Cooling Water Systems for Accelerator Components at the Advanced Photon Source

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Abstract

As in most accelerators at the Advanced Photon Source, water is the media of choice for absorbing heat generated by a multitude of accelerator components. A large cooling water distribution system with flow rate of nearly 10,000 gpm in the primary circuit and small closed-loop water systems with flow rates of less than 100 gpm are installed at the APS. The central plant houses primary water distribution pumps, heat rejection equipment, and polishing and make-up systems. All water used for heat rejection by accelerator equipment is deionized and filtered to provide minimum resistivity of 3 MΩ-cm and maximum particle size of 0.5 microns. Water temperature and pressure are being controlled at 35 secondary systems before water is delivered to the accelerator components. Temperature of various water systems is controlled to as tight as + 0.1 deg F. With most accelerator components interlocked on water flow and temperature, it is imperative that both are maintained with a high degree of reliability. It is also necessary for water systems to be designed with sufficient flexibility to allow for easy modifications, additions, and expansions. From the time original water systems were installed a number of system upgrades to improve reliability and to integrate new operating parameters were completed. Additional improvements are being planned. Lessons learned will be discussed.

Keywords: deionized, cooling, process water

1. Introduction

The various systems and components that comprise the Advanced Photon Source at Argonne National Laboratory generate a substantial amount of heat that must be removed while at the same time insuring that temperature stability of the equipment is maintained within the specified tolerances. While a portion of this heat is radiated and convected into the surrounding spaces, the majority of the heat is removed via a large and complex water-cooling system. Numerous magnets, power supplies, front ends, and vacuum chambers comprise the bulk of the components requiring cooling in the storage ring. Similarly magnets, accelerating structures, power supplies, and other devices are used in the linac and booster synchrotron. In all, these components require the removal of 8.8 megawatts (30×10^6 Btu/hr) of heat during peak operation of the APS.

Due to the critical nature of equipment alignment for the maintenance of a precise orbital particle path, the absolute temperature of most components must be maintained within a very specific temperature tolerance to minimize the effects of the thermal expansion and contraction of components. In order to obtain this temperature stability and at the same time maintain a specified temperature, equipment cooling must be provided in measured amounts to precisely balance system heat generation rates. The cooling of the APS technical components comes from a 10,000-gpm deionized (DI) water-cooling system that has a centralized heat rejection system and provides temperature control via a distributed pumping system.

2. System Configuration

The APS DI water system distributes cooling water from a central plant where all heat is rejected and the water is cooled to a baseline temperature that is maintained within a stable range of ±0.5 °F. This water is pumped out to the APS site at a relatively low pressure (approximately 30 psig) to local pumping stations where the pressure is boosted and the temperature controlled to its final temperature with a tolerance of ±0.2 °F. This basic configuration is commonly called an integral primary/secondary system (Figure 1).

