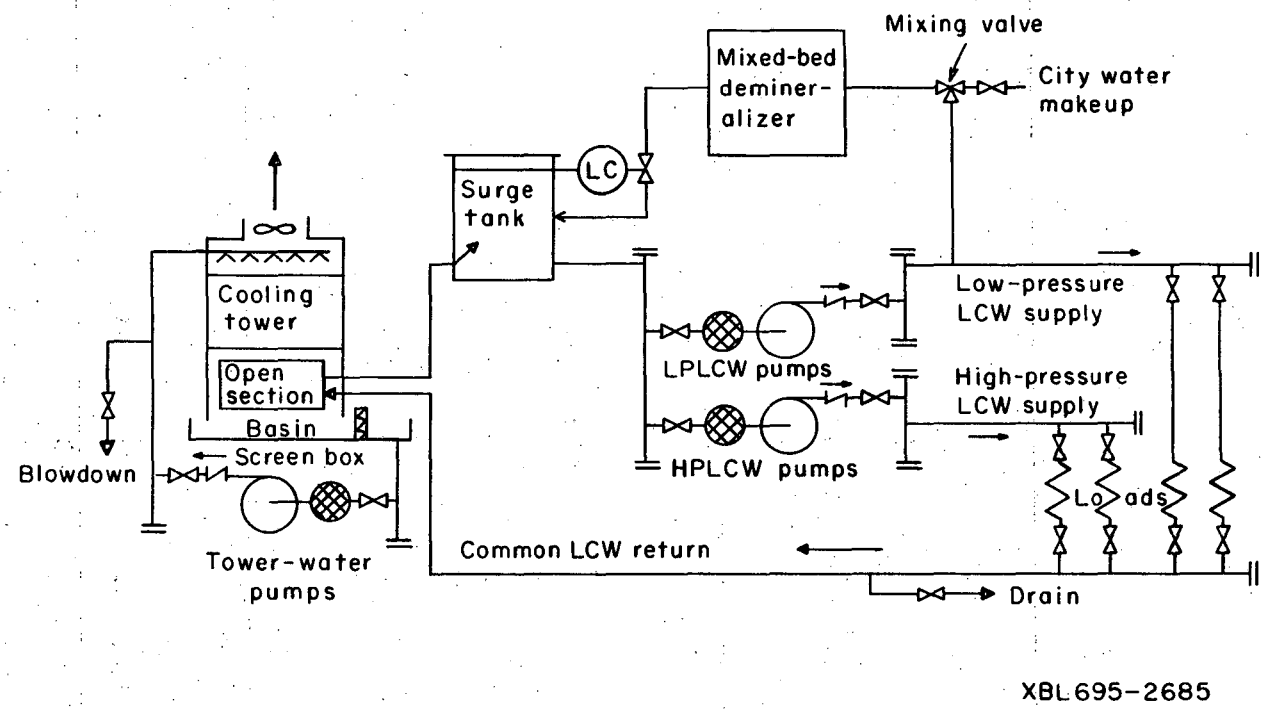


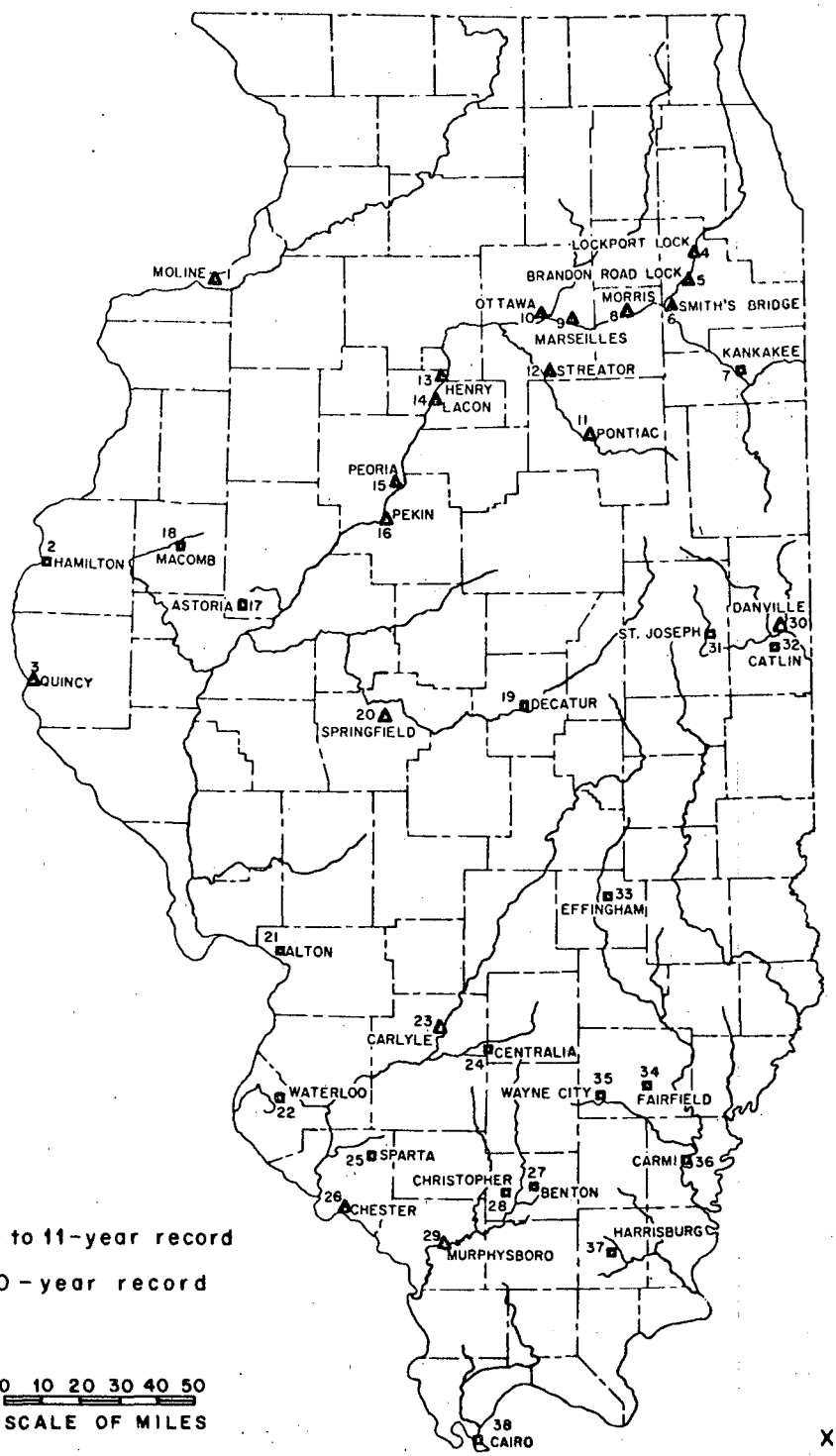
Fig. 19. Typical closed-circuit (LCW) cooling system. This is the best all around system for multiple pressure distribution. More pumps and circuits can be added as needed.

