# ENVIROCENTER PHASE II

JESSUP, MARYLAND

# FINAL REPORT

SPRING 2012 THESIS PROJECT

BY CHRISTOPHER LORENZ – MECHANICAL, FOR DR. BAHNFLETH

SUBMITTED

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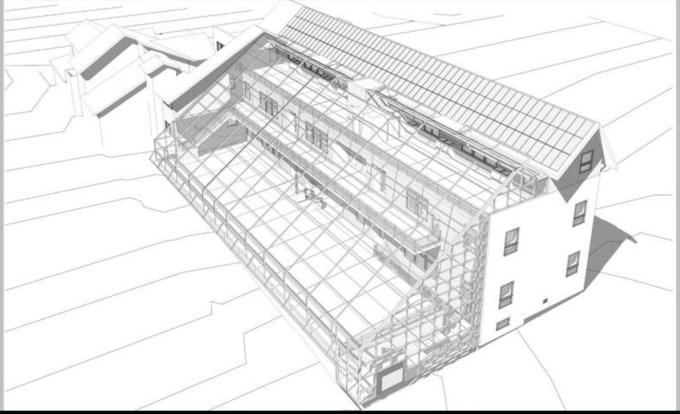

# ENVIROCENTER PHASE II

JESSUP, MARYLAND

CHRIS LORENZ | MECHANICAL OPTION | http://www.engr.psu.edu/ae/thesis/portfolios/2012/CSL5049/index.html

## GENERAL INFORMATION

OWNER - ENVIRONMENTAL DESIGN
AND RESOURCE CENTER
ARCHITECT - ASG, INC.
ENGINEERS - JDB ENGINEERING INC.
CONTRACTOR - FORRESTER CONSTRUCTION
DESIGN-BID-BUILD
SIZE - 24,000 SF

## MEP SYSTEMS

MECHANICAL SYSTEM
13, 500 CFM VAV AIR COOLING
SLAB, MASS WALL RADIANT HEATING
NATURAL VENTILATION
EARTH TUBES PRE-TREAT SUPPLY AIR
REVERSIBLE GROUND SOURCE HEAT PUMP

ELECTRICAL / LIGHTING SYSTEMS
ROOF-TOP SOLAR ARRAY
ENERGY EFFICIENT LED AND
HID LIGHTING

PLUMBING SYSTEM
COMPOSTING URINALS AND TOILETS
RAIN WATER STORAGE

## STRUCTURAL SYSTEM

SUBSTRUCTURE - CAST IN PLACE CONCTETE,
CMUs
SUPER STRUCTURE - STRUCTURAL STEEL FRAME,
AND CONCRETE SLABS.

## SUSTAINABILITY

GOAL:
LEED PLATINUM RATING

SUSTAINABILITY FEATURES
LOW EMISSIBITY WINDOWS
GREEN ROOF
THERMAL MASS WALL
ATRIUM GREENHOUSE
GEOTHERMAL HEAT PUMP
SOLARY ARRAY
RAIN WATER SELECTION
EARTH TUBES
COMPOSTING TOILETS AND URINALS

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The entire AE faculty - It was your instruction that made this all possible, instruction without which this project would have been hopeless.

Tim Warren, PE, LEED AP – Lead Mechanical Engineer for the Enviro Center Phase II

Lacy Brittingham, AIA, LEED AP, CPHC – Project Architect

Stan Sersen, NCARB, LEED AP, RS, PDC – Project Architect

Environmental Design and Resource Center – Owner

I'd also like to thank all of my friends and family who supported me through this endeavor.  I now know what it feels like not to sleep for 3 days and that is its own reward.

# EXECUTIVE SUMMARY

The following report is regarding the mechanical design of the Enviro Center Phase II, an environmentally conscious office building in Jessup, MD. The existing mechanical design was very innovative and was not wonting for much in terms of improvement. One feature of the existing system, the earth tubes was of particular interest, and it seemed like there was more potential there than was being used at the moment. This report focuses on two changes proposed for this mechanical system – sensible cooling with chilled sails, and the use of displacement ventilation. The goal is to see how the loads change with these different systems and how much less work is needed by the system to achieve a comfortable environment using different methods.

The use of radiant cooling is risky, especially in a humid environment like Maryland, so humidity control is a high priority. Condensation forming on the chilled sails could have very poor effects on the indoor air quality and potentially cause sick building syndrome. While the chilled sails will be handling the sensible loads, the displacement ventilation system will be responsible for all of the latent cooling. One experimental approach to humidity control shows great promise with the ability to use heated and cooled liquid desiccants to provide almost 200 MBH of latent cooling with very little energy input.

The use of displacement ventilation combined with chilled sails allowed for a substantial decrease in fan power required. During peak heating conditions, there was only a 9% reduction in fan energy. During peak cooling, however, the fan energy was reduced by over 90%.

It was determined that implementing a chilled beam / displacement ventilation system would provide energy savings for the building by allowing the use of smaller fans and less extreme cooling and heating of water. However, the use of less orthodox, experimental humidity control schemes make this set up less feasible in the real world.

# BUILDING BACKGROUND

The Enviro Centre Phase II is a 24,000 sf, 3 story (plus basement) spec office building being built by Environmental Design and Resource Center in Jessup, MD.  As its name suggests, the building strives to be an environmentally friendly place to work, and its target tenants are companies that would like to lessen their environmental foot print as well.  Living close to the environment doesn’t keep this building from having all of the modern luxuries, however including some less orthodox ones like a greenhouse for growing fruits and vegetables.

The building itself technically is an expansion onto the Enviro Center Phase I, which was a 19th century farmhouse-turned-modern-office space.  Phase II attempts to make a connection to that farmhouse with its steep pitched, wooden roof but its architectural style is all its own.  A large glass atrium is the defining feature of this building architecturally engulfing nearly half of its footprint.  The other half is leasable office space for whatever companies decide to move in.  Non-glazed facades are either a stylish brick or aerated concrete panel which while attractive on the outside, serves a dual purpose by being an excellent insulator as well.

The ECPII has a steel structure combined with cast in place composite slabs.  HSS columns and W shape beams and girders hold this building up.

Electrically, it has 277/480 V electrical system, with supplementary electrical energy coming from an array of solar panels on the roof.  The ECPII uses energy efficient HID and LED lighting and even has a bank of batteries for storing electrical energy from sunny days.

The mechanical system will be discussed at length in the following sections.

# EXISTING MECHANICAL SYSTEM DESCRIPTION

## DESIGN OBJECTIVES

As with the design of any mechanical systems for any office building, the primary objective of the EPCII's mechanical systems is to provide a comfortable atmosphere so that anyone working there can perform to his/her maximum level of output.

Of course there are a number of secondary objectives that the ECPII's systems intend to meet. One of the design goals of this project is LEED Platinum certification – a lofty goal to say the least. Additionally, the ECPII strives to be as energy efficient as possible, running its systems as close to full load as often as is viable. It is more efficient to operate smaller equipment near full load, than it is to operate oversized equipment at smaller fractions of their full load. This will stretch the capacity of the system and will require the cooperation of the tenants. It is assumed however, that the tenants of the ECPII are companies who wish to minimize their environmental footprints and as such are likely to go along with such measures.

On a related note, the design conditions are as follows. Note that the design set points are less conservative than typical in an effort to lessen the system size.

| ASHRAE WEATHER DATA | | |
|---|---|---|
| SEASON | DESIGN DB | DESIGN WB |
| WINTER (99.6%) | 12.3 F | - |
| SUMMER (0.4%) | 93.6 F | 75 F |

**Table-1, ASHRAE Weather Data**

| DESIGN CONDITIONS | | |
|---|---|---|
| SEASON | DESIGN DB | DESIGN RH |
| HEATING | 68 F | - |
| COOLING | 78 F | 60% |

**Table-2, Design set points**

Part of the challenge that these systems must face is the unique architectural features that this building possesses. A large glass atrium containing a green house will be the source of a great deal of solar heat gain in the summer season.

