SUSTAINABLE CONSTRUCTION AND CAMPUS INFRASTRUCTURE IMPROVEMENTS AT THE INSTITUTE FOR ADVANCED STUDY

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INTRODUCTION

Campus heating and cooling systems present a particular challenge to the incorporation of advances in technology to improve efficiency. An older system is generally more expensive to operate than a newer one would be, but extensive upgrades are often difficult. Lengthy shutdowns affect multiple buildings, and new central heating and cooling equipment is very expensive. Buildings added over the years incorporate various types of systems, affecting central plant operation. Buried distribution piping is costly and can be disruptive to modify.

The Institute for Advanced Study (IAS) has been engaged in an ongoing effort to modernize infrastructure and incorporate sustainable design features on its campus in Princeton, New Jersey. Under the direction of IAS Facilities Management, a multi-year plan for campus utility improvements has been implemented. Over the past eight years the same consulting engineers have been involved in each major campus project, providing necessary continuity.

The most recent project at the Institute was the construction of an addition to an existing building. Sustainable construction was prioritized in the design of the new building. This article will discuss some of these architectural and building system design features. Also addressed will be some of the recent history concerning measures to modernize the central campus cooling systems, focusing on the synergy between construction of the new building and the central system improvements.

INSTITUTE FOR ADVANCED STUDY

The Institute for Advanced Study is one of the world's leading centers for theoretical research and intellectual inquiry in the sciences and humanities. Adjacent to Princeton University in Princeton, New Jersey, but not associated with it, the Institute is a private, independent institution. The Institute was founded in 1930 by Louis Bamberger and his sister Caroline Bamburger Fuld, with the guidance and direction of educational visionary Abraham Flexner. The faculty at the Institute has included John von Neumann, J. Robert Oppenheimer, Kurt Godel, and Albert Einstein.

The Institute is unique in that formal instruction does not take place as at a college or university. Members of the Institute are free to work on any problems in which they are interested. In any given year, some of the members will collaborate with each other, with relevant Institute faculty members or scientists and scholars at other institutions.

Work at the Institute takes place in four schools: Historical Studies, Mathematics, Natural Sciences, and Social Science. Currently a permanent faculty of twenty-seven eminent academics guides the work of the schools. Each year they award fellowships to some 190 visiting members from about one hundred universities and research institutions throughout the world.

The Institute has been at the forefront of research in several fields. In the early years of computing, one of the first stored program computers was designed and built on the Institute's campus. Its structure (von Neumann architecture) has influenced the development of today's computers and formed the mathematical basis for modern computer software. The foundations of game theory, a powerful tool in economics, were formed in the School of Mathematics at the Institute, and much of the basis of modern theoretical meteorology was laid by research there. Research in the School of Natural Sciences has

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greatly advanced particle physics, including string theory and astrophysics.

Consistent with its mission to be at the forefront of research, the Institute has historically adopted the latest available concepts when designing campus buildings and infrastructure. The Institute has always prioritized its stewardship of the land with which it has been endowed, with over 500 acres of the Institute Woods accessible to the public, in perpetuity.

CAMPUS FACILITIES AND INFRASTRUCTURE

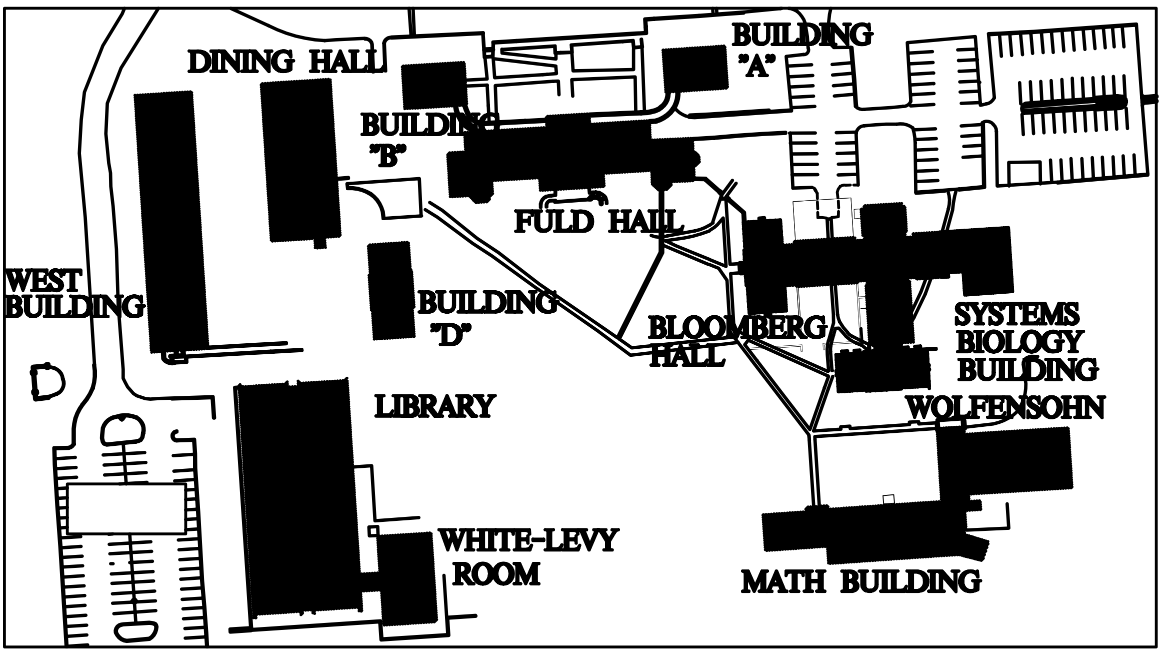
The Institute's main campus, located in Princeton, New Jersey, consists of 10 buildings, most of which are served from a central boiler and chiller plant. A campus plan is shown in Figure 1. There is also a large housing complex, served by a separate cooling and heating plant.