APPENDICES

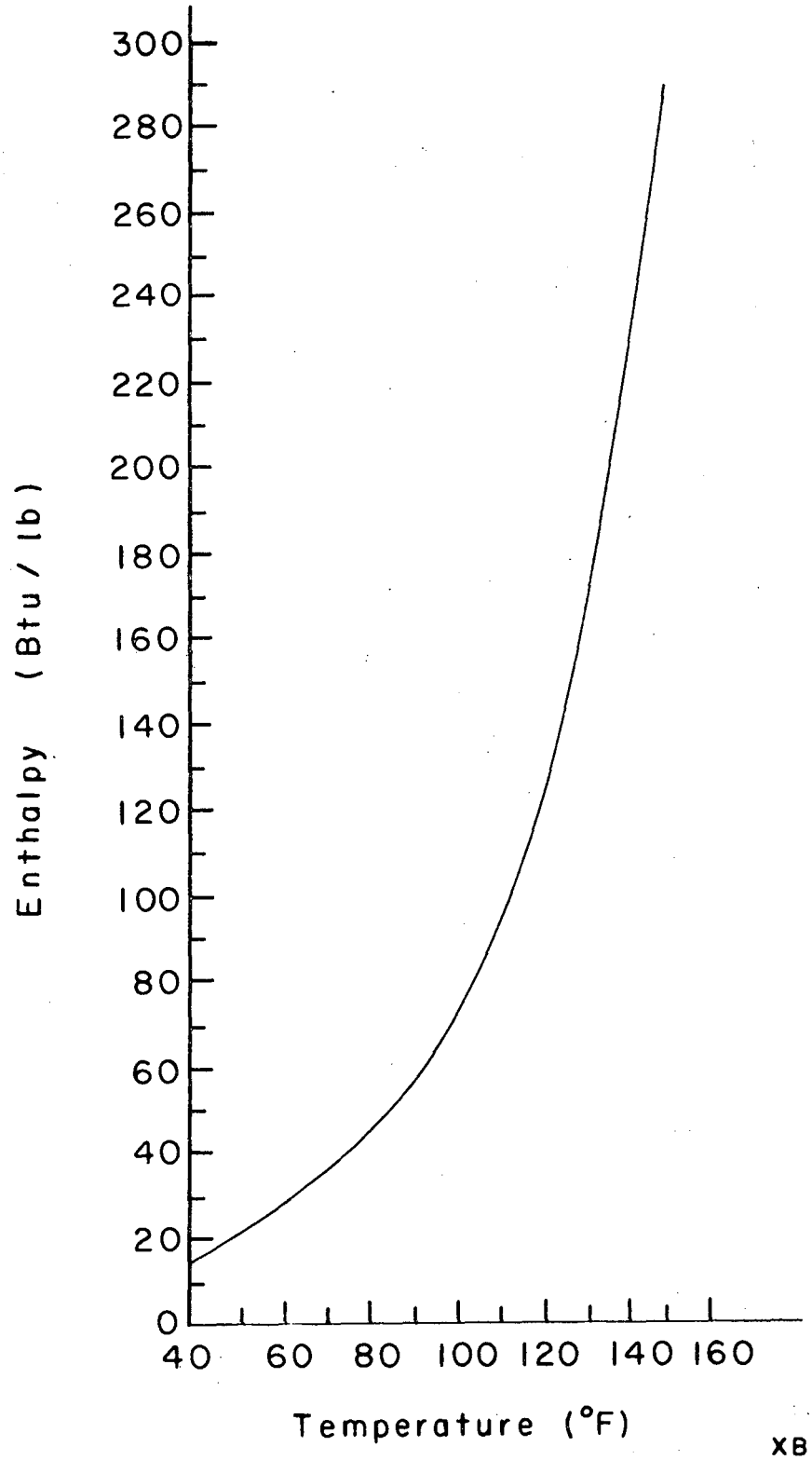
Appendix A. Averages of Mean Monthly Water and Air Temperatures in °F at Locations 1 through 38 on Appendix B.

Map number	Station	January		February		March		April		May		June		July		August		September		October		November		December		Years of record
		water	air	water	air	water	air	water	air	water	air	water	air	water	air	water	air	water	air	water	air	water	air	water	air	
1	Moline	33	22	33	28	36	34	48	50	62	61	73	71	79	75	78	74	70	65	57	54	42	38	34	27	11
2	Hamilton	39	23	39	26	42	36	54	51	66	62	74	71	79	73	81	74	74	67	61	55	48	40	41	28	4
3	Quincy	35	26	35	31	40	38	51	52	63	62	74	73	79	77	79	76	72	67	60	56	46	40	37	31	11
4	Lockport Lock	42	25	44	30	48	36	56	51	65	60	73	71	79	75	81	74	76	67	68	55	56	40	46	29	11
5	Brandon Road Lock	43	25	44	30	48	36	57	51	66	60	75	71	80	75	81	74	76	67	67	55	55	40	46	29	11
6	Smith's Bridge	41	25	44	30	47	36	56	51	66	60	75	71	80	75	81	74	75	67	66	55	54	40	45	29	11
7	Kankakee	34	23	35	29	41	35	53	50	63	61	74	70	78	74	78	74	73	69	58	54	45	39	38	29	3
8	Morris	38	24	40	29	44	36	54	51	64	61	73	71	78	74	78	73	73	67	63	55	50	40	41	29	11
9	Marseilles	39	25	41	30	45	37	55	52	65	62	75	72	79	76	80	74	73	67	63	55	51	41	42	30	11
10	Ottawa	36	25	38	30	42	37	53	52	63	62	73	72	78	76	77	74	70	67	59	55	47	41	39	30	11
11	Pontiac	38	25	38	30	44	37	55	51	65	62	75	71	80	75	80	73	72	66	60	55	45	40	39	29	11
12	Streator	37	25	36	30	41	37	52	52	63	62	72	72	78	76	78	75	70	67	58	55	44	40	38	30	11
13	Henry	34	25	35	30	42	37	51	52	63	62	74	72	79	76	79	75	72	67	60	55	46	40	37	30	11
14	Lacon	34	24	36	30	41	36	53	51	64	62	74	72	79	76	79	74	72	66	60	55	46	39	36	29	11
15	Peoria	34	24	35	30	41	36	53	51	64	62	75	72	79	76	79	74	71	66	59	55	45	39	36	29	10
16	Pekin	34	24	36	30	41	36	53	51	64	62	75	72	80	76	79	74	71	66	59	55	45	39	36	29	10
17	Astoria	40	25	38	30	39	37	47	52	60	63	69	73	72	76	75	77	73	70	67	56	51	40	41	30	3
18	Macomb	40	23	38	28	41	35	50	51	61	62	70	72	72	74	74	75	69	68	60	55	47	39	41	29	3
19	Decatur	36	26	36	32	41	39	51	53	61	63	70	72	75	76	77	76	72	69	59	56	46	46	37	32	5
20	Springfield	50	28	51	32	54	38	58	53	66	63	75	73	80	77	80	75	75	68	65	56	55	41	50	32	11
21	Alton	34	29	35	34	41	40	53	54	65	64	77	74	80	78	83	79	77	72	63	58	48	43	38	34	3
22	Waterloo	40	30	41	35	44	41	55	55	63	64	73	73	79	75	81	77	76	71	64	58	50	43	42	34	3
23	Carlyle**	45	32	45	37	50	44	56	56	65	66	76	75	81	79	80	78	74	71	61	58	50	44	46	36	10
24	Centralia	36	31	37	31	41	44	55	57	66	65	76	74	80	77	82	78	76	72	63	59	49	44	38	33	4
25	Sparta	39	32	40	37	46	43	58	57	68	65	77	74	83	77	84	78	79	72	64	60	47	44	40	36	3
26	Chester	37	34	41	39	46	45	57	58	68	67	77	76	82	79	83	79	76	72	65	60	50	46	40	37	11
27	Benton	44	32	43	37	46	42	54	57	63	65	72	74	76	77	78	78	76	72	67	60	57	44	45	36	3
28	Christopher	39	32	41	34	46	42	55	57	60	65	70	73	74	77	75	76	70	71	59	59	49	45	41	35	4
29	Murphysboro	40	35	42	40	48	45	58	58	67	66	76	75	80	79	80	77	73	71	63	58	50	46	42	38	10
30	Danville	37	28	38	33	43	39	53	52	64	62	74	72	78	75	79	74	72	68	61	55	47	41	38	32	11
31	St. Joseph	34	24	36	31	41	37	50	51	62	63	73	72	77	75	77	78	69	69	58	56	45	41	36	28	4
32	Catlin	35	28	37	33	43	40	55	53	64	62	72	73	78	76	78	74	69	67	58	56	44	41	36	34	5
33	Effingham	34	30	33	32	35	39	42	53	52	62	60	72	71	76	73	77	69	68	61	55	50	43	38	32	4
34	Fairfield	37	32	38	34	46	41	59	56	67	64	75	72	79	76	79	76	75	71	62	59	50	45	40	34	4
35	Wayne City	36	32	39	36	40	41	49	56	61	64	69	73	73	76	74	76	71	72	60	59	45	44	39	35	3
36	Carmi	40	32	40	34	46	42	58	57	67	65	76	73	78	77	80	78	76	72	64	59	52	45	42	34	4
37	Harrisburg	40	34	40	40	45	45	56	57	66	65	75	75	80	78	82	78	77	73	67	61	53	46	41	37	4
38	Cairo	37	35	38	39	45	45	53	60	66	68	73	77	77	80	77	80	75	73	64	61	52	48	41	37	5