## ENERGY SOURCES

Other than solar energy, which is free and used both for heating, and to power a photovoltaic array, the only energy purchased by ECPII is electricity. Both heated and chilled water are provided by electrically powered heat pumps. As such there is no gas or fuel oil to be purchased for powering boilers or absorption chillers, etc.

While a great deal of electricity is to be produced by the PV array on the roof, some electricity will need to be purchased from the grid at times. This purchased electricity comes from Baltimore Gas and Electric. Rates are as follows.

| ELECTRICITY COSTS | |
|---|---|
| TIME | $/kWh |
| ON-PEAK | 0.11351 |
| OFF-PEAK | 0.06033 |

**Table-3, Electricity costs**

## COSTS

The ECPII has significant costs associated with it. In spite of being a small system, the designers have gone to great lengths to use the most energy efficient systems possible. These tend to have significant initial costs, and lengthy payback periods – the bane of a typical building owner. The ECPII's owner's goal was to develop an advanced, highly sustainable building and recognized that such things do not come cheaply. Obviously cost was minimized as much as possible but within the constraints of the goals that the ECPII attempt to achieve.

In addition to equipment costs, installation costs can also be quite expensive. The well field for the ground source heat pumps but especially the underground tubing for the earth tubes add construction costs which are atypical in most mechanical applications.

Fortunately, there are numerous tax credits and rebates available to the owner as a result of the various sustainable technologies utilized in the building. Table-x below details a few of the incentives available to the ECPII.

| REBATES AND INCENTIVES | | |
|---|---|---|
| INCENTIVE | MAXIMUM INCENTIVE | REQUIREMENTS |
| CLEAN ENERGY GRANT | $500/TON UP TO $7,000 | GEOTHERMAL HEAT PUMPS |
| BG & E COMMERCIAL ENERGY EFFICIENCY PROGRAM | UP TO $1M/TAX ID/YR. COMMERCIAL REBATES: 50% | VARIOUS ENERGY SAVING TECH (LED LIGHTING, PROGRAMMABLE THERMOSTATS, VFDS ETC.) |
| HOWARD COUNTY PROPERTY TAX CREDIT | 75% CREDIT FOR A 5 YEAR TERM | LEED PLATINUM CERTIFICATION |

**Table-4, Tax Incentives, Rebates and Grants**

Actual mechanical system cost data was not available at the time of this report.

## EQUIPMENT

The ECPII contains two reversible heat pumps which provide the hot and chilled water for the entire mechanical system. This system involves a variety of equipment, the major players of which are listed briefly in the tables below:

| GROUND SOURCE HEAT PUMPS | | | | | | |
|---|---|---|---|---|---|---|
| SYMBOL | COOLING | | | HEATING | | |
| | MBH | KW | EER | MBH | KW | COP |
| HP-1 | 119.5 | 8.8 | 13.6 | 121.1 | 9.6 | 3.7 |
| HP-2 | 119.5 | 8.8 | 13.6 | 121.1 | 9.6 | 3.7 |

**Table-5, Heat Pumps**

| PLATE AND FRAME HEAT EXCHANGER | | | | |
|---|---|---|---|---|
| | EWT | LWT | GPM | WPD |
| Hot Side | 99.7 | 90 | 60 | 1.2 |
| Cold Side | 90 | 98 | 46 | 0.9 |

**Table-6, Heat Exchangers**

| PUMPS | | | | | |
|---|---|---|---|---|---|
| SYMBOL | GPM | HEAD | IMPELLER SIZE | HP | RPM |
| P-1 | 23 | 30 | 5 1/2 | 3/4 | 1750 |
| P-2 | 23 | 30 | 5 1/2 | 3/4 | 1750 |
| P-3 | 30 | 30 | 5 1/2 | 3/4 | 1750 |
| P-4 | 30 | 30 | 5 1/2 | 3/4 | 1750 |
| P-5 | 60 | 30 | 5 3/4 | 1 1/2 | 1750 |
| P-6 | 46 | 35 | 6 1/4 | 1 | 1750 |
| P-7 | 46 | 35 | 6 1/4 | 1 | 1750 |

**Table-7, Pumps**

| FINNED TUBE RADIATORS | | | |
|---|---|---|---|
| SYMBOL | LENGTH | MBH | GPM |
| FTR-1 | 5' | 9.3 | 12 |
| FTR-2 | 15' | 27.1 | 12 |
| FTR-3 | 15' | 24.5 | 12 |
| FTR-4 | 10' | 14.8 | 12 |
| FTR-5 | 15' | 20.8 | 12 |
| FTR-6 | 15' | 18.8 | 12 |
| FTR-7 | 8' | 9.1 | 12 |
| FTR-8 | 15' | 17.1 | 12 |
| FTR-9 | 10' | 19.1 | 12 |
| FTR-10 | 15' | 28.7 | 12 |

**Table-8, Finned Tube Radiators**

| AHU | | | |
|---|---|---|---|
| CFM | OA | | POWER |
| | MIN | MAX | |
| 13500 | 3100 | 13500 | 208/3 |

**Table-9, Air Handling Unit. Note that the main Cooling coil is not contained within the AHU**

The ECPII is served by one air handler, located on the first floor. That air handler supplies 13500 CFM, ranging from 3100 up to the full 13500 CFM of outdoor air. Before reaching the air handler, however, outside air is pretreated as it travels through a bank of earth tubes, being heated or cooled by the relatively stable temperature of the Earth. It then mixes with the return air in the AHU and is sent back through the earth tubes where it comes out, and hits the cooling coil. It then makes its way to the various terminal VAV boxes, and their associated spaces. During the heating season, the minimum ventilation air is supplied, heating by hot water reheat coils located in the VAV boxes.

Heating is accomplished via radiant slabs and mass walls throughout the building. Additionally, Hot water is supplied by two reversible geothermal heat pumps which transfer heat to the heating hot water via a plate and frame heat exchanger before being pumped to the loads. Chilled water for use during the cooling season is also provided by those heat pumps by the same means. Of course, during the cooling season, chilled water is not supplied to the radiant floors the way the hot water is.

## LOST SPACE

The sad truth about mechanical systems is that they occupy space that could otherwise be used towards other productive ends. Relative to the size of the ECPII, its mechanical system takes up a great deal of space, especially when plumbing and electrical spaces are taken into account.

| LOST SPACE | | |
|---|---|---|
| Floor | Floor Area, SF | Shaft Area, SF |
| Basement | 961 | 0 |
| 1 | 250 | 12 |
| 2 | 0 | 12 |
| 3 | 0 | 12 |

| | |
|---|---|
| TOTAL: | 1247 |

**Table-10, Lost Usable Space**

The total lost space accounts for about 5% of the ECPII's floor area. The size of the basement mechanical room houses more than just mechanical equipment , containing large urine composters that are part of the sanitary plumbing system. However, extra space is taken up due to the earth tubes that run along the building underground. These cause there to be two mechanical rooms: The air handler on one end of the building, and the cooling coil on the other. Space occupied by underground earth tubes and heat pump wells were not counted as that space is not, strictly speaking, a “usable” part of the building.

# MECHANICAL SYSTEM OPERATION

## AIRSIDE

The Enviro Center Phase II has a VAV cooling system, with one air handler inside of the mechanical room on the first floor. Outdoor air comes in through a gravity vent next to the parking lot and is then naturally pretreated as it flows through a series of earth tubes before mixing with return air and finally reaching the air handler. When in peak cooling mode, the mixed air then travels back through another bank of earth tubes where it can be even more pretreated. It then comes up on the other side of the building where it hits the cooling coil. Finally, the cooled air continues on toward the terminal units. Cool air enters the space, then returns to mix with new outside air.

During winter heating months, the air flows as in the peak cooling case, allowing only the minimum required ventilation air into the vent, and with no temperature drop across the cooling coil. Instead, the pretreated air is heated by the reheat coils in the VAV boxes in each zone.

When sensible outdoor air temperature and total enthalpy are appropriate, an economizer cycle kicks in. In economizer mode, outside air enters both banks of earth tubes from the vent outside. It then travels through the tubes and up into the mixing plenum where it meets the return air, if any. This mixed air is then blown from the AHU to the terminal units without traveling through the earth tubes as had been done in the peak cooling scenario.