The original building, Fuld Hall, was constructed in 1939 with a basement boiler room. A library building was constructed in 1964, necessitating the extension of underground steam service to the new building. Cooling for the library was provided by a chiller; condenser water for this unit was well water that was discharged to an artificial pond. While a very efficient system for its time, the use of well water for this application would not be permitted under current regulations. Though this system was "grandfathered," one of the goals of the ongoing improvements was to retire this chiller.

A major expansion of the campus was undertaken in 1969. At that time, a central boiler and chiller plant was constructed in one of the new buildings and the older structures re-fed from the new central equipment via a buried piping system. New buildings were constructed periodically, some connected to the central plant, some on their own systems. The Institute has had an ongoing commitment to sustainable practice; a mathematics building built in 1991 was constructed with an ice storage system to take advantage of lower nighttime energy rates and allow for downsizing of the cooling equipment.

At the time of its original construction, the central plant was a state-of-the-art design. The campus system distributes low pressure steam to the various buildings. Each building had a steam-to-water heat exchanger for the heating system. The chilled water system consisted of a centrifugal chiller, of 315 ton

FIGURE 1. Institute for Advanced Study academic campus.



capacity with an open cooling tower. Chilled water was pumped at a constant volume through the chiller and throughout the buildings. The original architects and engineers had the foresight to design the central mechanical room with space for additional capacity for future campus expansion. A schematic of the original campus chilled water system, with upgrades to the year 2000, is shown in Figure 2. Figure 3 shows a schematic of the original central chiller plant.

Until relatively recently, the central chilled water plant had been shut down for the colder months. The HVAC systems varied from building to building; few had airside economizer capability, which would allow bringing in cool outside air. Most buildings, however, had sufficient envelope losses and few interior zones that required year round cooling.

As the campus expanded, however, the lack of year-round chilled water became a problem. The advent of central computer rooms with high cooling requirements created the need for year-round cooling; these were provided with direct expansion environmental control systems with outdoor condensing units. Unfortunately, these were an annoyance due to the noise they created, and were unattractive visually. They were also becoming an increasing maintenance burden.

In addition, comfort problems were increasingly being experienced, especially in the newer buildings. Many of the buildings used individual perimeter fan coil units as the basic HVAC system. This allowed buildings to be constructed without extensive ductwork and permitted lower floor-to-floor heights. Architecturally, it has been a general goal of the campus design to maintain a low-rise, low-impact appearance.

The older fan coil buildings were poorly insulated by today's standards and few areas required

FIGURE 2. Campus chilled water distribution in year 2000.

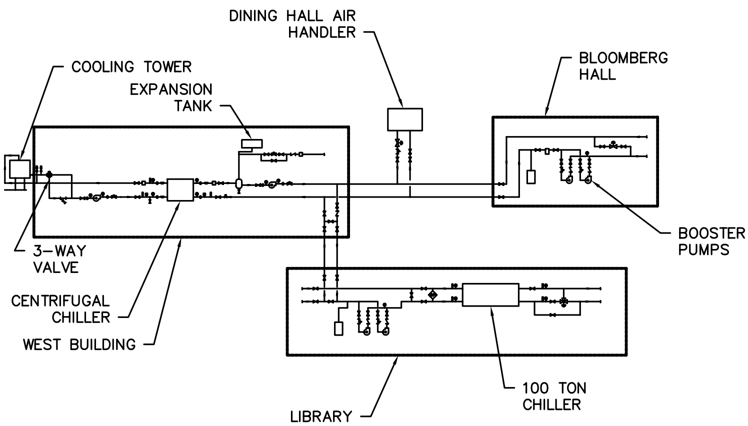
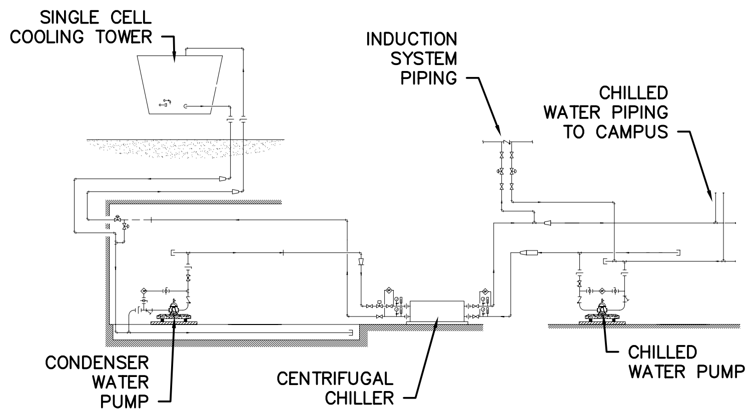


FIGURE 3. Chilled water plant schematic in year 2000.



winter cooling. The newer fan coil buildings were constructed to modern energy codes, but office occupants were increasingly complaining of overheating during even the coldest of winter months. This was especially prevalent, as would be expected, in south and west facing offices, and those with windows facing façade interior corners that were sheltered from the wind.

