The Milton S. Hershey Medical Center Academic Support Building

AE Senior Thesis
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Kari Anne Donovan
Mechanical Option

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Hershey, PA

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PROJECT TEAM

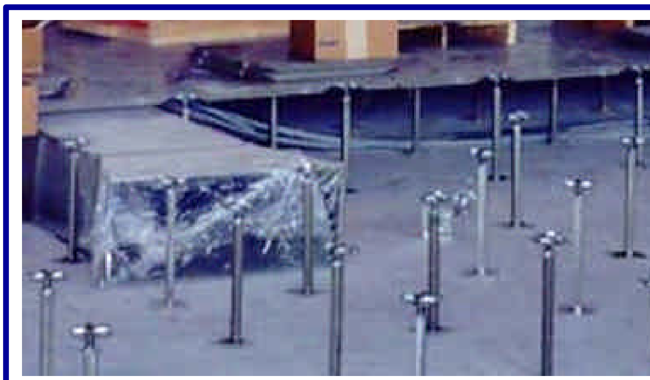
- Owner - The Pennsylvania State University
- Architect - Williams Trebilcock and Whitehead
- Construction Manager - Barclay-White, Incorporated
- Site and Civil Engineers - Rettew Associates
- Structural Engineers - Whitney Bailey Cox and Magnani
- Mechanical and Electrical Engineers - Brinjac-Kambic Associates

PROJECT DESCRIPTION

The Milton S. Hershey Medical Center Academic Support Building is a mixed use office building located on Penn State land in Hershey, PA. The 5 story, 145,316 gross sq. ft building houses departments for both Penn State College of Medicine and Hershey Medical Center. The 19 million dollar design-build project was designed to facilitate flexibility of the building program. Its central core houses an elevator bank, restrooms, a stairwell, and shared conference spaces. The angled wings contain suites with distinct entrances for each department.

STRUCTURAL

- ASTM A-572 structural steel floor beams
- ASTM A-36 structural steel columns and brackets
- 400psi elevated floor slabs on composite metal deck
- 1900psi foundation block walls



Access flooring with underfloor ductwork and cable tray installed.

MECHANICAL

- Underfloor air distribution system
- 7,513 sq ft return air plenum mechanical penthouse
- (4) 42,500/3,750 cfm minimum OAT AHUs w/ VFD fan motors and 400lb/hr gas fired humidifiers
- (3) 48.2 boiler hp/1615 MBH gas fired boilers
- (2) 225 ton packaged air-cooled chillers
- 27.1 ton reciprocating winter chiller w/ remote chiller barrel
- 12-16” perimeter hot water radiant heating panels

Floor diffuser and cable tray access.

Access flooring panel.

ELECTRICAL/LIGHTING

- 15KVA transformer 13.8KV/480Y/277V
- Main distribution board 2500amp, 480Y/277V main bus, metered
- 208Y/120 112.5KVA transformers on each floor
- 150KW roof mounted generator set
- Moveable underfloor junction boxes housing outlet & data jacks
- General interior lighting from compact fluorescent and T-8 lamps
- Outside lighting is 175W metal halide post-top lighting

Kari Anne Donovan

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Mechanical Option

Executive Summary

The Milton S. Hershey Medical Center Academic Support Building is a 5 story, 146,316 square foot office building located on Penn State's College of Medicine land in Hershey, PA. The Penn State University owned building houses various departments of Penn State College of Medicine and The Milton S. Hershey Medical Center. The intent of the existing mechanical system design was to provide a flexible system that would decrease utility costs, reduce maintenance calls, and reduce renovation costs due to office space churn. While the building's variable air volume (VAV) underfloor air distribution provided the flexibility required, its performance left much to be desired. There were significant thermal, acoustical, pressurization, and performance problems with the system. After a little over two years since building occupation, more than half a million dollars has been spent to correct the mechanical system's problems.

The proposed mechanical system redesign brings back into focus the original design intent of the building owner. Because there is a year round building cooling load and the current design does not meet ASHRAE Standard 62 ventilation requirements, a parallel Dedicated Outdoor Air System (DOAS)/Radiant System was implemented. The integrated proposed redesign reduced first cost of the building ($231,800), operating costs, and improved IAQ and thermal comfort compared to the existing VAV underfloor air distribution system. The lamps were changed from T8s to T5s to increase energy savings and decrease the installation cost. The electrical service to the building was reduced due to the changes in the proposed mechanical system design. The potential total annual energy savings of the proposed integrated redesign is $43,185. The proposed redesign still accommodates office churn due to layout and retaining the access flooring system.

Building Overview

The Milton S. Hershey Medical Center Academic Support Building is located on The Pennsylvania State University's campus in Hershey, PA. The building is owned by The Pennsylvania State University and was built on university owned land. The five story, 146,315 gross square foot building houses various departments of Penn State College of Medicine and The Milton S. Hershey Medical Center. The intent of the new mixed office use structure was to relocate departments previously located off-campus or in the existing mega-structure, reducing travel time from off-campus properties, and allowing Penn State to use prior lease payments to build equity and own the facility. (Penn State Milton S. Hershey Medical Center)

The building was designed for versatility to house the School of Medicine and Hershey Medical Center departments. The building consists of a central core connected to two angled wings. The building wings house the departments' suites with offices on the perimeter and open floor plans in the center. The central core houses a stairwell, elevators, rest rooms, and shared conference spaces.

Primary Project Team

Owner	The Pennsylvania State University
Architect	Williams Trebilcock and Whitehead
Construction Manager	Barclay – White, Incorporated
Site and Civil Engineers	Rettew Associates
Mechanical and Electrical Engineers	Brinjac – Kambic Associates
Structural Engineers	Whitney Bailey Cox and Magnani

Design Process

The design process for the building was unique in that not all of the groups involved in the initial design for the Academic Support Building ended up as building occupants. During the design phase, Penn State and Geisinger merged, creating complications when design standards for both institutions needed to be met. Geisinger Health System approached the design being bottom line burdened and throughout the merger exhibited a desire to be in full control of all decision making. It was made clear that they were tenants in this Penn State building and that the interior space would be fit out to suit their needs by the University. As a result, Geisinger Health System was very adamant about the cost per square foot of the building. This required a guaranteed maximum price at an early stage in the project. Once bidding was underway, a de-merger between Penn State and Geisinger occurred, causing the design compromises between them to ultimately be unnecessary.

Design Objectives and Requirements

The intent of the building's mechanical system was to decrease utility costs, reduce maintenance calls, and reduce renovation costs due to office space churn. The underfloor air distribution was chosen to facilitate the need for building program versatility. The system provides control over personal air supply through the adjustable floor diffusers as well as the flexibility of adding and removing diffusers based on zone occupancy. Underfloor mounted junction boxes with additional 10 ft electrical and data cable slack allowed power and data receptacles to be relocatable as well

Site Factors

The Academic Support Building is located on the east side of the campus due to the desire to have it located as close as possible to the main complex for those employees who wanted to walk. The building was placed as close to the center of campus as possible to reduce the visual impact on the residential neighbors to the east.

Central Utility Plant

A central utility plant (CUP) on the campus produces steam and chilled water and distributes them to the connected buildings. The use of utilities from the CUP was considered in the design phase of the Academic Support Building but was not pursued based on the first cost. For Penn State, the financial analysis was lease vs. own. For Geisinger Health System, it was leases in the community. All of the community rentals have standalone chillers and are not burdened with the first cost of extending piping and central plant equipment.

Energy Sources and Rates

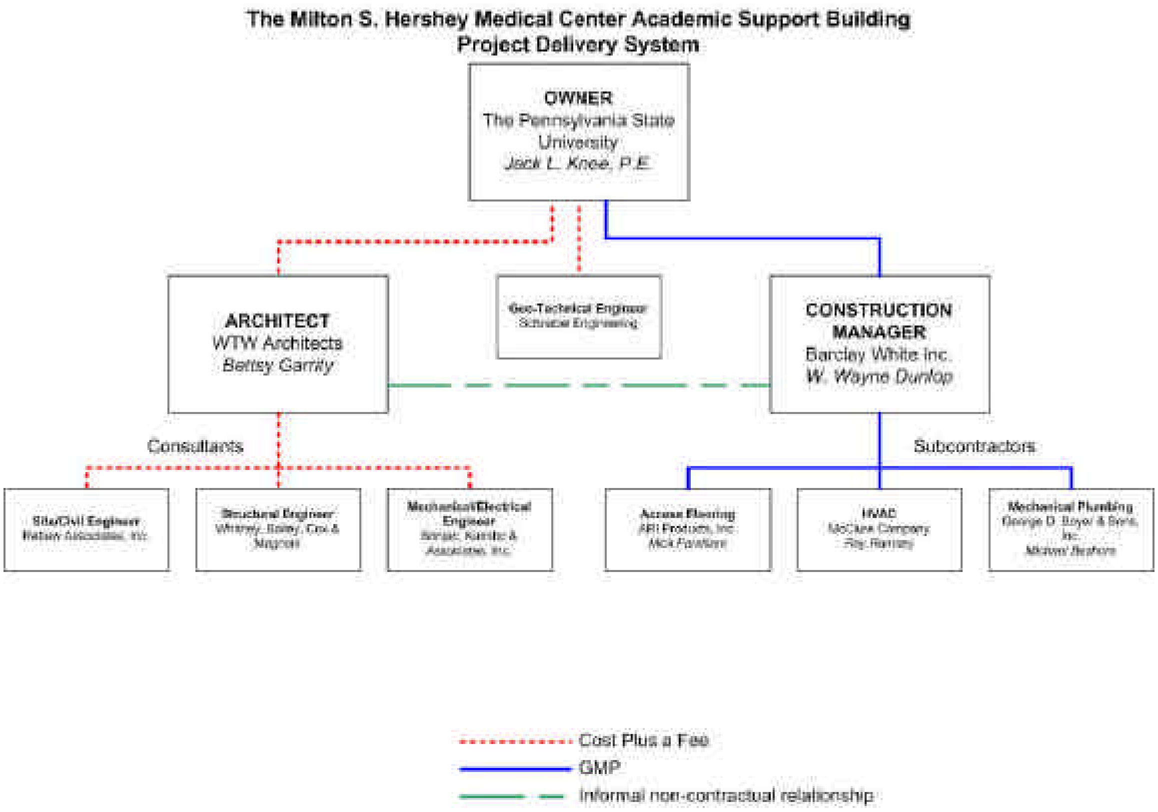
There were no utility rebates that influenced the design. The energy sources and utility rates for the building include the following:

Natural Gas - \$5.8853/MCF
Electric - \$4.821/kW monthly demand charge
- \$0.04512/kWh for 1st 200 kWh/kW
- \$0.03763/kWh for 2nd 200 kWh/kW
- \$ 0.03203/kwh for remaining kWh
Water - \$4.4033/MGAL
Sewer - \$3.269/MGAL

Construction Summary

Project Delivery System

The project delivery system was a construction project management approach where the owner has a project manager. The owner hired both the architect and the construction manager. The owner also hired an independent geo-technical engineer. The architect hired the engineering consultants and the construction manager hired the sub contractors.



Dates of Construction

Construction Start	2/28/1999
Date of Completion	4/2000
Occupancy	5/2000

Cost Information

Division	Estimate*	Percent of Total
General Requirements	$991,146.00	5%
Sitework	$1,553,539.00	8%
Concrete	$1,850,000.00	10%
Masonry	$45,000.00	0%
Metals	$1,529,500.00	8%
Wood and Plastics	$451,250.00	2%
Thermal and Moisture Protection	$811,810.00	4%
Doors and Windows	$1,425,928.00	8%
Finishes	$1,292,359.00	7%
Specialties	$1,458,323.00	8%
Equipment	$-	0%
Furnishings	$595,770.00	3%
Special Construction	$-	0%
Conveying Systems	$160,000.00	1%
Mechanical	$2,864,835.00	15%
Electrical	$2,424,336.00	13%
Contingency	$850,000.00	4%
Permits & Contractor Bonds	$320,316.00	2%
CM Fee	$372,482.00	2%
GMP	$18,996,594.00	100%

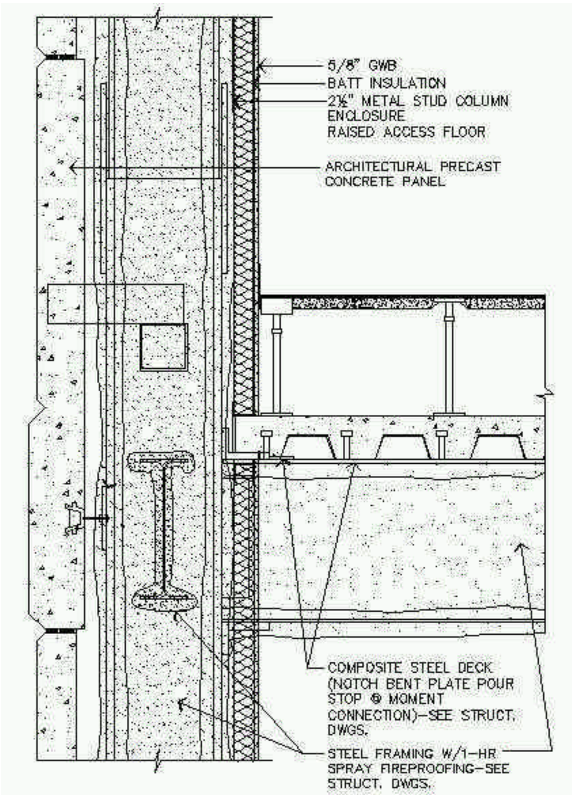
* Figures from 2/19/1999 Revised GMP estimate prepared by Barclay White, Inc.