It is estimated that during peak heating, the earth tubes bring 11°F design outdoor air up to 37°F. Also, that during peak cooling, the earth tubes cool 97°F design outdoor air temperature down to 67°F.

## WATERSIDE

Hot and chilled water for use in the cooling and reheat coils is provided by two reversible ground source heat pumps in the mechanical room – 119 MBH Cooling, 121 MBH Heating.

A well field located under the parking lot for the ECPII will be where the ground source heat pumps reject their heat when cooling water, and absorb heat when heating the water. The heat pumps will have an anti-freeze solution flowing through them, which will transfer heat with the heating and cooling water via a plate and frame heat exchanger.

The ECPII uses a hydronic radiant heating system to heat its spaces. This is achieved by radiant piping in concrete slabs, as well as a mass wall separating the tenant spaces from the atrium. The mass wall will absorb solar energy and slowly radiate it, and the heat from the hot water piping into the space. The solar heat gain of the mass wall is meant to help lessen the load of the heating system.

## LOAD AND ENERGY SIMULATION

As part of this project, a load / energy model was constructed in Trane's Trace 700 software. These loads were used as the basis for the main mechanical analysis.

## LIGHTING AND EQUIPMENT LOADS

The lighting and equipment loads used were done based on watts per square foot. Lighting loads were calculated based on the space by space method, with a level of 2.04 W/sf. Because the ECPII is a spec office building, exact equipment loads are unknown, so a generic assumption of 0.5 W/SF allowance for various office equipment was used.

## OCCUPANCY LOADS

Not knowing exactly how many people are going to be in the EPCII at any given time because it is a spec office building, required that a general allowance for various people be applied to the spaces. A density of 143 SF per person was assumed, with each person providing a sensible load of 250 BTU/h and a latent load of 200BTU/h.

# ASHRAE STANDARDS EVALUATION

## ASHRAE 62.1

The Enviro Center's mechanical ventilation rate is slightly below what is prescribed in ASHRAE 62.1. ASHRAE 62.1 calls for 3577 CFM of outside air, but the mechanical system only provides 3100 CFM. This is because the primary means of ventilation for the Enviro Center is natural ventilation. The atrium on the south side of the building will create a natural convection current, taking air up and out of vents on the roof, drawing air from the office spaces, and similarly drawing fresh air into them. This will make up for the 500 CFM of ventilation that is not met by the mechanical system. Of the 13,500 CFM supplied by the air handler, 3100 CFM are outside air, creating a fraction of 23% with which to supplement the natural ventilation that will be occurring. In an effort to reduce energy consumption, the mechanical ventilation was kept to a minimum, relying more heavily on natural ventilation in the building. The ASHRAE 62.1 ventilation rates can be seen in the table in Appendix A.

## ASHRAE 90.1

Upon analysis of several of the Enviro Center Phase II's systems, like building enclosure, HVAC domestic hot water, power and lighting, this building on the whole performs quite well. One area where it does fall short is in the lighting.

The ECPII's LPD of 1.07 W/ft$^2$ is just over the 1.0 W/ft$^2$ guideline prescribed by ASHRAE 90.1.This is likely due to the extra lighting provided to the glass enclosure and empty spaces of the atrium, which isn't used on a task surface like most of the other lighting in the building.

The electrical power and HVAC systems on the other hand, do meet the standards set forth by ASHRAE 90.1 Fan power efficiencies surpass the standard, though the fans in the air handler just barely so. This is likely due to the fact that it has to force the air through two MERV filters – a MERV 7 and a MERV 13. Tables of energy use by various pieces of equipment can be found in Appendix A.

# PROPOSED ALTERNATIVE SYSTEMS

## PASSIVE CHILLED BEAMS WITH DISPLACEMENT VENTILATION

The current means of cooling the spaces in the ECPII is a VAV system, but with radiant heating in slabs and mass walls. Another alternative to this system would be one which uses passive chilled beams in the ceiling to cool the spaces, while providing the necessary ventilation air by means of displacement ventilation. Displacement ventilation has been shown to have benefits for indoor air quality and have possible benefits to energy use. The DV air will still be pretreated with the earth tubes to maximize the amount of free cooling available to the building.

As with any radiant cooling, care must be taken to avoid condensation on the chilled beams. Although they are generally supplied with slightly warmer cold water, the possibility of condensation is still something which must be considered. Humidity control will be an issue, again likely dealt with by use of desiccants. Dehumidification with a cooling coil would be less desirable because of the added loads to the heat pumps.

Passive chilled beams and displacement ventilation are interesting systems that I’ve seen considered on real world projects. In addition to possible IAQ and energy benefits, I feel that working with these systems would be a valuable would be an educational benefit to me.

**I will evaluate the chilled beam and displacement ventilation systems and compare them with the current VAV system. The loads on each system will be compared, as well as differences in fan energy from one system to the other.**

# BREADTH STUDIES

## ARCHITECTURE

The ECPII has no drop ceiling, so the chilled beams would be used to create a drop ceiling of sorts. These beams come in a number of sizes and designs, and they could be chosen to create an architecturally pleasing ceiling. Additionally, the displacement ventilation diffusers would need to be near the floor, taking up space. These could be used in an aesthetically pleasing way, such as a free standing floor diffuser being used with a table top, or being incorporated into some sort of decorative column. Renderings, and reflected ceiling plans will be produced to demonstrate the architectural significance of these changes.

## STRUCTURE

With chilled beams being added to the ceilings, the structure of those spaces will also need to be modified. A significant load is being added to the structure with the inclusion of chilled beams. The suggestion of adding these larger pieces of equipment without considering the effect on the buildings structure would be unwise. As such calculations will be done to make sure that the current structure is capable of supporting this equipment. If not, a suggestion will be made as to how the structure could be changed to accommodate it.

# TOOLS AND METHODS

## CHILLED BEAMS AND DISPLACEMENT VENTILATION

First, an accurate model of the building must be produced in order to design and evaluate the effectiveness of these systems. This will be accomplished using a modeling and simulation program like Trane's Trace 700. Also, many calculations will be made in Microsoft Excel.

Additionally, the availability of any extra software to aid in sizing equipment will also be explored for the purposes of comparing with the data obtained from the other modeling software. Alternatively, online manufacturer catalogs will be used.

## STRUCTURAL AND ARCHITECTURE

AutoCAD and Revit will be used extensively during this project.  A 3-D model is incredibly helpful with both architecture and structural work.  It will be used to create the renders and new reflected ceiling plans for the architectural breadth.

# MECHANICAL ANALYSIS (DEPTH)

## DISPLACEMENT VENTILATION

### INTRODUCTION

Displacement ventilation systems are a means of ventilating a space using low velocity air, supplied much closer to the space set point temperature than traditional mixing ventilation. The air is always supplied cooler than the room air such that it falls to the ground due to buoyancy effects and then moves up through the occupied space as it is heated up by the space. This creates an upward draft which, along with the air, carries contaminants in the air up and out of the occupied zone, improving the indoor air quality for those inside.

### PROCEDURE

The procedure followed in creating a DV system first starts with finding out the ventilation requirements for the zones being served. As determined previously, the existing ventilation rates in the ECPII did not meet ASHRAE standard 62.1, so the ASHRAE 62.1 rates were used. Because this DV system is being paired with a radiant cooling system (see chilled sails, p.XX) only the minimum ventilation rates are necessary. For the sake of simplicity, these rates were rounded up to the numbers shown in the table below. See Table-A1 in Appendix A for the original ventilation rates.

| DV RATES | |
|---|---|
| ZONE | VENT CFM |
| 110 | 310 |
| 120 | 250 |
| 121 | 220 |
| 130 | 570 |
| 210 | 360 |
| 220 | 420 |
| 221 | 390 |
| 230 | 240 |
| 231 | 280 |
| 310 | 360 |
| 320 | 220 |

**Table-11, Design DV flow rates**

Subsequently, DV diffusers were selected from the Price Industries online catalog. Diffusers were chosen and placed in a way that is appropriate for the space. Because the spaces in the ECPII are spec offices, it was important to keep as much open space as possible. Therefore, price DR180 diffusers were chosen for their wall hugging abilities, 180 degree discharge and attractive appearance. Because these diffusers will be sitting out in the open, it is important that they look nice.