With no air side economizer option, the Institute was forced to operate the entire chilled water system for a longer portion of the year for just a handful of offices. This was very expensive, since a chiller had to operate, as well as the cooling tower, chilled water pumps, and condenser water pumps. The cooling tower was fitted with variable speed fans but the other equipment remained as constant volume units. The chiller was an inefficient unit using a refrigerant that is a highly reactive ozone depleting compound.

Since the cooling tower was not winterized, the portion of the year that the central system could operate was limited. Still, overheating complaints continued even through January and February.

SYSTEMS BIOLOGY ADDITION

To house the Simons Center for Systems Biology, a part of the Department of Natural Sciences, the Institute decided to build an addition to the existing Bloomberg Hall (Figure 4). The structure would house the main computer facility for the campus; several satellite facilities were to be combined to centralize the data processing operations.

Additionally, the Institute has a program for ongoing improvements to the central chilled water plant and distribution. The construction of the data center at the new Systems Biology Addition was a factor in implementing changes that would address some of the issues that had arisen from continued operation of the original system.

Given the desire to avoid local outdoor equipment, the new data facility was to be cooled from the central plant. This required year-round chilled water operation. The need for reliable cooling for the computer equipment required an increased level of dependability from the central plant system. With the move to year-round operation, however, the Institute was becoming increasingly concerned about operating costs, most of which related to energy usage.

FIGURE 4. Systems biology addition.

The construction of the Systems Biology Addition, therefore, became a two-part project. Despite being a relatively small building at less than 14,000 square feet, central plant improvements, which had been ongoing for years, received a new impetus to meet the goals of the project.

BUILDING SYSTEMS

The choice of building HVAC systems for the Biology Building was driven by several factors:

1. The building is an addition to an existing building that has low floor-to-ceiling heights.
2. The high visibility of the site militated against installation of rooftop or on-grade outdoor equipment.
3. The building is relatively small and it was desired to limit mechanical space allocations on the upper floors.
4. Each office required individual temperature control, and it was considered desirable to install systems similar to those in the existing building.
5. Incorporation of sustainable features was to be implemented where consistent with the other requirements.

The original building was conditioned by ceiling mounted fan coil units; it was decided to use this type of system in the new addition as well. This allowed matching of floor heights with the existing building. This type of system does not easily lend itself to energy saving features. A traditional candidate for energy use reduction would be a water side economizer for cooling. Since the building was served by a central chilled water plant, a local economizer system was not feasible. Energy savings on the chilled water side had to be addressed at the central plant.

The central plant also provided low pressure steam to the campus. However, extensive new buried distribution piping would be required to serve the building. The central system was also not particularly efficient, dependent as it was on older firetube steam boilers, gas fired. Even though additional maintenance would be required, it was decided to install local boilers. This afforded the opportunity to use high efficiency condensing boilers and was less expensive than the additional cost the buried distribution piping would have been. Resetting the boiler water temperature with outdoor temperature allowed for optimization of boiler efficiency. Energy use and carbon dioxide footprint of the local heating system is now approximately 25% less than that which would be produced by the central plant.

INDOOR AIR QUALITY AND RECYCLED CONTENT

The architectural program for the Biology Addition was also focused on sustainable design. All adhesives, sealants, paints, and carpet were required to meet the SCAQMD (South Coast Air Quality Management District) guidelines for VOC content. This is the reference standard that LEED uses for indoor air quality. The correlated LEED NC points are:

- 4.1 Low-Emitting Materials, Adhesives & Sealants
- 4.2 Low-Emitting Materials, Paints & Coatings
- 4.3 Low-Emitting Materials, Carpet Systems

Materials with recycled content were specified where there was low financial impact. Materials from regional fabrication plants were preferentially chosen. Recycled materials were only used when the manufacturing plant was local. Concrete masonry units (CMU) with 40% post-industrial recycled content were supplied by a New Jersey firm, Clayton Block. A synthetic gypsum wallboard with 100% post-industrial content came from USG in Aliquippa, Pennsylvania. The average recycled steel content is above 30% for steel framing and above 60% for structural steel. All cabinetry was constructed from medium density fiberboard made from 100% recycled content with no added urea formaldehyde.

While no formal IAQ plan was put in place, the base requirements from SMACNA's Sheet Metal and Air Conditioning National Contractors Association (SMACNA) IAQ Guidelines for Occupied Buildings under Construction, 1995, Chapter 3 were included for duct protection. Protection requirements for duct interior surfaces were strictly enforced during construction.

GREEN ROOF

The Systems Biology building has been provided with the first green roof in Mercer County, New Jersey. The roof system affords the benefit of increased insulation for the building envelope and reduces heat island effect. This roof system was designed to handle the storm water requirements for the building footprint in lieu of increasing the on-site retention pond. The cost of the green roof system is partially offset by cost savings resulting from elimination of the need to increase on-site storm water retention.

The roof is constructed in an IRMA composition. The layers, from bottom up, are as follows: fully adhered membrane, roof protection, four-inch Styrofoam insulation, drainage mat, moisture retention mat (.12 gallon/sf), drainage/aeration panel (.27 gallon/sf), four to six inches soil (1.04 gallon/sf) and an extensive planting of local sedums. The overall roof can retain approximately 1.43 gallons per square foot, which is about 45% of a 100 year storm. See Figure 5 for a photo of the green roof and Figure 6 for a cross section of the roof construction.

For additional relief from storm retention requirements, porous pavement was used for the reconstructed roadways around the building.

DEMAND CONTROLLED VENTILATION

A dedicated ventilation air unit has been provided for the building, located in a ground level mechanical room. This type of unit would ordinarily be on a time clock controller so that it operates during normal occupied hours.

