DESIGNS, PARAMETERS AND PROBLEMS IN THE ASSOCIATED COOLED EQUIPMENT OF A HIGH PURITY LOW CONDUCTIVITY WATER SYSTEM RATED AT 7,500 GPM AND 25.5 MEGAWATTS*

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Summary

This paper describes this water system and some of the construction parameters of the water cooling complex; it presents recommended solutions to many of the problems encountered in operation and maintenance. Particular attention is given to: The selection of strainers and filters; maintaining a high purity low oxygen content water system in the presence of a mixture of materials; the choice of proper insulating hoses and other fittings when voltages up to 600 volts dc are impressed across the hoses. Magnet design problems, and problems associated with a conductive deposit that forms on the inside surface of hoses subject to voltage gradients are also discussed.

Introduction

The target area cooling water system at the Stanford Linear Accelerator Center (SLAC), located at Stanford University, Stanford, California, serves the beam line magnets, protection collimators, power supplies, water cooled cable and many other miscellaneous pieces of equipment. The largest single magnet requires 500 gpm for cooling.

The system has a volume of approximately 42,500 gallons and includes five circulating pumps and eight heat exchangers which are cooled in a cooling tower coil shed.

The eight heat exchangers are constructed of type 316L stainless steel headers, boxes and connections with 70-30 copper nickel tubes. They are rated at a total load of approximately 25.5 megawatts.

The piping headers are constructed of 16 inch diameter type 304L stainless steel pipe with the main branches of stainless and most of the small distribution piping of copper. The system includes a 16,900 gallon storage tank and a 6,300 surge tank, both constructed of type 304L stainless steel. A bypass water treating plant filters, de-aerates and demineralizes approximately 100 gpm on a continuous basis. The five circulating pumps are constructed of type 316 stainless steel and are each rated at 1,500 gpm at 269 psi; ceramic faced mechanical seals are incorporated.

The reader is referred to Chapter 24 of Ref. 1 for a detailed description of the physical construction of the cooling system.

This report will deal with maintenance and use of the supplied low conductivity water.

Water System Operating Experience

Water Temperature

At 25.5 MW, the temperature rise in the LCW system is 13^{o}C. The temperature of the cooling water supply is maintained at 30^{o}C by a bypass regulator. This warm water supply prevents condensation of moisture in magnet coils when the air temperature is low and the humidity is high. The consistency of the temperature allows the water to be used to cool heat sinks for temperature sensitive devices and limits the range of thermal cycling of magnet coils (which is especially important for large magnets). The flow through individual items of apparatus is unregulated.

A much larger load could be handled with the existing equipment if a larger average temperature rise could be achieved, without exceeding the maximum permissible temperatures. This could be done by installing flow regulators on individual large magnets, to make cooling water flow proportional to load. It might be necessary to restrict the rate of increase of power to these loads to allow time for the flow regulator to respond, but this would not be a severe operating limitation.

Water Quality

The mixed bed (cation and anion) resin for the demineralizers which hold 30 cubic feet each is regenerated approximately every six months. There are two units in parallel so that the system is under continuous protection, even while one unit is being changed.

The water is maintained at an electrical resistance of approximately 5 megohm-cm (it can be as low as 100,000 ohm-cm) with a pH of 6.0 to 6.5. The water treating section has a vacuum type de-aerator for oxygen removal and the surge tank and storage tank are blanketed with nitrogen to keep the oxygen content down, as oxides appear to be one of the contaminants best kept to a minimum; the dissolved oxygen content normally runs about 0.07 ppm.

Before any new equipment or piping is added to the system it is thoroughly flushed with phosphoric acid, then flushed with high purity water until a resistance of 1 to 2 megohm-cm is obtained. All air accumulations are removed before the returned water is connected into the system. Once a clean system is obtained, maintenance is not difficult.

The selection of the proper strainers and filters in the cooling water system is a compromise to avoid plugging of small passages but still not requiring a large maintenance cost. The by-pass water treating system contains two parallel 5 micron filters for continuous cleanup of minute particles. Each individual piece of equipment is protected by 100 mesh stainless steel wire cloth screens in Y type strainers. The screens are backed up with large perforation heavy gauge screens to help hold their shape and to enable them to withstand large differential pressures. The 100 mesh screens which collect small particulate matter begin to be coated with copper and copper oxides and are cleaned on a 6 month schedule to prevent a restricted flow to the equipment.

Every reasonable effort has been made to keep threaded joints to a minimum in the piping distribution system as most pipe thread compounds seem to have shortcomings. Many compounds contain materials which would contaminate the high purity water and collect or plate out on the heat transfer surface. Numerous kinds of material have been tried and none have been fully satisfactory. Teflon tape has worked well, but in spite of careful instructions in its use, particles do get into the system and plug small openings. Liquid teflon has not been fully satisfactory either and neither is being used at the present time. Currently we use Loctite pipe compound.