** Water heated during coldest months (November–March, approximately)*



Appendix B. Map of Illinois showing location of measurement stations in Appendix A.



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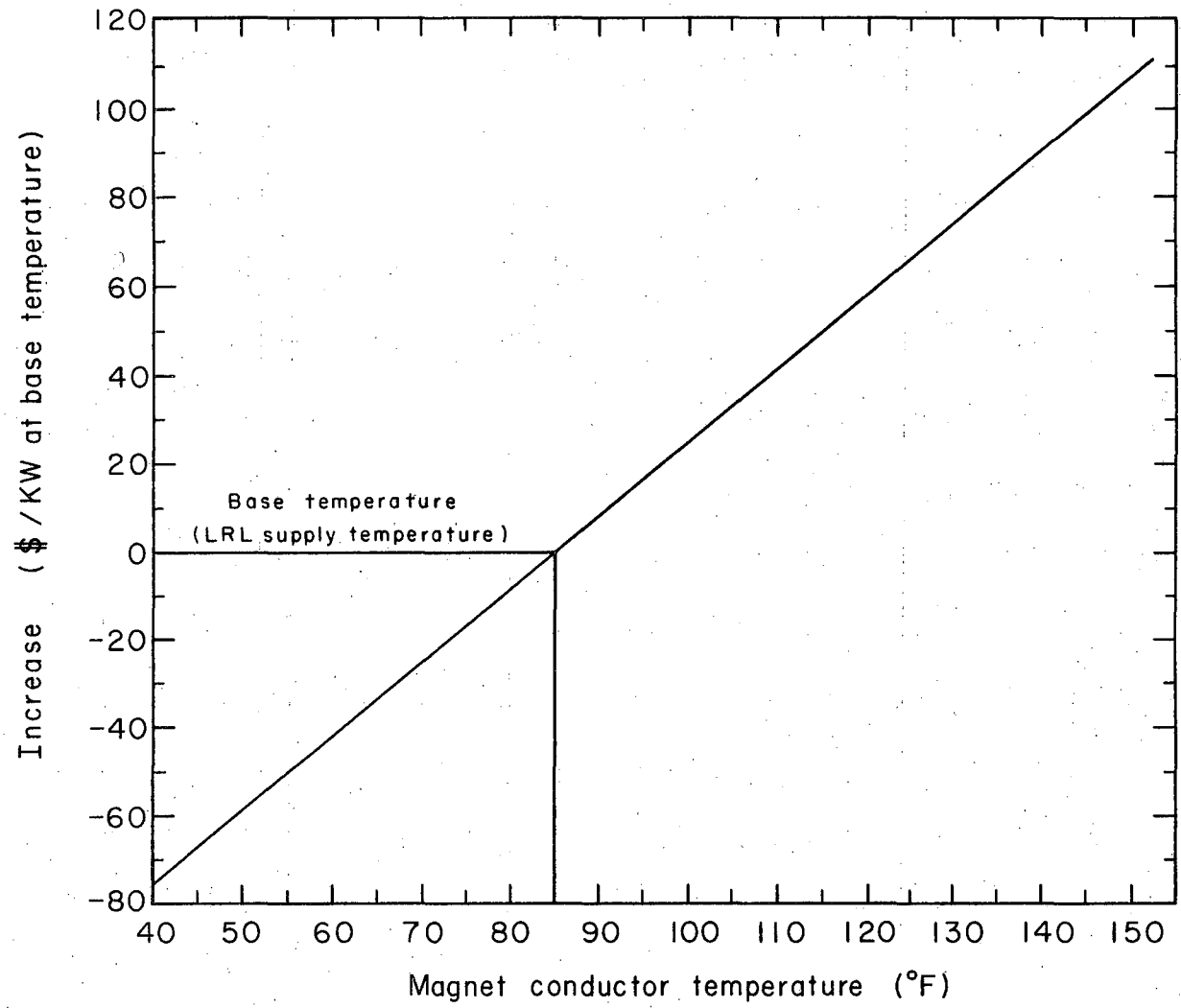
Appendix C. Enthalpy vs temperature for saturated air.



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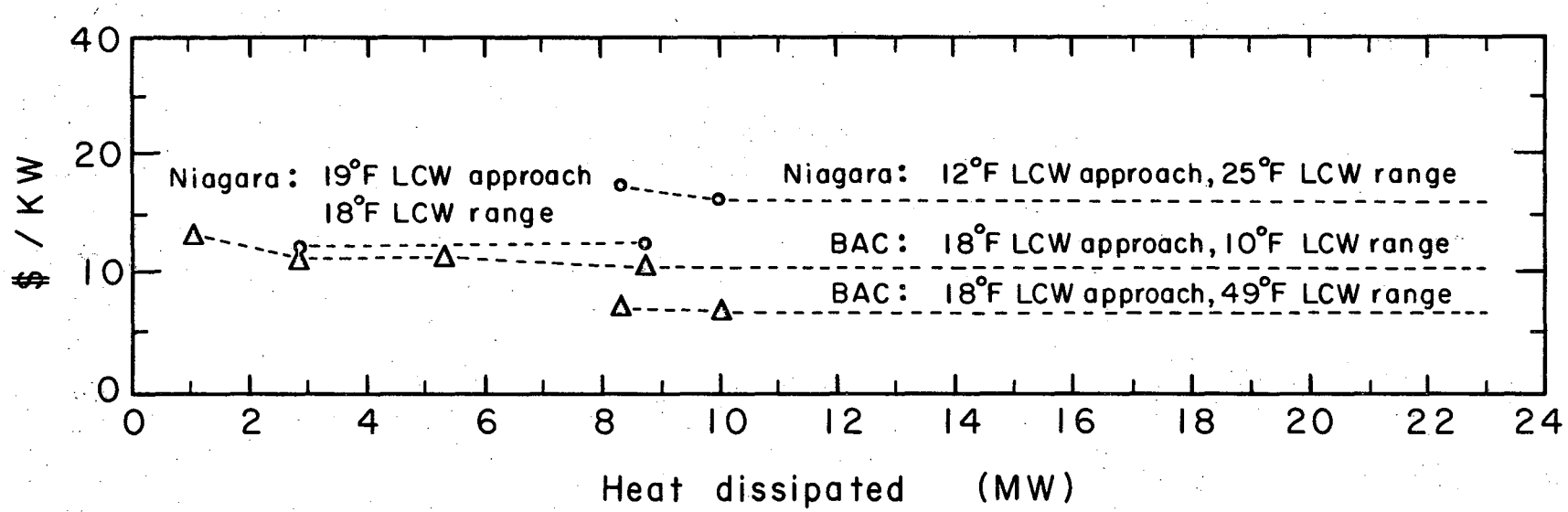
Appendix D. Increase in power cost over a 10-year period due to an increase in magnet temperature. The increase is based on a power cost of \$0.009/kWh, copper magnet conductors, and the relationship $R_2 = R_1 (234.5 + t_2)/(234.5 + t_1)$ where R_1 is the resistance in ohms at temperature t_1 (°C) and R_2 is the resistance in ohms at temperature t_2(°C).

