Overcoming Low Delta *T*, Negative Delta *P*

At Large University Campus

Bourns Engineering building at UCR.

By **Lucas B. Hyman, P.E.,** Member ASHRAE, and **Don Little**

The University of California, Riverside (UCR) in Southern California is the fastest growing campus in the UC system. The campus has approximately 3 million ft^2 (279 000 m^2) of assignable facilities, including many science buildings with 100% outside ventilation air.

Planning and modifying the campus' chilled water system has occurred slowly, as resources were available. Unfortunately, those modifications have not always kept up with the campus' rapid expansion. Moreover, a lack of enforced chilled water system design standards resulted in many different building interfaces.

The resulting problems with the chilled water system included unexpected low, and even negative, differential pressure (Delta *P*) near the end of chilled water distribution mains, and high chilled water system Delta *P* near the central plant. The unexpected low and negative Delta *P* resulted in low chilled water flow and thermal comfort complaints in buildings located at the affected ends of the distribution system.

At the same time, high Delta *P*s near the central plant forced open control valves, contributing to the central plant experiencing low chilled water temperature differential (Delta *T*). This resulted in loss of thermal energy storage (TES) capacity, increased pumping energy, and reduced available cooling capacity.

Specific causes of the chilled water problems include:

1. A mixture of constant-speed series tertiary pumps and tertiary pumps with bridge connections;
2. Secondary distribution piping constraints caused the secondary pumps to be inadequate to the task of keeping the distribution system positive;
3. Lack of variable speed drives (VSDs) on the series tertiary pumps;
4. Flow limitations through the TES system which could no longer carry the full peak load;
5. Coils selected for low Delta *T*s (10°F to 12°F [5.5°C to 7°C]);
6. Some chilled water bypassing; and
7. Reverse or inoperable controls.

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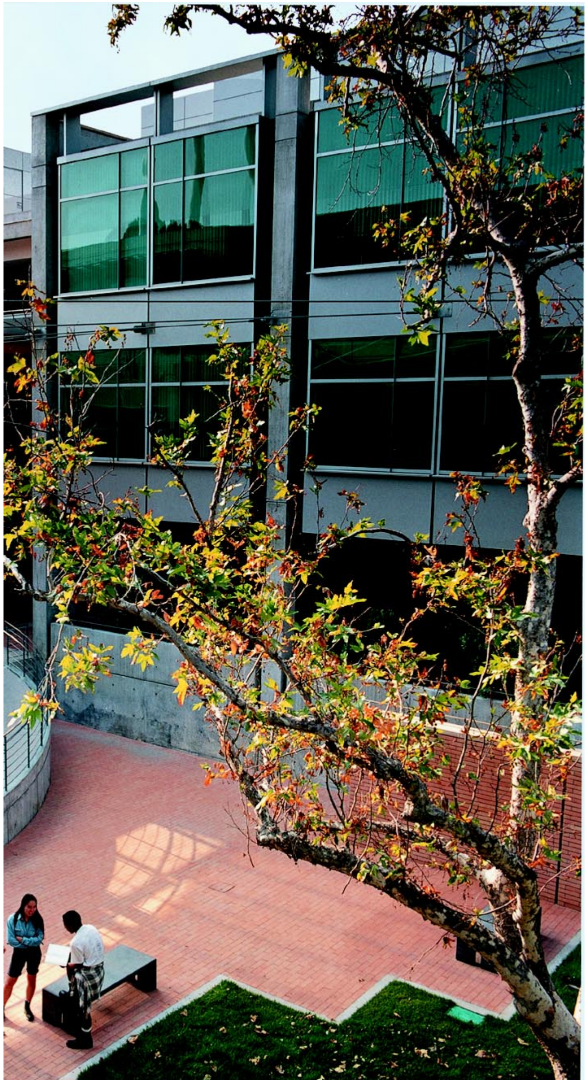

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Thermal comfort complaints resulted primarily from a lack of chilled water flow to the buildings experience negative differential pressures. The chilled water systems for the affected buildings were not designed for negative differential pressures (i.e., the chilled water pumps did not have enough head for this condition).