Magnet Cooling

Over the past 20 years water cooling of magnets has become almost universal. This has posed some unique problems in magnet design and maintenance. The designer must arrange a large number of turns of hollow conductor of the proper cross section connected electrically to provide the requisite number of ampere turns, the proper terminal voltage and current characteristics. All turns must be well insulated from each other and the magnet steel structure, and be restrained to resist magnetic forces. Sufficient water flow must be

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supplied through each turn to limit temperature rise to something below that which will cause mechanical or electrical weakening of the insulation. On large magnets the hydraulic circuit may have as many as 70 parallel paths electrically isolated by hoses at both supply and return ends with an average voltage across each hose of 250 volts. It is obvious that with so many potential leakage paths the control of ground current places restrictions on hose resistance, maximum diameter, minimum length and cooling water resistivity. The general rule is to procure hoses with the highest possible resistance in ohms per foot, then make the hoses as small in diameter and as long as possible, commensurate with pressure drop, burst pressure, and room available.

In general, the higher the exit water temperature from a water-cooled magnet the lower will be the costs of the magnet, the water cooling system, and the operating expenses. Higher temperatures will increase the magnet power cost and shorten the life of the magnet insulation and water hoses. 70°C is a practical upper limit for exit water temperature because above this figure epoxy resins generally used to insulate the coils and resist the magnetic forces begin to lose mechanical strength. With exit water temperatures much below 40°C the cost of the cooling water system increases in terms of $/KW dissipated due to poor heat exchanger efficiency and poor cooling tower utilization. This rather restricted range of exit water temperature plus the fact that supply pressure of the cooling water is usually limited to around 250 psi leaves very little leeway in the choice of flow velocity through the hollow conductors. The flow velocity usually works out to be about 10 to 17 ft. per second, which in most cases means that the flow is well up in the turbulent range, and yet far below the point where hydraulic erosion becomes a problem. Normal current densities may be 200 amps per sq. cm and heat flux may be 4 watts per sq. cm across the water film.

Magnet Cooling Hoses

The choice of hose length, wall thickness and material are determined by the voltage, maximum water pressure and temperature, and cost. Buna-N rubber hose with nylon reinforcing braid has been used for several years and has been satisfactory except for a buildup of material on the inside which increases the leakage current, and a tendency to harden in service. The former problem is discussed below. Buna-N hoses vary in resistance and in dimensions. The resistance has been known to vary as much as a factor of 10 and a factor of 2 is common. Low resistivity is probably the result of the addition of carbon black to improve mechanical properties. The carbon black may be a factor in the buildup of the conductive deposit and in the hardening process. Differences in diameter can be as much as 0.015 in. It is our recommended practice to install end fittings on a piece of each new batch of hose received and test it for electrical resistivity and burst pressure. The hoses should be long enough to be changed easily, usually at least 10 inches, which is sufficient for 600 volts.

Our experience with plastic hose has been poor. All plastic hose, even the reinforced variety will creep under load, especially at elevated exit water temperatures; leaky connections, blow-offs or ruptured hoses are the inevitable result.

We have avoided the use of chloride-containing hose materials such as PVC because of the danger of chloride corrosion of the stainless steel.

Magnet Hose Fittings

Magnet hose fittings have long been a subject of discussion. They must be designed to hold drip-tight for years since water sprayed on electrical equipment can cause serious damage. For system pressures below 125 psi, standard hose barbs, with the hose held in place by hose clamps are satisfactory, but for higher pressures reusable swivel hose end of the JIC type are required. Hose fittings must be of corrosion resistant material since they become the anode and the cathode of an electrolytic cell driven by the voltage across the hose. Experience has shown that 18-8 stainless steel (type 300) will outlast copper, brass, mild steel or aluminum by at least a factor of 10. Even stainless steel will corrode away, causing the fitting to fail under pressure, if the electrolytic currents are large enough. The remedy in such cases is either make the hoses longer or improve the water purity or both. Sacrificial electrodes should be avoided because their use tends to degrade the water quality and metallic gums and soaps form at the electrode, which will eventually plug the water passages.