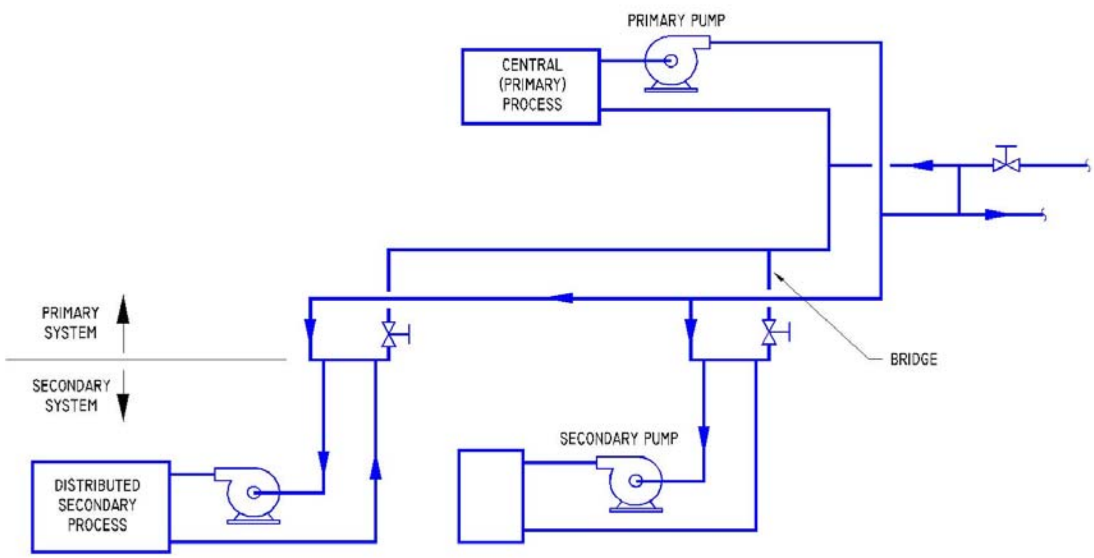

Figure 1: Integral primary secondary system.

In such systems water is distributed in a primary loop at relatively low pressure throughout a network that consists of secondary pipe loops connected in a manner to decouple the secondary loop pressure distribution from the primary loop. Within the secondary loops the system operates at higher pressures with the pressure distribution unique to each individual loop. Another feature of this arrangement is that waste heat from the devices connected to the secondary piping can be used to adjust and control the water temperature in the secondary loop (Figure 2).

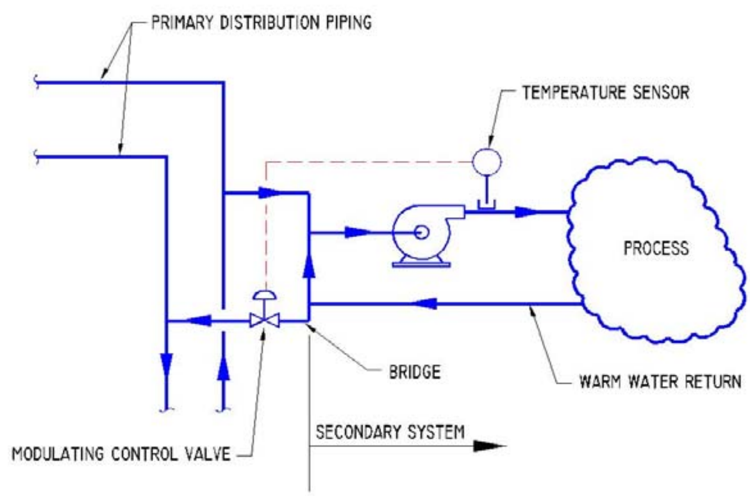

Figure 2: Temperature control via secondary mixing.

The basic components of this circuit consist of a pair of primary water main distribution pipes that form a central pipe loop that supplies and returns water from the secondary piping circuits. The interface between the two loops is commonly referred to as a bridge and consists of a pipe element that directly connects the supply and return primary mains forming a short circuit. Inserted into this short circuit is a resistor (control valve), which can be fixed or modulating, that controls the flow across the bridge. The secondary loop consists of two closely placed connections (inlet and outlet) in the bridge designed such that there is insufficient pressure drop between the bridge connections to induce water flow into the secondary loop. A pump is placed in the secondary loop such that when operated it induces flow into and out of the bridge in proportion to either the fixed or modulating resistor (control valve) placed in the bridge [1]. This induced water is mixed with the return water from the secondary loop and supplied to the secondary (induction) pump. With a signal from a temperature sensor located in the secondary supply line, a modulating control valve in the bridge will adjust the amount of recirculation and control the supply water temperature. In essence the APS primary and secondary loops operate as codependent but semiautonomous systems with each system configured as described below.

The primary water distribution system provides both the final heat removal process in the system and the main conditioning (polishing) of the water to maintain quality (water quality and the deionization process is not a topic of discussion in this paper). The configuration and operation of this system underwent a modification after construction to respond to changes in the design parameters of the storage ring. In the initial design and construction, the APS DI water system was to reject all of its heat by an evaporative cooling process, thereby maintaining a supply water temperature of 90 ±1 °F. This water temperature was set by the lowest limit that can be economically achieved via evaporation in this geographic area during the hottest and most humid summer conditions [2].