The design team developed a multifaceted approach to solve the problems. Solutions included:

1. Modifying the existing chilled water distribution system to reduce system drops and system constraints;
2. Adding a central plant secondary chilled water distribution pump to increase pumping capacity;
3. Installing, at buildings near the central plant, modulating two-way pressure-independent control valves (PICVs) to improve controllability at high Delta Ps and to help prevent chilled water bypassing via forced open control valves;
4. Converting from a full storage TES operational strategy to a partial storage strategy; and
5. Stopping short circuits (bypass of chilled water supply to return), correcting reverse logic on some control valves, and addressing other control deficiencies.

VFDs were not added to tertiary pumps because the campus limited the scope of any actual building chilled water system work. After the modifications were completed, the UCR chilled water distribution system achieved a positive Delta *P* at the end of the piping mains, achieved cooling thermal comfort in previous problem buildings, and attained a 20°F (11°C) Delta *T* in the chilled water and TES system.

Chilled Water System

The campus central plant produces chilled water, steam, and compressed air that are distributed to the campus buildings. Piping mains are routed primarily in underground walkthrough utility tunnels, with some direct-buried mains. Chilled water is used for space conditioning and some lab process. Steam is used for space heating, domestic hot water (DHW) production, industrial hot water (IHW) production, swimming pool heat, and laboratory building local steam generation.

The central plant operates 24-hours-per-day, seven-days-a-week with only occasional (once a year) maintenance shutdowns. Cooling is required year-round. The central chiller plant consists of large electric-drive centrifugal chillers, field-erected cooling towers, a stratified chilled water TES tank, pumps, controls, and associated piping.

The five central plant chillers range in size from 1,000 to 1,250 tons (3500 to 4395 kW) of cooling with a total nominal capacity of approximately 5,700 tons (20 047 kW). The chillers are piped in series arrangement to generate a 20°F (11°C) Delta *T* (based on design conditions of 39°F [4°C] chilled water supply and 59°F [15°C] chilled water return).

The chilled water TES system, which was added in 1992, was designed for a capacity of 24,000 ton-hours (84 408 kW-h) and holds approximately 2 million gallons (7.6 million L) of chilled water. The partially buried concrete TES tank is located at a high elevation above the main campus and near the central plant. The TES system was designed to shift cooling production from the high electric cost on-peak period to the lower cost off-peak period. *Figure 1* provides a simplified schematic diagram of the central plant chilled water system. A primary loop bypass is used to maintain primary loop leaving water temperature by blending some of the chilled water supply back to the inlet of the chiller.

For the most part, UCR developed the chilled water system with a primary-secondary-tertiary pumping arrangement. The primary loop circulates chilled water through the chillers and TES tank, while the secondary system distributes chilled water from the central plant to campus buildings. The secondary chilled water distribution system consists of a direct-return network system as shown in *Figure 2*. The figure shows the UCR campus layout with existing and future buildings, existing chilled water piping, the new piping added as part of these recent modifications, and future proposed chilled water piping to complete the loop.

Central plant secondary chilled water pumps are equipped with variable frequency drives (VFDs), which attempt to modulate the chilled water pump speed to maintain a small fixed positive differential pressure across the most hydraulically remote building connection as illustrated in *Figure 3b*. Typically in a primary/secondary/tertiary system the secondary pumps maintain pressure at the connection of the most remote building and the tertiary pumps maintain pressure at the most remote coil. Even with tertiary pumps in series with the secondary pumps, one would still want to employ this strategy to prevent over

