ACCELERATOR COOLING-SYSTEM DESIGN AND ECONOMICS*

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Summary

This paper is a condensation of an unfinished report on accelerator cooling systems. When published, it will be made available to interested parties. It is based on approximately twenty years experience with a number of accelerators, on materials testing and engineering analysis, and on information obtained from other laboratories.

1. The relative cost of cooling depends on geographic location and atmospheric conditions, on cooling water supply temperature and temperature range, on the cooling method used, and on the degree of cooling-system centralization.

2. The cooling water supply temperature and temperature range affect the operating costs of other accelerator components.

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

Cooling Costs

Capital Outlay for Equipment ($/kW)

1. The costs of similar pieces of cooling equipment is nearly the same throughout the United States.

2. Alternate methods of cooling such as the use of cooling ponds or spray ponds are economically and functionally less desirable than conventional cooling-tower methods.

3. Evaporative coolers are cheaper than cooling towers for small cooling loads. Cooling towers are cheaper for large loads. Evaporative coolers are designed for small loads, and multiple units must be used for large loads. There is no economic gain from load consolidation, such as exists with cooling towers.

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

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

6. Cooling equipment is cheaper when designed to operate within a larger temperature range.

7. 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.

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

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

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

11. 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.

12. For each laboratory, there is an optimum economic degree of cooling-system centralization. In each case, there is a point where the costs of such things as additional length and size of piping begin to outweigh the savings realized by the consolidation of equipment.

Temperature Effect on Magnet Operating Costs

Power Cost. 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 according to

$$R_2/R_1 = (T + t_2)/(T + t_1),$$

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, using copper coils, a 85° F cooling-tower supply temperature, and a 10° F range, we have

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$t_1 = 85 + 10/2 = 90° F = 32.22° C$ (average). For a 95° F cooling-water supply temperature and a 10° F range, we have $t_2 = 95 + 10/2 = 100° F = 37.78° C$ (average). Therefore $R_2 = R_1(234.5 + 37.78)/(234.5 + 32.22) = 1.02\ R_1$.

Let the power cost at temperature t_1 be \$ 0.009/kWh = \$ 78.84/kW-year. Thus 1 kW at temperature t_1 costs \$ 78.84/year. The power cost for the same current at temperature t_2 is (1.02) (\$ 78.84) = \$ 80.42/year. The increase in power cost at temperature t_2 is \$ 80.42 - \$ 78.84 = \$ 1.58/year or \$ 15.80 per 10 years to produce the same magnetic field.

Magnet Life. The life of electric motor insulation is doubled for each 10°C lowering of the operating temperature. We can assume magnet insulation life is similarly extended. In view of new inorganic insulation and comparatively rapid obsolescence of magnets, this life extension may not be significant.

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 will increase considerably the cost of cooling.

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

Lawrence Radiation Laboratory Cooling Costs

1. The capital outlay for cooling equipment is generally higher than at other accelerator laboratories, chiefly because the cooling water is maintained at a lower temperature. In addition, 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 over the years corresponding to the approval and funding of new installations.

2. The total cost of cooling (capital outlay plus ten years operational cost including the economic effect on other facilities) is generally less than at other laboratories, chiefly because the cooling water is maintained at a lower temperature. Savings in magnet electric power cost brought about by lower temperature far outweigh the added cost of maintaining this lower temperature.

3. The cooling-water temperature is sufficiently low so that chillers are not required to cool the magnet power supplies. This results in a significant savings.

4. Accelerator down time and the accompanying financial loss are much less, one reason being lower water temperature.

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

Evaluation of Cooling Methods

Once-Through Cooling

1. This method, consisting of circulating water from a river or other similar source through a heat exchanger and back to the river, 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 considerable debris along with various forms of life. This can lead to rapid fouling of heat-exchange 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. These have the highest capital cost of any of the cooling methods if the pond itself must be constructed.

2. A large land area is required.

3. The shallow depth of the pond and the large surface area exposed to sunlight are extremely conductive to algae growth.

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

5. A cooling pond cannot be certified by contract as to performance.

6. No fire protection is required.

7. Temperature control is poor.

Spray Ponds

1. Spray ponds are competitive economically with cooling towers.

2. The algae problem is less than that with cooling ponds.

3. Fire protection is not usually required.

4. When there are high winds, water from the sprays will be blown over a considerable 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.

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

3. They have small size and weight. They can be rendered portable if 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 supply water temperature is limited to a minimum which is about 20°F higher than the ambient dry-bulb temperature. (A closer approach is not economically feasible because of the large heat-exchange area which would be required.)

5. They may be used in combination with cooling towers in order to lower the closed-circuit water temperature to some desired minimum. This is a two-step process in which the closed-circuit water is precooled in air-cooled heat exchangers and finally cooled by cooling-tower water.

Cooling Towers

1. Performance can be certified by contract.

2. Fire protection is required for wood towers.

3. The induced-draft cooling tower is generally the preferred type. Forced-draft cooling towers cause too much recycling of the moist effluent air and are susceptible to having seeds, dust, and debris sucked into the tower fan. Atmospheric (hyperbolic) cooling towers are intended for larger loads than exist at accelerator laboratories. While their operating cost is lower, their capital cost is over twice that of induced-draft cooling towers.