The original configuration of the DI water primary system is shown in Figure 3 and consists of four plate-type heat exchangers arranged in parallel with one heat exchanger operating in a stand-by mode. Water from the APS counter-flow-type cooling towers is pumped through a main tower water distribution system that supplies both centrifugal chillers (chilled water system) and the DI water heat exchangers. In order to achieve accurate temperature control and maintain flow in the heat exchangers in the turbulent flow range, tower water secondary pumps were installed and provide a constant flow of tower water with a variable inlet temperature that changes to maintain a DI supply water temperature set point. These pumps are connected to the tower water system across their own secondary bridges, and tower water temperature to each heat exchanger is modulated via a three-way mixing valve to maintain the primary DI water temperature. The use of evaporative cooling results in a very energy efficient method for heat rejection and drove the effort to operate the APS with warm water. When it became evident that colder water was required, it was deemed essential that the reconfigured system should not completely abandon the use of evaporative cooling in the heat rejection process.

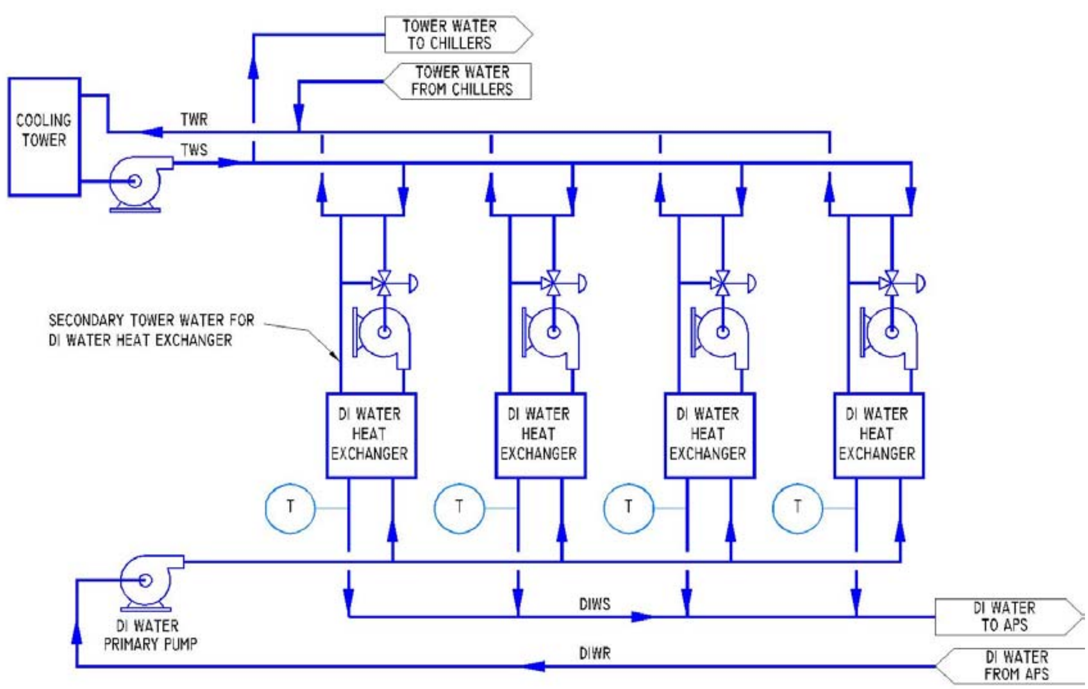

Figure 3: Original DI water primary system.

Due to the fact that the conventional facilities design and construction preceded that of the APS accelerator by one phase, the plant construction was completed in advance of the final design of the accelerator. Near the end of the accelerator design process it became apparent that alignment issues and operating constraints would require a colder DI water temperature more in line with the storage ring space temperature set point of 75 °F. Given the inherent flexibility of the primary secondary configuration, it was possible to easily reconfigure the water plant to accommodate this revision; this provides an excellent example of the versatility available in this type of system approach.