Appendix E. Comparative Costs of Alternate Methods of Cooling

The following table lists the estimated costs of alternate methods of cooling an accelerator now under construction. In the cases of the spray pond and the cooling ponds, the ponds themselves must be constructed. The design wet-bulb temperature is 78°F, the design dry-bulb temperature is 95°F, and the temperature range is 25°F. Different atmospheric and operating conditions will slightly alter the listed cost relationships, but the table illustrates the general comparison.

Type of system	Cost ($)	% of Cooling-tower system cost
Cooling towers	1 020 000	100
Evaporative coolers	1 020 850	+100
Spray ponds	1 060 690	104
Cooling ponds	1 360 000+	133 to 190
Air-cooled heat exchangers (20°F approach to ambient dry-bulb temperature, 30°F LCW range)	8.30/kW	(comparable to cooling-tower system cost)



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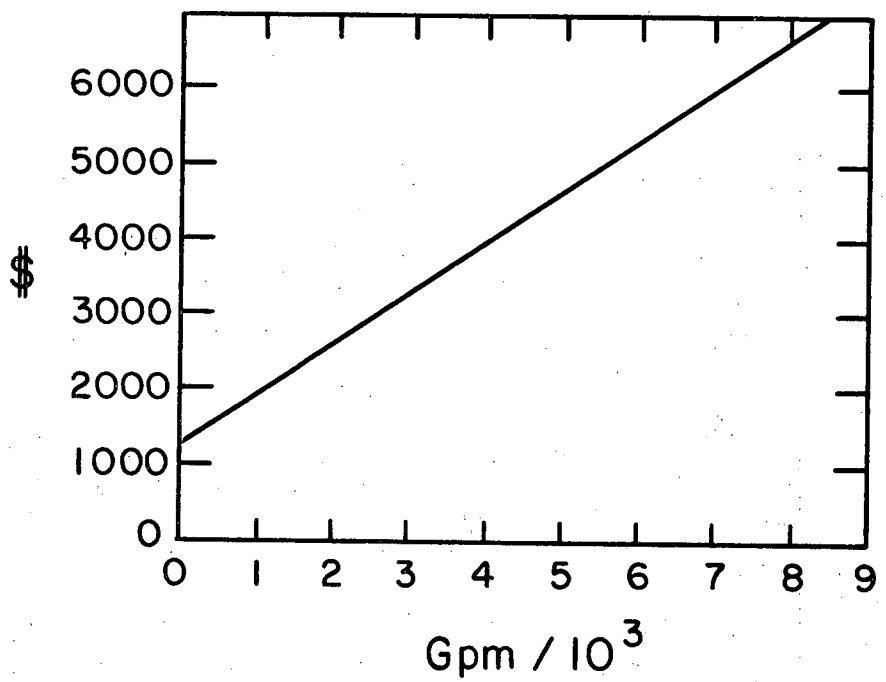
Appendix F. Cost of evaporative coolers. The design wet-bulb temperature is 78°F.



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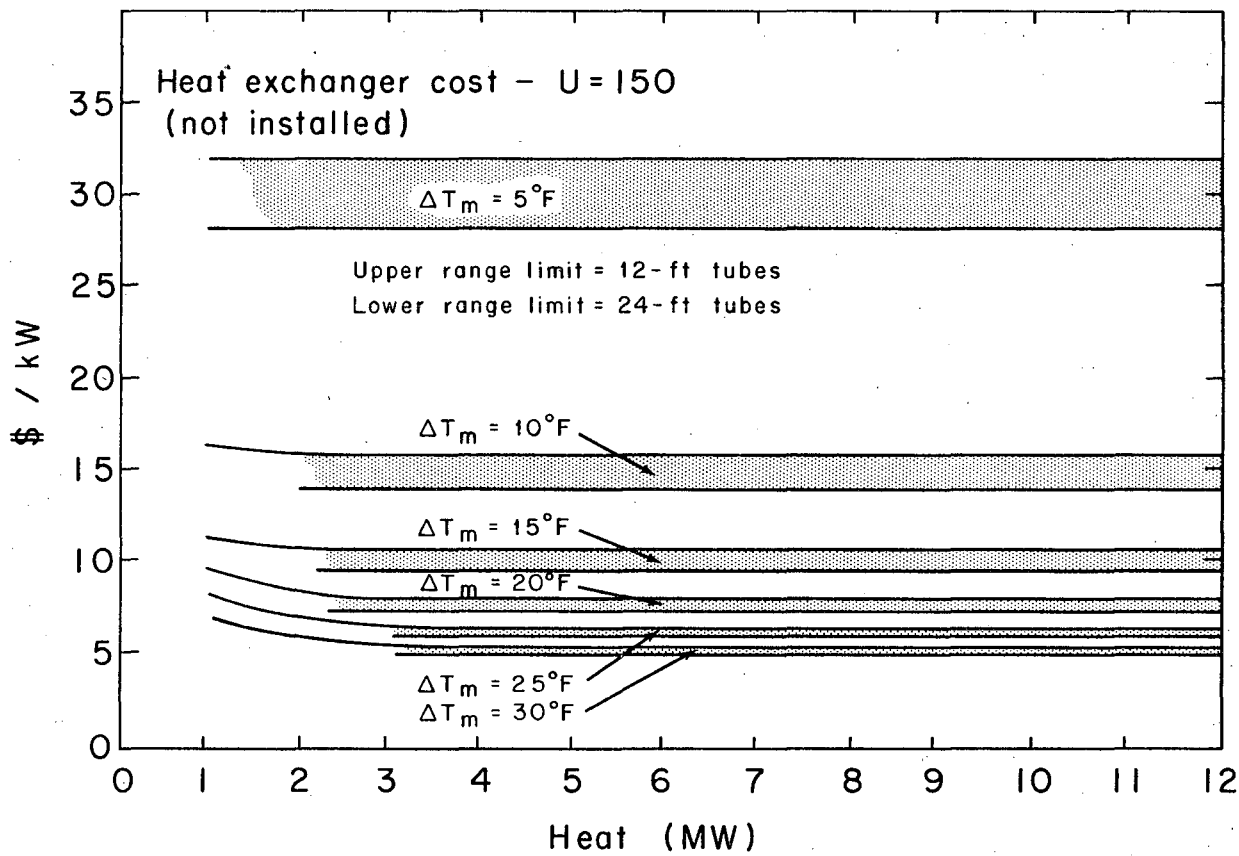
Appendix G. Cost of uninstalled 50-ft-head tower water pump.