Architecture

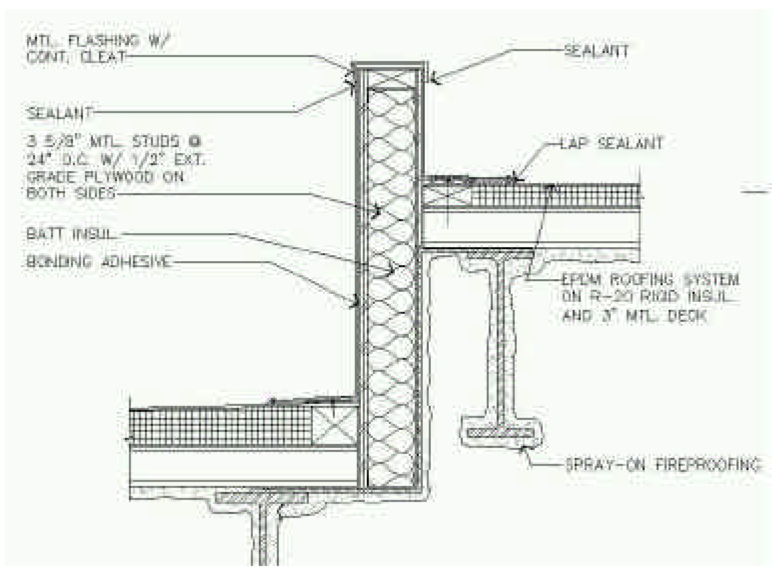
The exterior of the building is not extravagant. Materials are dominantly pre-cast concrete and glass. An abundance of landscaping and parking surrounds the building. The central core consists of common space including an elevator bank, stairwell, rest rooms, and shared conference spaces. The angled wings have private perimeter offices and the center floor area is an open office setup that allows each of the department to reconfigure the space as needed. Each wing also has a distinct entrance for each department. A staff eating area located on the first floor is provided for the entire building. The mechanical penthouse is enclosed in high quality painted metal.

Building Systems

Building Envelope



- 5/8" GWB on metal studs with mineral fiber blanket batt insulation
- Architectural pre-cast concrete panels
- Aluminum framed double pane class windows
- Exterior spandrel glass



- Manufactured painted metal panels (for penthouse)
- EPDM roofing on minimum R-20 insulation board

Electrical

The electrical service to the building is supplied from the owner's 15kV distribution system in a concrete encased duct bank. Other building electrical components include

- Outdoor dual load break selector switches.
- 15kVA transformer 13.8kV/480Y/277V.
- Main distribution board 2500 amp, 480Y/277 main bus, metered.
- 480 delta to 208Y/120 112.5kVA transformers on each floor
- 150kW roof mounted generator set, 400 amp automatic transfer switch and area protection panel.
- Door security card reader system.
- Video with room for future cameras and satellite dish for the roof.
- Site Lighting control panel hand/off/auto integrated 365 day, 8-channel time clock photocell. Time clock control and photocell control (auto/bypass) is in series for permitting site lighting.

Emergency Power

The emergency power system includes a 480Y/277 3-phase 4-wire panel and a 208Y/120 3-phase panel for each floor. The building also has 2 emergency dry transformers, a 30kVA serving floors 1-3 and a 15kVA serving floors 4-5 and the penthouse. A 120/240V panel serves the food service/storage area. Power is provided by an emergency generator that is activated by the emergency transfer switch.

Fire Alarm System

The fire alarm system is an addressable multi-plex system designed to have 100% spare capacity over designed points. It is listed for auxiliary and remote station service in accordance with UL 860 – *Control units for fire protective signaling service*. The fire alarm panel has an interface module to the main ATC panel, fire alarm annunciation (120VAC normal emergency supply), manual pull stations, fire alarm visual signaling, sprinkler system interface, and tamper switches on the control valves. Smoke detectors are located in ducts and occupied areas. Elevator shafts have both heat and smoke detectors while the cars only have heat detectors. The fire alarm panel is also tied into the smoke proof enclosure systems.

Lighting

The outside lighting is 175W metal halide post-top lighting. Architectural area lighting is compact fluorescent bollards. Spotlighting is achieved through flush mounted 75W incandescent well lights. General interior lighting is compact fluorescent and F-32 T-8 277V with electronic ballasts, some with dimming capabilities. Exit signs are LED 277V type. There is some specialty decorative lighting using incandescent lighting.

Underfloor Junction Boxes

The underfloor junction boxes are mounted on the concrete floor and feed flexible/detachable connectors to plug into relocateable floor boxes. The floor box installation includes 2 duplex telephone/data jacks, 2 duplex outlets with a minimum of 10 ft of wiring slack to permit flexibility of location.

Telecommunications

The telecommunications service to the building is fed from the site owned concrete encased duct bank. The data cable trays are in the raised floor supply air plenum. There is CAT 3 voice distribution in the main risers and CAT 5 for data distribution on the floors. There is a minimum of 10 ft of CAT 5 wiring slack to permit the flexibility of the location of the floor boxes.

Mechanical

The building’s HVAC system is a variable air volume (VAV) underfloor air distribution system. Automatic floor diffusers serve perimeter spaces and manual floor diffusers serve interior spaces. Each floor has a ceiling plenum return with return air dampers leading to the return airshaft and the return air plenum penthouse. Controls included in the underfloor system are temperature, humidity, and pressure. The penthouse is a 7,513 sq ft return air plenum that also houses the air handling units, boilers, and pumps. There are four 42,500 cfm supply air (3,750 cfm minimum outside air) air handling units

(AHUs). The units have an outdoor air mixing box, 30% pre-filters, 90% filters, face and bypass dampers for both the hot water heating coil and the chilled water cooling coil with 2 position, 2 way valves, and 400lb.hr gas fired humidifiers. Two units operate in an AHU system to serve a wing. One of the system's units has a variable frequency drive (VFD). There are three gas fired boilers rated at 48.2 boiler hp and 1615 MBH. There is a 27 ton winter reciprocating chiller with a remote chiller barrel and two 225 ton packaged air cooled chillers. The primary chilled water pumps and the secondary hot water pumps have VFD's.

Four-pipe fan coil units serve the lobbies, vestibules, elevator waiting areas, electric rooms, and data rooms. Hot water cabinet unit heaters serve the stairwells, penthouse, and receiving rooms. Hot water radiant ceiling panels are located in the perimeter spaces on all floors. Ceiling supply fans recirculate air from the ceiling return air plenum to the occupied space in the conference rooms and workrooms.

Plumbing

Gas lines are from the local utility provider. The owner owned metered water distribution system with a back flow preventor and booster pumps feeds the entire building. A 240 MBH gas fired water heater, with 100 gallon storage, serves the two toilet banks on each floor. There is a water softener in the penthouse for the closed chilled water loop. There are electric water coolers and an electric hot water heater. There are 9kW, 277V no storage, instantaneous water heaters under remote floor sinks, only cold water is supplied throughout the building floors aside from the toilet banks. The gas fired water heater has a recirculating pump. The storm water, soil, waste, and vent underground piping is hubless cast iron.

Fire Protection

The fire protection for the building was designed using the area density method. Wet pipe automatic sprinkler systems exist throughout the building. The sprinkler heads are UL listed and FM stamped. There is a flush type, wall-mounted fire department connection and an inside/outside hose stream demand of 250 gpm. The system has a double-detector-check backflow preventer. The fire alarm control panel is integrated to the building fire alarm system through water flow switches (alarms) and supervisory switches on valves. There is a valve control station on each floor.

Structural

Footings for the building are 3'-6" below finish grade on soil bearing pressure of 6500 psf. There are 1900 psi foundation block walls. Steel framing consists of both bolted and welded connections, and 400 psi elevated floor slabs on composite metal decking. The structural steel floor beams are 50,000 psi (ASTM A-572) and the columns, channels, angles, and miscellaneous structural steel is 36,000 psi (ASTM A-36). The structural steel has spray on fireproofing. The stairways are steel with concrete fill.

Conveying Systems

There are two 60 hp hydraulic elevators. The elevator controllers are interlocked with the automatic transfer switch so only one can operate at a time on emergency power.

Mechanical System - Existing

Existing System Schematics and Sequences of Operation

Air Handling System

An air handling system is defined as two (2) variable volume AHUs in parallel serving a common plenum, one (1) return air fan unit (with two parallel return air fans) with VFDs and the capability of a 100% outside air economizer cycle. An air handling system serves the east wing and a second air handling system serves the west wing of the building.

Safeties (Each AHU):

Smoke Detection – Smoke detectors located in the supply and return air ducts send a signal to the fire alarm system when products of combustion are sensed. The fire alarm system de-energizes the unit supply fans and closes the hard-wired isolation smoke dampers. The direct digital control (DDC) controller closes the outside air dampers and the alarm annunciates throughout the DDC system.

Freezestat – A low temperature cutout thermostat de-energizes the AHU when sensing a temperature below 35^{o}F and the alarm annunciates throughout the DDC system.

Overpressure Cutout – A high-pressure cutout switch de-energizes the AHU when the sensed discharge pressure is above 6" W.C. and the alarm annunciates throughout the DDC system.

Occupied Operation:

(The unit is run in occupied operation 6:00 AM to 6:00 PM, 7 days a week.)

Occupied Mode – On a signal from the DDC system, the AHUs and VFDs will sequence in a heating or cooling mode as determined from the general office thermostats and the dampers gradually open or close based on the thermostats' signal to maintain setpoint. On start-up, the minimum outdoor air dampers remain closed until the general office thermostats reach their occupied setpoints (75^{o}F summer/70^{o}F winter). Once the setpoints are reached, the minimum outdoor air dampers modulate open to provide the minimum outdoor air needed as determined by the airflow monitoring station.

Supply Air Volume Control – The VFD AHU for each AHU system is sequenced to maintain the duct static pressure (2/3 of the way down the supply airshaft). The lead VAV AHU VFD ramps up until the AHU approaches 100% airflow. If duct static pressure is not reached, the lag AHU is energized and modulating the VFD's equalizes the airflow between the units. The DDC controller continuously sums the airflows. When speeds are reduced in response to plenum pressure and total airflow decreases to a value achievable by a single AHU, the lag unit stops and the isolation and minimum outside air dampers close, and the VFD on the lead unit ramps up to meet the load.

Underfloor Air Plenum Control – A discharge damper located at each underfloor distribution duct modulates to maintain the plenum pressure setpoint of 0.10" W.G. If the general office temperature drops below the low limit setpoint of 68^{o}F, then the discharge dampers modulate close and override the pressure control.

Discharge Temperature Control – The face and by-pass dampers modulate o maintain the discharge temperature setpoint (60^{o}F cooling/90^{o}F heating). On a call for cooling, the chilled water valves open and the two-position heating valves shall open on a call for heating. The heating and cooling valves will not open simultaneously.

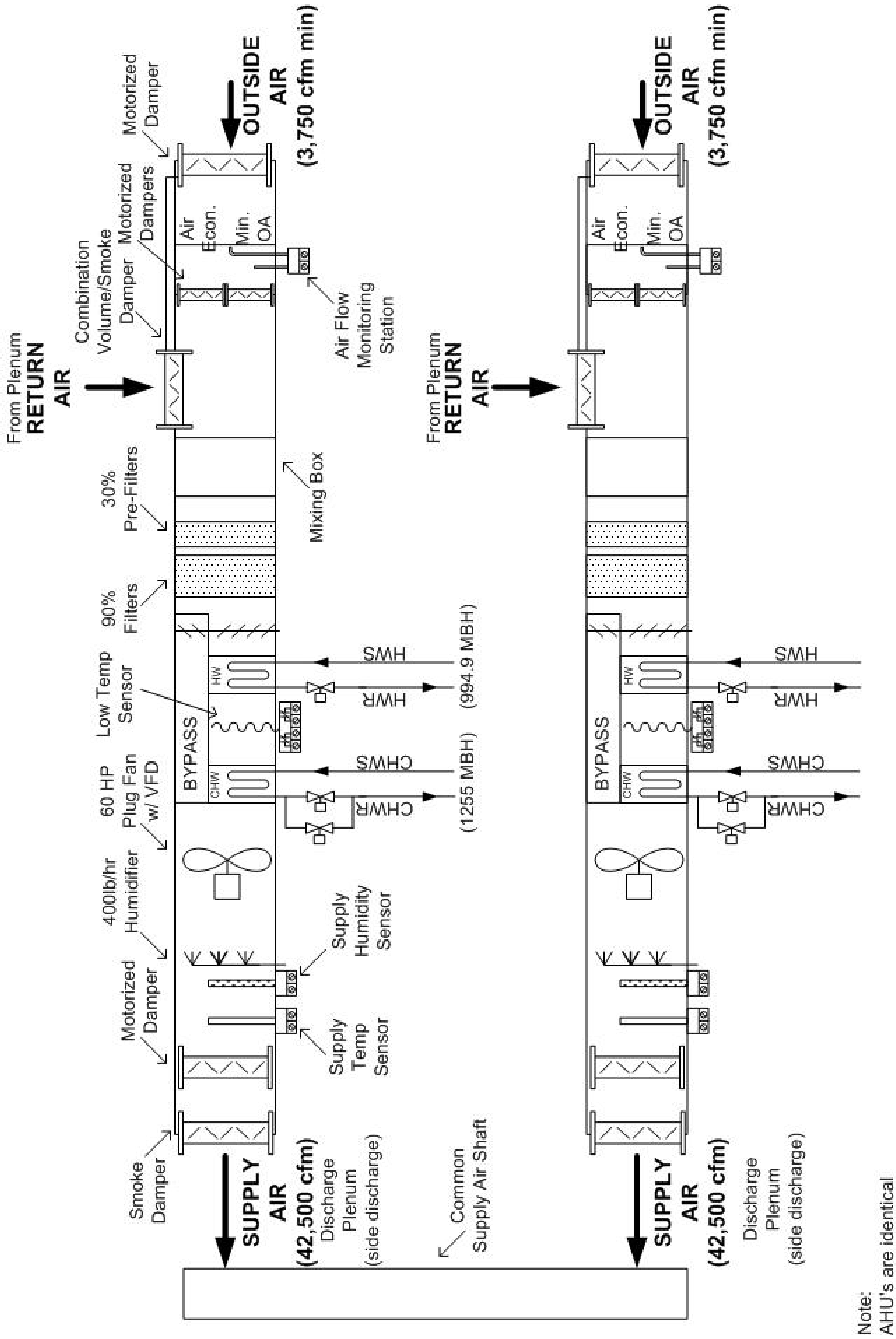
Economizer – The system operates on integrated enthalpy control. When the outdoor enthalpy is less than the return air enthalpy, the economizer (outside air) dampers modulate with the return air dampers to maintain the AHU discharge temperature setpoint. If the space relative humidity rises above 55% and the outdoor grains of moisture is higher than the return air grains of moisture, then the economizer dampers close and only minimum outside air is provided to the AHU.

