1. BACKGROUND

Chilled water system limitations are a common challenge for many facilities, especially campus configurations (higher education, manufacturing, airports, etc.). Princeton University has successfully operated a district cooling system for more than 40 years. When faced with a major increase in campus cooling demand, Princeton took the opportunity to study and improve many areas of the system that would not meet today's design standards. Some limitations were discovered that involved reduced cooling (tonnage) and distribution (flow) capacity, fluctuating supply temperature and low return temperature – challenges familiar to many district cooling system operators. These technical limitations, which can result in suboptimal economic operation, are typically overcome by adding pumps and chillers; this may not be the most cost-effective solution to install or to operate, however.

Since year 2000, when Princeton began planning how to provide significant additional cooling capacity due to a major increase in climate-controlled area, it has taken a broad, campus wide approach to resolving system deficiencies and improving operational flexibility. At its central plant and distribution network, and with local building improvements, Princeton is taking proactive steps to overcome capacity, flow, and temperature limitations and optimize economic dispatch of equipment. Typically, efforts to deal with chilled-water limitations are undertaken in isolation, which can reduce the overall value of each individual change. By studying overall system impact, Princeton is able to maximize the cost-effectiveness of each change.

Prior to the upgrades, Princeton had a single chilled-water central plant located in the southwest corner of its 500-acre campus in Princeton, N.J. Two-thirds of this 15,000-ton plant capacity is in steam turbine-driven chillers. The remaining capacity is electric-driven. Chilled-water production is supported by a cogeneration plant rated at 15MWe and 300,000 lb/hr of steam. The existing cooling system has primary pumping at the plant, with tertiary pumps located in many campus buildings.

In the early 1960s, Princeton’s original chilled-water plant and underground distribution system were designed based on a net campus temperature differential, or Delta T, of 15°F. Inefficient coil selections, campus expansion and ineffective cooling-coil control valves have resulted in a pumping and distribution system that was no longer matched to the chillers and has only been marginally adequate for the last several years with continued campus growth. It was common for operators to run all the pumps on design days and just barely be able to meet the load. Motivated by campus expansion, Princeton evaluated the system’s performance for improvement opportunities.
2. **UPGRADES AT AIR HANDLING UNITS**

Over the years, the Princeton system used many different designs for coil chilled-water Delta T. This has resulted from the many different engineers involved with it, each applying their own standards, and the continued evolution of Princeton’s design standards. The University’s academic, athletic, administrative, research and residential facilities also present a wide range of design constraints. Coils range from 8°F to 20°F and resulted in an average system summer differential of 12.3°F. With the range of conditions on campus, Princeton has been working to improve the coil Delta T in the most cost effective manner – evaluating larger coil loads with lower Delta T’s and preferentially replacing coils that were old or had maintenance problems. Prospective coils were evaluated in 2003 for opportunities to increase Delta T and the corresponding impact back at the central plant. Evaluation for additional opportunities remains an active item at Princeton.

The evaluation identified 28 coils within a total of 10 air-handling units with capacities ranging from 100 to 400 tons per air-handling unit. Design Delta T’s ranged from 14°F to 19°F. Although these are not normally considered low Delta T’s, increasing them to 20-24°F for these large loads has significant benefits. The design intent of the recommended improvements was to add no increase to water-pressure drop with only a minimal increase in airside-pressure drop (as long as the existing fan could be resheaved to accommodate without a reduction in airflow).

The projected Delta T improvement at the central plant is only 0.4°F with the limited coil replacements. This may seem small, but with an existing plant Delta T of 12.34°F, there would be a projected flow savings of 675 gpm. This savings could satisfy a new 560-ton building with a Delta T design of 20°F without new pumping capacity. This analysis shows that although conventional design standards may indicate good temperature differential, the opportunity to provide additional flow capacity needs to be evaluated to identify potential cost effective system improvements.

In addition to the chilled-water coils evaluation, flow control through each coil was also reviewed by Princeton University and Carter & Burgess. At air handlers known to be performing at less than design Delta T or with older control valves, new pressure-independent flow control valves were recommended. The University has installed 104 of these new control valves, over the last 4 years, and has seen excellent results, both at part load and at peak load. This represents approximately 1/4 to 1/3 of the total flow on campus. The ability to limit flow fluctuations and provide steadier service at the coils has improved chilled-water usage efficiency (increased Delta T).