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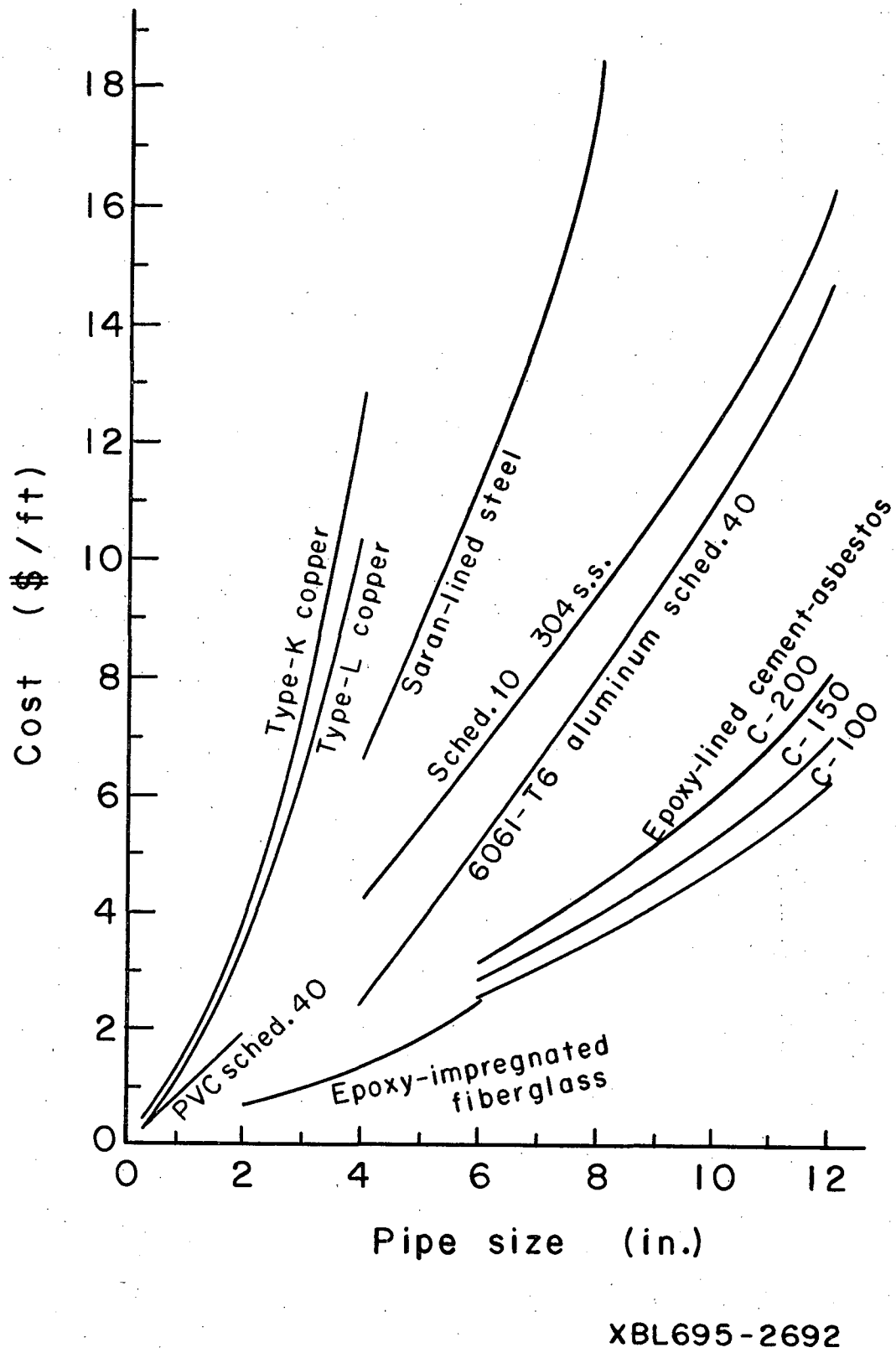
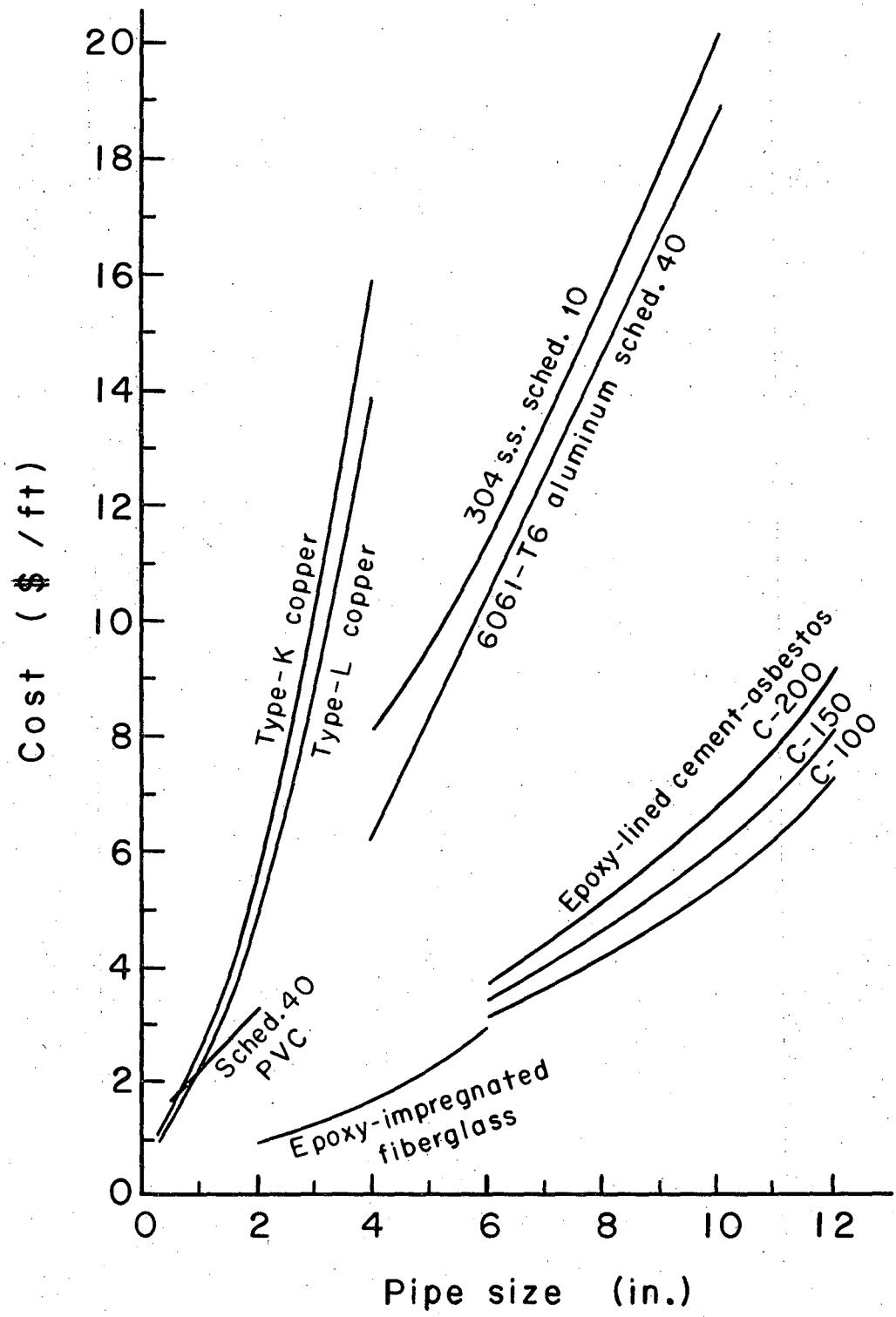
Appendix H. Uninstalled cost of heat exchanger; U = 150.



Appendix I. Cost of piping materials.



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Appendix J. Cost of installed pipe, excluding cost of excavation and hangers.

Appendix K. Comparison of Cooling Systems Costs at Various Sites

A. General Remarks

The following pages list the costs of various cooling systems. All costs are expressed in dollars per kilowatt of cooling load. Capital cost is the capital outlay. Total cost is the capital outlay plus ten years operating cost, including the effect of the cooling-water temperature on other accelerator components. Both actual costs and costs adjusted to the year 1967 are listed. The adjusted costs were derived from the historical average index listed in Means' Building Construction Cost Data 1968.* (See Table K1.)

Generally, the basic cooling system costs are quite comparable. In many cases the costs are affected by particular conditions existing at the accelerator site. For example, the concrete and site work costs for LRL cooling tower CT-3-64 are disproportionately large because of the difficult building site, the quality of the source water at the accelerator in the Midwest necessitated an expensive water-treatment plant, and the accelerator in the East is forced to use costly pilings because of site conditions.