A proposal to convert the system into a two-stage cooling process was examined and found to provide an expedient method to reduce the system operating temperature while maintaining some of the energy efficiency afforded by the evaporative cooling process. The reconfiguration of the initial design is illustrated in Figure 4; the standby heat exchanger was disconnected from the tower water cooling system and a portion of the supply water from the first three heat exchangers was redirected to flow into the fourth heat exchanger where it was cooled by chilled water. DI water leaving heat exchanger number 4 was then mixed back into the main supply line conveying water from heat exchangers 1, 2, and 3, resulting in a mixed water temperature equal to the desired 75 °F supply water temperature. As only a portion of the total supply water was routed through the fourth heat exchanger, the temperature of its discharge DI water had to be subcooled below the 75 °F set point in order to achieve the desired final supply water temperature. As ambient conditions allow for colder tower water, the portion of heat dissipated by evaporation increases until all heat is removed by the tower water system. A fifth chilled-water-to-DI-water heat exchanger was added two years later to provide standby capacity.

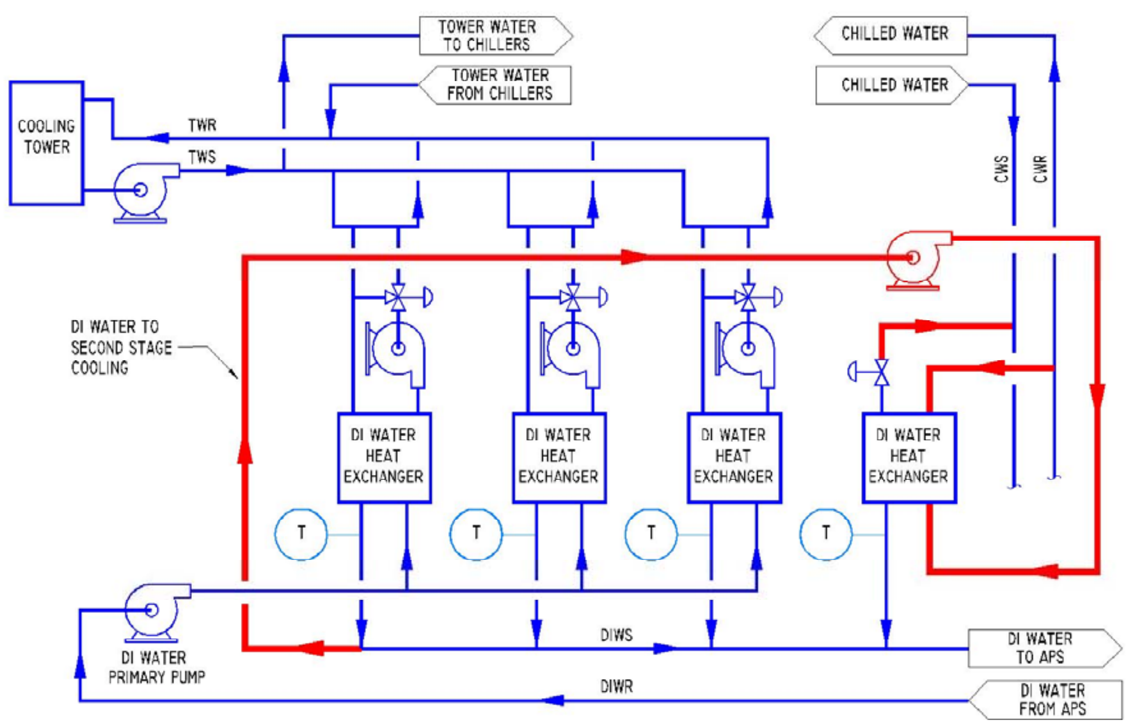

Figure 4: Reconfigured DI water primary system.

3. DI Water Secondary Systems

The arrangement of the secondary pump systems is fairly straightforward; each secondary pump loop consists of two pumps: one operational and one standby. A secondary bridge is connected across the DI water primary mains, and water is regulated into the secondary bridge using a three-way mixing valve. This valve responds to an output from a programmable controller and modulates to maintain a given supply water temperature set point. The status of each secondary loop pump is monitored, and in the event that the operating pump fails, the standby pump is programmed to automatically start (see Figure 5).