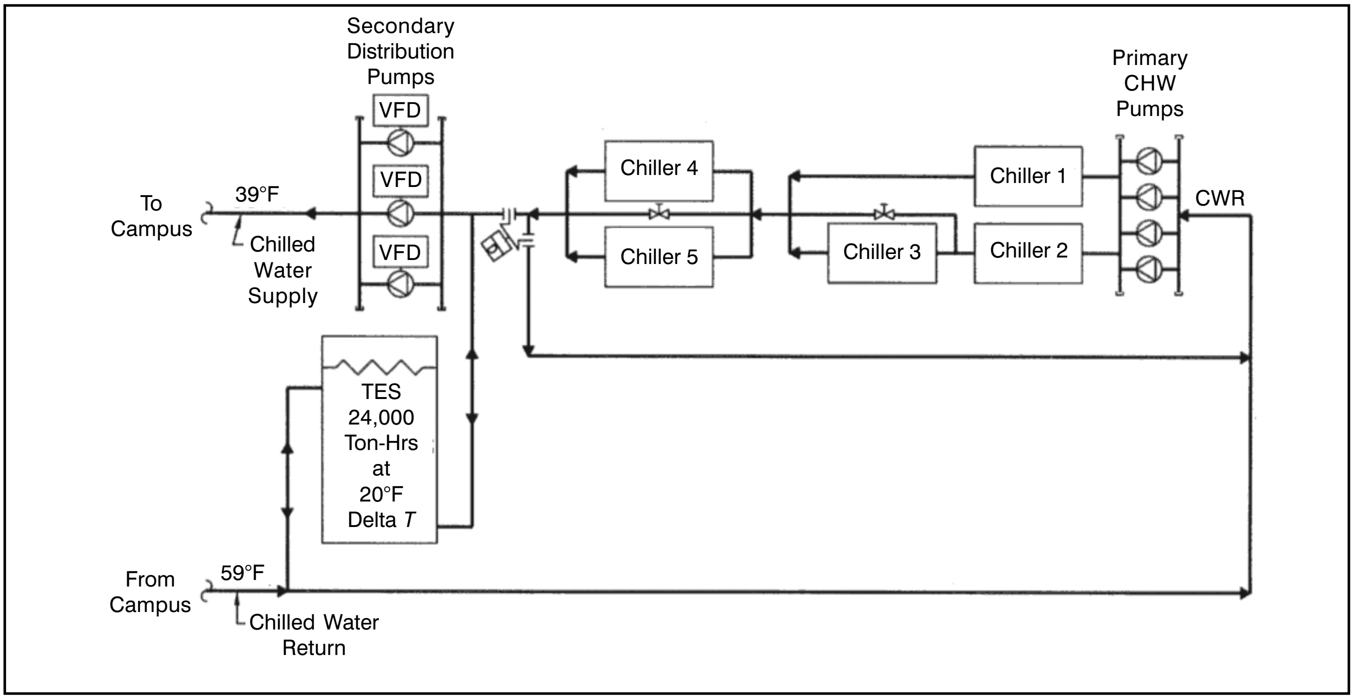

Figure 1: Central plant chilled water schematic for the University of California, Riverside.

pressurization of the system. If the remote buildings do not have tertiary pumps, then a higher differential pressure at the remote building is required.

Unfortunately, no campus building chilled water design standard was followed or enforced as the campus grew over the last 50 years. Many of the older buildings' hydronic chilled water systems were designed with constant speed pumps, 10°F to 12°F (5.5°C to 7°C) Delta *T* coils, and three-way coil control valves. The tertiary pumps included a hodge-podge of different systems with some buildings designed with chilled water pumps upstream of cooling coils and with some buildings designed with chilled water pumps downstream of cooling coils. Most tertiary pumps were piped in series with the central plant secondary chilled water pumps (see later discussion). Note tertiary pumps in series with secondary pumps can function well if the tertiary pumps are equipped with variable speed drives.

New buildings constructed at UCR also have included a variety of chilled water systems and methods for interconnection to the campus secondary chilled water distribution system. A few newer buildings have been equipped with VFDs on the building chilled water pumps, and a few areas and facilities do not use tertiary building chilled water pumps (see later discussion). This variation of chilled water systems and interfaces has not always been compatible with the chilled water distribution system or the chilled water TES system requirements. For example, the chilled water TES system economics depend on a high Delta *T*, since the capacity of the TES tank is directly proportional to the Delta *T* between chilled water supply and return temperatures. Buildings without pumps do not work well when those buildings are adjacent to other buildings with constant speed pumps not hydraulically decoupled. *Figure 3a* shows a simplified schematic of a sample mix of building CHW systems at UCR. Note, many buildings are now hydraulically decoupled, and most buildings have multiple coils

When UCR constructed the TES system, some effort (but not the ideal project) was made to improve the building chilled water interfaces and campus Delta *T*. Due to project constraints imposed by the campus, the building work was limited to some major campus buildings and then only included closing off the bypasses on coil three-way valves and installing a chilled water bypass (hydraulic decoupler) at the building/secondary interface.[1]

To prevent chilled water supply bypassing to the chilled water return resulting in low Delta *T* and reduced TES capacity, the bypass on coil three-way control valves were closed in an attempt inexpensively to convert the three-way valves to two-way valves (this resulted in poor valve control and contributed to chilled water system problems). Also, building/secondary chilled water bypasses were installed on some buildings to hydraulically decouple the building from the secondary chilled water system to help prevent the building constant speed pumps from impacting the secondary distribution system.