The diffusers noted in the table below were chosen for each of the spaces. See performance data for the diffusers in Fig-A1, Appendix A.

| DV DIFFUSER SELECTIONS | | |
|---|---|---|
| ZONE | VENT CFM | DIFFUSER |
| 110 | 310 | (2) 30x24 |
| 120 | 250 | 30x24 |
| 121 | 220 | 24x24 |
| 130 | 570 | (2) 30x36 |
| 210 | 360 | 18x24, (2) 24x36 |
| 220 | 420 | 30x36 |
| 221 | 390 | (2) 24x36 |
| 230 | 240 | 30x24 |
| 231 | 280 | 24x24, (2) 18x24 |
| 310 | 360 | (2) 18x36 |
| 320 | 220 | (2) 18x36 |

**Table-12, Displacement Ventilation Diffusers**

## LOW FLOW LIQUID DESICCANT DEHUMIDIFICATION

Being paired with a radiant cooling system, the ventilation system is responsible for 100% of the latent cooling loads in the building. Typical DV systems supply air near 65 °F DB, 55 °F WB. It is estimated that the pretreated air coming out of the ECPII’s earth tubes will be at 67 °F DB, 65 °F. The dry bulb temperature is very close to what is needed for supply, but with a dew point far too high (65 °F ) for use with a radiant cooling system. Rather than wasting so much cooling energy dehumidifying the air only to heat it almost exactly where it was before, desiccant dehumidification could be used. Desiccant wheels exist, which do a good job of dehumidifying the air, but also heat up the supply air, requiring it be cooled again.

The solution to this is a novel technology called low flow liquid desiccant dehumidification, wherein supply air flows (at low velocities) across liquid cooled plates, known as the conditioner, covered with a thin film of liquid desiccant (In this case, a 44% lithium chloride solution). The velocity of the air is low such that particles of desiccant do not get picked up in the stream, but rather flow down into an interchange heat exchanger and then recharged in a similar fashion but with waste air flow and hot water. This is called the regenerator. The process is demonstrated in the following figure .

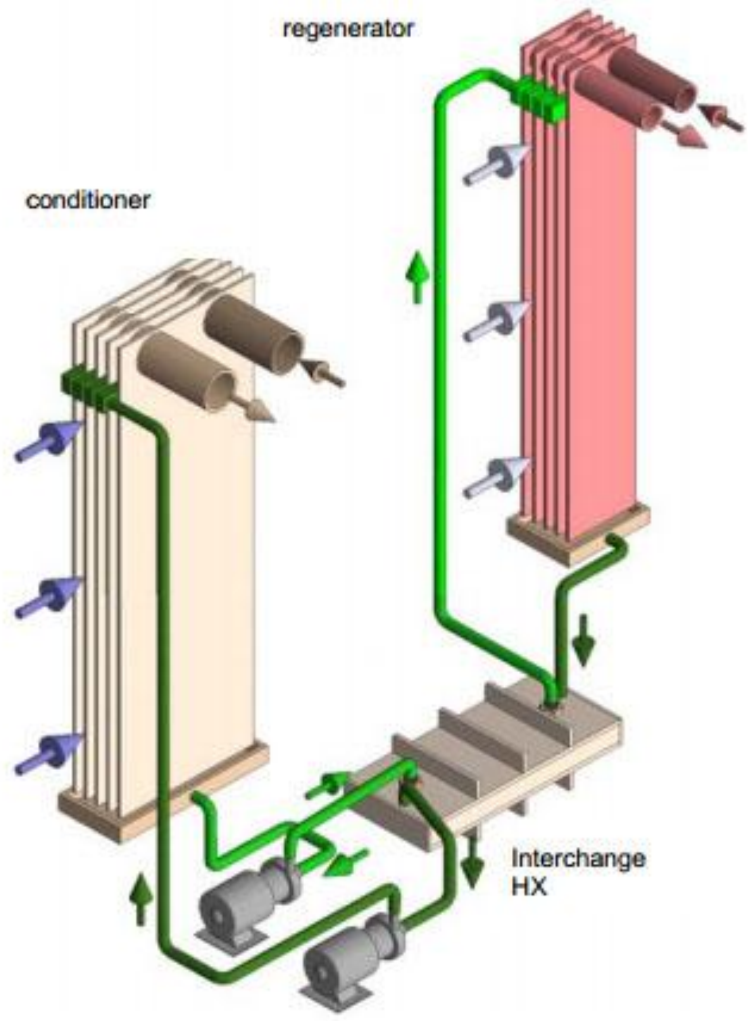


**Figure-1, Low Flow Desiccant Dehumidifier.**
**Image Courtesy National Renewable Energy Laboratory**

This process allows for the removal of a great deal latent energy while only slightly reducing the sensible energy. In the case of the ECPII, that sensible energy loss is helpful for getting the supply air down to the supply conditions. Though it does require cold and hot water flowing to operate, the cold water can be supplied at temperatures much higher than standard, HVAC applications, as high as 86 °F. That can be accomplished using the return water from the radiant cooling. The hot water should be supplied at or above 150 °F, which can be provided with a small electric resistance boiler. The desiccant circulation pump requires little energy, 1/5HP, because of its low flow rate. In laboratory tests under these conditions, the dehumidifier was able to supply 6000 CFM of 92 °F DB, 66 °F WB, from an initial condition of 95 °F DB, 76 °F WB. That equates to 196 MBH of latent cooling.

While this technology would be quite useful, it may be somewhat cost prohibitive. Given its experimental nature, cost information was not readily available, but I feel safe assuming that it would be very expensive. However, this sort of technology is exactly something that embodies the ideals of the Enviro Center at its core values, so it was definitely something to consider.

Similarly, regarding humidity control, sophisticated controls will need to be in place to prevent excess infiltration. For example, sensors on tenants' windows will detect if it has been opened and will shut off distribution to that zone as a result. That way uncontrolled amounts of humidity do not condense on chilled surfaces.

## PERFORMANCE

The fact that this DV system is only providing the minimum ventilation rates year round, allows for a great deal of savings of fan energy. This can be calculated using the fan affinity laws, specifically:

$$\frac{P_1}{P_2} = (\frac{Q_1}{Q_2})^3$$

Using $Q_1$ = 3260 CFM, and $Q_2$ = 13500 CFM, we find that the required new power for the fan is significantly less, just under 2% of the original power. This allows for a much smaller fan, and air handler creating more space in the mechanical room for dehumidification equipment.

Additionally, the differences in supply temperature allow the DV system to operate more efficiently than the VAV system even when running under similar conditions. During the heating season, the ECPII's VAV system runs down at minimum ventilation, but is still supplying 75 °F air to the space, as opposed to the DV system's 70 °F air. The differences in the amount of heating required can be seen in the tables below.

| DV HEATING | | | |
|---|---|---|---|
| ZONE | VENT CFM | ΔT HEATING °F | q MBH |
| SYSTEM | 3620 | 33 | 129 |

**Table-13, DV Peak Heating Loads**

| VAV HEATING | | | |
|---|---|---|---|
| ZONE | VENT CFM | ΔT HEATING °F | q BTUH |
| 110 | 310 | 36 | 12053 |
| 120 | 250 | 36 | 9720 |
| 121 | 220 | 38 | 9029 |
| 130 | 570 | 34 | 20930 |
| 210 | 360 | 37 | 14386 |
| 220 | 420 | 37 | 16783 |
| 221 | 390 | 35 | 14742 |
| 230 | 240 | 36 | 9331 |
| 231 | 280 | 38 | 11491 |
| 310 | 360 | 38 | 14774 |
| 320 | 220 | 38 | 9029 |

| TOTAL (MBH) | 142 |
|---|---|

**Table-14, VAV Peak Heating Loads**

In peak heating season, the displacement ventilation system is required to do only 129 MBH of heating compared to the VAV system's 142 MBH. That is a reduction of over 9%.