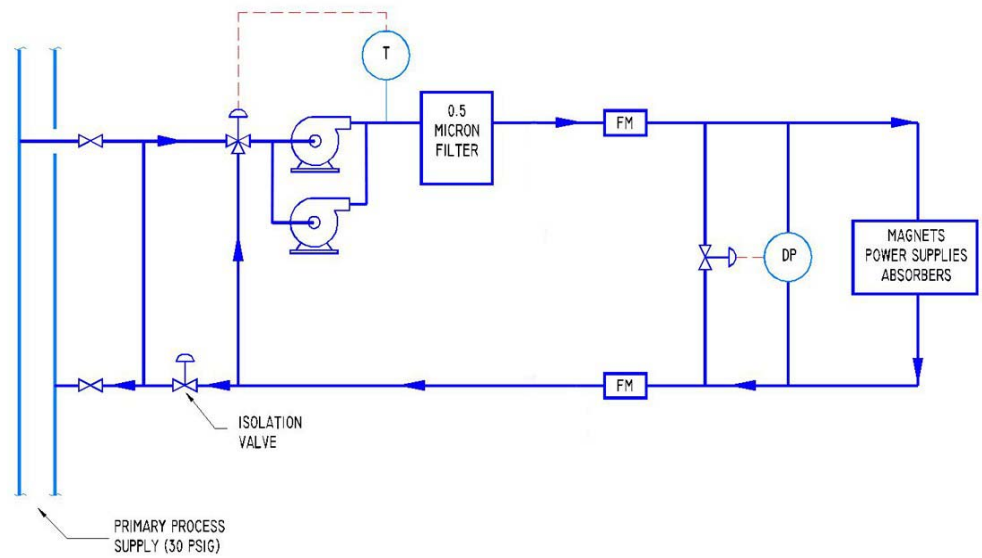

Figure 5: DI water secondary loop.

However, it was found that when manually initiating the automatic switchover to the standby pump operation, the sequence did not occur quickly enough to prevent the loss of stored beam in the storage ring. It was further discovered that the possibility of one pump having a complete failure without showing signs in advance did not occur and the need to have an automated switchover was deemed to be unnecessary. A more likely scenario was that the operational pump would begin to show signs of failure and the operator would be required to manually initiate a pump switch over without any significant change in flow rate. With the facility operating 24 hours per day, any loss of experimental time must be kept to an absolute minimum. As the APS has evolved, the time allocated for equipment maintenance has become increasingly shorter, which required the modification of the pump control system to allow placing a given pump out of service for maintenance or repair without shutting down any individual loop.

The control algorithms were changed and flow sensor trip points adjusted such that the second pump could be started in parallel with the operating pump, and then the operating pump was shut down for service. The adjustment of trip points and the operating pressure without overpumping the system was made possible due to the fact that multiple parallel pump combined flow rates are not directly proportional to the number of pumps operating. When two pumps are placed in parallel and run simultaneously, the total flow rate does not double but is, in fact, substantially less and is a function of the superimposition of the pump curves over the system operating curves.

Another system feature that enhanced flow and pressure stability is due to differential pressure bypass valves installed downstream of the secondary pumps. They have proven to be very useful in maintaining system pressure during start-up and the commissioning process when parts of the system were isolated. It continues to be very useful serving first as high-pressure relief (a hardwired high-pressure switch is also installed in the supply of each secondary system) and in maintaining design pressure during machine maintenance periods when, again, parts of the system could be isolated to flow.

Flow meters mounted on both the supply and return lines monitor system flow rate and differential between the lines. If the differential exceeds a preset level, a leak alarm is initiated, and the secondary system can go into shutdown and is automatically isolated to prevent failure of the primary and other secondary systems. All flow in the secondary systems passes through 0.5-micron filters that were originally designed to be 20 micron. Even though present filters are much finer than originally planned they only have to be replaced once a year.

The flexibility of the primary/secondary system has allowed for easy adjustments of the secondary system operating set points and parameters with regard to both temperature and pressure distribution [3]. This has proven to be very beneficial, as the number of systems has increased and the operating conditions of the accelerator have changed over time.