The conversion of three-way valves to two-way valves and lowering the chilled water supply temperature allowed for the existing 12°F (7°C) Delta *T* system to become at least a 17°F (9°C) Delta *T* system. It was hoped that these modifications would help ease distribution constraints, and for a time they did. *Figure 4* shows a schematic diagram of an existing building hydraulically decoupled chilled water system at UCR (*Figure 4* does not show all building types).

System Problems

Unfortunately, at the end of the 1990s, the campus still had a mixture of constant-speed series tertiary pumps and tertiary pumps with bridge connections, and new building chilled water systems continue to include a variety of systems depending on the engineer of record (one recent building only had a 50°F (10°C) chilled water return temperature, a 10°F [5.5°C] Delta *T*). As the campus added new buildings over the last decade (with a variety of tertiary chilled water systems and connection methods), the campus again experienced secondary chilled water system problems of low and negative differential pressures and low Delta *T*s. As UCR added new cooling loads, the chilled water distribution system experienced excessive pressure drops. The TES system had excessive flow (above design) and could no longer carry the full peak load. Most of the older buildings still have the low Delta *T* coils designed for a 10°F to 12°F (5.5°C to 7°C) Delta *T* with the correspondingly high building chilled water flow rates.

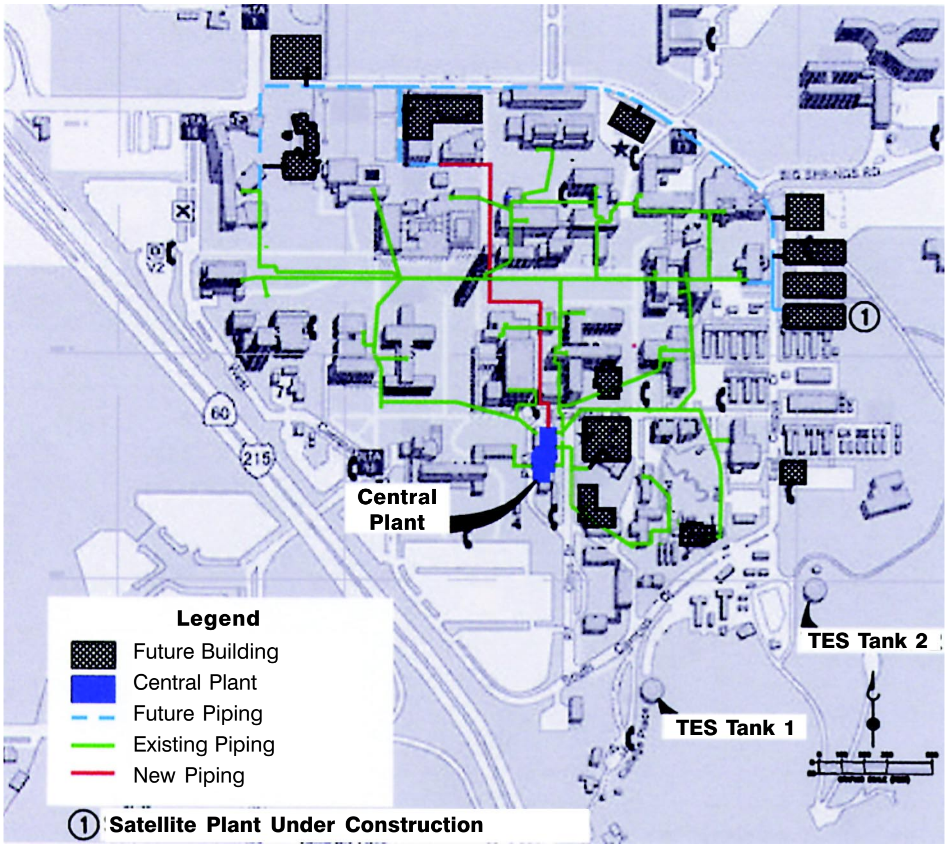

Figure 2: Secondary chilled water distribution system.

Constant speed (vs. variable speed) building tertiary chilled water pumps (especially oversized pumps) in series (vs. hydraulically decoupled) with inadequate central plant secondary chilled water pumps/distribution-mains tend to reduce chilled water supply pressure and increase chilled water return pressure. This resulted in a phenomenon at the end of the system where the chilled water return pressure was higher than the chilled water supply pressure (i.e., negative Delta *P*) as shown in *Figure 3C*. The unexpected (vs. expected[2]) negative Delta *P* reduced chilled water flow to affected buildings causing thermal comfort complaints.