In this case, this scheduled operation is not appropriate for the faculty and staff at the Institute,

FIGURE 5. Green roof.

who work odd hours. Instead, occupancy sensors were provided to turn lights on when each office was occupied. These same sensors were interlocked with the HVAC controls system so that heating, cooling and ventilation could be controlled to operate when the space is actually occupied.

Upon occupancy of a particular office, a motorized damper in a dedicated ventilation duct opens, admitting the required amount of outside air. Each ventilation duct is fitted with an automatic airflow device which assures proper airflow independent of pressure in the supply system. The outdoor air supply unit is fitted with a variable speed drive to maintain approximate constant pressure in the supply duct, but the flow control fitting automatically compensates for pressure changes so that the outdoor air flow required by code is provided. When the motion sensor detects that the office is unoccupied, the damper in the outdoor air duct closes. A photo of a controls assembly is shown in Figure 7; the fan coil unit and ductwork had not yet been installed.

During system commissioning, an unexpected problem developed. The motorized dampers were selected as power open and spring closed. When the damper cycled to the closed position, a high pitched whine was emitted by the spring return mechanism. Since the dampers were generally located in the occupied space, the sound was audible to anyone in

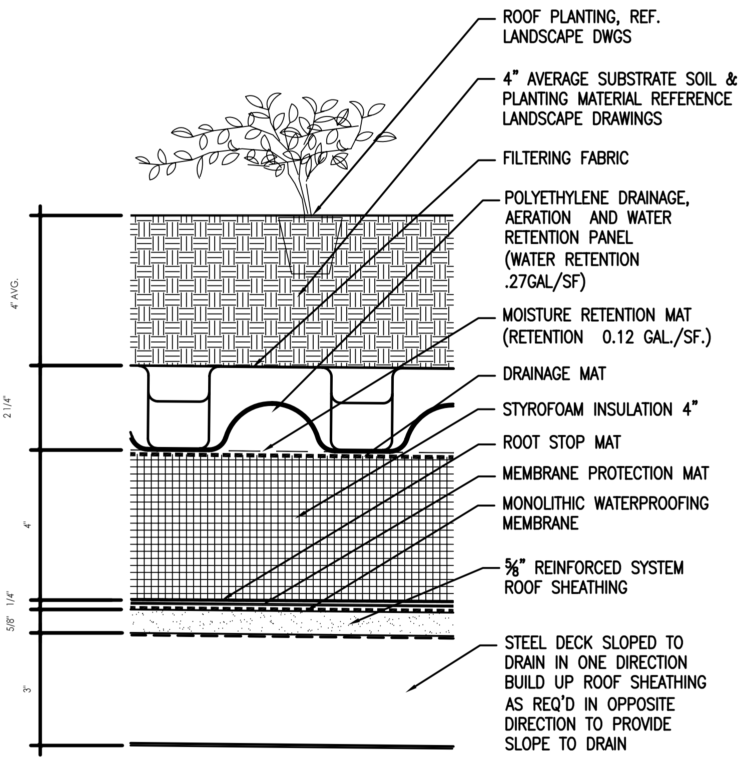


FIGURE 6. Typical green roof section.

FIGURE 7. Ventilation air control assembly.

the room. Fortunately, time delay could be adjusted so that the occupant had left the room when the damper cycled closed, thus preventing the sound from becoming an issue.

CONFERENCE ROOM DEMAND CONTROLLED VENTILATION

Most of the space in the building, aside from the computer room, consists of individual offices. Additionally, there is one large conference room with a maximum occupancy of 20 persons. Ventilation for this space is handled by the ventilation air handling unit. Since occupancy of this room can vary widely, it was decided to use carbon dioxide levels, as permitted by code, to control the amount of outside air. A standard straight shutoff variable air volume box controls the outdoor air flow, with a CO_2 sensor located in the space.

OCCUPANCY INITIATED TEMPERATURE CONTROL

The same occupancy sensor controls temperature setpoint within each space. When the space is unoccupied, temperature is allowed to drift to a setback or setup temperature.

One of the concerns was that the recovery time, once the office is reoccupied, would be too long and that the occupant would experience a lengthy period of discomfort upon re-entering the space. For this reason, three modes of operation were specified:

Occupied—Whenever occupancy sensor indicates someone is present in the room.

Standby—Whenever occupancy sensor indicates no one is present in the room between the hours of 8 AM to 6 PM.

Unoccupied—Whenever occupancy sensor indicates no one is present in the room between the hours of 6 PM to 8 AM and on weekends.

The default occupied temperature was set to 70°F during the winter and 75°F during the summer. In standby mode, the winter setback temperature was limited to 65°F. This allows for a quicker return to comfort temperatures during periods during which the offices are more likely to be occupied. For the rest of the day and weekends, the winter setback temperature is reduced to 55°F. In cooling mode the standby setback temperature is limited to 80°F; in unoccupied mode, there is no cooling.

All setpoints and schedules are individually adjustable to suit the occupant of each space. It is intended that setpoints and schedule be reviewed periodically to optimize energy use while minimizing occupant discomfort. For example, if a particular staff member never works Wednesday, his or her occupancy schedule would be amended appropriately.

COMPUTER ROOM HEAT RECOVERY

The Institute for Advanced Study has created a significant data processing facility in the Systems Biology Addition. The environmental control system is designed to supply 60 tons of cooling with standby capability of an additional 20 tons. The design team investigated means of recapturing some of the energy released by the computer equipment.