Humidification – The general office humidistats on each floor modulate the active AHU's humidifiers to maintain the space setpoint of 35% RH. A duct humidity sensor insures supply duct humidity doesn't exceed 85% RH.

Floor Plenum Sensors – Floor plenum temperature and humidity, and slab temperature sensors are located at each floor for each AHU system. If the slab temperature approaches within $3^{o}F$ of the space temperature, the DDC system annunciates an alarm and the AHU humidification setpoint is lowered.

Unoccupied Operation:

On a signal from the DDC, the AHU systems de-energize, the outside air dampers, floor plenum discharge dampers, and relief air dampers close, and the return air dampers open. When heat is needed, as determined by the general office thermostats, the supply air fan cycles on until the setback conditions are met.



Existing Air Handling System Schematic
(Typical for 2)

Chilled Water System

The chilled water system is comprised of a two flow, primary loop piping system with three air cooled chillers: two ‘summer’ chillers and one smaller chiller primarily for ‘winter’ use. The two ‘summer’ chillers operate in a lead/lag fashion when the outside air temperature is above 60^{o}F. The chillers are de-energized and the outside piping is valved-off and drained-down during the ‘freezing’ season.

The ‘winter’ chiller with remote chiller barrel provides chilled water to the telecommunications equipment room during the ‘air economizer’ season.

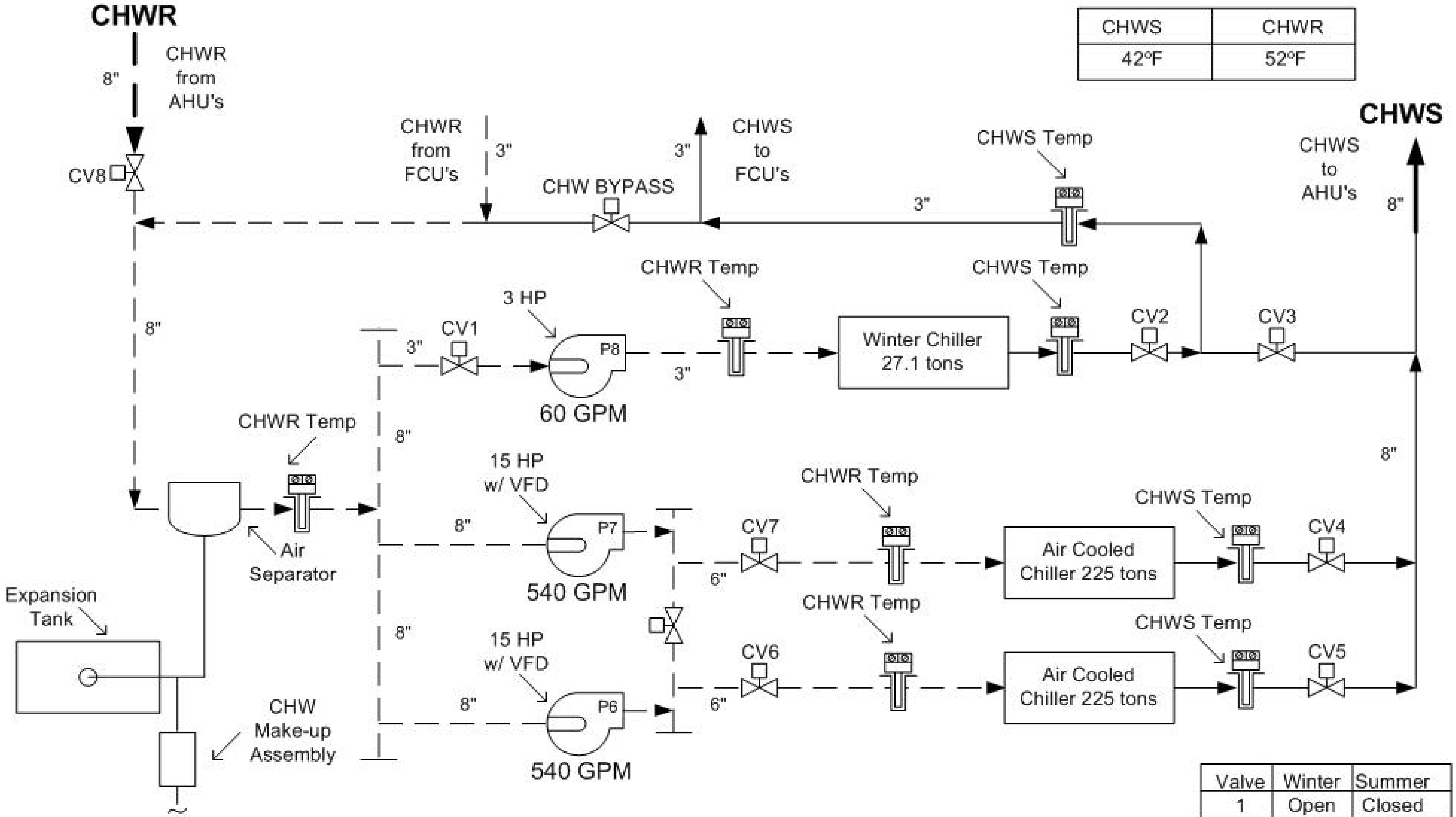
The chilled water flow quantity is varied as the ‘summer’ chillers are staged. Chilled water pump VFDs maintain a constant water flow through their chillers as the secondary system water flow varies. The ‘winter’ chiller energizes if the other chillers are unable to maintain supply temperature setpoint.

There are no backup pumps for the chillers, but the pumps have been sized so that if a ‘summer’ pump fails, the remaining ‘summer’ pump can provide the minimum required water flow to both chillers. This is not an automatic operation and requires manual operation of valves.

Summer Mode – The DDC system energizes the chilled water system when the outside air temperature rises above 60^{o}F. The lead chiller pump energizes and ramps up to the required speed. The AHUs first stage, two-position cooling coil valve opens to the coil. Water flow is proven and the lead chiller energizes in stages to maintain chilled water supply temperature setpoint of 42^{o}F. If the lead chiller is unable to maintain setpoint, the lag chiller is energized in the same sequence. The AHUs second stage, two-position cooling coil valve opens to the coil if additional chilled water is required. If both chillers are unable to maintain setpoint, the ‘winter’ chiller pump energizes and the DDC system annunciates an alarm.

Winter Mode – The ‘winter’ chiller pump energizes and runs continuously. When water flow is proven, the ‘winter’ chiller is energized in stages to maintain chilled water supply temperature setpoint of 42^{o}F. The pressure by-pass valve modulates to maintain chilled water flow and prevents dead-heading. A high temperature alarm is generated if the space temperature rises above 90^{o}F.

CHWS	CHWR
42ºF	52ºF



Valve	Winter	Summer
1	Open	Closed
2	Open	Closed
3	Closed	Open
4	Closed	Open
5	Closed	Open
6	Closed	Open
7	Closed	Open
8	Closed	Open

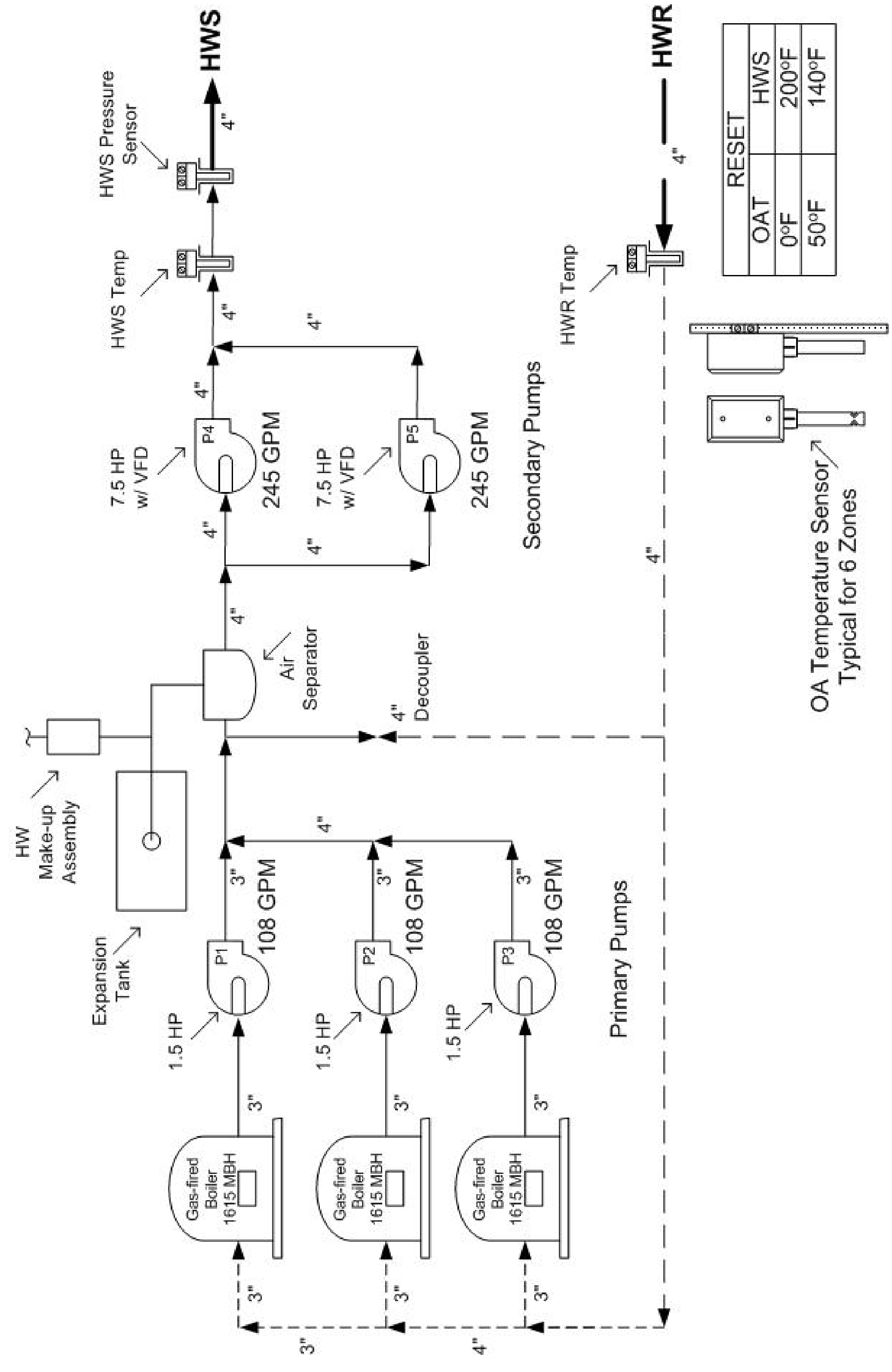
Existing Chilled Water System Schematic

Hot Water System

Three gas-fired boilers are controlled by the DDC system to supply the building heating primary/secondary loop system. The hot water system is automatically indexed from the outside air temperature, and incorporates a reset schedule that resets the hot water temperature setpoint. If the lead boiler is unable to maintain temperature setpoint, then the remaining boilers and pumps will energize in the same sequence to maintain setpoint.

Secondary Hot Water Pumps – The lead pump is started by the DDC controller with the outside air temperature is less than 50^{o}F. The lead pump is alternated monthly to equalize the run times. The pump VFD modulates the pump speed to maintain secondary loop pressure setpoint.

Primary Hot Water Pumps – The lead primary pump energizes, the combustion air intake damper opens, and the boiler energizes once water flow is proven to maintain secondary hot water temperature setpoint. Alarms will be sent throughout the DDC system if a pump fails to operate after a 5 second delay.



Existing Hot Water System Schematic

Existing System Critique and Operating History

The building's VAV underfloor air distribution system is still unique in office buildings when compared to the more traditional ceiling VAV supply system. The omission of a return air fan system and the placement of the gas-fired equipment in the negatively pressured return air plenum penthouse were intriguing. The gas-fired humidifiers have been changed to electric and the gas-fired boilers were reconfigured to allow them to operate properly. The building owner representatives mentioned watching water gurgling out of the drains and onto the floor in the plenum because of the negative pressure in the space.