Thermal comfort complaints resulted primarily from lack of chilled water flow to those buildings experience negative differential pressures as those affected building chilled water system were not designed for negative differential pressures (i.e., the chilled water pumps did not have enough head for this condition). Obviously, at the same time some building chilled water pumps had more than enough dynamic head and pressurized the chilled water return system.

As the campus experienced negative Delta *P* problems in the secondary loop, the secondary chilled water pumps, per the programmed control sequence, would increase speed in an attempt to maintain a positive Delta *P* of 5 psid (34 kPa) at the end of the secondary loop. On peak cooling days, even when both secondary distribution pumps operated at 100% rated speed. Positive differential pressure could not be achieved at the ends of the secondary distribution system.

To make matters worse, when the secondary chilled water pumps would ramp up to 100%, the chilled water return temperature would decrease lowering the chilled water system Delta *T* (please see investigation discussion below). This decrease in chilled water return temperature reduced the TES capacity. On a 20°F (11°C) Delta *T* system, a 1°F (0.5°C) drop in Delta *T* to 19°F (10.5°C) represents a 5% loss of capacity.

When the TES system was designed in 1992, it was sized as a full storage system and shifted approximately 24,000 ton-hours (84 408 kW) from the on-peak window. A full storage TES system allows for all the electric-drive chillers to be off during the utility's on-peak period (six hours in this case). With a full storage system, during the on-peak period, all cooling is provided directly from the chilled water TES tank. The central plant chillers operate during the off-peak and mid-peak periods to charge the TES tank and serve the campus cooling loads.

The TES tank diffusers were sized for a peak flow rate of approximately 5,000 gpm (315 L/s). As more buildings were constructed and added to the central plant chilled water system during the 1990s, the campus peak cooling loads and subsequent chilled water flow rates exceeded that of the original TES capacity.

With current peak campus chilled water flow greater than 7,000 gpm (442 L/s), the peak design diffuser flow rate has been exceeded. Even increasing the diffuser flow rate, the storage would not be adequate to meet the cooling needs during the six-hour on-peak period. Without additional storage capacity, UCR's central plant operating strategy needed to change to a partial storage strategy, where some chillers are operated in parallel with the TES during the on-peak period.

Due to agreements with the utility, the staff at the UCR physical plant believed that they could not, or should not, operate chillers during the on-peak period. To meet the increased cooling loads, the flow rate through the tank was increased. While the TES had an excellent octagonal diffuser design that could handle the increased flow rate, the 40% increase in flow nearly doubled the pressure drop through the TES system, which is in both the primary and secondary loops. This decreased the flow pressure to the campus loop, since the central plant secondary pumps have a fixed maximum combined flow and pressure performance capacity (as all centrifugal pumps do for a given rpm). It also appeared to increase the thermocline thickness, which in turn reduced TES tank capacity. Operating at the original conditions, the TES tank had typically maintained a thermocline of 1 ft (0.3 m) thick. At the higher flow rate, the thermocline increased to more than 3 ft (0.9 m) thick.

Even if the pumps and diffusers could handle the higher flow rate and pressure differential, it is not clear how the extra ton-hours would be achieved without additional thermal storage and/or chiller output.