Complete data were not always available and in the absence of such data, we have made assumptions. These assumptions are specified. Also, there are many intangible factors which are not included. These factors include such things as costs arising from accelerator down time or from labor and materials expended on unscheduled maintenance.

In the total cost figures, we have assumed that the temperatures arising from design conditions persist for the four summer months (one-third of the

*Robert S. Means, Building Construction Cost Data 1968 (Robert S. Means Co., Inc., Duxbury, Massachusetts, 1969).

Table K1. Comparison of cooling-system costs.
No chillers were used except as noted.

Cooling tower	Date	Capital cost ($/kW)	Total cost ($/kW)
Actual Costs			
LRL CT-7-37	1955	15.96	
LRL CT-5-51	1956	16.63	20.80
LRL CT-6-51	1959	20.38	24.55
LRL CT-8-37	1961	24.20	25.14
LRL CT-1-64	1961	20.00	24.17
Mid-West Lab	1961-3		
No chiller		18.05	24.16
With chiller		33.30	39.41
East Lab	1962		
Exp. mags.		8.35	12.58
Accel., no chiller		12.05	
with chiller		64.55	63.66
LRL CT-3-64*	1968	45.00	46.00
Costs Adjusted to Year 1967			
LRL CT-7-37	1955	23.50	
LRL CT-5-51	1956	23.80	27.97
LRL CT-6-51	1959	25.60	29.77
LRL CT-8-37	1961	29.10	30.04
LRL CT-1-64	1961	24.00	28.17
Mid-West Lab	1961-3		
No chiller		21.70	27.81
With chiller		40.05	46.16
East Lab	1962		
Exp. mags.		9.80	14.03
Accel., no chiller		14.55	
with chiller		75.35	74.46
LRL CT-3-64*	1968	42.50	43.50

*Unusually high site cost.

year). This is not strictly true, but the relationships between cooling systems in this regard are approximately true. It would be an exceedingly complex process to arrive at a true median summer temperature. For example, when the wet-bulb temperature lowers, the tower must have a larger approach to accomodate the same load, etc.) Figs. K1 and K2 show relationships of atmospheric conditions at several localities.

An electric power cost rate of $0.009/kWh has been assumed in all cases to maintain comparison uniformity. Because of the large variation between laboratories in the required operating parameters (e.g., system pressure and allowable temperature range), the operating costs of tower water and closed-circuit water pumps are not included. Figure K-3 gives the yearly operating costs of cooling-water circulating pumps versus the water temperature range at various system pressures. The unavailability of complete data precluded tower fan operating cost inclusion.

In general, where the capital outlay is reduced by using higher average cooling-water temperature, the operating cost is increased.

We notice some laboratories use tower water to cool some of their magnets. We have found this practice unsatisfactory for our purposes and have discontinued it. We now use low-conductivity water for all magnet cooling.

Our cooling-water temperature is sufficiently low that, as of this time, we have not found it necessary to use chillers for accelerator components.

We believe low-pressure cooling-water systems (~ 100 psi) are cheaper and less likely to cause trouble than high pressure systems.

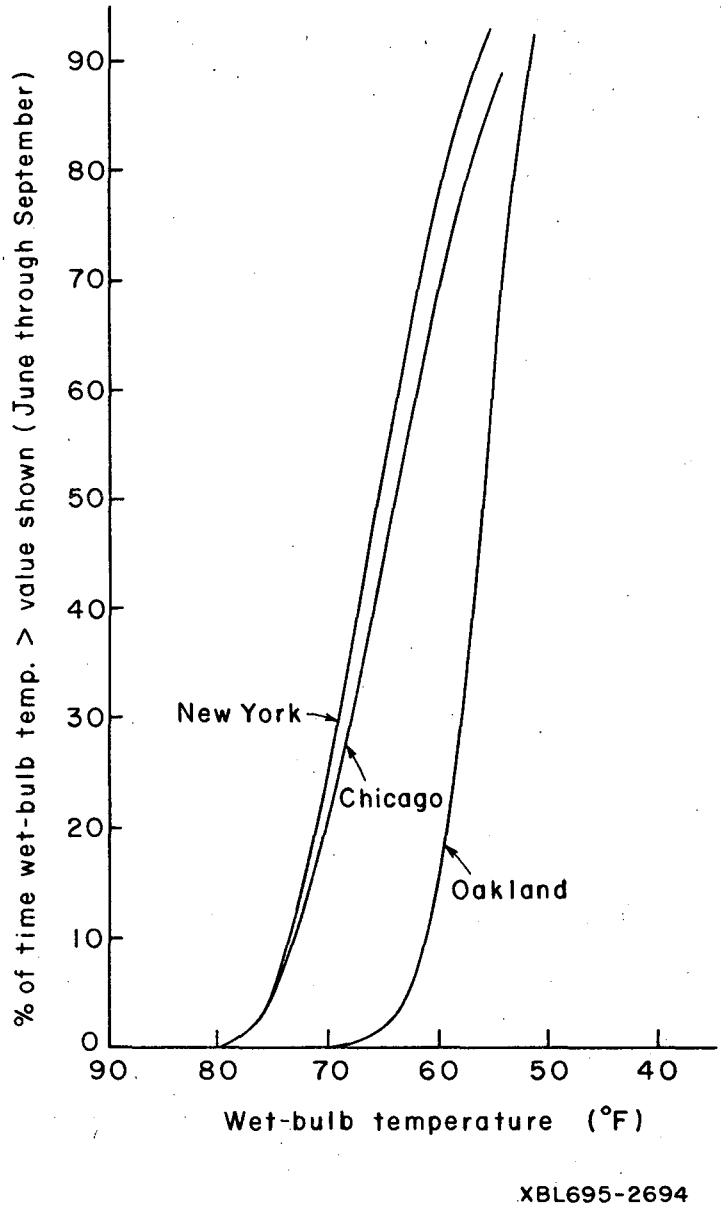

Fig. K1. Design wet-bulb temperature for New York City, Chicago, and Oakland. The wet-bulb frequencies in °F are:

City	1%	5%	15%	50%
Oakland	65.6	62.8	60.3	56.5
Chicago	77.7	74.8	71.5	64.6
New York City	77.0	74.9	72.2	65.7