4. Temperature Control

The most effective method to achieve temperature stability is to provide relatively large flow rates of cooling medium with inlet temperatures close to the desired operating temperature. While in theory this appears to be a rather simple process given the steady-state nature of component heat generation, the extreme temperature tolerance required (±0.2 °F) and the potential for variation of the water temperature due to perturbation of the mechanical cooling equipment achieving the desired temperature stability requires considerable effort. The main challenge is the configuration of a system and the creation of a control system that can operate in an inherently stable manner. Given that the APS cooling system is centralized and must distribute cooling water over a fairly large area, control of water temperature is distributed and localized in discrete portions of the APS system yielding more than 35 water circuits each with independent control over both its design operating point and its level of control tolerance. Through the use of waste heat via recirculation, each secondary loop is capable of establishing a set point independent of the other loops (equal to or greater than the primary loop water temperature). This inherent flexibility allows the central system to provide cooling water for different components tailored to the specific equipment specification requirements. Currently different secondary systems supply water at temperatures varying from as low as 75 °F to as high as 90 °F while maintaining the same temperature stability range of ±0.2 °F.

The ability to provide precise temperature control is enhanced by maintaining the primary water temperature as constant as possible. This minimized the need for the secondary control loop to respond to changes in the supply water temperature. Through the use of precision control valves and a tightly constrained proportional, integral, derivative control loop, the secondary loops can achieve the required temperature control. Further control enhancement was achieved by replacing the original thermo-wells-mounted sensors with fast-response direct-immersion RTD-type temperature sensors with matching transmitters. The new transmitters were calibrated to a narrower temperature range in order for controllers to be able to read temperatures to finer resolutions. Finally, higher-bit controllers capable of reading temperature changes on the order of less that 0.01 °F were installed [4]. All of the above, along with a properly tuned PID loop, allowed the primary system to be controlled to within ±0.5 °F and the secondary systems to within ±0.2 °F.

As beam stability requirements increase, we foresee the need for even better temperature control for water systems in the future.

5. Summary of APS DI Water System Operating Parameters

Primary system

Flow rate: 10000 gpm
Supply pressure: 30 psig
Supply temperature: 73°F
Temperature stability: ±0.5 °F

Secondary systems (35)

Flow rate (varies): 50-500 gpm
Supply pressure: 150 psig
Supply temperature: varies
Temperature stability: ±0.2 °F

Vacuum chamber cooling skids (20)

Flow rate: 50 gpm
Supply pressure: 50 psig
Supply temperature: 78 °F
Temperature stability: ±0.1 °F

Linac skids (4)

Flow rate: 80 gpm
Supply pressure: 90 psig
Supply temperature: varies
Temperature stability: ±0.1 °F

Make-up, polishing and deaeration

5000 gallon storage tank
Make-up water production capacity 2500 gal/day
Dissolved oxygen (DO) content <10 ppb
Resistivity of primary water maintained >4-5 MΩ-cm
UV treatment
Ultrafiltration

6. Conclusion

The design of the DI water system at the APS has proven itself to be highly robust and capable of a great deal of flexibility. The ability to adjust to changes in operating parameters, including ever increasing demands on the precision of the temperature stability of the system, has allowed advances in the scientific agenda without incurring excessive cost or time delays in implementing these changes.

As reliability is critical in meeting the objective of a minimum beam availability greater than 95%, the DI water system must perform with a reliability that yields at least 99.5% availability. Key to this availability has been the provision of system component redundancy and the ability to bring standby equipment online without disrupting the performance of the accelerator. Meeting this goal has been a prime objective achieved by the system.

In addition, to providing a reliable and precisely controlled system, the current design has sought to achieve as energy-efficient an operating strategy as possible and has accomplished this through the use of accelerator waste heat for temperature control and evaporative cooling for rejecting excess waste heat. Further improvements in the operating efficiency via reclamation of excess waste heat are planned as the APS continues to expand its operations. This flexible, energy-efficient design coupled with continuous improvement and diligent system maintenance have been and continue to be instrumental in maintaining the high reliability of the system and its adaptability to the changes required by the evolving scientific program at the APS.

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7. References

[1] E. G. Hansen, "Hydronic System Design And Operation," New York, McGraw Hill, 1985.

[2] "ASHRAE 2000 HVAC Systems and Equipment," American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA.

[3] M. Kirshenbaum, "Variable Flow Chilled Water Systems - A System Analysis," ASHRAE Journal, August 1987.

[4] M. White, R. Dortwegt, S Pasky, "Improved Temperature Regulation and Corrosion Protection of APS Linac RF Components," Proceedings of the 1999 Particle Accelerator Conference, New York, pp. 1414-1416, 1999.