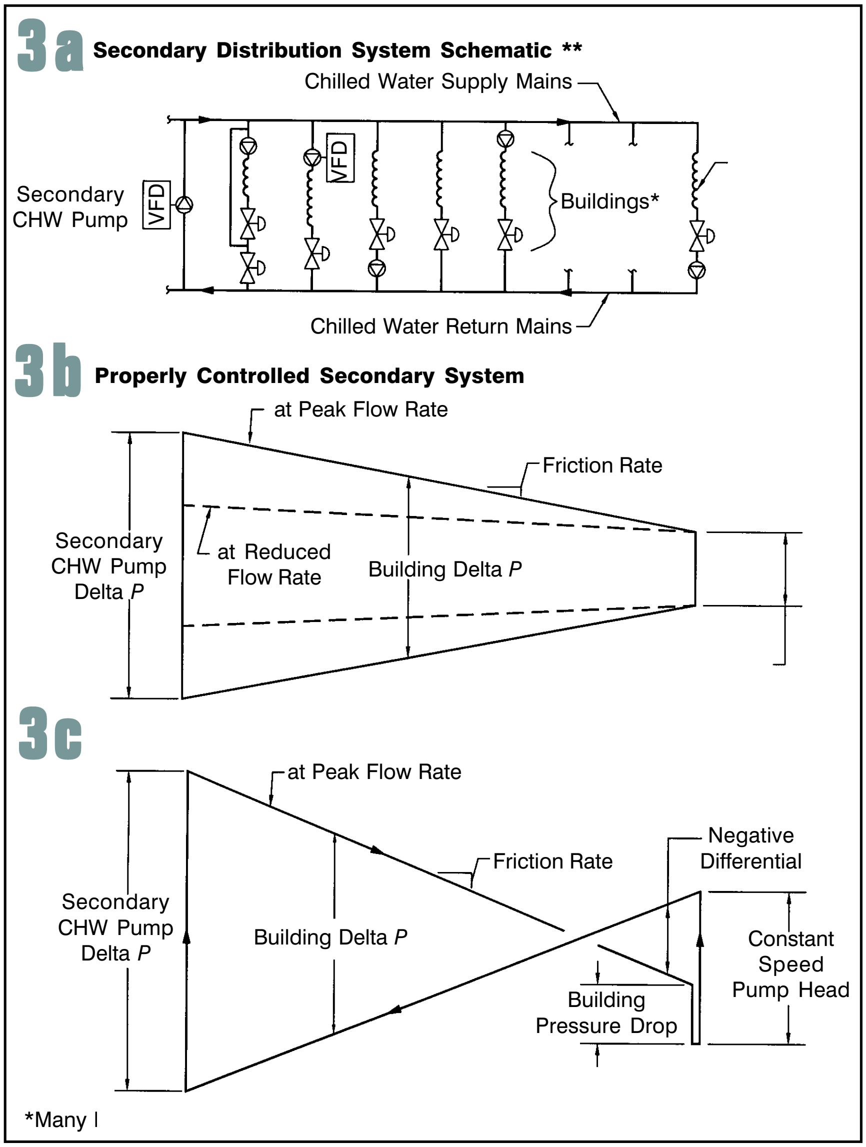

Figure 3: Chilled water distribution system—pressure vs. position.

Investigation and Analysis

In 1998, UCR had the chilled water system evaluated and analyzed. As briefly discussed above, this investigation found that problems and challenges existed with the generation, distribution, and building interfaces of the chilled water distribution system. The evaluation also estimated that the peak campus cooling loads in 2010 would be approximately 12,000 refrigeration tons (42 204 kW) of cooling.

To alleviate the low and negative Delta *P*, it was apparent that: the secondary distribution system excessive pressure drops had to be reduced; additional secondary chilled water pumping was needed; building constant speed chilled water pumps could not be allowed to "pressurize" the chilled water return mains; and that control valves near the central plant had to be prevented from being forced open by high differential pressure thereby bleeding off chilled water needed for the end of the distribution system and contributing to low Delta *T*.

During field data collection, as noted earlier, it was discovered that chilled water two-way control valves in some buildings near the central plant, could be forced open by secondary distribution system high differential pressure. This resulted in bypass flow in the tertiary system. That is, the control valves could not withstand the high Delta *P*s causing excessive flows and low Delta *T* due to the chilled water supply flowing to the chilled water return without any controlled heat gain.

Hydronic control valves need to be selected not only for the maximum system supply static pressure and the operating pressure differential with controllability over the range of flows and differential pressures, but also importantly, in this case, for the impact of maximum Delta *P* on the valves ability to close off.[3,4] In pneumatic valves, the ability to close off is a function of the spring rate, the diaphragm size, and the available air pressure.

As the secondary chilled water distribution system was obviously constrained, a computer hydraulic model of the existing chilled water distribution system was developed to analyze the flow and pressure requirements. The hydraulic model was calibrated by taking actual flow and pressure measurements at different pump speeds throughout the secondary distribution system. After calibration, the chilled water distribution system and secondary chilled water distribution pumps were then analyzed with the computer model to simulate different distribution system expansion alternatives trying to maintain the use of the two existing 250 hp (187 kW) secondary distribution pumps. The model was used to determine the most cost effective method of expanding the secondary distribution system to meet existing and future cooling loads. The team developed a proposed loop system as shown in *Figure 2*.