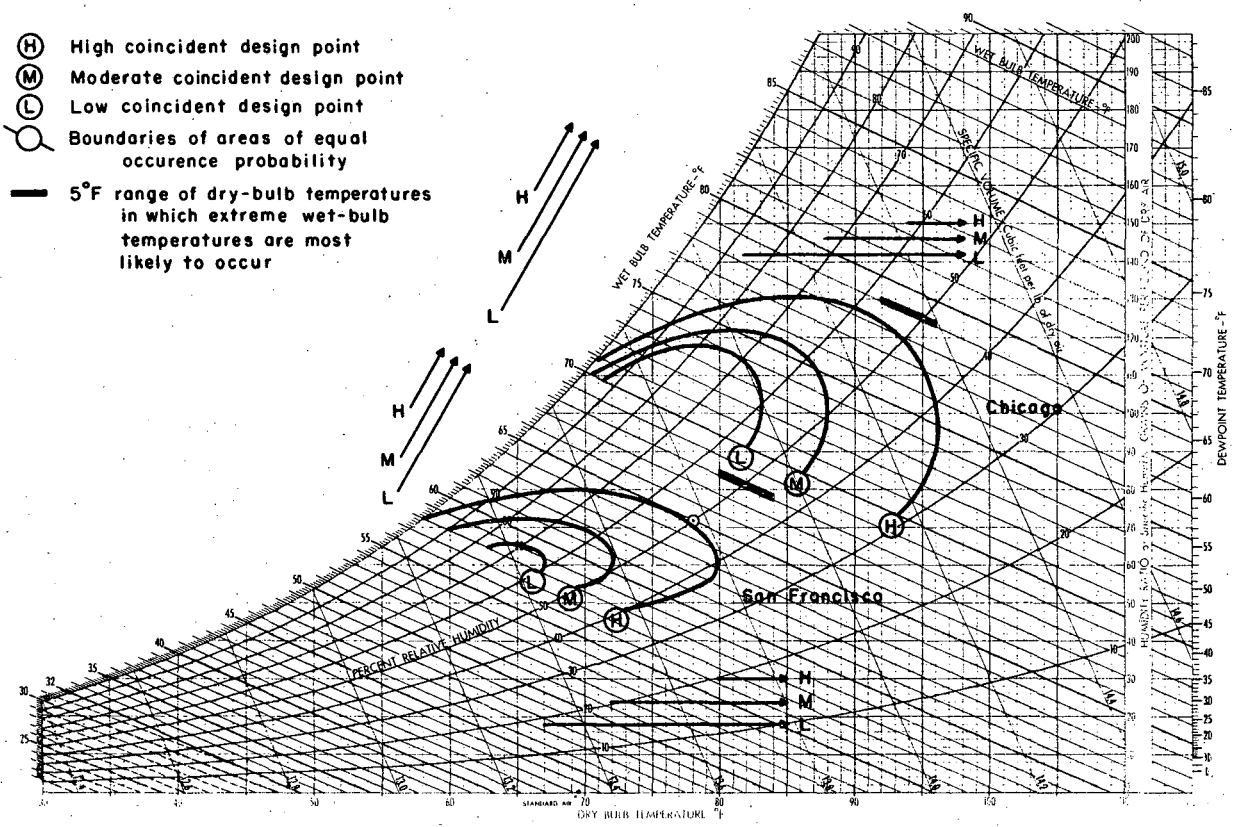

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Fig. K2. Wet-bulb and dry-bulb temperatures for high, medium, and low coincident design points at Chicago and at San Francisco.

Location	Design level	Wet-bulb temp. (°F)	Hours above wet-bulb-temp.	Dry-bulb temp. (°F)
Chicago	H	77	21	94
	M	74	131	88
	L	71	387	82
San Francisco	H	64	23	80
	M	61	123	72
	L	59	316	67

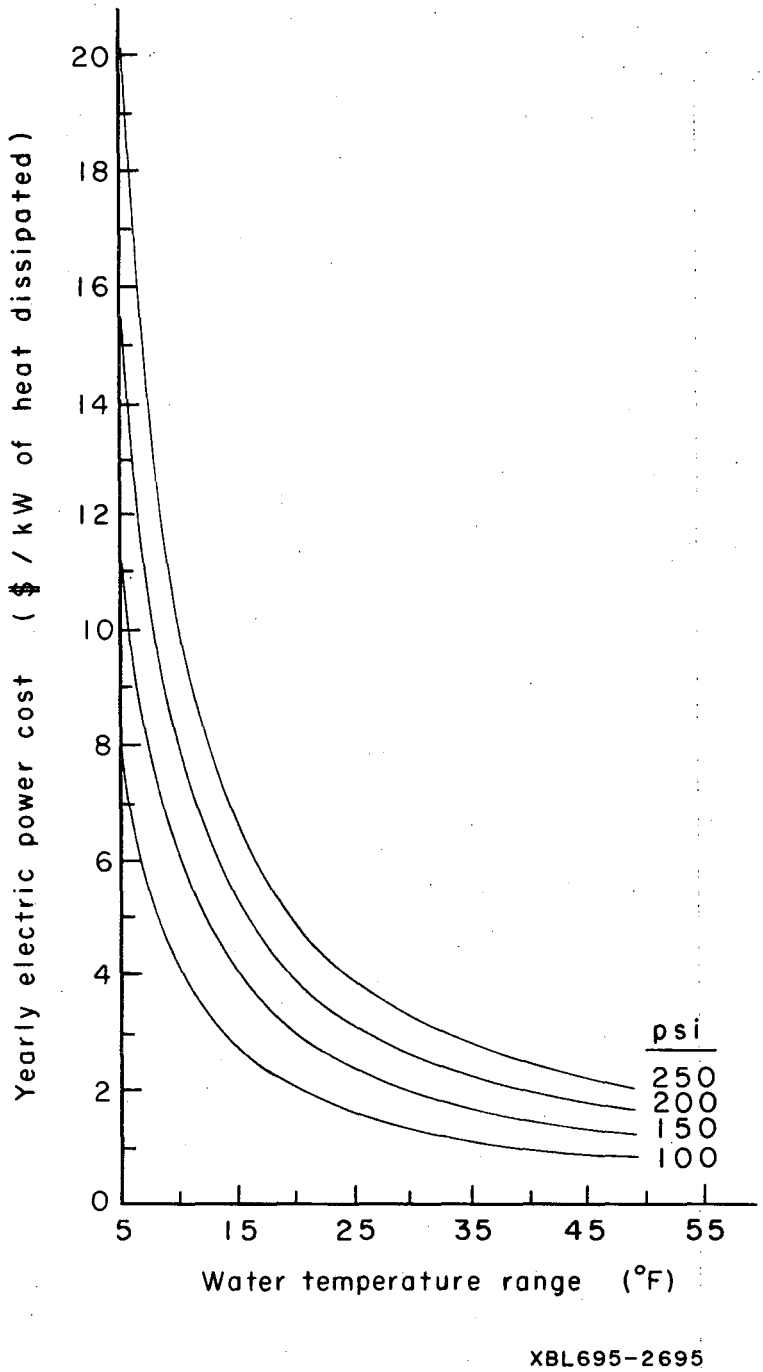

Fig. K3. Yearly operating cost of closed-circuit water-circulating pumps vs cooling-water temperature range at various system pressures. The cost is based on an electric power rate of $0.009/kWh:

$$\$/\text{kWh} = \frac{(0.1687)\,(\text{pump head in feet})}{\text{temperature range in °F}}$$

Costs of cooling towers and fans are compared in Fig. K4; heat-exchanger costs are compared in Fig. K5.

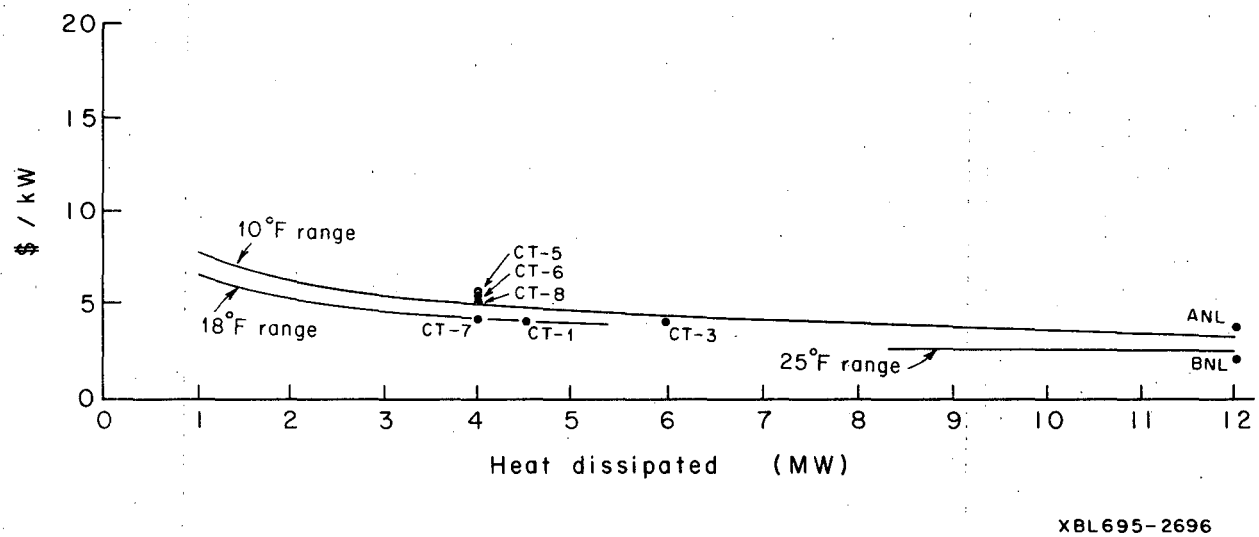

Fig. K4. Vendors' quotations vs actual costs of cooling-tower and fan installations at accelerators (corrected to 1967 costs). The curves are derived from vendors' quotations for installed cooling towers and fans, excluding foundations, and are based on a 78°F wet-bulb temperature, 7°F approach, and the ranges shown. Parameters for the various installations are:

Installation	Dissipated heat (MW)	Wet-bulb temp. (°F)	Approach (°F)	Range (°F)
CT-1	4.5	65	10	25
CT-3	6	65	10	14
CT-5	4	65	10	25
CT-6	4	65	10	25
CT-7	4	65	10	
CT-8	4	65	10	10
ANL	48	78	7	13
BNL	12	78	7	46

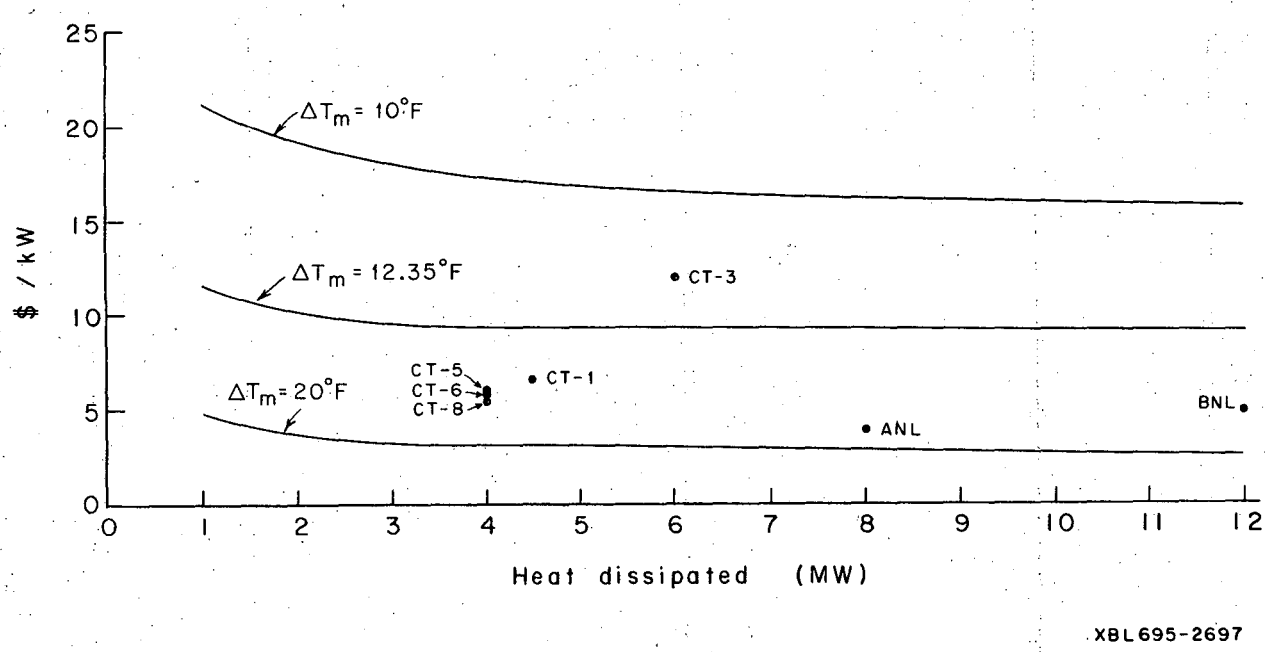

Fig. K5. Vendors' quotations vs actual costs of heat exchangers at accelerators (corrected to 1967 costs). The curves are derived from vendors' quotations for atmospheric-type heat exchangers for installation in coil-shed cooling towers (not installed). Values of ΔT_m for various cost curves are:

Installation	ΔT_m (°F)
CT-1 atmospheric coils	18
CT-3 atmospheric coils	12.22
CT-5 shell and tube	18
CT-6 atmospheric coils	18
CT-8 atmospheric coils	10
ANL shell and tube	22.1
BNL shell and tube	15

B. Comparative Costs

Cooling System	Cost ($/kW) Actual	Adj to 1967
LRL CT-7-37, built in 1955		
Cooling tower: 4 MW, 65°F WB, 10°F approach, 10°F range	3.06	4.43
Total capital cost	15.96	23.50
LRL CT-5-51, built in 1956		
Cooling tower: 4 MW, 65°F WB, 10°F approach, 25°F range	4.25	5.84
Heat exchanger: tube and shell, ΔT_m = 18°F	3.16	4.33
Pumps, LCW + TW: 100-psi LCW pressure	1.26	1.71
Piping: aluminum	4.50	6.16
Electrical	1.24	1.70
Concrete and caissons	1.65	2.26
Total capital cost	16.63	23.80
LCW average summer temperature (1/3 year) = 107.5°F. Assume magnets are used at an average of full power one/third of the time. Additional electric power cost for ten year period =	4.17	4.17
Total cost	20.80	27.97
LRL CT-6-51, built in 1959		
Cooling tower: 4 MW, 65°F WB, 10°F approach, 25°F range	4.60	5.75
Heat exchanger: coil-shed, ΔT_m = 18°F	5.64	7.05
Pumps, LCW + TW: 10-psi LCW pressure	0.75	0.94
Piping: copper	6.55	8.17
Electrical	0.97	1.21
Concrete and caissons	1.37	1.71
Total capital cost	20.38	25.60

B. Comparative Costs (Continued)

Cooling System	Cost ($/kW) Actual	Adj to 1967
Experimental magnets average summer temperature (1/3 year) = 108°F. Assume magnets are used at an average of full power one/third of the time. Additional electric power cost for ten-year period =	4.23	4.23
Total cost (experimental magnets)	12.58	14.03
Accelerator magnet cooling		
Heat exchangers, aluminum tube and shell (1958): ΔT_m = 15°F	3.70	4.75
Cooling tower (from above)	8.35	9.80
Total capital cost (no chillers)	12.05	14.55
If chillers are used in cooling the accelerator components, cost of chillers	52.50	60.80
Total capital cost (incl. chillers)	64.55	75.35
LCW average summer temperature (1/3 year) = 80°F. Assume magnets are used at an average of full power for one/third of the time. Additional electric power cost for ten-year period =	- 0.89	- 0.89
Total cost (incl. chillers)	63.66	74.46
LRL CT-3-64, built in 1968		
Cooling tower: 6 MW, 65°F WB, 10°F approach, 14°F range	4.40	4.15
Heat exchangers: coil-shed, ΔT_m = 12.22°F	12.45	11.75
Pumps and surge tank, LCW and TW	2.70	2.54
Piping, exposed: copper	8.40	7.95
Piping, buried: epoxy-lined cement-asbestos	2.75	2.60
Electrical	1.99	1.88
Concrete and site preparation	8.55	8.05
Total capital cost	45.00	42.50

B. Comparative Costs (Continued)

Cooling System	Cost ($/kW) Actual	Adj to 1967
LCW average summer temperature (1/3 year) = 94°F. Assume magnets are used at an average of full power for one/third of the time. Additional electric power cost for ten-year period =	1.00	1.00
Total cost	46.00	43.50

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