The data room is cooled by chilled water from the central plant. The selected approach was to use the return chilled water from the computer room cooling units in a water-to-water heat pump. The heat pump would extract energy from the return chilled water, thus reducing the chilled water temperature back to the central plant. The heat pump would then supply warm water to a reheat coil in the air handling unit, which provides 100% outdoor air to the building. A schematic for the system is shown in Figure 8.

In heating mode, the air handling unit uses hot water from the building boilers at 180°F (reset by

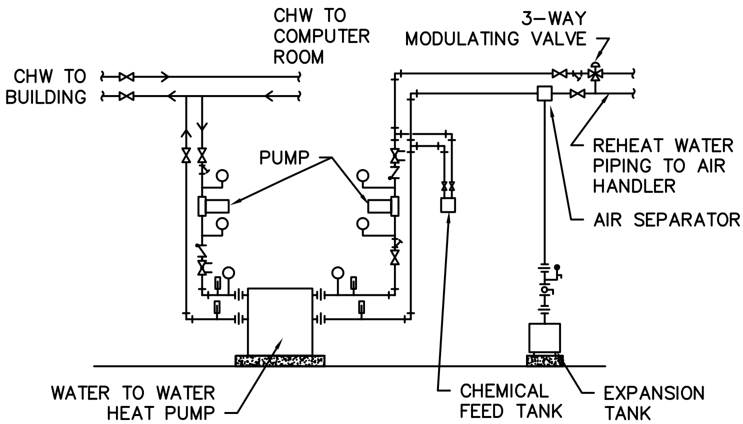


FIGURE 8. Computer room heat recovery system.

outdoor temperature) in order to preheat the incoming air to 50°F. A heat pump system is not efficient at very low entering air temperatures. The water-to-water heat pump produces 120 degree water to send to the reheat coil which warms the air to a neutral 70 degrees (winter setpoint).

At a water supply temperature of 120 degrees and a source (return chilled water temperature) of 50 degrees, the COP of the heat pump is 3.9. An additional small circulating pump is required that uses less than 100 watts. Coils were selected to minimize pressure drop, thus reducing pump energy. This is in contrast to an efficiency of approximately 90 percent for the gas fired boiler.

During cooling operation the reheat coil is activated when the outdoor air handling unit is in dehumidification mode. When the space relative humidity is above 65 percent, the chilled water coil sub-cools the air to reduce the moisture content of the discharge air. The heat pump supplied reheat coil is used to return the air to a neutral temperature of 75 degrees (summer setpoint). Heat is absorbed by the heat pump in both of these processes from the chilled water returned to the central plant serving to reduce the load on the chiller system.

The cost of operation of the reheat coil using the heat pump is only 55 percent of that for boiler operation. The additional benefit to the central chiller plant varies depending on time of year. During the summer, the total heating and cooling energy cost of the heat pump system is 41 percent of the combined cost of the central chiller and boiler operation. During the winter, the chiller plant savings are less due to the lower operating cost of the chillers in available free cooling mode.

The computer room cooling capacity is approximately 720 MBH, though the present IT hardware is not close to needing the full capacity of the cooling system. Only a small portion, 45 MBH, of that rejected heat could be easily utilized by the building systems. Theoretically, when the computer room is at full capacity, its waste heat would be capable of supplying all of the building's design heating load. A different sort of heating system, such as a distributed heat pump system, could more fully take advantage of the computer room energy. For various reasons, including noise and maintenance issues, the design team did not pursue this option.

COMPUTER ROOM CONTROLLED SHUTDOWN

A major concern of the Institute was the reliability of the computer room operations. Upgrades to the central plant were instituted to more fully ensure that chilled water flow to the facility was not interrupted. The second major concern was the effect of a power outage.

Putting the central chiller plant and the computer room on an emergency power source was not an affordable option. Also, the relative rarity of power outages did not warrant such a large investment. The IT department felt that its major concern was loss of a major computer run if it was suddenly interrupted part-way through. A UPS system was installed which would allow 20–30 minutes of computer operation to enable a controlled shutdown to save data.

The concern then was that the room would overheat in a very short period of time, before the shutdown could be properly completed. The space is relatively small and is completely sealed off from the rest of the building. Computer equipment heat dissipation would raise room temperature to damaging levels in a matter of minutes. There was no ready means of providing cooling even for the relatively short period of time needed for the shutdown.

The computer room is mostly below grade but located against an outside wall. Mechanical ventilation using outside air was feasible, but if the power outage occurred during very hot weather, which historically has been the case, the cooling effect of the ventilation air would be compromised.

A more effective approach arose when it was realized that there was a large reservoir of cool air available for the computer room. Four motorized dampers were installed in the demising wall between the computer room and the adjacent corridor. An additional opening with a motorized damper was placed to connect the corridor with the building atrium. All dampers were selected to fail open. Upon a power outage an exhaust fan in the computer room, powered by the UPS, would activate. The dampers separating the rest of the building from the computer room would open and the space would have a supply of conditioned air to help keep the data equipment cool while shutting down. A plan of the computer room, with emergency exhaust system, is shown in Figure 9.

The exhaust fan load required only a modest increase in UPS capacity. The corridor dampers were required to be fire and smoke rated. Ultra low leakage dampers were chosen so as to minimize energy loss from the computer room, which required temperature and humidity control. While not technically a sustainability feature, this system avoided the need for an elaborate emergency power system for mechanical cooling.