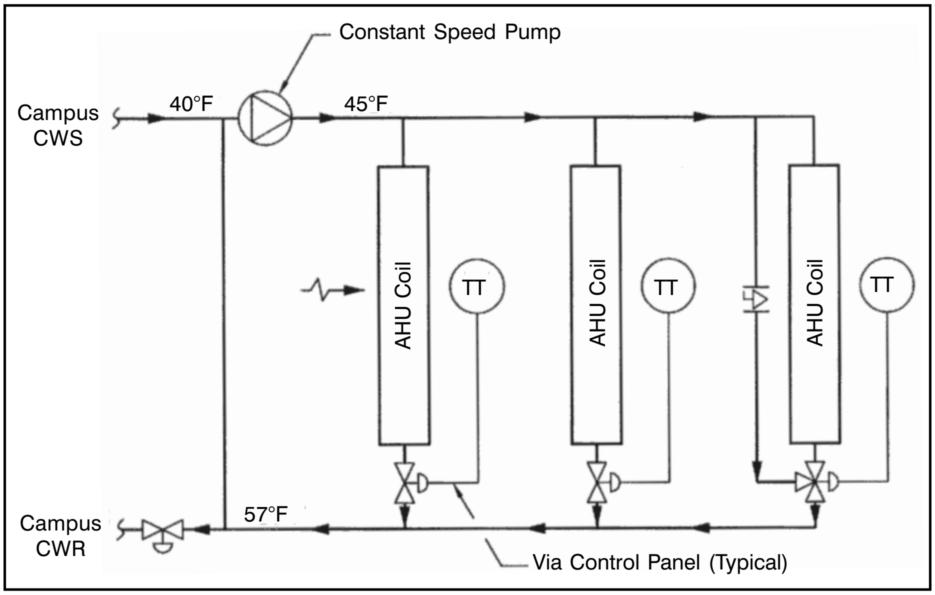

Figure 4: Decoupled building chilled water system.

The team also determined that some of the building pumps close to the central plant were not required since the differential pressure was enough head to provide for building chilled water flow. While not within the scope of this article to discuss the various types and advantages/disadvantages of different distribution system, it should be noted that it is possible to have a primary-secondary chilled water system without tertiary building pumps. The elimination of building tertiary pumps may be a more efficient system due to less overall losses (multiple fitting/motors) provided that the there is not a hydraulically remote building (or group of buildings) increasing the required dynamic head on the secondary distribution pumps. It is also possible to design a system without secondary distribution pumps using the building pumps to pump water through the distribution system.

Where building pumps are used, the required pump head should be equal to the building pressure loss (i.e., coil, control valve, piping, fittings, etc.) minus the available secondary differential pressure. Note that the secondary differential pressure varies from the minimum remote differential pressure set point at low flow to the maximum differential pressure at peak central plant flow. VFD driven pumps make it easy to match pump and building requirements (assuming the pumps are oversized as is often the case) since the pump can slow down to match the building Delta *P* requirements. Where pumps may only sometimes be needed, a pump bypass with check valve can be installed.[5]

To reduce existing tertiary pump head (an important element in preventing the unplanned for negative differential challenges), the options are: remove/bypass pumps if not needed, add VFDs, trim impellers, replace with new appropriately sized pumps, or throttle the pumps. The best option is the option with the lowest life cycle costs and should be determined on a case-by-case basis. From a technical and energy perspective the variable speed pumps (either existing or with new pumps) is the best option. Throttling the pumps requires no capital costs but has a high energy penalty; however this method does not work at all flow conditions, since at low flow rates when the pump "rides up its curve," the pump can still draw down the supply and pressurize the return.

The TES System

It is extremely important to maintain a constant and a high Delta *T* for successful stratified chilled water TES. This cannot be overstated; it is key to the economic success of TES. A system operated or designed for 10°F (5.5°C) vs. 20°F (11°C) Delta *T* requires twice the TES tank capacity and flow rate throughout the primary and secondary system to achieve the same cooling load. Also, pumping energy in the same distribution system is roughly proportional to the cube of the flow. Thus, all else being equal, twice the flow rate requires nearly eight times the pumping horsepower and energy. High Delta *T* chilled water systems versus low Delta *T* systems generally have:

- Greater TES capacity, for a given tank size,
- Greater cooling capacity for a given pipe size,
- Lower TES and piping capital costs, and
- Lower pumping energy costs.