With coils typically being oversized due to design conservatism, standard valves have a tendency to hunt, even under design conditions; peak load may only require 50 percent to 75 percent of design flow as a result of cooling-coil performance characteristics (fig. 1). When the load is at 90 percent, the flow required is only 50 percent. As such, the selected valve must be able to offer tight control at flows well below design.
Only a part of the planned coil and valve replacements have been implemented. These replacements have already increased campus Delta T by more than 1.5°F (fig. 2). This demonstrates that valve replacements can have a significant positive impact on Delta T as the projected impact of coil replacement was only 0.4°F and that project is not yet complete. The Delta T increase represents approximately 1,500 tons of cooling now available on design days and reduced pumping energy requirements the rest of the year.
3. UPGRADES TO DISTRIBUTION

A distribution system thermal-hydraulic study of Princeton’s chilled water system was undertaken by Katner FVB from 2002-2003. HEATMAP software was used to locate “choke” points and cost-effective locations to reinforce the distribution system piping. All existing loads and a 10-year construction forecast were included in the model. Where available, historical temperature, pressure and flow operating data were used to verify the model.

The study identified two major piping additions as “required” to meet specific construction deadlines and recommended several smaller projects be done “when possible.” The first project added 2,500 linear feet of 30-inch supply pipe and converted the existing supply line into a parallel return. Completed during the winter of 2003, it resulted in a noticeable reduction in total differential head and pumping energy. A second part of this project includes installation of 1,000 linear feet of 24-inch supply and return piping this spring. In addition, about 800 linear feet of 20-inch supply and return lines were tested and restored to service after being removed from service about fifteen years prior to allow for other underground piping.

4. REDUCED CHILLED WATER SUPPLY TEMPERATURE - DISTRIBUTION

To further enhance distribution capacity, the new chilled water plant can operate at reduced chilled water supply temperatures – down to 34°F supply. The goal with the lower supply temperature is to further increase system temperature differential (more energy per gallon of water) and therefore reduce overall flow requirements. Data is not yet available from a design day; however, results to date are very favorable. The figure below shows the overall effect of lower chilled water supply temperature for the entire Princeton University campus. When the chilled water supply temperature is reduced by 12°F (46 to 34), the return temperature reduces by only 3°F (51 to 48). This is a significant improvement on overall system temperature differential.

![Figure 3: Campus CHW Supply & Return While Running TES Heat Exchangers](image)

Further review of a laboratory building on campus with new control valves and newer coils reveals even better results related to temperature differential. The figure below shows that with a decrease in chilled water supply temperature, the chilled water return temperature actually increases for a much larger effect on temperature differential. With the quality valve and coil installation, the chilled water is used even more efficiently in the air handling unit. The colder water allows for a longer transit period through the coil and more energy is transferred from the air to the water.
5. UPGRADES WITH ECONOMIC DISPATCH

In August 2003, commercial electric purchases in New Jersey were deregulated. Prior to that, the electric tariff provided a simple price structure and less opportunity to reduce operating costs. With deregulation, Princeton now purchases power at the wholesale market rate. At night prices are often as low as $20/MWh – far below Princeton’s marginal cost to generate power.

With a traditional tariff system, the cogeneration plant was run in a load-following manner. Any campus load not met by cogeneration was imported from the grid. Demand structure can penalize cogeneration for reduced capacity. In a dynamic deregulated energy market, cogeneration output can be reduced when the cost to generate is higher than the market. With economic dispatch in a volatile market, even a cogeneration system with a relatively low capacity factor remains an extremely valuable asset.

During the day, prices can rise into the hundreds of dollars per MWh. With a cogeneration system and boilers that can burn either diesel fuel or natural gas, the choice of steam- or electric-driven cooling, and the opportunity to purchase and/or generate power, the most cost-effective means to deliver energy at any given time is far from obvious. Historically, the plant was operated for high reliability with simple rules based on conventional wisdom, such as “steam chillers are cheaper than electric.”

In response to the volatile wholesale market, a real-time economic dispatch system (see fig. 3) was developed by Princeton and Icetec, Inc. It predicts campus energy demands, compares the cost of on-site generation to purchased power, and recommends the most cost-effective combination of equipment for operators to use to meet those requirements. The model inputs include real-time data for weather, NYMEX gas and oil prices and futures, campus energy demands, equipment efficiencies and availability. Using this system allowed the plant operator’s focus to shift from simply meeting demand to delivering energy in the most cost-effective manner.
While this system could be fully automated, Princeton chooses to use it as expert recommendation to plant operators who can also take into account reliability issues such as local storms and campus events. The addition of thermal storage to Princeton’s energy plant provides even more operating flexibility and cost-saving opportunities. Based on the limited operational period to date (approximately $28,000 saved in November), annual savings are projected at $500,000 to $800,000.