In the cooling season, the savings are a little more difficult to see, because instead of chilled water VAV systems, this DV system is paired with a radiant cooling system – chilled sails.

## CHILLED SAILS

### INTRODUCTION

Chilled sails are a radiant cooling technology that involves water cooled panels hanging above the zone, absorbing radiant, sensible energy from the space. Chilled sails are a lot like chilled beams in the fundamental ways that they operate, and vary mainly on appearance. Chilled sails, especially the Architectural Chilled Sails used in this analysis, tend to be more attractive than standard chilled beams and can be seen as an architectural feature in-and-of-themselves.

While architectural appearance was a factor in selecting this particular variety of radiant cooling, the more important part is that way it operates. Cold water is supplied through hydronic piping to the chilled sails, which act as heat sinks absorbing sensible energy from the room and transferring it to the water.

These systems tend to be quite efficient at sensible cooling when hung from a ceiling. This is due to the convection currents that are created by cooling the air at the top of the room. Cold air becomes more dense and sinks down below, where it absorbs heat from the zone. After heating up, the air rises again, to repeat the process. This can be seen in the figure below.

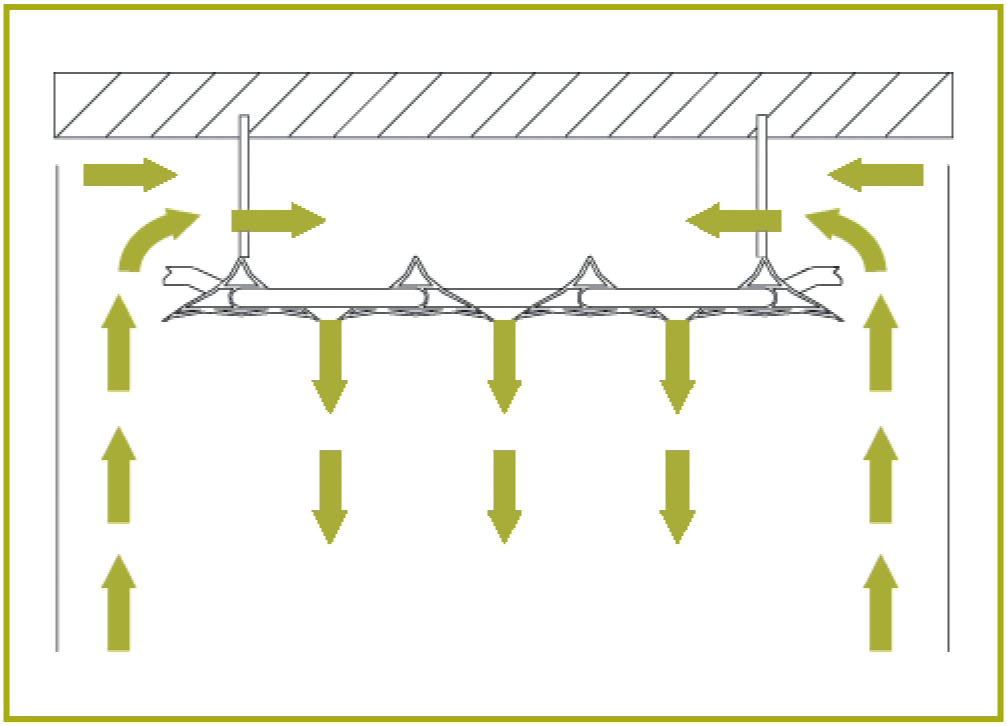


**Figure-2, Convective Airflow Through a Chilled Sail**

## PROCEDURES

The process for selecting chilled sails is fairly straight forward.

1. Determine the sensible cooling loads for each zone. These can be calculated by hand or gotten from a modeling program like Trace 700.

| ZONE SENSIBLE COOLING LOADS | |
|---|---|
| ZONE | ROOM SENSIBLE LOAD |
| 110 | 3291 |
| 120 | 2551 |
| 121 | 2041 |
| 130 | 5091 |
| 210 | 3875 |
| 220 | 3061 |
| 221 | 3571 |
| 230 | 2041 |
| 231 | 2551 |
| 310 | 4600 |
| 320 | 6632 |

**Table-15, sensible cooling loads**

2. Determine ventilation cooling contribution. While the chilled sail is going to be providing most the sensible cooling, a portion of that sensible load is taken care of by the ventilation system. It is important to account for this at the risk of oversizing your system. These numbers are then subtracted from the total room loads from step 1.

$$q_s = 1.08\ Q\ \Delta T$$

Where, $q_s$ = sensible cooling (BTUH), Q = Volumetric flow rate (CFM), $\Delta T$ = temperature change (°F)

For a displacement ventilation system, a $\Delta T$ of 5 °F is a reasonable assumption. This gives us the results in the following table.

| VENTILATION COOLING | | |
|---|---|---|
| VENT CFM | VENT COOLING | CSA LOAD (BTUH) |
| 310 | 1252.4 | 2038.6 |
| 250 | 1010 | 1541 |
| 220 | 888.8 | 1152.2 |
| 570 | 2302.8 | 2788.2 |
| 360 | 1454.4 | 2420.6 |
| 420 | 1696.8 | 1364.2 |
| 390 | 1575.6 | 1995.4 |
| 240 | 969.6 | 1071.4 |
| 280 | 1131.2 | 1419.8 |
| 360 | 1454.4 | 3145.6 |
| 220 | 888.8 | 5743.2 |

**Table-16, Ventilation cooling and corrected sensible load**

3. Determine the area / quantity of chilled sail required to meet that load.

Per-square-foot cooling ability is given in manufacturers catalog performance data. This can be used to determine how much is required. A sample from Price Industries' chilled sail catalog is figure-A2 in Appendix A.

Once the chilled sails are selected and quantified, the next step is to lay them out. There are no easy formulas to remember for laying out chilled ceilings. In more involved applications, Computational Fluid Dynamics (CFD) is used to analyze various layouts and select the best. Other than that, layout is based primarily on experience.

## PERFORMANCE

As stated earlier, because the chilled sails handle the sensible load, the ventilation system may continue to operate at its minimum volume flow. Not only does this save on fan energy, but it also saves on coil load as well.

During peak cooling, the ventilation accounts for 8 MBH of cooling as a result of the pretreated earth tube air being so close to supply temperature already. The sum of all of the cooling provided by chilled sails, which are essentially zone level cooling coils, is 25 MBH as shown in the following table.

| CSA LOAD (BTU/HR) | SAIL CAPACITY (BTU/HR) | SAIL AREA (SF) | REQ. SAILS |
|---|---|---|---|
| 2039 | 322 | 12 | 7 |
| 1541 | 322 | 12 | 5 |
| 1153 | 322 | 12 | 4 |
| 2789 | 322 | 12 | 9 |
| 2421 | 322 | 12 | 8 |
| 1365 | 322 | 12 | 5 |
| 1996 | 322 | 12 | 7 |
| 1072 | 322 | 12 | 4 |
| 1420 | 322 | 12 | 5 |
| 3146 | 322 | 12 | 10 |
| 5744 | 322 | 12 | 18 |
| | | | |
| **24686** | | | |

**Table-17, chilled sail cooling**

This results in a total cooling coil load of 33 MBH. Even just the sensible cooling done by the cooling coil in the VAV system is 102 MBH, significantly higher than the chilled sail system. This of course means more energy spent chilling water to achieve the same effect as the chilled sail which uses warmer water than a typical cooling coil.

## LEED ANALYSIS

The Leadership in Energy and Environmental Design (LEED) system, has been developed by the United States Green Building Council (USGBC) as a way of evaluating the sustainability of buildings that are being constructed or renovated. This project is striving for LEED Platinum certification, and is counting on that for rebates and tax benefits. As such it is appropriate that a LEED evaluation be done on the ECPII.