A return fan system has been added within the past year, placing the return fans in the airshafts and ducting the shafts to the AHUs. The addition of the ductwork removed the penthouse from the air stream, thus eliminating the negative pressure problem. The airshafts have a common wall with conference and meeting rooms on several floors. The noise from the new fans was so great that conversations could not be heard from one end of a 10 ft table to the other. Additional steps had to be taken to dampen the fan noise.

The building occupants have registered many complaints about the thermal comfort of the building. After a year of occupancy, half a million dollars was spent to attempt to resolve the performance of the mechanical system. Reheat had to be added to the first floor because the floor was concrete slab-on-grade in direct contact with the underfloor supply air plenum and the supply air temperature was too low. Humidity control in the spaces was also a problem; at one point, paychecks couldn't be printed because of the conditions. Other issues that had to be addressed after occupancy were related to noise and building envelope leakage. The chillers are not located on the structural concrete slab that the remaining mechanical equipment inside the penthouse is. They are placed on an isolated concrete island on the membrane roof at the center of each wing. As a result, high frequency compressor noise and vibration noise were a problem for the tenants on the fifth floor.

The existing mechanical system does not comply with minimum outdoor air requirements described in ASHRAE Standard 62. The design was not required by the owner to meet ASHRAE Standard 62 at the time. Building occupants have a great deal of personal control over the placement of diffusers in their spaces by relocating the floor diffusers or covering them up with magazines, further reducing the ventilation air in some spaces. The system takes up minimal rentable space because the majority of the mechanical equipment is located in the penthouse. The mechanical system cost figure was taken from the GMP estimate mentioned in the Cost Information section.

Lost Rentable Space (Mechanical System)	Mechanical System Cost (HVAC and Plumbing)	Annual Electric Consumption*	Annual Gas Consumption*
1.50%	$16.96/sq ft	2.7 million kWh	7,000 MCF

*Values reflect mechanical system operation during and after the above-mentioned renovations.

The total annual energy use of the building was compared with office buildings from "A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures." The building's annual energy consumption is 42% less energy per square foot than other office buildings polled in the study.

Mechanical System – Redesign

The less than desirable general performance of the mechanical system has already caused the system to be modified as previously mentioned. The basis of the building analysis thus far has been from the as-built drawings supplied by the building owner. These drawings represent the system as it was during building occupancy in May 2000 and is the basis for the new construction redesign, not a retrofit redesign. The redesign will also be conducted under the assumption that the constraints due to the Penn State and Geisinger merger were lifted prior to design. Specific redesign goals include:

- Improved thermal comfort and humidity control
- Improved indoor air quality (IAQ) by system compliance with ASHRAE Standard 62
- Reduced energy costs
- Reduced 1st cost
- Meet the criteria of building program

These areas will be addressed with the intention of better performance without drastically elevated construction, operating, and 1st costs compared to the system operation depicted on the as-built drawings.

Distributed Chilled Water Feasibility Study (AE Depth)

District Utilities

District energy systems produce steam, hot water, or chilled water at a central plant. These utilities are then delivered to buildings via piping networks for space heating, domestic hot water heating, and air conditioning. Buildings that receive utilities from a central plant do not need their own boilers, furnaces, or chillers, or the space to contain them. Benefits of central plant systems over similar standalone systems include lower life cycle costs, increased design and operation flexibility, and increased energy efficiency.

The lower life cycle costs are a result of a reduction in building upfront costs as well as operation, maintenance, and labor costs. If boilers, furnaces, and chillers are not a part of the building, there will be a lower building project capital cost leading to lower principal and interest payments and annual maintenance contracts. Because the more sizeable mechanical equipment is not in the building, there is a decrease in lost rentable space due to mechanical equipment in the building.

The greater design flexibility is due to the exclusion of designing for boilers, cooling towers, and other mechanical equipment within the building project. This allows for a more aesthetically pleasing building for the occupants, including less noise production from the mechanical system. The plant has more operating flexibility than a standalone mechanical system because it can take advantage of using a variety of fuels including coal, oil, and natural gas. The plant can use whichever is the most cost effective at the time whereas a standalone system is limited to the system design fuel and is ultimately at the mercy of the energy market.

Because of a utility plant's larger size, it can more easily take advantage of the use of renewable fuels including biomass, geothermal, and incorporate combined heat and power strategies. The utilities that are distributed arrive at the connected buildings ready to use, meaning 100% efficient. If the same utilities are produced in a standalone system, there is an efficiency of 80% or lower for natural gas or fuel oil. This increased combined heat and power utility plant production efficiency exists because the rejected heat of burning fuels can be utilized at the plant to generate electricity or power other equipment. Utility plants can also use higher efficiency chillers and boilers because of the increased size of the equipment than what would be contained in a separate standalone system. Utility plants are also more reliable than what would be contained in a separate standalone system. Utility plants are also more reliable than standalone systems because of around-the-clock operators and well-defined backup systems.

District cooling plants displace peak electrical power demand with steam-based cooling, district cooling, and thermal energy storage. District cooling plants can generally be designed to meet a load that is less than the sum of the connected peak loads because of load diversity effects. Different building loads that are connected to a single district cooling plant can peak out of phase. It is therefore possible to provide reliable cooling capacity to a collection of buildings having installed a fraction of the peak capacity required at each building in a standalone system. A district cooling plant also provides a greater degree of redundancy than what is usually found in standalone systems. When thermal energy storage (TES) is added to a district cooling plant, the plant is better able to accomplish load shift. A load leveling chilled water thermal storage tank can be discharged during the peak load instead of bringing another machine online to meet the increase in load. This provides energy cost savings because peak loads generally occur during the same time of day when energy rates are the highest. Once the load decreases to where the online machines can meet it, the thermal storage tank is once again placed in charge mode.

Strategic planning is required for district energy systems. The plant capacity and space for additional equipment must be estimated and implemented prior to both short and long term anticipated needs. Decisions based on energy sources and refrigerant types must be addressed in capital and master planning sessions on the basis of budget and expected energy costs; overall, a very complex process.

Central Utility Plant

(Refer to Distributed Utilities Map – Appendix A)

Prior to the time of design and construction of the Academic Support Building, an engineering study concerning the utility expansion program of the central utility plant (CUP) was conducted by ZBA, Inc. out of Cincinnati, Ohio. The study, published in January 1998, stated the following characteristics for the existing plant.

Existing CUP Chilled Water System

1	Carrier 1200 ton centrifugal	CFC-11	Steam Turbine Drive
2	Carrier 800 ton absorber	LiBr	Low Pressure Steam
3	Carrier 800 ton absorber	LiBr	Low Pressure Steam
4	Carrier 1200 ton centrifugal	CFC-11	1000 hp Electric Drive
5	Carrier 1000 ton centrifugal	CFC-12	1000 hp Electric Drive
6	Carrier 800 ton absorber	LiBr	Low Pressure Steam
7	Carrier 1000 ton centrifugal	CFC-12	1000 hp Electric Drive
8	FES 1000 ton screw	HCFC-22	1000 hp Electric Drive
9	FES 1000 ton screw	HCFC-22	1000 hp Electric Drive
TES	CHWTR Storage Tank	1.4 million gal	12,5000 ton-hr capacity

The CUP was operating at full capacity at the time of the design phase of the Academic Support Building. It was documented in the *Chiller No. 6 Replacement Study* by ZBA, Inc. that 'the operating logs indicated that the peak cooling load and the chilled water flow experienced at the CUP during the summer of 1997 reached 9,500 tons and 16,000 gpm. This load has been met by the CUP only by operating all chillers and the TES' (Thermal Energy Storage). During the design phase of the building, one of the central plant's 30 year old, low pressure absorption chillers (Chiller 6) experienced a freeze-up of its refrigerant, which was severe enough to destroy many of its tubes and the absorber shell. The chiller was part of a 'piggy-back' arrangement. The 'piggy-back' arrangement was once popular but is now less common because of the numerous failure situations. Chillers 5 and 6 were operated in parallel and received exhaust steam from chiller 4, a machine with a steam turbine drive that was later converted to a three-pass machine with an electric motor drive (as indicated above).

System Comparison

The existing standalone chilled water system efficiency in the building for one 225 ton air cooled screw compressor chiller is calculated as:

$$\frac{291.1kW}{225tons} = 1.294kW / ton$$

The hand calculated annual cooling load for the building is 1,226,400 ton-hours at an averaged electric billing rate of $0.04999/kWh (obtained from the building owner, including the averaged demand charge). Therefore the estimated annual energy cost of the chilled water production of the existing standalone chilled water system is:

$$(1.295kW / ton) \times (1{,}226{,}400ton - hours) \times (\$0.0499 / kWh) = \$79{,}250.58$$

The efficiency of chilled water production in the CUP operating in electric mode was crudely estimated using the following data.

CUP Equipment

Chiller 8	1600 gpm chilled water 3000 gpm condenser water	1000 hp
Primary Pump 1	2250 gpm	250 hp
Secondary Pump 7	2400 gpm	200 hp
Condenser Water Pump 8	5000 gpm	75 hp
West Cooling Tower Fan	9500 gpm	150 hp

Using the affinity laws, a ‘worst case scenario’ efficiency of the CUP chilled water production operating in electric mode was estimated for single chiller operation.

Chiller 8 => 1000 hp

Primary Pump 1 => $\left(\frac{250}{hp}\right) = \left(\frac{2250^3}{1600^3}\right)$ => 90 hp

Secondary Pump 7 => $\left(\frac{200}{hp}\right) = \left(\frac{2400^3}{1600^3}\right)$ => 59.26 hp

Condenser Water Pump 8 => $\left(\frac{75}{hp}\right) = \left(\frac{5000^3}{3000^3}\right)$ => 16.2 hp

West Cooling Tower Fan* => $\left(\frac{150}{hp}\right) = \left(\frac{9500^3}{3000^3}\right)$ => 4.72 hp

*For lack of a better estimate, was assumed to be proportional to condenser water flow.

The total estimated electric mode operation horsepower for the CUP operating a single chiller was 1170.18hp. The efficiency of the operation was:

$$(1170.18\ hp) \times (0.743\ kW / hp) / (1000\ tons) = 0.869\ kW / ton$$

The estimated annual energy consumption in the electric mode is therefore:

$$(0.869\ kW / ton) \times (1{,}226{,}400\ ton\ hours) \times (\$0.0499 / kWh) = \$53{,}180.51$$

Energy Analysis Summary

Chilled Water Production	Existing Standalone System	CUP Electric Mode Operation	CUP Savings
Efficiency	1.294kW/ton	0.869kW/ton	0.425kW/ton
Annual Energy Usage	1,555,188kWh	1065742kWh	552,466kWh
Annual Energy Cost	$79,250.58	$53,180.51	$26,070.07

(Note: The existing dedicated chiller pump was excluded from both system analyses because its use is common to both systems. Costs associated with maintenance were also excluded because the same maintenance staff and tools are applicable to both systems.)

While there is an estimated annual energy savings through CUP chilled water production, the existing site conditions require additional equipment and utility piping. In the 'best case scenario' during the design phase of the Academic Support Building, there exists sufficient capacity in the CUP capable of meeting the connected load of the Academic Support Building and the utility piping network reaches the building site. Load diversity effects could be used to only require an extra 60-80% of the 450 ton Academic Support Building peak load of the CUP's capacity.

Because the CUP was documented at full capacity during the design phase of the Academic Support Building, diversity effects of the building's peak load cannot be used in sizing the equipment to meet the peak load of the building. Therefore the entire design capacity of 450 tons must be installed in the CUP. This is an impractical solution unless the CUP required a smaller machine to aid in part-load efficiency of the plant. It is more reasonable to assume that future building load connections or increase of existing loads would be anticipated and a larger machine would be added. Another possible solution would be to increase the capacity of the TES with a low temperature additive. According to RS Means 2003, the approximate cost of installing a 2,000 ton water cooled centrifugal chiller and (2) 1,000 ton fiberglass draw thru cooling tower cells in 1999 using Harrisburg, PA as the closest city is about $522,350. The cost of adding the extra capacity not required by the Academic Support Building's connected load would not be treated as a penalty to the building's construction budget. The funding would most likely be from a campus master planning budget and would be considered in future building construction with loads connected to the CUP. A simple payback for this scenario is calculated as follows:

$$\frac{\left(\frac{\$522,350}{2000\,tons}\right)\times(450\,tons)\times(60\%)}{(\$26,070.07/year)} = 2.7\,years$$

Additional underground utility piping is required for connecting the Academic Support Building to the CUP. In a 'best case scenario', it is assumed that the existing 16" chilled water loop piping connection the campus mega-structure to the CUP has sufficient flow capacity for the mega-structure lines to be tapped and extended to the Academic Support Building site. Both the CUP chilled water system and the Academic Support Building's existing system operate on a 10^{o}F temperature differential. The design chilled water flow rate for the Academic Support Building's two air-cooled screw chillers is 1,080 gpm. The extended underground chilled water piping, designed at a 4 ft per 100 ft pipe length pressure drop, is 8" diameter pipe. It is assumed that the piping will be buried in a 5 ft deep utility line trench with at least 4 ft of ground cover; therefore no piping insulation will be required. The cost of the trenching and (2) 8" un-insulated, cement lined, ductile iron chilled water pipes is about $234,860 for a run of approximately 4,500 ft. A simple payback for this scenario is calculated as follows:

$$\frac{\$234,860}{(\$26,070.07/year)} = 9\,years$$

Conclusion

The benefits of district energy systems make them an attractive alternative to individual building standalone systems, especially for a privately owned campus of buildings like the Penn State College of Medicine. The reduced kW/ton of the CUP provides not only increased efficiency and therefore energy savings, but it also reduces the campus electric demand charge. In addition to energy savings, there are operation and maintenance savings that are more difficult to evaluate. The energy savings provided in this example do not appear to outweigh the added cost of increasing the plant size and extending utility lines, but it must be understood that the costs presented do not reflect the additional cost to the building project. Only a portion of the burden will be felt by the building construction budget and the rest will be paid for by the campus master plan and utility expansion budgets. For the specific case study of the Academic Support Building, it is clear that situational factors during the design phase of the building, including its remote location, no immediate plans for nearby construction, and a CUP already at capacity did not allow for its connection to the CUP. There is currently a proposal up for review to add a second utility loop from the CUP south of the mega-structure to reach future construction on the east side of the campus, however possible implementation of that proposal is still at least five years away. A satellite CUP on the east end of campus is also a possibility, however such plants are generally located further apart.