The graphic below shows the value of the projection capabilities of the dispatch model. Traditional operations would have utilized the thermal storage tank earlier in the day around 12 noon. However, due to the projection capabilities of the model, thermal storage capacity was saved until later in the day (4 pm) to maximize potential savings due to the significant increases in the cost of electricity.
6. UPGRADES FOR CAPACITY GROWTH – PLANT EXPANSION

As the Princeton University campus continues to grow, the additional chilled-water system capacity requirements cannot be met with temperature differential improvements alone. Additional chiller and pump capacity is required. In a study performed in 2002 by Princeton and Goss Engineering, it was determined that a new plant was the best solution, as the existing plant has limited expansion capability. Further, a new plant would provide opportunities for thermal storage and low chilled-water supply temperatures. Detailed plant design was performed by Carter & Burgess with concept architecture by Leers Weinzapfel & Associates.

Two-Plant Flow Sequencing and Control

Although the new plant is located immediately adjacent to the existing chilled-water plant, there are separate sets of distribution pumps for each plant. A plan to operate flow sequencing and control was necessary to provide an efficient system that does not work against itself. The plants operate in a lead-lag arrangement. Based on the real-time economic dispatch system feedback, operators select the lead plant based on economic merit. This lead plant operates base-loaded, at a constant flow rate. The lag plant modulates flow in response to load.

Thermal Energy Storage System

As part of the chilled-water expansion, a stratified chilled-water thermal energy storage (TES) system is included. This system provides up to 40,000 ton-hours of storage to be utilized as recommended by the economic dispatch system. It can be discharged in as little as four hours and charged as quickly as eight hours. The plant expansion includes 5,000 tons of chiller capacity but can support 10,000 tons of cooling load combined with output from the TES. The distribution pumps set the upper limit on plant capacity with the TES.

Figure 6: TES Dispatch Model – Volatile Day – Projections Successful
With the flexibility of energy sources in the cogeneration plant, a combination of steam-and electric-driven chillers, and flexibility in the time of power purchases allowed by TES, the University can optimize energy costs and take advantage of deregulated market opportunities.

To further improve system performance and capacity, the overall chilled-water supply temperature can be reduced to below 40°F. The new plant is decoupled from the distribution system with plate-and-frame heat exchangers. This enables the atmospheric-pressure thermal storage tank to support a high static-pressure campus system. It also provides chemical separation between the vented TES system and closed-loop campus chilled water system, and allows greater operational flexibility.

To maximize thermal storage capacity and improve the campus temperature differential (as discussed previously), the supply temperature on the plant side of the heat exchanger is 32°F, resulting in 34°F available to the campus distribution system. Low storage temperatures can be achieved without the risk of freezing by using a density-depressant additive. The low storage temperature and 24°F Delta T effectively increase TES capacity to 40,000 ton-hours. If the system operating temperature had remained at 40°F, the capacity of the TES tank would be only 26,667 ton-hours.

With the lower temperature on the plant side of the heat exchanger, when decreased chilled water supply temperatures are not required for improved distribution, the tank can be used for an extended period (slow rolled), guarding capacity in the event of utility or load spikes.

7. CONCLUSIONS

Princeton University has and continues to proactively work to overcome its chilled water system limitations – tonnage, flow, Delta T – with a comprehensive plan of attack that encompasses the central plant, distribution network and local buildings. Typically, efforts to deal with chilled water limitations are undertaken in isolation, which can reduce the overall value of each individual change. By studying overall system impact, Princeton is able to maximize the cost-effectiveness of each change.

The comprehensive upgrade program strongly positions Princeton for significant campus growth with an efficient, reliable and cost-effective operation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the leadership and support of Thomas Nyquist, and Mike McKay at Princeton University Facilities Engineering and Scott Clark at Carter & Burgess. The success of these projects would not have been possible without the excellent support and teamwork between: Carter & Burgess, Icetec, Goss Engineering, FVB Energy, Leers-Weinzapfel, Skanska USA, Van Note Harvey, Quennel Rothschild Partners, the entire Princeton Energy Plant operating staff, and numerous other individuals throughout Princeton Facilities Engineering.