CENTRAL PLANT IMPROVEMENTS

As discussed previously, the critical nature of the operation of the new computer facility required that the central chilled water system be upgraded.

The previous central computer rooms used direct expansion, split system environmental control units. The efficiency of these units was on the order of 1.5 kW/ton. The central plant, utilizing an open cooling tower system, had the potential to produce chilled water at a lower cost. In addition, there was no reasonable location near the building to place the condensing units. Both sound and appearance were obstacles.

Original Plant Configuration

The original 1969 central cooling plant consisted of a 315 ton centrifugal chiller, an open single cell cooling tower, and constant volume chilled and condenser water pumps. The chillers used an ozone depleting refrigerant and ran at a full load efficiency level of 0.87 kW/ton. At 25 percent load, the efficiency decreased to 1.04 kW/ton. The condenser water temperature to the chillers was controlled by a three-way valve so that the condenser water could bypass the cooling tower in order to maintain a minimum condenser water temperature to the chillers. Centrifugal chillers generally require a minimum condenser water temperature of approximately 60°F.

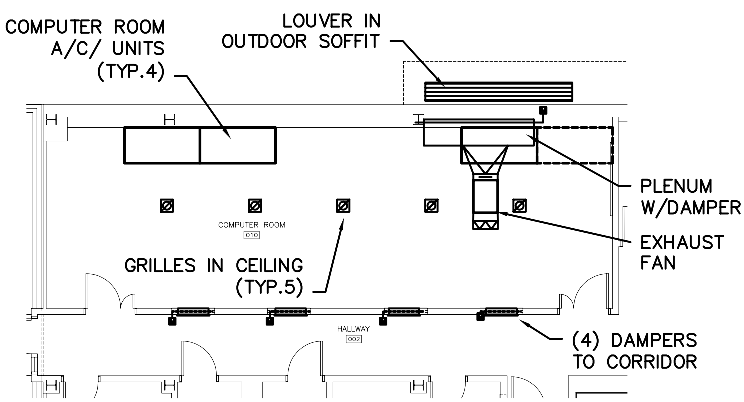


FIGURE 9. Computer room emergency ventilation system.

The condenser water pump and cooling tower fan operated constantly. Chilled water was pumped continuously at a constant volume through both chillers, and circulated throughout the campus.

With a single pump circulating water to the furthest points in the campus, the pump operated at full capacity at all times. The vast majority of the time, chilled water circulated with very low temperature difference between the supply and return water. The system was nominally sized for a 10°F temperature increase. Differential temperatures of as little as 2°F were the norm. This arrangement was common for older chiller plants before the advent of computer based automation systems and variable speed controls.

Ongoing Plant and Chilled Water Distribution Improvements

Subsequent to the original installation, a variable frequency drive was installed to control the cooling tower fan. This allowed better temperature control for the condenser water and some energy savings.

The Institute then embarked on a long-term plan to reduce pumping energy. Starting in 2002, HVAC systems in each new and renovated building were modified with secondary chilled water pumps. The terminal units in these buildings were provided with two-way control valves. The secondary pumps only provided as much flow as needed to satisfy the cooling load; they very seldom ran at full capacity. With pump motor horsepower varying with the cube of the flow, significant energy savings were realized from variable flow systems.

The primary chilled water pumps benefit from this arrangement since they only have to pump around the main underground piping loop rather than through the buildings and to the chilled water coils. Since not all of the buildings have been converted to variable secondary flow, the full benefits of the primary-secondary system have not yet been realized. However, most of the buildings more distant from the central plant have been so converted. At the present time, the central chilled water pumps are programmed to provide constant volume flow through use of a flow meter. As more systems are converted to secondary pumping, the pressure against which the primary pump works will decrease and horsepower will drop.

In 2004, a second centrifugal chiller was installed in the central plant. Anticipating the need for winter cooling, the new chiller was selected as a variable refrigerant flow type, providing better part load efficiency than a constant speed unit. This chiller was also chosen with oversized condenser and evaporator tube bundles for increased overall efficiency. The high efficiency of this chiller enabled the Institute to obtain rebates from a New Jersey utility program.

A new two-cell cooling tower was installed. While, at that time, the connected campus cooling load was approximately 300 tons, the cooling tower was oversized at 600 nominal ton capacity. This would accommodate further campus expansion and would increase the efficiency of the chillers by allowing cooler condensing water temperatures at design conditions. The two-cell design allows isolation of one of the cells while the other is cleaned.

A new chilled water and condenser water pump was also installed at that time to supplement existing equipment. Variable frequency drives were provided for the new pumps.

New Central Plant Improvements

When the Biology Building was in the planning stage, replacement of the older chiller and the last original chilled water and condenser water pump was felt to be vital to assure maximum reliability for computer room operation. This provided an opportunity to select a chiller that would provide for the highest overall plant efficiency.

The previous chiller addition provided a 350 ton variable speed machine. However, for the second unit, a constant speed chiller was provided. The constant speed chiller is more efficient than the variable speed chiller at close to full load, while the variable speed unit is more efficient at part loads. The constant speed chiller also was selected with "free" cooling capability that allowed approximately 40 tons of cooling to be produced without operation of the compressor. The new chiller was also equipped with oversized evaporator and condenser tube bundles to increase efficiency throughout the operating range.