Dedicated Outdoor Air System/Radiant Cooling Panel System (AE Depth)

Introduction

Traditional all-air variable-air volume (VAV) systems mix a portion of return air with outdoor air at the air handling unit (AHU). The proper distribution of this air is a function of VAV box minimum settings, space sensible loads, local exhaust and exfiltration, short circuiting paths, and interzonal air transfer (Mumma, Lee 1998). Understanding where all of the ventilation air terminates is not possible. A dedicated outdoor air system supplies 100% outdoor air to the space, ensuring that a design in compliance with ASHRAE Standard 62 ventilation requirements will deliver the design ventilation air to the correct spaces. When only a portion of the supply air is ventilation air, some spaces are over ventilated due to the multiple spaces equation of ASHRAE Standard 62. With a dedicated outdoor air system, the introduction of excess outdoor air is greatly reduced and therefore reduces the amount of energy required for outdoor air conditioning.

Dedicated outdoor air systems provide improved humidity control by conditioning the primary source of humidity in the building; outdoor air. Properly controlling humidity levels in the conditioned space can prevent mold growth and improve indoor air quality. The outdoor air meets the latent load in the space as well as a portion of the sensible load. A parallel sensible system can then be run at higher cooling temperatures that improve energy efficiency (DOE-1999). There is extra energy expended in conventional systems where only a portion of the supply air (SA) is outdoor air to condition both the return air (RA) from the space and the outdoor air.

The use of radiant cooling panels as the sensible system in parallel with the DOAS has many aspects. Chilled water flows through pipes on the upper surface of the radiant panel and cools the space through natural convection and radiative heat transfer. While this technology is common in Europe, it is not widely applied in the United States. A major sticking point in industry is the possible formation of condensation on the panels, potentially leading to damaged ceiling materials and possible biological growth. For radiant cooling panels to be applied, proper humidity control and tight building envelopes are necessary. For this reason, coupling the radiant cooling panel system and a DOAS system is a natural union because of the DOAS's superior humidity control. With the chilled water supply temperature to the panels several degrees above the design space dewpoint temperature, condensation formation on the panels should not be an issue. Condensation sensors can be applied to vertical runs on the supply side to detect condensation, and supply pipes in unconditioned and critical spaces should be insulated.

Radiant cooling panel systems should only be considered if there is a parallel system used to de-couple the space sensible and latent loads.

The use of an energy recovery wheel was also explored. ASHRAE Standard 90.1-1999 section 6.3.6.1 refers to exhaust air energy recovery in systems with a design outside air supply of 70% or greater than the total supply air volume and a design supply air volume of 5,000 cfm. Such a system must have an energy recovery unit with at least 50% recovery effectiveness. Using a total energy recovery wheel has the potential to reduce required heating and cooling equipment capacities. Energy recovery between exhaust and supply air can reduce peak cooling and heating load to condition the outdoor air as well as the plant equipment size needed. The added installation cost of an energy recovery wheel is most often the reason their application in design suffers. Often, designers do not take credit for the reduction in the heating and cooling plant to offset the first cost of an energy recovery wheel, thus making its addition to the system more costly than it is. Other reasons they may not be used include increased maintenance, possible frosting, and increased fan power requirements.

Replacing an all air system with a parallel air-water system would appear to have a higher installation cost because of the additional equipment for the two systems. The reality is that there is potential installation cost savings in implementing a DOAS/radiant system. The radiant panels do contribute to the installation cost of the system, but there are still areas for potential savings. The major items are addressed below (Mumma, 2001):

- Chiller size reduction (result of less OA and Energy Recovery)
- Reduced pump size (result of chiller reduction)
- Reduced ductwork installation cost (result of less SA)
- Reduced plenum depth; envelope materials, building height (result of less SA)
- Air handling unit size reduction
- Electrical service to mechanical equipment reduction
- Piping reduction (integration of fire suppression system)
- Acoustical ceiling panel reduction (where replaced with radiant panels)
- Less lost rentable space due to mechanical shaft needed for SA and RA ductwork

Through the reduction of equipment sizes and improved chiller COP, there is a potential energy savings. Modeling this is more difficult than perceived. Conventional modeling software does not simply and effectively model a DOAS/radiant system. A new software package would increase the ability of HVAC designers to design and sell such a system to clients.

System Redesign

The dedicated outdoor air system (DOAS) was designed to deliver 20 cfm/person to the building via high aspiration diffusers located in the suspended ceiling. The occupancy rate was determined by the larger of the Architect's design occupancy for the building and the ASHRAE Standard 62 section 6.3.1 design occupancy. For the conference rooms and the perimeter office spaces, the larger of the two occupancies was given by ASHRAE Standard 62. ASHRAE Standard 90.1-1999 section 6.3.2.1 discusses conditions where simultaneous heating and cooling is allowable. Included is when the volume of air that is reheated is no larger than the volume of air required to meet the ventilation requirements defined in ASHRAE Standard 62 section 6.3.1.

There are several types of outdoor treatment and ventilation systems. The two pursued in this study are outdoor air delivered to the space and outdoor air delivered to a terminal unit. The building wing floor plan is divided into three zones for each wing; 1 - north facing private perimeter offices, 2 - central open offices with minimal glazing, and 3 - south facing private perimeter offices. Conditioned air is supplied from the wing's AHU to all zone ductwork at a common supply air temperature of 45^{o}F in both the heating and cooling season. The central offices have a year round cooling load because there is minimal envelope load, if any. These spaces are supplied with conditioned outdoor air directly to the space from the AHU. The private perimeter office spaces are supplied with conditioned outdoor air through a terminal reheat coil at each floor to handle the heating loss through the glazing in the heating season. Zones 1 and 3 have separate terminal reheat coils to accommodate for the difference in solar loads on opposite sides of the building. Conference rooms and work rooms with variable and more dense occupancies are supplied via Zone 2 with terminal reheat VAV boxes with CO2 sensors to control the volume.

The room conditions were modeled in HAP4.1b to determine the building loads. The loads were then de-coupled to determine the sensible and latent cooling done by the DOAS. The remaining sensible load left in the space determined the pendant mounted radiant cooling panel area. Redec's radiant panel sizing software was used to size the panels. A typical section was modeled for 3 panels connected in series to determine capacity, pressure drop, and flow characteristics. Lay-in hot water radiant heating panels were sized similarly, after taking into account the reheat temperature provided in Zones 1 and 3.

(Refer to Mechanical Depth Calculations – Appendix C)

(Refer to Equipment Cut Sheets – Appendix D)

AHU Sequence of Operation

Air Handling Units:

There are two air handling units for the Dedicated Outdoor Air System (DOAS). One serves each wing of the building.

Safeties (Each AHU):

Smoke Detection – Smoke detectors are located in the supply and return air ducts send a signal to the fire alarm system when products of combustion are sensed. The fire alarm system de-energizes the unit supply fan and closes the hard-wired isolation smoke dampers. The DDC controller closes the outside air dampers and the alarm annunciates throughout the DDC system.

Freezestat – A low temperature cutout thermostat de-energizes the AHU when sensing a temperature below 35^{o}F and the alarm annunciates throughout the DDC system.

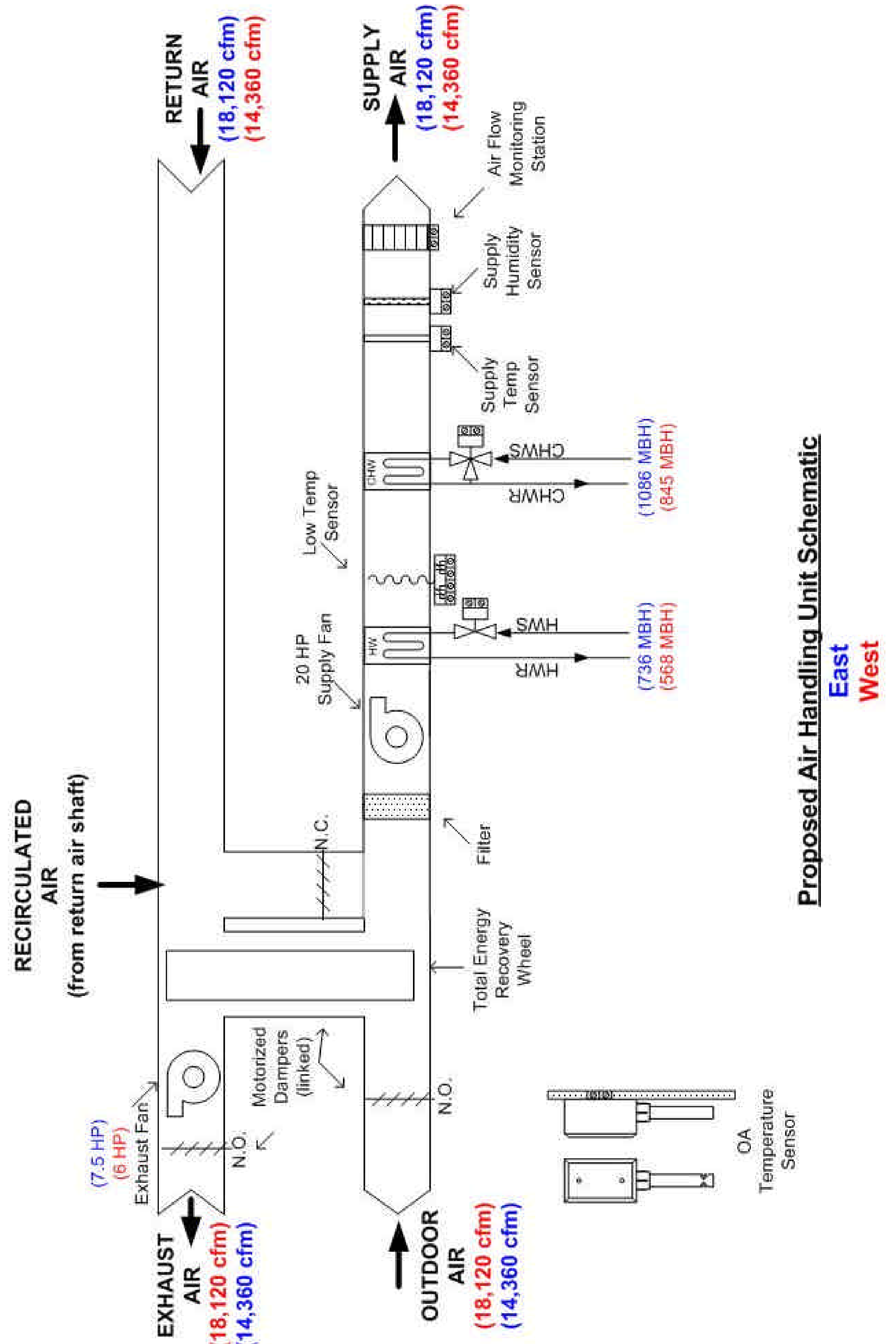
Occupied Operation:
(The unit is run in occupied operation 5:00 AM to 6:00 PM, 7 days a week.)

Occupied Mode – On a signal from the Direct Digital Control (DDC) system, the AHUs will sequence in a heating or cooling mode as determined from the general office thermostats. On start-up, the outdoor and exhaust air dampers remain closed and the mixed air dampers are open. The building air is recirculated by the constant speed supply air fan until the general office thermostats reach the occupied dry bulb setpoint (75^{o}F summer/70^{o}F winter). Once the space dry bulb setpoint is reached, the outdoor and exhaust air dampers open and the mixed air damper closes to provide 100% outdoor air to ventilate the building. The exhaust fan is energized when the exhaust air dampers open. The supply air temperature is maintained at 45^{o}F. When the outdoor air temperature is less than the supply air temperature, the heating coil valve modulates open to maintain 45^{o}F supply air temperature. When the outdoor air temperature is greater than the supply air temperature, the cooling coil valve modulates open to maintain 45^{o}F supply air temperature. The heating and cooling valves will never be open simultaneously. On a call for heating in the perimeter zones by space thermostats, the heating valves on the reheat coils will modulate open to meet space temperature setpoint (detailed in Typical Floor Sequence of Operation).

Supply Air Volume Control for Conference Rooms – The conference rooms will be conditioned via variable air volume (VAV) boxes at 45^{o}F. On a signal from a conference room CO2 sensor relaying to the DDC system that a conference room is occupied, the space VAV box will modulate to full open to allow 100% ventilation air to the space. On a call for heating from the space thermostat, the heating valve on the terminal reheat will modulate open to maintain space setpoint temperature. On a signal that a conference room is unoccupied, the VAV box will modulate closed to maintain the unoccupied setpoints of (80^{o}F summer/65^{o}F winter) for the space.