### SUSTAINABLE SITES -19 POINTS

1 – (Credit 1) Site selection
12 – (Credits 4.1 – 4.4) Alternative transportation: Public transit access, bicycle storage, Low-E vehicles, parking capacity
1 – (Credit 5.2) Maximize open space on site
2 – (Credits 6.1, 6.2) Storm water quantity and quality control
2 – (Credits 7.1, 7.2) Heat Island effect, Non-roof and roof
1 – (Credit 8) Light Pollution reduction.

### WATER EFFICIENCY -10 POINTS

4 – (Credit 1) Water Efficient Landscaping. No potable water use or irrigation.
2 – (Credit 2) Innovative wastewater Technologies
4 –(Credit 3) Water use reduction. Reduce by 40%

### ENERGY AND ATMOSPHERE – 35 POINTS

19 – (Credit 1) Optimize Energy Performance. Improve by 48% for new buildings.
7 – (Credit 2) On Site renewable energy. 13% renewable energy.
2 –(Credit 3) Enhanced commissioning.
2 – (Credit 4) Enhanced Refrigerant Management
3 – (Credit 5) Measurement and Verification
2 – (Credit 6) Green Power

## MATERIALS AND RESOURCES – 10 POINTS

2 – (Credit 2) Construction waste management.  75% recycled or salvaged.
2 – (Credit 3) Materials Reuse.  Reuse 10%
2 – (Credit 4) Recycled Content.  20% of content
2 – (Credit 5) Regional Materials.  20% of materials
1 – (Credit 6) Rapidly Renewable Materials
1 – (Credit 7) Certified Wood

## INDOOR ENVIRONMENTAL QUALITY – 15 POINTS

1 – (Credit 1) Outdoor Air Delivery Monitoring.
1 – (Credit 2) Increased Ventilation (Based on designer's calculations)
2 –(Credits 3.1, 3.2) Construction IAQ Management plan.  During Construction and Before Occupancy
4 – (Credits 4.1 – 4.4) Low-E Materials
1 – (Credit 5) Indoor Chemical and Pollutant Source Control
2 – (Credits 6.1, 6.2) Controllability of Systems.  Lighting and Thermal comfort
2 – (Credits 7.1, 7.2) Thermal Comfort.  Design and verification
2 – (Credits 8.1, 8.2) Daylight and Views.

## INNOVATION IN DESIGN – 6 POINTS

5 – (Credit 1) Innovation or Exemplary Performance.
1 – (Credit 2) LEED Accredited Professional

## REGIONAL PRIORITY – 4 POINTS

4 – (Credit 1) Regionally Defined Credit Achieved

## TOTAL – 99 POINTS.  LEED PLATINUM

Totaling 99 LEED points, the ECPII is on track to achieve its Platinum certification.  As the LEED system becomes more and more ubiquitous in the building industry, it is important that the way LEED credits are assigned to be a part of a designer's vocabulary.  Even if not striving for LEED certification, they are good guidelines for the design of a sustainable building.

## CONCLUSIONS

Based on the above data, it is clear that installing a chilled sail / displacement ventilation setup will save energy. Less required fan power, and lower demand for hot and chilled water all allow components in the building to shrink down to a much more energy-sipping size. Low flow desiccant dehumidification seems promising, but its experimental nature and unavailability make it a less feasible option for humidity control over something more conventional like a desiccant wheel. As such, while this analysis was a unique and interesting learning experience, the design itself may not be feasible.

# STRUCTURAL BREADTH

## INTRODUCTION

With the addition of these chilled sails to the ECPII, care must be taken to assure that the structure of the building is not adversely affected. The ECPII is supported by a structural steel frame with cast in place concrete slabs with composite deck. Each floor / ceiling consists of such a slab being supported by girders and beams. For this structural analysis, the new dead load from the chilled sails was added to the slabs as a distributed load. Then, three different worst-case members were checked for maximum moment, maximum shear stress, and maximum deflection – 2 beams and a girder. Two different beams were chosen from different parts of the frame, and each was chosen as the worst case for having the widest tributary area.

A few assumptions were made to the end of simplifying these calculations, though always erring on the side of being conservative. An office live loading of $L_o$ = 70 psf was assumed, as well as a superimposed dead load of 15 psf. The chilled sails themselves were listed by Price as being 2.77 psf, and were rounded up to 3 psf. Note that for the purpose of this analysis, it is assumed that $L_u = 0$ because of the deck bracing the beams.

## METHOD

Each of the members is considered simply supported with a distributed load, and the girder with a distributed load and two point loads from framed in beams. Plans showing the framing for each of the members can be found in Appendix B. Max moment, and max shear were compared against $\phi Mp$ and $\phi Vn$ from the AISC steel manual.

Load factoring of PLF = 1.2D + 1.6LL was used. The following equations were used:

| | |
|---|---|
| Live load reduction: | $LL = L_0 * (0.25 + 15/\sqrt{Ai})$ |
| Max allowable Deflection: | $\Delta_{LL} = L*12/360$ |
| | $\Delta_{TL} = L*12/240$ |

## BEAMS 1&2

Maximum moment: $M_u = WL^2/8$

Maximum Shear: $V_u = WL/2$

Max Deflection: $\Delta = 5*WL^4 / 384*EI$

### GIRDER

Maximum Shear: $V_u = WL/2 + P$

Moment: $M = \int Vdx$

Max Deflection: $\Delta = (PL^3 / 28*EI) + (Wx / 24*EI)*(L^3 - 2Lx^2 + x^3)$

## CALCULATIONS

STRUCTURAL CALCULATIONS

| | | |
|---|---|---|
| Slab/Deck Load | 70 | psf |
| S.I. Dead Load | 15 | psf |
| Chilled Sail Load | 3 | psf |

| | Beam 1 | Beam 2 | Girder 1 |
|---|---|---|---|
| | W12x22 | W12x26 | W18x46 |
| I | 156 | 204 | 612 |
| Length | 18.5 | 23.5 | 22.75 |
| Self Wt. (plf) | 22 | 26 | 46 |
| Influence Area (sf) | 133 | 118 | 700 |
| Tributary Width (ft) | 7.667 | 5 | 15.333 |
| Live Load (psf) | 70 | 70 | 70 |
| LL red (psf) | 70 | 70 | 58 |
| LL red (plf) | 537 | 350 | 890 |
| DL (psf) | 88 | 88 | 88 |
| DL (plf) | 697 | 466 | 1396 |
| PLF | 1696 | 1120 | 3100 |

**Table-18, cont. on next page**

| | | | |
|---|---|---|---|
| Mu (ft-kip) | 73 | 78 | 215 |
| ϕMp (ft-kip) | 110 | 140 | 294 |

| | | | |
|---|---|---|---|
| Vu (kip) | 15.7 | 13.2 | 44.5 |
| ϕVn (kip) | 95.9 | 84 | 169 |

| | | | |
|---|---|---|---|
| Max Allowable Δ (LL) | 0.6166 | 0.7833 | 0.7583 |
| Max Δ (LL) | 0.3129 | 0.406 | 1.0163 |

| | | | |
|---|---|---|---|
| Max Allowable Δ (TL) | 0.925 | 1.175 | 1.1375 |
| Max Δ (TL) | 0.7189 | 1.2992 | 0.9144 |

**Table-18 Calculations for Beams 1&2**

Note, that the live load for Beams 1 and 2 were not reduced because their influence areas are too small.

## CONCLUSION

It turns out that Beam 2 fails max total load deflection, so a quick hand calculation was performed – $L/240 = (5Wl^4)/(384EI)$ – solving for I for a new beam. Beam 2 had to be upsized to a W14x26. Otherwise, the ECPII is capable of handling the loads from its new chilled sail system.

# ARCHITECTURAL BREADTH

## INTRODUCTION

The ECPII is a very modern looking building, incorporating clean lines and a great deal of glass into its design while maintaining a connection to the residential style architecture that it is attached to. Curiously contradictory to this is that in the original design, the office spaces did not have ceilings, preferring to keep the ordinarily hidden away parts of the building exposed in the open.