During the investigation, several direct bypasses (open short circuiting in the tertiary systems) were found. These were closed off. In addition, some secondary system and building controls were not set or functional and could not operate properly. For example, key signal wires were cut and some control valves were operating in reverse. A repair deficiency list was developed as part of the study.

Solutions

An effective solution required a multifaceted approach to address the generation, distribution, and building interface challenges.

Making changes to the chilled water generation strategy was the easiest problem to resolve, once the issues were understood. Discussions with the City of Riverside on energy management and available options led to the approval and construction of a second chilled water storage tank. The existing TES system currently operates as a partial storage load shifting plant with some of the central plant chillers concurrently operating in parallel. This allows the central plant with TES to meet the daily cooling load and peak cooling rate, while preventing excessive flows and pressure drops in the TES tank loop.

The results and analysis of the hydraulic model showed, as observed, that the chilled water distribution system capacity was constrained. A phased plan to modify and to expand the distribution system to meet existing and projected chilled water flow requirements was developed as shown in *Figure 2*. A loop system was developed to include a proposed satellite chiller plant. The loop system allows for multiple chilled water flow paths and resultant reduction in required pump head as well as increased system reliability.

The first phase of the distribution system modifications involved the construction of direct-buried 20 in. (0.5 m) chilled water supply and return mains from the central chiller plant across campus (as shown in red on *Figure 2*). Connections to the existing chilled water distribution system were made at key locations along the way to support "starved" areas and boost supply pressure to these buildings.

The modifications also included adding at the central plant a third 250 hp (187 kW) VFD driven secondary chilled water distribution pump. This third pump is in parallel with the two existing pumps. The three chilled water pumps operating in parallel will be able to deliver approximately 8,500 gpm (536 L/s), which corresponds to approximately 7,100 tons (24 970 kW) with a 20°F (11°C) Delta *T* (the goal of the chilled water system).

To prevent chilled water bypassing in control valves some insufficient springs were replaced. For better control at high differential pressures and to prevent bypassing, the team used PICVs in the critical buildings near the central plant. Eight locations for PICVs were identified and buildings modifications were completed in February 2002. The modulating two-way PICVs provide the proper variable flow rate regardless of the secondary system differential pressure (up to a maximum range).

As a short-term fix, due to a lack of available capital, in buildings that are not decoupled, constant speed pumps were throttled to help reduce unnecessary pressure effects. When capital becomes available it is hoped that building systems will be converted to variable flow.

The team also recommended using high Delta *T* coils. Some of the new and retrofitted 100% OSA laboratory buildings at UCR were provided with 40°F (4°C) chilled water coils. The goal is to have all new building equipped with high Delta *T* coils. As existing building coils are replaced, they should be retrofitted with high Delta *T* coils. Each existing coil replaced helps to improve the aggregate campus chilled water Delta *T*.

Summary

Since the central plant/TES operational strategy was changed from full storage to partial storage, the new 20 in. (0.5 m) piping mains installed, the addition of a third secondary chilled water pump, and chilled water bypassing prevented through the installation of control valves capable of withstanding the differential pressure; the UCR campus has for the first time experienced a stable positive Delta *P* at the most hydraulically remote building, achieved thermal cooling comfort in buildings, reduced central plant chilled water flow rates, and obtained a 20°F (11°C) Delta *T*. The Delta *P* has gone from –25 psid (–172 kPa) (uncontrollable) to 5 psid (34 kPa) (controlled) in the most adversely effected sector. The VFDs for the most remote building (Bourns) chilled water pumps now run at minimum speed.

The main conclusion from this chiller and TES plant analysis is that an integrated approach must be taken. The central plant cannot be sized to meet the peak and 24-hour cooling load without analyzing the hydraulics and performance of the complete system. This includes operation and control of tertiary loads to meet the users requirements (both high and low temperature needs, laboratory needs, research needs, ventilation needs, and humidity requirements) and the system hydraulic requirements. Otherwise, the economic expectations will not be achieved.

To achieve the maximum benefits from the campus chilled water system, the campus needs to:

- Require high Delta *T* coils on all new campus buildings,
- Continue to retrofit existing building cooling coils with high Delta *T* coils,
- Require all buildings to be variable chilled water flow to ensure Delta *T*s remain high as possible under all load conditions,
- Verify the proper selection of chilled water control valves,
- Continue to expand the chilled water distribution system into a loop system, and
- Add additional chiller/TES capacity as loads grow (in progress).

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