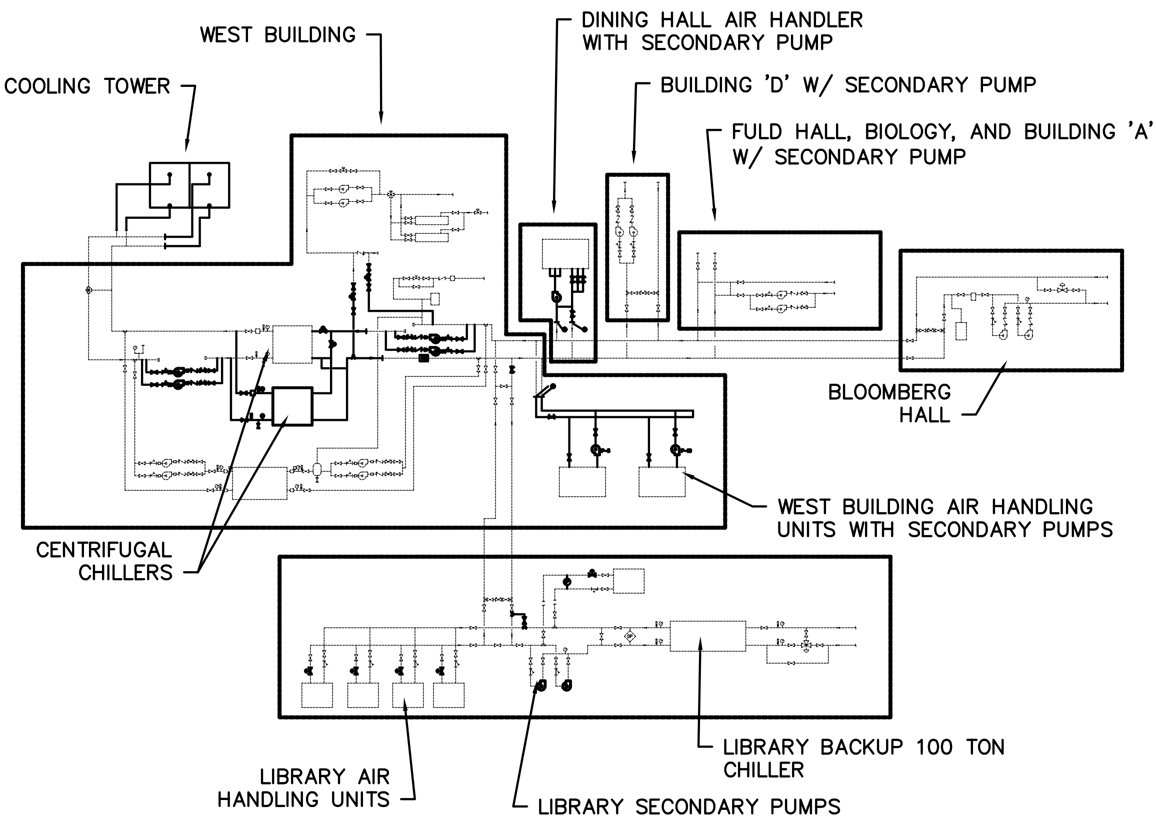
"Free" cooling cycle is a misnomer since the cooling tower and condenser water pumping systems have to operate, but this mode of operation still uses significantly less energy than cooling with the compressor operating. This mode uses the natural migration of refrigerant from the evaporator to the condenser sections when the condenser water temperatures are low enough. With the requirement for year-round cooling for the Biology Building computer room, a substantial savings in winter season energy use could be realized. Even though the computer room is sized for 60 tons of cooling, the available 40 tons of cooling without compressor operation will be adequate for the majority of the time. The cooling system will also benefit from the approximately 3.75 tons of additional capacity added to the cooling system by the computer room heat recovery system.

The cooling tower was modified to allow lower energy use during part load operation. Variable speed fans were retained for both cells and the second cell was winterized. A valve was installed that allowed the tower water to be bypassed directly into the basin at very low load conditions. The three-way mixing valve was retained so that condenser water temperatures could be controlled to be above the minimum necessary for proper chiller operation.

A further improvement was made to the cooling tower water filtration system. The cooling towers are located adjacent to a wooded area and strainers required constant maintenance. Debris in the condenser water reduced flow and system efficiency.

A large capacity dual chamber basket strainer was installed in the condenser water piping to the chillers. A diverting valve allowed full flow to be switched from one strainer to the other, allowing easier clearing of the system without need for a shutdown. A cleaner system also would reduce chiller efficiency losses due to condenser tube fouling and lower pumping energy use. Chilled water system upgrades are shown in Figure 10. Figure 11 shows a schematic of the new central plant configuration.

FIGURE 10. New campus chilled water distribution system.



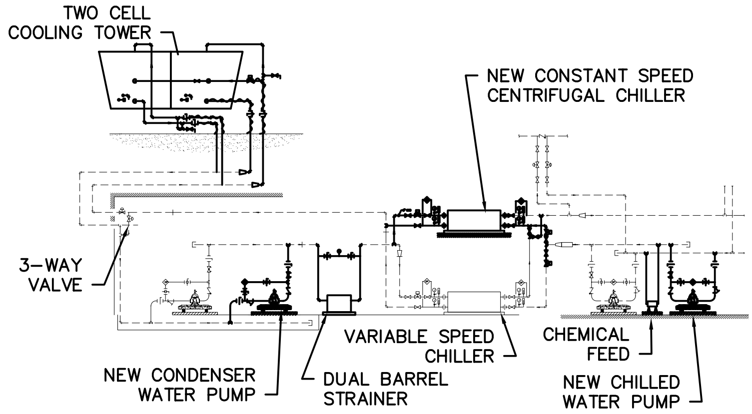


FIGURE 11. New central chiller plant configuration.