Within the proposed addition of chilled sails in the ceilings of the ECPII, is the opportunity to design an architecturally pleasing drop ceiling – one which embodies the attributes of the rest of the building. Price Industries' chilled sails were selected for the radiant cooling in the ECPII because of their modern, linear design which can draw the eye across the ceiling, elongating the room. These will be placed within a drop ceiling made of perforated ceiling tiles. The use of perforated tiles is partly to accommodate the convective airflow necessary for the chilled sails to operate, but also to add to the ceiling visually. Rather than a bland plain surface, it has a repeating pattern of circular holes which complement the lines created by the chilled sails.

Following are sample renderings and reflected ceiling plans.

## REFLECTED CEILING PLANS

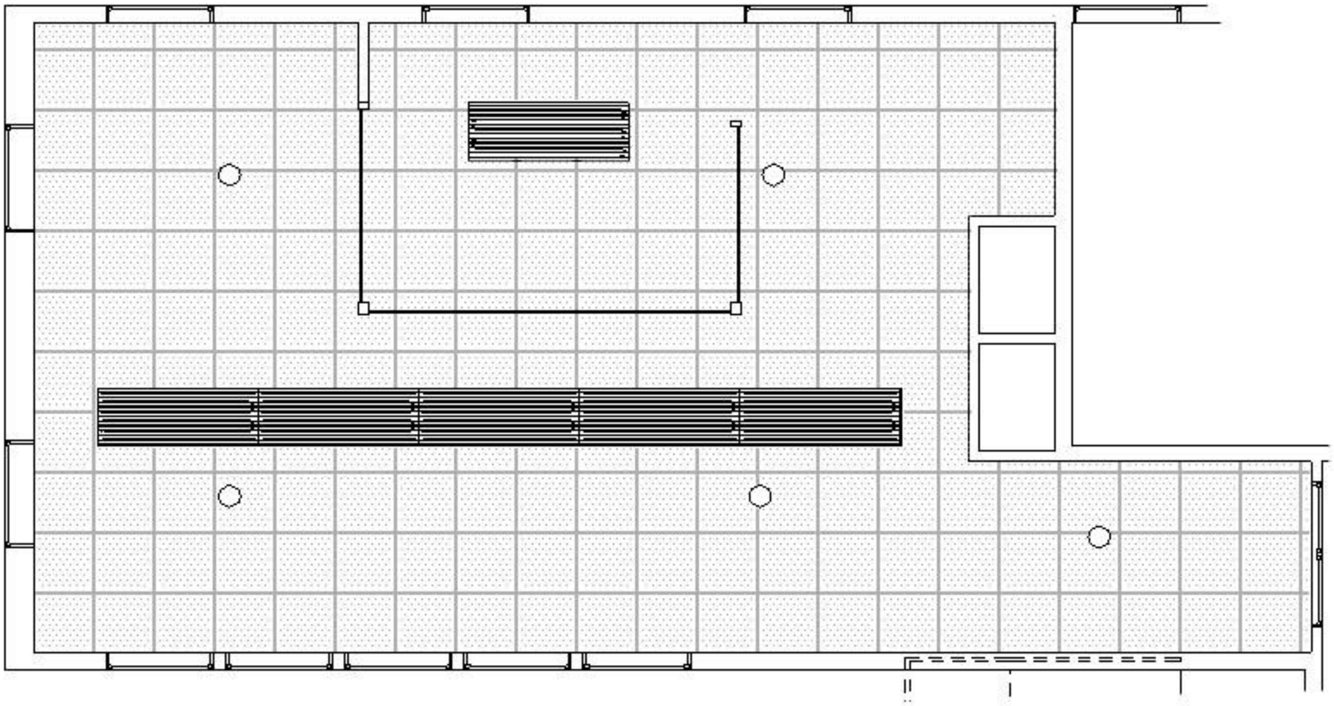


**Figure-3, room 110**

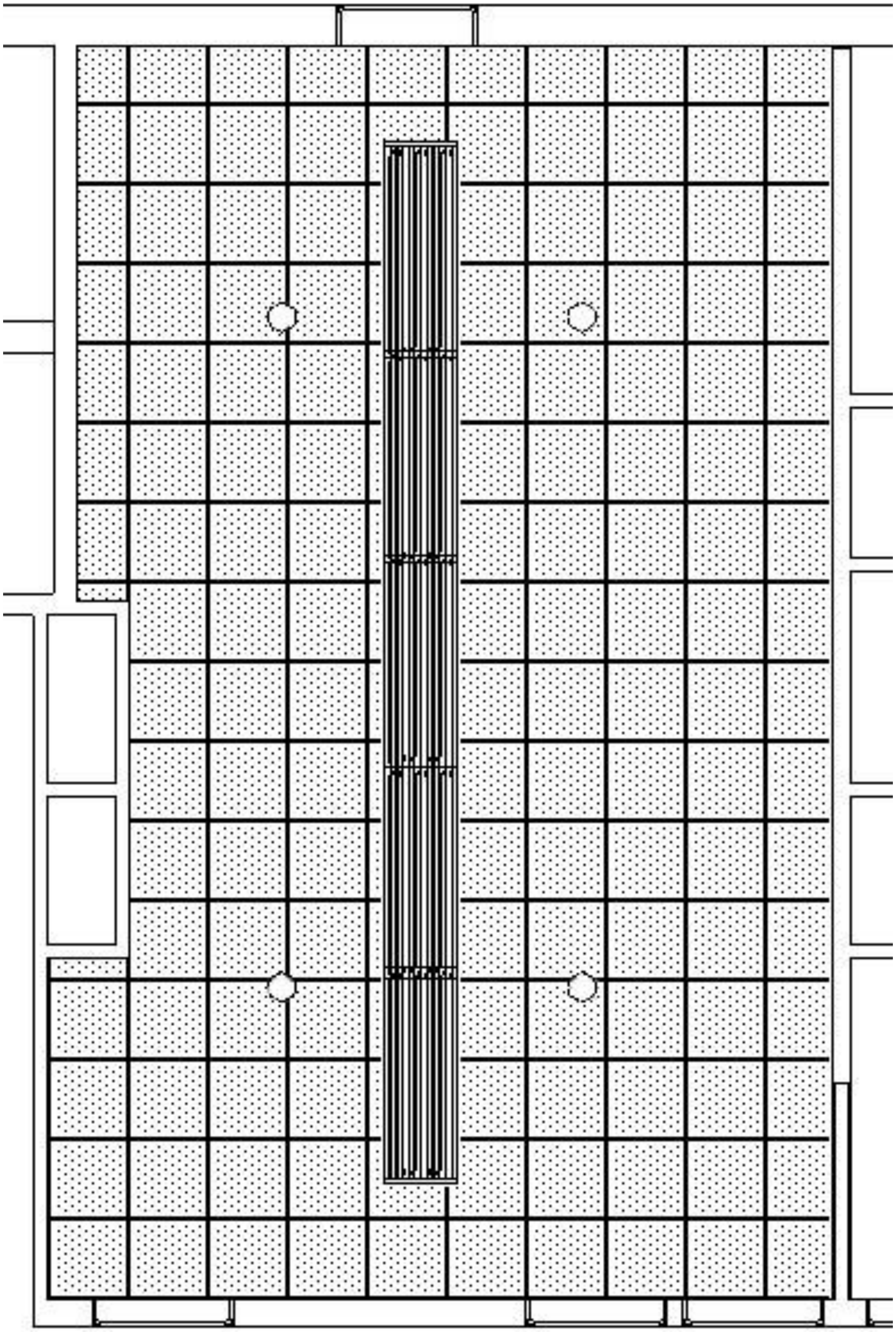