Enthalpy Wheel Operation – The enthalpy wheel will be powered by a VFD motor. The wheel will be energized to recover exhaust energy to approach a 45^{o}F supply temperature in both the heating and cooling seasons. Frosting of the wheel will be prevented by speed control using temperature sensors and simple control logic.

Unoccupied Operation:
On a signal from the DDC, the outdoor and exhaust dampers close and the mixed air damper opens. The system will condition the spaces with 100% recirculated air by the supply air fan to maintain the unoccupied space setpoints of 80^{o}F summer/65^{o}F winter. The supply air fan will cycle as needed and the exhaust fan de-energizes when the exhaust air dampers close. Upon a call for cooling from the space thermostats when the outdoor air temperature is less than the space thermostat temperature, the outdoor air dampers and exhaust air dampers will modulate open and the exhaust fan will energize to provide free cooling. If further cooling is required, the cooling coil valves will modulate open. If the outdoor air temperature is not less than the space thermostat temperature, the outdoor and exhaust dampers remain closed, the exhaust fan remains de-energized, and the cooling coil valve modulates open. Upon a call for heating, the heating coil valve will modulate open. If further heating is required, the control valve on the reheat coil will modulate open to provide reheat to the floors.



Proposed Air Handling Unit Schematic
East
West

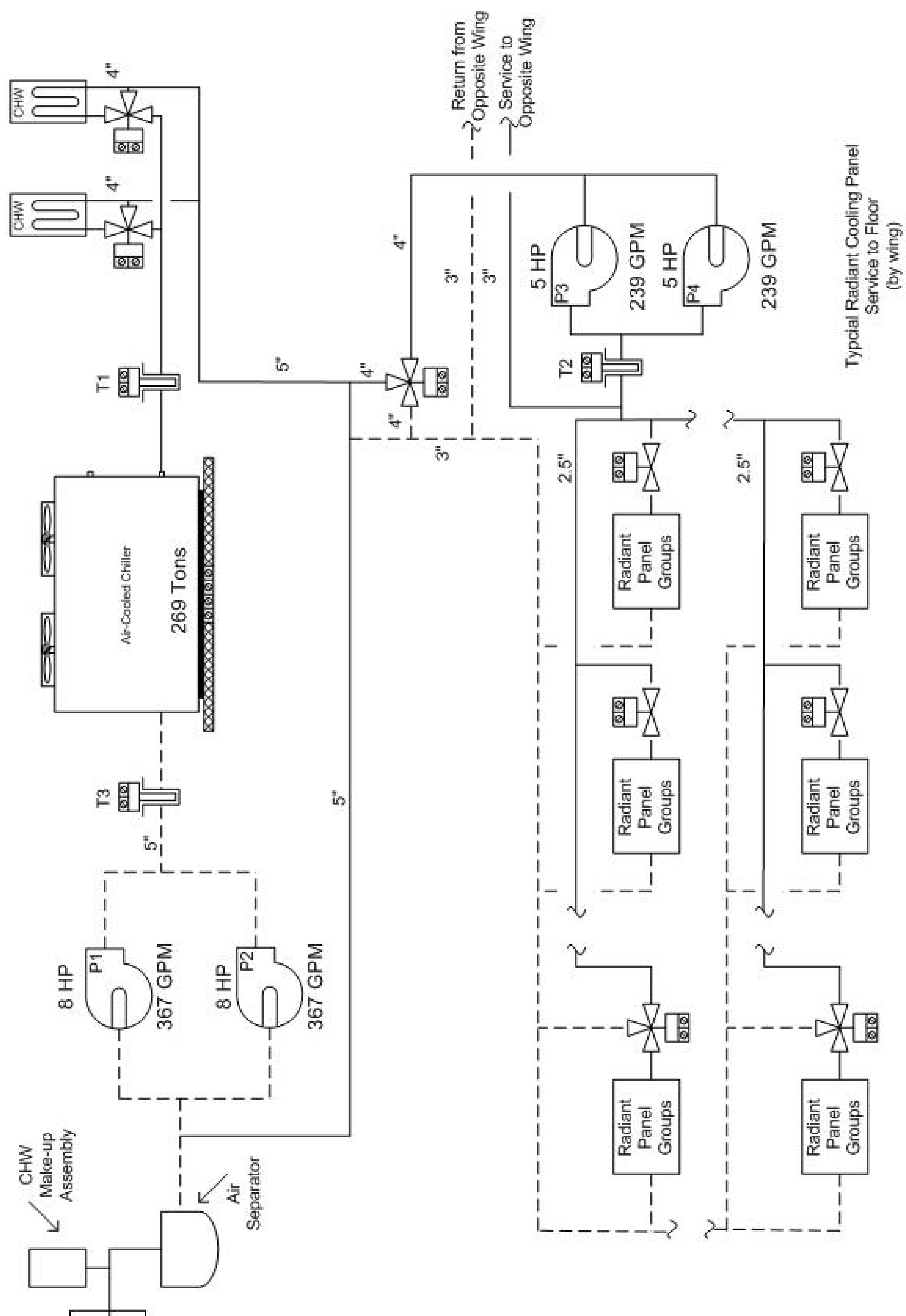
Chilled Water System:

The chilled water system is made up of a 267 ton air cooled chiller, two DOAS cooling coils, radiant cooling panels, a 7.5 HP primary chilled water pump, a 5 HP variable frequency drive (VFD) secondary pump, an air separator, expansion tank, make-up water assembly, and control valves.

The 7.5 HP primary chilled water pump maintains constant water flow through the air-cooled chiller and the secondary 5 HP VFD pump varies the flow to the secondary loop as needed.

Occupied Mode – On a signal from the Direct Digital Control (DDC) system, the primary chilled water will be energized. When the flow sensor proves water flow, the air cooled chiller will be energized. On a call for cooling from the DDC system, the cooling coil valve will modulate open to maintain setpoint. On a further call for cooling, the secondary VFD chilled water pump will be energized and the mixing valve will open to the secondary loop. The secondary chilled water loop mixing valve will position to maintain a chilled water supply temperature no less than 53^{o}F.

Unoccupied Mode – On a signal from the DDC system, the secondary VFD chilled water pump will be de-energized and the secondary chilled water loop mixing valve will remain closed to the secondary loop, de-energizing the radiant cooling panels. The cooling coil valve will modulate closed. The chiller will de-energize and the primary chilled water pump will de-energize. On a call for cooling from the DDC system, the primary chilled water pump will energize and upon proven flow from the flow sensor, the air cooled chiller will energize. The cooling coil valve will modulate open until a signal is received from the DDC system that the unoccupied setpoint has been met, and then the equipment will cycle off in reverse sequence.



Temperature Sensors	
T1	CHWS to Coils
T2	CHWS to Panels
T3	CHWR

Proposed Chilled Water System Schematic

Energy Recovery

Note: Manual isolation valves not shown for clarity.

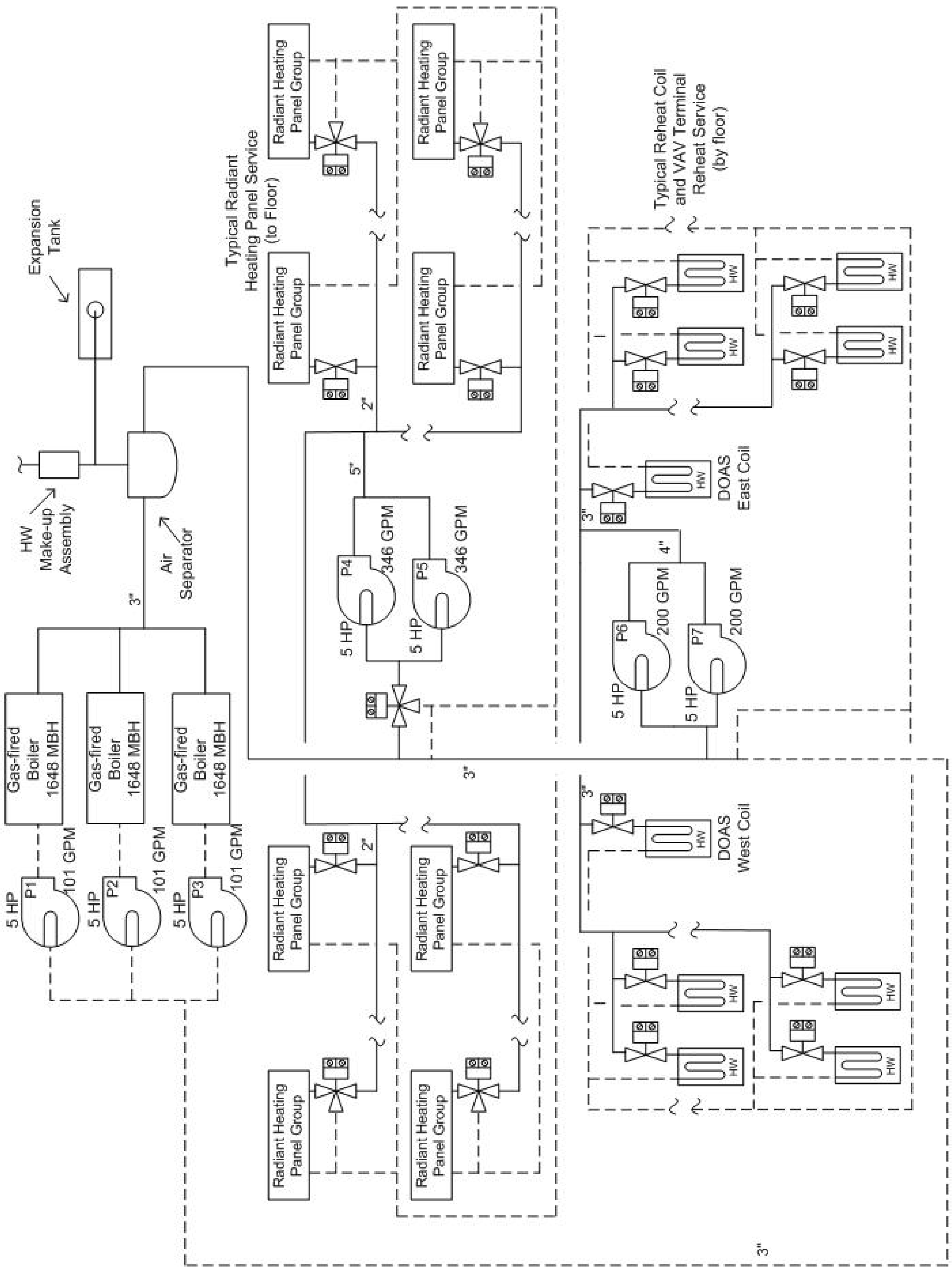
Hot Water System:

The hot water system is made up of three gas-fired boilers, 1.5 hp constant speed primary loop hot water pumps, 5 hp VFD secondary loop pumps, reheat units, expansion tank, air separator, make-up water assembly, and control valves.

If the lead boiler is unable to maintain temperature setpoint, then the remaining boilers and pumps will energize in the same sequence to maintain setpoint.

Secondary Hot Water Pumps –There are two secondary hot water loops. The DDC controller energizes the coil loop secondary pump when the outside air temperature is less than 45^{o}F on a call for heating. The pump VFD modulates the pump speed to maintain the secondary coil loop pressure setpoint. The heating coil valve modulates open to maintain setpoint. On a further call for heating by the DDC system from the space thermostats, the reheat coil valves modulate open to maintain space setpoint and the secondary radiant heating panel pump energizes and the panel group valves modulate open.

Primary Hot Water Pumps – On a call for heating from the DDC system, the lead primary pump energizes, the combustion air intake damper opens. The boiler energizes once the flow sensor proves water flow and the primary loop maintains the secondary hot water temperature setpoint.



Proposed Hot Water System Schematic

Typical Floor Sequence of Operation

(Refer to Proposed Typical Floor Duct Layout, and Proposed Typical Radiant Panel Piping Plan – Appendix A)

Occupied Operation:

(See Air and Water Sequence of Operation above for detailed equipment operation).

On a call for cooling in Zones 1, 2, or 3 from an office thermostat, the radiant cooling panel control valve serving the office will modulate open to meet the space thermostat setpoint. On a call for heating in the open office space of Zone 2, the control valve for the radiant heating panels will modulate open to meet the load. On a call for heating in Zone 1 or 3, the respective reheat coil control valve serving the zone will modulate open to reheat the supply air from 45^{o}F until one of the office thermostats reaches the dead band between heating a cooling space setpoint conditions. When one thermostat is in the dead band region, the supply air temperature will remain at the current elevated supply air temperature and the offices whose thermostats are still calling for heating will be further heated by their respective radiant heating panels. The individual control valves on the office radiant heating panels will modulate open until their respective thermostat's setpoint is met.

Unoccupied Operation:

(See Air and Water Sequence of Operation above for detailed equipment operation).

In unoccupied mode, the supply air is recirculated and the DDC system will average the Zone setpoints in the building. On a call for cooling, 100% outdoor air is supplied to the space if the outdoor air temperature is less than the unoccupied space setpoint. If the outdoor air temperature is not less than the unoccupied space setpoint, then the cooling coil valve modulates open to ensure all space thermostats meet the unoccupied space setpoint. On a call for heating in Zones 1 or 3, the terminal reheat control valve will modulate open to meet or exceed the Zone thermostat unoccupied setpoint.

Variable Supply Air Volume:

(See Air and Water Sequence of Operation above for detailed equipment operation).