The use of dissimilar metals in contact in magnet water systems should be approached with caution. For example, when stainless steel is brazed or silver soldered to other materials in the water system, care must be taken to insure 100% wetting of both materials by the soldering alloy, otherwise a crevice is exposed to the water, and crevice corrosion will destroy the joint in a matter of weeks or months. On the other hand, when stainless steel fittings are threaded into aluminum conductors, one would expect galvanic corrosion to destroy the joint but such is not the case. Literally hundreds of such joints have been in service at SLAC for 3 to 4 years without a failure or evidence of galvanic corrosion in the joints. Aluminum pipes have been known to corrode very badly when included in a copper system, but aluminum conductor magnet coil water passages have shown no such corrosion in 4 years of service at SLAC, probably because of the good dielectric isolation of the aluminum from the copper water piping provided by the hose connections between each water circuit in the coil and the grounded water manifolds. Local corrosion cells on the surface of the aluminum caused by the deposition of metal compounds such as copper-oxides have not been a problem.

Some of the magnets on the SLAC water system have high zinc (15%) brass fittings. We have experienced no problems with these fittings, perhaps because of the high quality of the water.

Problems Due to Conductive Deposit on the Inside of Hoses

While the low conductivity water (LCW) is of exceptionally high purity, this does not mean that the remaining impurities can be ignored. The LCW contains a particulate suspension of some form of copper or copper oxide. The total copper content has been measured to be 0.06 ppm out of the pumps after the demineralizer, but it can be as high as 0.1 ppm elsewhere in the system.

These particles will pass through a one-half micron filter. The oxides are evidently the result of oxidation of the walls of the copper pipes by the remaining dissolved oxygen in the water; the origin of the copper particles is unknown. Even the most rigorous control of the deoxygenation equipment does not seem to prevent the formation of the oxides. Particulates of this nature can be removed from high dielectric strength liquids such as LCW or various petroleum liquids by electrostatic precipitation techniques,[2] but these systems are expensive and we believe it is better to learn to live with the particulates in the water.

These particles cause difficulties because they tend to deposit on the inside of magnet cooling water hoses, increasing current leakage.

The dc circuits of magnet power supply systems used at SLAC are grounded with a resistor of about 100 ohms. This "soft grounding" is used to prevent large short circuit currents from flowing due to accidental grounding of one of the magnet conductors or leads. The current through the grounding resistor is monitored as an indication of leakage current to ground. A typical magnet connected with 64-1/2 inch cooling hoses, each about 18 inches long, will measure about 56,000 ohms leakage due to the conductivity of the water. The leakage through hoses having a vinyl jacket and teflon or nylon inner core will be negligible compared to the water leakage while rubber hoses with Buna-N inner cores may have a current leakage ten times that of the parallel water path.

The leakage current for the typical magnet may be about 5×10^{-3} amps, when only the LCW water is causing the leakage. This would be negligible compared with an operating current of 3,000 amps. We have found that deposits in the hoses can increase this leakage current to about 0.3 amps, which is then on the borderline of the permitted calibration errors between current and magnetic fields.

In tests on nylon, teflon and Buna-N and experience with ceramic insulating sections, we have discovered the following:

1. Only Buna-N hose (our preferred hose material) shows an appreciable buildup.
2. Our usual acid cleaning does not remove the coating.
3. The coating occurs only when voltage is impressed across the hose.
4. The coating grows more rapidly at voltages above 200 volts than at lower voltage.
5. The voltage gradient in the hose does not seem as important as the total voltage across the hose in promoting deposition.
6. Buna-N hose is different from the other materials in that it contains carbon black which is exposed on the inner surface. This surface is rather rough compared with the other hoses.

Our method of handling the problem at present is to change hoses when the leakage current becomes excessive. This can cost over a thousand dollars for a large magnet. We are continuing our study in an attempt to find a satisfactory way to reduce the rate of buildup or to remove the deposit once formed.

A special problem arises in some low-flow circuits such as for cooling of high current transformer windings in power supplies with passages of 1/8 inch or less. There have been instances where the cooling passages were plugged by deposits that may have been sloughed off hoses or resulted from "scaling"* due to high heat flux densities and incomplete O_2 removal in the water system. We have not experienced any trouble with scaling, probably due to the low concentration of O_2 in the water and the low heat flux in our apparatus.

References

1. The Stanford Two-Mile Accelerator, ed. R. B. Neal, (W. A. Benjamin, Inc., New York, 1968).

2. Herbert J. Hall, "Apparatus for Removing Contaminants from High-Resistivity Fluids," United States Patent Office, No. 3,368,963, February 13, 1968.

3. L. C. Bratt, C. F. Clark, E. P. Farley, "Investigation of the causes of scaling on klystron collectors," Stanford Research Institute, Project No. SRI-3425F, March 1961.

*Stanford Research Institute[3] reports a problem due to deposition of oxides on the water-cooled anodes of klystrons. The deposition occurs in water which contains dissolved O_2 and CO_2 on hot surfaces having a high heat flux (300 watts per square cm or more in the case of klystrons). The deposition is known as "scaling."