Plant Optimization

With the central plant equipment upgrade complete, the remaining task will be to operate the plant using the least energy possible. This process is ongoing; an implementation plan has been put in place that includes seasonal verification of equipment operation.

As the largest single users of power, the first focus was on the chillers. Chillers are operated with bypass valves allowing flow through either or both chillers. When plant load exceeds the capacity of a single chiller, the chillers operate in series. The flow meter maintains constant volume flow whether the flow is through a single chiller or both chillers. A comparison of chiller efficiencies at various load conditions is shown in Figure 12.

The intended sequence of operation of the two chillers is as follows, from low to high cooling load:

1. Constant speed chiller, free cooling mode (approximately 0–70 tons)
   a. Flow is directed through the constant speed chiller only.
   b. Compressor does not operate.
   c. Condenser water temperature (CWT) is allowed to fall to 35°F. The cooling tower fans, tower bypass valves, and mixing valve are sequenced to maintain the minimum CWT. In order to extend free cooling operation, the cooling towers are to lower the condenser water temperature by routing additional water through the fill, increasing fan rpm and activating a second tower, as appropriate.
   d. Chilled water supply temperature is monitored. When required temperature cannot be maintained, free cooling mode is disabled.
   e. The ability of the chiller to provide sufficient cooling depends on the condenser water temperature and the building cooling load requirements. Only at a CWT of 40 degrees and below can sufficiently cold chilled water be produced. At this CWT the chiller will produce approximately 74 tons of cooling. This would be sufficient for the Biology Building computer room and miscellaneous winter cooling requirements throughout the campus. There may be times when campus cooling load is low, but the required chilled water temperature cannot be maintained. This situation could occur, for example, during a relatively warm winter day. Chiller free cooling capacities are tabulated in Figure 13.

2. Variable speed chiller (approximately 70–325 tons)
   a. Mixing valve brings condenser water temperature up to minimum operating level for compressor operation, approximately 65°F.
   b. Flow is redirected through variable speed chiller only.
   c. Compressor operates at level needed to maintain required discharge chilled water temperature.
   d. Compressor speed is monitored; when variable speed chiller reaches the capacity level

FIGURE 12. Chiller efficiency vs. load.

% Maximum Capacity		100	90	80	70	60	50	40	30	20	10
CONSTANT SPEED CHILLER	Tonnage	350	315	280	245	210	175	140	105	70	56
	Efficiency (kw/ton)	0.5422	0.5103	0.4935	0.4857	0.4862	0.4944	0.5308	0.584	0.6805	0.7439
VARIABLE SPEED CHILLER	Tonnage	355	319.5	284	248.5	213	177.5	142	106.5	71	35.5
	Efficiency (kw/ton)	0.5601	0.4955	0.443	0.4005	0.3655	0.3333	0.3456	0.3738	0.4254	N/A

Efficiencies are based on 42 degrees F leaving evaporator water temperature.

FIGURE 13. Chiller free cooling capacities.

FREE COOLING CAPACITY AT 35 DEGREE F ECWT								
TONS	49	74	99	124	149	174	199	224
Entering Evaporator Water Temp	39.5	41.2	42.8	44.4	46	47.6	49.3	50.9
Leaving Evaporator Water Temp	38.2	39.1	40	40.9	41.8	42.8	43.7	*44.6*
FREE COOLING CAPACITY AT 40 DEGREE F ECWT								
TONS	49	74	99	124	149	174	199	224
Entering Evaporator Water Temp	44.5	46.1	*47.7*	*49.3*	*50.9*	*52.5*	*54.1*	*55.6*
Leaving Evaporator Water Temp	43.1	44.1	*45*	*45.8*	*46.7*	*47.6*	*48.5*	*49.3*

at which it is less efficient than the constant speed chiller, this chiller shall shut down and condenser and chilled water shall be diverted to the constant speed unit.

3. Constant speed chiller (approximately 325–350 tons)
   a. At close to full capacity, constant speed chiller operates.
   b. Flow is redirected through constant speed chiller only.
4. Chiller series operation (over 350 tons)
   a. When campus load exceeds the capacity of the constant speed chiller, valves shall direct chilled water flow in series through both chillers. Return water shall first pass through the constant speed chiller that shall operate at full capacity.
   b. Chilled water pump shall increase speed to maintain constant flow. Both condenser water pumps shall operate.
   c. Constant speed chiller shall operate at full capacity; variable speed chiller shall operate to maintain required discharge chilled water temperature.
   d. Sequence shall reverse when campus cooling load decreases.

Future Improvements

Planning is underway for further upgrades to the campus systems. Eventually, all the individual building chilled water systems will be equipped with secondary flow pumps. This will afford the opportunity of varying the primary chilled water flow, consistent with the requirements of the chillers. Aside from reducing pumping energy, the number of annual hours free cooling can be implemented can be extended. With reduced flow rates, evaporator discharge water temperature can be lowered.

Some of the older buildings do not yet have direct digital controls. Upgrade of these control systems will have comfort and energy saving benefits. Conversion from constant volume reheat systems to variable flow for these buildings is under investigation.

Changes to a multi-building complex are necessarily implemented incrementally. The improvements executed to date are only initial steps in an ongoing process. As technology improves and energy sources evolve, opportunities for improvements will present themselves. As best we can, we should anticipate these changes and specify systems that can best take advantage of them.

PROJECT TEAM

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