The VAV boxes will be closed in unoccupied operation as determined by a CO2 sensor in each conference room. On a call for heating in a conference room in unoccupied operation, the control valve on the terminal reheat coil on the VAV box supplying the conference rooms will modulate open until and the VAV box will modulate open to meet the space thermostat setpoint. On a call for cooling in unoccupied operation, the VAV box will modulate open to meet the space thermostat setpoint. In occupied operation as determined by a CO2 sensor in each conference room, the VAV box will modulate open to meet the space thermostat setpoint.

Modeling

Accurately modeling the proposed mechanical system using a commercial software package was difficult. Commercially available simulation software is not intended to be used as a research tool to model newer technology. The DOAS/Radiant system was simulated in Carrier's Hourly Analysis Program (HAP v 4.1b) as a twp-pipe fan coil unit with a common ventilation system. There were several discrepancies in the simulation and actual intent of the building's proposed system. The common ventilation system indicated in the model was the DOAS system. It was not able to be modeled as a 100% exhaust system and therefore there was a penalty to the cooling coil and the chiller for the recirculated return air. The fan coil units indicated in the model were to simulate both the radiant heating and cooing panels. Flow rates for the cooling and heating fluids for these fan coil units were determined by the overall 10^{o}F and 20^{o}F temperature differential intended for the DOAS cooling and heating coils, respectively. The actual radiant panels in the proposed design operate at design temperature differential of 5^{o}F and 2^{o}F, respectively, resulting in lower pumping energy consumption than the actual system would operate at with the higher flow rates than were simulated. The fan coil units were also simulated with no fan hp so there was no electrical power consumption included in the simulation. The secondary pumps for both the radiant heating and cooling panels were added to the building heating and cooling plant specification sections. The enthalpy wheel simulation was also processed differently than its intent in the proposed redesign. The intent of the energy recovery system was to maintain a 45^{o}F supply air temperature. The program simulates the enthalpy wheel at the design effectiveness for the months selected, regardless of the leaving condition intended. For this reason, there is a larger cooling load on the cooling plant in the winter months if the enthalpy wheel is in operation. However, if the enthalpy wheel is turned off for the winter months, there is a penalty to the heating plant load. The simulation was run twice, simulating the enthalpy wheel in operation yearlong and again in operation only half the year to extract the heating and cooling loads pertaining to the proposed intention of the energy recovery system.

Potential Energy Savings

The existing system does not meet ASHRAE Standard 62 ventilation requirements, only delivering 15,000 cfm of ventilation air to the building. A multiple spaces equation analysis for the building yields a required ventilation flow rate of 43,500 cfm, a difference of 28,500 cfm, almost double the original design. DOAS/ Radiant systems' energy savings are often compared to all-air VAV systems that meet ASHRAE Standard 62 ventilation requirements. For the purpose of this energy analysis, the proposed redesign potential energy savings was compared to the existing system as designed, and the existing system with the corrected ventilation flow rate. Potential energy savings were compared by energy consumed by system components as well as total system energy consumption. *(Refer to HVAC System Energy Comparison - Appendix B)*

The total system potential energy savings of the proposed redesign is 60% of the existing system with the corrected ventilation flow rate. The analysis of the component energy savings was not as expected because both the chiller and pump energy consumption for the proposed redesign system increased by 44% and 123%. The real savings was the 80% reduction in fan energy consumption by the proposed redesign. The potential reduction in natural gas consumption of the boilers in the proposed redesign system is

98%. Values were taken from HAP energy analysis with corrections made in the proposed system for the energy recovery performance and pumping energy.

Based on the modeling results, approximately $42,628 a year (43%) can be saved in energy costs.

First Cost

The first cost of the proposed DOAS/Radiant mechanical system was estimated using the existing GMP estimate prepared by the construction manager and RS Means Data. The estimated 1st cost of the proposed mechanical redesign is 85% of the cost of the existing mechanical system. This estimate includes the chilled water pipe savings inherent with integrating the fire suppression and hydronic thermal transport systems. Redundant equipment in the system estimates was removed. The controls package estimate, a significant part of any mechanical system was neglected for both cases because a breakdown for the existing system was not included. The most noteworthy change in the controls package for the proposed redesign would be the substantial number of control valves needed to provide individual office control. If the DOAS/Radiant system were to be reviewed only on a 1st cost analysis, lumping zone offices together and controlling flow with a single control valve could substantially reduce the individual control valves for each perimeter office. However occupant comfort levels have a considerable effect on worker productivity. While difficult to relay in numbers, the advantage of improved indoor environment quality should be carefully weighed against an elevated 1st cost of the system.

(Refer to HVAC Estimate – Appendix B)

Conclusion

The proposed mechanical system redesign meets ASHRAE Standard 62 ventilation requirements as well as ASHRAE Standard 90.1 energy recovery and reheat guidelines. There is a significant annual energy savings with out a substantial 1st cost penalty. The equipment size is reduced and the possibility for further installation savings can be obtained through system integration. Returning to the 9 areas for potential savings with a DOAS/Radiant system as proposed (Mumma, 2001):

- The chiller required to meet the building cooling load was reduced by 183 tons (40%)
- The primary chilled water pump sizes were reduced from 15 hp to 7.5 hp
- The ductwork installation cost was reduced by 75%
- The total supply air cfm was reduced by 81%
- The electrical service to the mechanical penthouse can obviously be reduced due to the equipment size reduction (analysis follows)
- No savings in acoustical ceiling tile due to pendant mounting radiant cooling panels and existing in-lay radiant heating panels in perimeter spaces
- Less lost rentable space due to mechanical shaft reduction due to reduced supply air volume (not analyzed)

Redesign Impact on Building Systems (AE Breadth)

The redesign of the building's mechanical system impact other systems in the building as well. Returning to the list of potential building system savings inherent in a DOAS/Radiant system, the effects on the following systems were explored; fire suppression and hydronic thermal transport system integration, electrical service to mechanical equipment, and overall building height and layout changes. Potential energy savings through a lighting redesign was also determined for a typical open office space in the building.

Fire Suppression and Hydronic Thermal Transport Integration

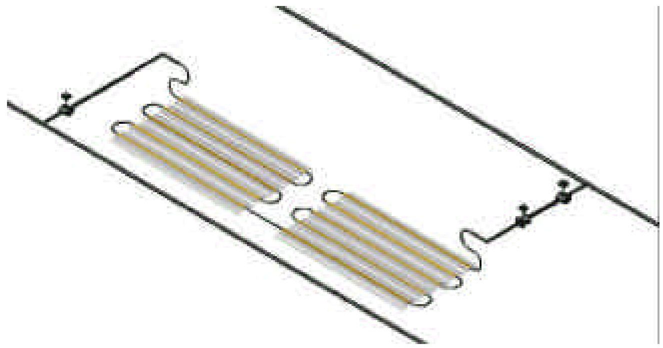
Air-water systems are viable for many cooling applications but have not been widely used in the United States. The industry is bottom line burdened and air-water systems generally have higher installation costs than a typical all air VAV system. The integration of hydronic thermal transport systems (in this case radiant cooling panels) and the fire suppression systems has a potential to offset the added first cost of the radiant panel system by using the thermal transport distribution piping as fire protection piping.

The integration of the two building systems still requires the combined system to meet codes and standards. The NFPA allows the dual use of sprinkler piping for other purposes in the *NFPA 13 Standard* provided the following (from W. Janus, 2001):

- The primary duty of the combined system is fire protection and all portions of the system must comply with NFPA 13.
- All components of the combined system must be rated for the working pressure of the sprinkler system.
- During a fire, water serving the sprinkler heads must not pass through auxiliary equipment or piping.
- The combined system must be a closed-loop circulating system.
- There must be shutoff valves between the sprinkler system and all auxiliary equipment and piping to ensure continuous availability while the auxiliary system is being serviced.
- The water must be less than 120^{o}F. If water is greater than 100^{o}F, intermediate or high temperature sprinklers must be used.
- Special signage needed for fire control valves.
- No additives to the water that would inhibit the suppression characteristics of the water.
- Operation of the auxiliary system must not inhibit sprinkler alarms or cause false alarms.

The auxiliary system is the radiant cooling panels; therefore the high water temperature constraint will not be a factor in system integration. The system is a closed-loop circulating system and the chemical treatment for the system does not interfere with the fire suppression characteristics of the water.

The existing sprinkler head layout was used to develop the Proposed Typical Integrated Fire Suppression and Hydronic Thermal Transport System Plan. The required diffusers and radiant cooling panels were also laid out to determine placement within the confines of the sprinkler head grid. Sprinkler head branch lines were laid out first and then main supply and return lines for the radiant cooling panels. The supply and return mains are connected to every other sprinkler branch line. The supply lines to the radiant cooling panels have globe valves shown to ensure continuous availability of the sprinkler system during maintenance of the radiant panel system. Automatic control valves isolate the primary chilled water loop from the secondary/sprinkler loop to prevent water serving the sprinkler heads from passing through the chilled water system equipment. The life safety requirements of the integrated system must always come first.



Typical Radiant Cooling Panel Piping Detail

The piping for the integrated system is sized first for sprinkler duty and then compared to the chilled water flow duty to the radiant cooling panels. The larger of the two pipe sizes is used. The potential savings in this arrangement is the reduced cost compared to the installation of the two systems separately. Specifically, the piping savings comes from the need for only one set of risers and "supply" mains for the integrated system. There will be additional costs incurred for the integration of the systems, including the control configuration and additional automatic valves to isolate the sprinkler system from the HVAC system.

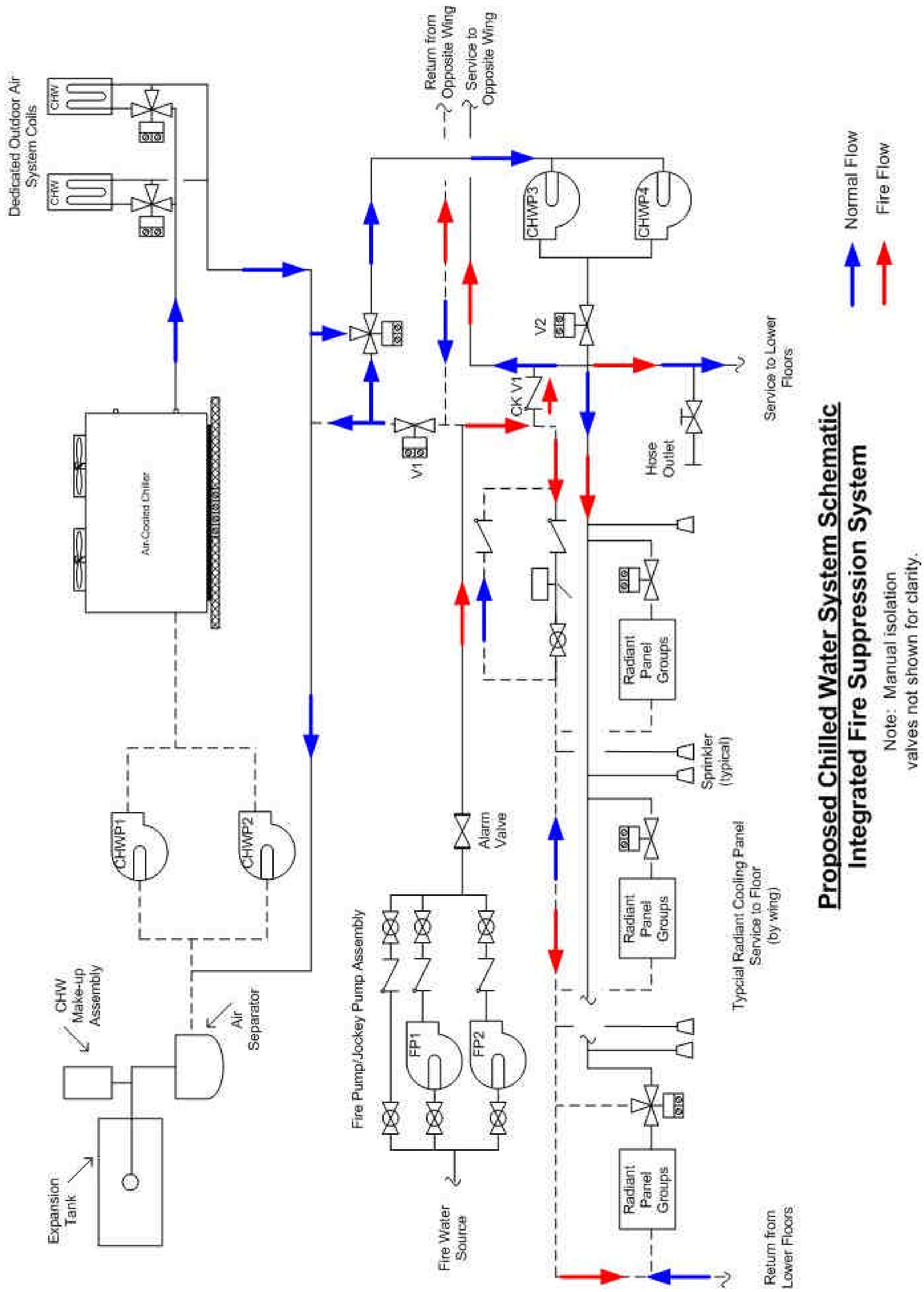
Combining two systems that would normally be provided by two separate sets of sub-contractors and designers involves careful attention to project management. NFPA requirements must be followed and the building code official must be involved early to approve the installation. Close coordination at the time of construction is crucial and the duties of each must be clearly identified in the project manual to avoid future possible litigation. The sprinkler sub-contractor will be responsible for the sprinklers, branches, mains, and all fire water service main piping and equipment until the shutoff valves that isolate the HVAC piping from the fire suppression piping. The remainder of the piping will be left to the HVAC sub-contractor. The redundant piping savings for the proposed integration for 10 open offices (2/wing/floor) is $75,540, obtained by eliminated the smaller duty of the required sprinkler main piping and the HVAC main piping.