Heat Exchangers

Atmospheric Coils (Coil-Shed Towers)

1. We prefer this type of heat-exchange equipment. It would be less desirable where there is freezing weather.

2. No land area is required beyond that needed for the cooling tower.

3. The heat-exchanger tubes can be examined easily and cleaned without disassembly of equipment.

4. There is some evidence that the overall heat transfer coefficient may be a little better than that of other types of heat exchangers.

U-tube Shell and Tube Heat Exchangers

1. We do not recommend this type of heat exchanger.

2. It is cheaper than other types since only one tube sheet is required.

3. It is very difficult to clean adequately.

4. There have been many reports of tube failure in the region of the tube bends.

Fixed Tube-Sheet Shell and Tube Heat Exchangers

1. The low-conductivity water should pass 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 exchanger where most of the fouling occurs.

2. Since 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 stainless steel or copper.

Floating-Heat Shell and Tube Heat Exchangers

1. The low-conductivity water should pass through the tube side of the heat exchanger to eliminate the necessity of expensive corrosion-resistant materials for the shell.

2. This type of heat exchanger permits reasonably simple disassembly and cleaning. It also allows for the expansion and contraction brought about by variations in temperature.

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

4. 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.

5. 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.

Exchange Media for Chilled Water Systems

1. Ethylene glycol-water solutions are often used in chilled-water systems. They are extremely poisonous and should not be used where the chilled water is used to cool domestic water. The nontoxic propylene glycol - water solutions should be used in these cases.

LCW Piping Materials

Iron

1. Iron, steel, galvanized 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 corrosion products plug small lines, orifices, and equipment.

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

3. We have found that steel tanks coated with polyvinyl chloride are very satisfactory for use in low-conductivity water systems.

4. Phospho-nickel nonelectrolytic plated cast iron pumps and valves have proven reasonably successful in low-conductivity water systems.

Aluminum

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

2. For strength, larger sizes of aluminum pipe must be alloyed. The alloy of choice is 6061-T6. Alloy 6063 is not as satisfactory, and alloy 3003 is much less satisfactory.

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

4. Buried aluminum pipe should be adequately coated or wrapped to prevent corrosion. Any pinholes 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

1. Where financially and structurally feasible, copper is probably the metal of choice. Copper low-conductivity water systems have operated trouble-free for many years where the conductivity of the water has been maintained well below 1μmho/cm.

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

3. The solder used should be selected carefully. Generally, brazing or 95-5 silver soldering have proven most successful. Zinc brass fittings should be avoided. Copper deteriorates rapidly in the presence of ammonia.

Stainless Steel

1. Alloys of 300 series stainless steel pipe have been used successfully in many accelerator applications.

2. Careless welding of stainless steel pipe can cause intragranular corrosion adjacent to the weld. Rapid inert-gas welding and the use of low-carbon stainless steel alloys help avoid this type of corrosion.

3. If the weld on the inside of the pipe is not smooth and continuous, crevice corrosion may occur.

4. Alloy 316 (18-8 Mo) and alloy 347 (18-8 Nb) are more corrosion-resistant than alloy 304 (18-8). They are also more expensive.

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

Glass Polyvinyl Chloride, Polyethylene, etc.

1. These substances are inert and are unaffected by other materials in the system. Most 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

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

2. This very inexpensive 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

1. This piping can be obtained with a pressure rating of 300-psi pulse pressure and 450-psi steady pressure. 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, Elastoids, etc.

1. 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 many of the elastoids will harden under radiation.

Effect of Radiation of Piping Materials

1. In general, the effect of radiation on metals resembles that of the cold rolling of the metals. Radiation affects organic material 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.

Polymetallic Systems

1. In general, it is poor practice to circulate low-conductivity water through poly-metallic systems. It is particularly poor to use a system consisting of a mixture of aluminum and copper where there is a potential difference between the metals of over 2V.

2. The problem of potential difference cannot be solved by simply adding insulators to separate the different metals. Copper ions are continuously being forced into solution in the low-conductivity water by the positive potential at one end of the magnet coils. These ions plate out when contacting a less noble metal such as aluminum. The aluminum, in turn, becomes oxidized to aluminum ions which combine with water to form troublesome, gelatinous aluminum compounds.

Demineralized Water

1. Higher purity water is obtained from mixed-bed demineralizers than from two-bed or multi-bed units.

2. Sulfuric acid is cheaper than hydrochloric acid for regenerating the cation resins. Also less storage volume is required.

3. If more than 20% of the ions in the makeup water to the demineralizer is calcium, and if sulfuric acid is the regenerant, the demineralizer should be preceded by a sodium-cycle water softener.

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

5. If about 1 to 2% of the low-conductivity water system flow is recycled through the demineralizer, the system conductivity can usually be maintained within satisfactory limits.

Equipment Costs (not installed)