(Refer to Proposed Typical Integrated Fire Suppression and Hydronic Thermal Transport System Plan – Appendix A)

System Integration Sequence of Operation and Modified Flow Schematic

Normal Operation: The primary pump will circulate water through the primary chilled water loop and the VFD secondary pump will circulate water to the radiant cooling panels on each floor through a common riser in each wing. There is a check valve configuration in each wing at each floor that prevents HVAC flow across the flow switch and between the supply and return mains on the floors. This assembly contains a fire flow switch, two check valves, and a shut off valve. There is also a check valve CK V1 on each floor between the supply and return piping. The isolation valves V1 and V2 are energized open when in normal operation mode. The control valves on each of the radiant panel groups modulate to accept the flow required to satisfy the cooling needed as determined by the space thermostat. The jockey pump maintains the hydronic system pressure so the fire pump does not have to.

Fire Suppression Operation: When a sprinkler head is activated, the discharge flow through the sprinkler head activates the alarm valve and sends a signal to the fire alarm panel via the DDC system. The check valve configuration forces fire flow across the flow switch. The DDC system then shuts down the primary and secondary chilled water loop pumps, de-energizes the isolation valves V1 and V2 closed to isolate the main HVAC equipment from the system, and closes the control valves on each radiant panel group. The system pressure will drop below the set pressure and the fire pump will begin to operate. The HVAC circulation flow in the return piping is reversed allowing the sprinkler heads served by that line to be fed. The fire flow switch on the floor where the sprinkler head is open helps to identify the location of the fire. The check valve CK V1 is typical for each floor and allows the HVAC supply piping to also feed the sprinkler heads on the fire floor. There are hose outlet valves at each floor.



Proposed Chilled Water System Schematic

Integrated Fire Suppression System

Note: Manual isolation valves not shown for clarity.

Electrical Service Changes

The DOAS/Radiant system redesign has reduced the size of a majority of the mechanical equipment. The following tables only represent the mechanical equipment changed in the redesign.

Original Design

Equipment	HP	kW
Fan	287.4	214.5
Chiller	814.5	607.8
Pump	43.5	32.5
Total	1145.4	854.7

DOAS/Radiant –ER

Equipment	HP	kW
Fan	53.7	40.0
Chiller	460.7	343.8
Pump	24.0	17.9
Energy Recovery	0.17	0.1
Total	538.5	401.9

Using a conservative power factor for the building of 0.9, the kVA change for the building is 503 kVA. The redesign implementing energy recovery causes a change in the building's transformer. The current fluid-filler, pad-mounted transformer is 13.8 kVΔ, 480/277Y, 1500 kVA, 60Hz. The resulting redesign transformer can be downsized to a 1000 kVA unit with a resulting 1^{st} cost savings of $4,400. Additional 1^{st} cost savings can be attained through resizing the feeders to the penthouse equipment.

Overall Building Changes

The DOAS system uses only 19% of the volume of air required by the previous all-air VAV underfloor air distribution system. Both systems utilize a ceiling return air plenum, however the existing underfloor air distribution system supplies the air to the space via a partially ducted raised floor system and the DOAS system supplies the air via ducted ceiling supply. The versatility of the access flooring system has been beneficial to the building due to its versatility of building program and high office churn rate. For this reason, the access flooring system remained part of the redesign. The original height of the access flooring system was 1'-3" and housed supply air ductwork, underfloor junction boxes, and relocatable floor boxes. The height of the access flooring system was adjusted to 6", now only required to house the underfloor junction boxes and relocatable floor boxes. On the typical east wing floor plan ductwork layout, the duct dimensions called out are for round duct. The largest is the partial supply for Zone 2 at 16". If the supply duct from the mechanical shaft is changed to rectangular duct, a dimension of 13"x16" could be used for the same design pressure drop. If this change is made, the return plenum height could be changed from 1'-9" from suspended ceiling to structural steel to a height of 1'-6". This is a conservative change to accommodate not only the ductwork, but also leaves 5" of plenum height under the steel needed to install the drop ceiling panels and other miscellaneous return plenum equipment. The resulting total floor-to-floor change in the height of the building is then 1 foot per floor, from 14' to 13' floor-to-floor height, or an overall building height change of 5'.

To estimate the installation cost savings for a 5' reduction in the overall building height (removed by 1' high bands between the suspended ceiling and finished floor, no glazing changes), the GMP estimate and date from RS Means Assemblies Cost Data, 2000 was used. To estimate the potential savings, only the structural steel and the pre-cast concrete panels were priced.

Pre-Cast Concrete Panel Data

System	Surface Area of 6" Panel	Cost (from GMP estimate)
14' floor-to-floor height	32,2875.5 sq ft	$1,200,000
13' floor-to-floor height	27,562.5 sq ft	$1,024,390*
Savings	4,725 sq ft	$175,610

* Estimate taken as a percentage of GMP estimate.

The structural steel potential savings were determined conservatively by obtaining cost per linear foot for the columns. The column data was taken from the column schedule on the structural drawings.

Structural Steel Data

Column	#	lb/ft	Sub-Total Weight Savings lb	Sub-Total Savings 13 ft Unsupported Height
W8x31	24	31	744	$30.05
W14x74	10	74	740	$58.20
W14x68	11	68	748	$24.98
W14x61	22	61	1342	$55.45
W14x99	5	99	495	$85.95
W14x90	19	90	1710	$37.33
W14x82	5	82	410	$30.08
W14x109	10	109	1090	$85.70
W14x145	2	145	290	$117.58
W14x43	2	43	86	$40.10
W14x120	26	120	3120	$94.08
W14x132	4	132	528	$102.70
W14x35	6	35	210	$26.33
W14x176	11	176	1936	$141.58
W14x40	4	40	160	$34.70
W14x48	4	48	192	$42.08
W14x159	3	159	477	$128.58
W14x193	3	193	579	$141.70
			Sub-Total	$1,277.13
			Corrected Total*	$1,210.22

* Corrected for location and time.

The total potential savings for the overall building height change of 5’ is $176,820. This is a conservative estimate and does not take into account other potential savings including but not limited to fewer stairs, shorter duct and piping risers, shorter elevator shaft, and possibly downsizing the columns.

(Refer to Existing Penthouse Plan and Proposed Penthouse Plan – Appendix A)

The DOAS and parallel radiant panel system equipment is much smaller than the existing system’s equipment. The Existing Penthouse Plan shows 4 large AHUs, 3 boilers, pumps, and electrical distribution panels inside the penthouse and the transformer and air-cooled chillers on the adjacent roof sitting on separate concrete islands. The Proposed Penthouse Plan shows 2 significantly smaller AHUs, boilers, pumps, and electrical distribution panels inside the penthouse, and the transformer and air-cooled chiller now located on the existing penthouse floor. The exterior of the penthouse will look the same, however there will be an added wall and smaller penthouse roof area to enclose the smaller equipment and still allow the air-cooled chiller direct access to outdoor air while remaining hidden from view from the ground. The proposed new wall will be constructed out of the same insulated painted steel panels of the existing penthouse. A structure detail change would be advised for the placement of the additional penthouse wall to ensure its placement along a column line to avoid potential leaks and stability issues. The new placement of the chiller should eliminate the acoustic problems experienced by the building occupants. Building occupants located on the 5th floor of the building voiced many complaints of high frequency compressor noise from the air-cooled chillers located above them. By moving the chiller onto the penthouse floor, the larger surface area and mass of the poured concrete will be better able to contain the chiller noise. The potential installation cost savings are as follows.

Penthouse Layout Data			
Material	**Changed Area**	**Cost**	**Savings**
EPDM fully adhered singly ply membrane roofing	Remove: 2,650.13 sq ft	$1.51/sq ft	$4,001.70
Insulated Steel Panels	Add: 1,596 sq ft Remove: 1,983.4 sq ft	$7.45/sq ft	$2,885.98
		Sub-Total	$6,887.68
		Corrected Total*	$6,526.77

* Corrected for location and time.

Lighting Energy Savings

The majority of the building's interior lighting consists of indirect fixtures mounted at 8'-0" above finished floor (1'-0" below the suspended ceiling). The fixtures are lit with two 4' 32W T5 lamps and are generally hung 9'-4" on center. An analysis consisting of a simple payback and energy savings was conducted to study the use of two 4' 54W T5 lamps instead. For this analysis, the lowered height of the access floor was taken into account, allowing the fixtures to remain mounted at 8'-0" above finished floor, but will now be 1'-9" below the suspended ceiling. The new layout is designed with the fixtures at 11'-0" on center. *(Refer to Proposed Typical Floor Reflected Ceiling Plan – Appendix A).* After reviewing the literature on the specified indirect light fixture common to both designs, the redesign has a ceiling uniformity that meets IESNA (Illuminating Engineering Society of North America) recommendations for open plan office with intensive visual display use and the existing design did not.

For the typical east wing, the original open office design called for 124 fixtures. Characteristics for Sylvania's 4' 32W Octron 800 series lamp was chosen to do the analysis.

$$\left(124\ fixtures \times \frac{2\ lamps}{fixture}\right) \times \left(\frac{2{,}347\ lumens}{lamp}\right) = 582{,}056\ lumens$$

$$248\ lamps \times \left(\frac{32\ W}{lamp}\right) = 7{,}936\ W$$

The redesign of the typical east wing open office was calculated to provide the same number of lumens to the space. Characteristics for Sylvania's 4' 54W Pentron High Output series lamp was used because of its similar color rendering index and rated life.

$$\left(\frac{582{,}056\ lumens}{4{,}136\ lumens/lamp}\right) = 140.73\ lamps \cong 142\ lamps = 71\ fixtures$$

$$142\ lamps \times \left(\frac{54\ W}{lamp}\right) = 7{,}668\ W$$

The number of T5 lamps was chosen on a more conservative level and increased to 142 lamps. T5 lamps have a higher average lumen output when operating at higher ambient temperatures. The T5 system will be mounted at the same height as the radiant ceiling panels and should be expected to have a slightly lower lumen output than the rating provided by the manufacture because of the lower ambient air temperature close to the panels.

The demand charge and energy savings were calculated for 10 typical open offices (2 wings per floor at 5 floors). The annual demand charge savings is

$$\left(\frac{7{,}936\,W - 7{,}668\,W}{1{,}000\,kW/W}\right) \times 10\ spaces = 2.68\ kW$$

$$2.68\ kW \times \left(\frac{\$4.821}{kW}\Big/month\right) \times \left(\frac{12\ months}{year}\right) = \frac{\$155.04}{year}$$

The annual energy savings using the highest block rate from the rate schedule is

$$2.68\ kW \times \left(13\ hours/day\right) \times \left(30\ days/month\right) = \frac{1{,}045.2\ kWh}{month}$$

$$\frac{1{,}045.2\ kWh}{month} \times \frac{\$0.03203}{kWh} \times \frac{12\ months}{year} = \frac{\$401.73}{year}$$

Total annual savings with the T5 redesigned system is

$$\frac{\$155.04}{year} + \frac{\$401.73}{year} = \frac{\$556.77}{year}$$

The installation costs were determined by obtaining material cost estimates from a representative of Whitehill Lighting in State College, PA. The original and redesigned system installation information is as follows.

Original T8 System

Equipment	**Number of Units**	**Unit Cost**	**Total Cost**
Ballast	124	$22	$2,728
Lamp	248	$3.08	$763.84
Fixture	124	$88	$10,912
Sub-Total			$14,403.84
System Total	10	$14,403.84	$144,038.40

Redesigned T5 System

Equipment	Number of Units	Unit Cost	Total Cost
Ballast	71	$30	$2,130
Lamp	142	$11.35	$1611.70
Fixture	71	$88	$6,248
Sub-Total			$9,989.70
System Total	10	$9,989.70	$99,897.00

The lower installation cost of the T5 system as well as the annual energy savings over the original T8 system makes it more attractive. As T5 lamps and ballasts become more common, the difference in lamp pricing should decrease as the market share increases, making the system even more attractive during its life cycle.

Proposed Redesign Conclusion

The goals for the proposed redesign included improved thermal comfort and humidity control, improved indoor air quality by system compliance with ASHRAE Standard 62, reduced energy costs, reduced 1st cost, and building program criteria compliance. Thermal comfort and humidity control for the conditioned space was achieved through the DOAS/Radiant proposed redesign, which allows for greater humidity control and personal climate control in the perimeter offices. The existing system did not comply with the ventilation requirements of ASHRAE Standard 62, however the proposed system clearly delivers the proper volume of ventilation air to each space, clearly improving the indoor air quality. The energy analysis of the proposed redesign shows an annual energy savings over the existing system of 60%, which would also decrease the environmental impact of operating the building. The 1st cost of the integrated study yields a potential first cost savings of over $231,800, not including the potential 1st cost savings of the DOAS/Radiant system itself. The annual energy savings for the integrated study is $43,185. The total annual energy use of the proposed redesign for the building was compared with office buildings from "A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures." The building's annual energy consumption is 76% less energy per square foot than other office buildings polled in the study.

The proposed integrated system redesign for the Academic Support Building shows merit on the basis of the analyses performed within this academic project. More thorough investigation and detailed design would validate and further define the potential of this system for consideration in new construction.

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