Figure-4, Room 120

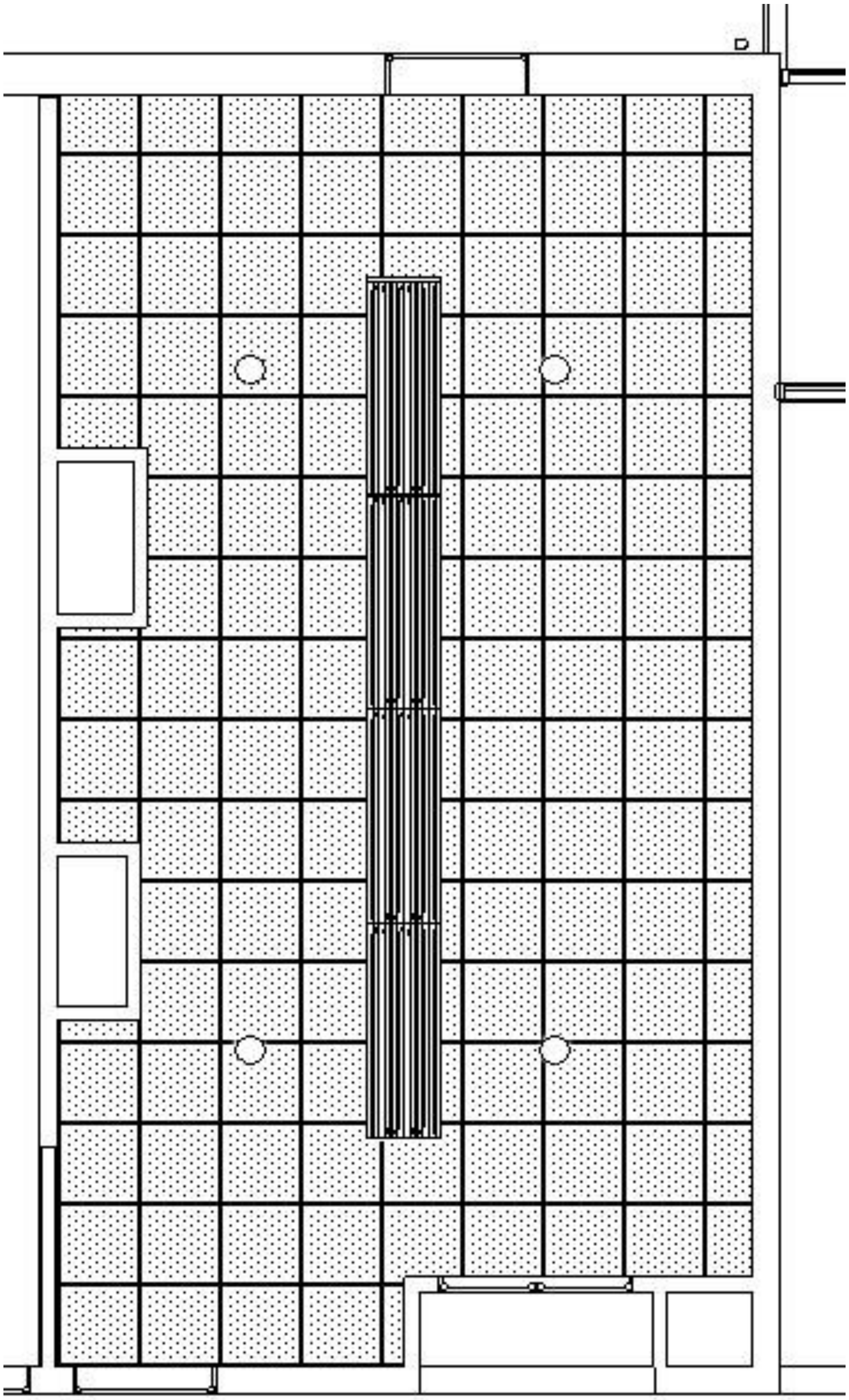


Figure-5, Room 121

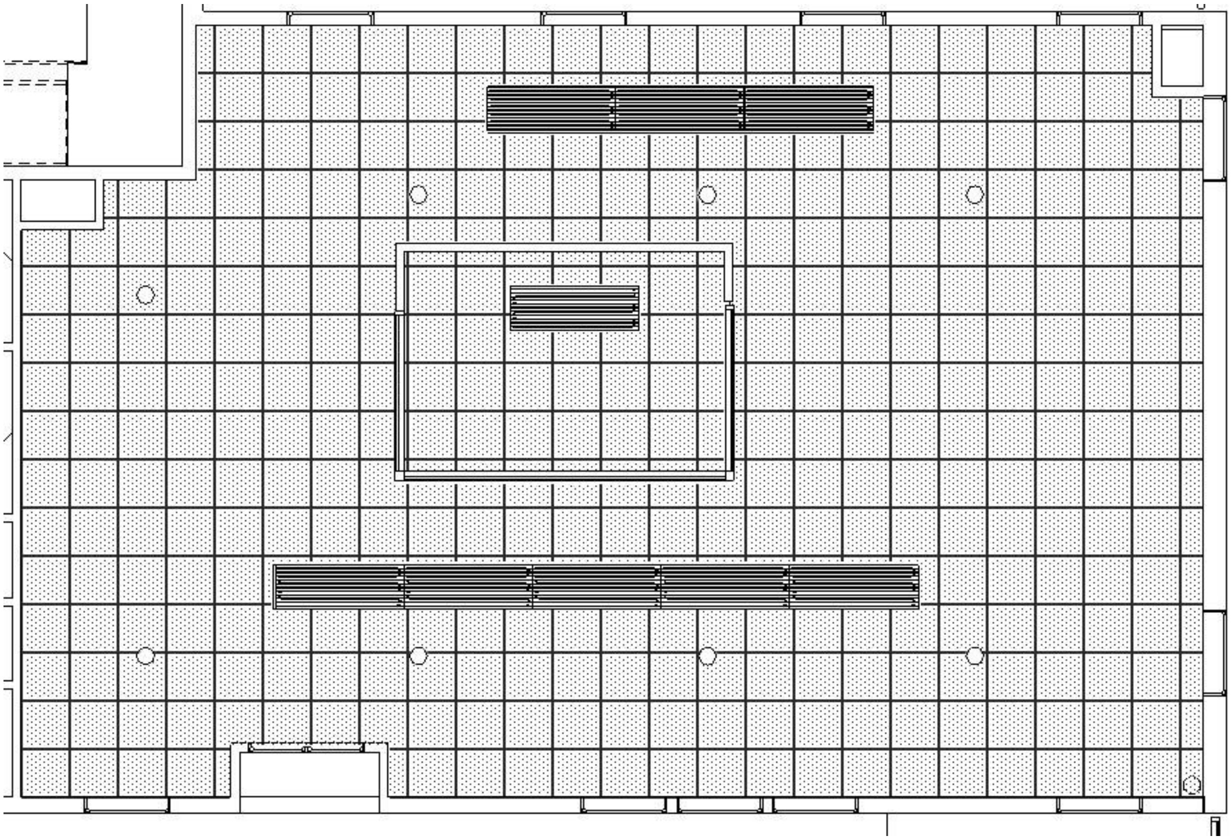


Figure-6, Room 130

## RENDERINGS

Figure-7, Room 110

Figure-8, Room 130

# APPENDIX A

## MECHANICAL TABLES & FIGURES

| ASHRAE 62.1 VENTILATION RATES | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ROOM # | ROOM NAME | Room Data | | | | | Vbz = Voz CFM | TOTAL SUPPLY | O.A. SUPPLY | OUTDOOR AIR FRACTION (Zp) |
| | | Az | Pz | Rp | Ra | | | CFM | CFM | |
| 110 | Office | 934 | 5 | 5 | 0.3 | | 306 | 1000 | 230 | 0.23 |
| 120 | Office | 755 | 4 | 5 | 0.3 | | 247 | 1000 | 230 | 0.23 |
| 121 | Office | 647 | 4 | 5 | 0.3 | | 215 | 800 | 184 | 0.23 |
| 130 | Office | 1730 | 9 | 5 | 0.3 | | 564 | 2000 | 459 | 0.23 |
| 210 | Office | 1093 | 6 | 5 | 0.3 | | 358 | 1200 | 276 | 0.23 |
| 220 | Office | 1256 | 7 | 5 | 0.3 | | 412 | 1200 | 276 | 0.23 |
| 221 | Office | 1173 | 6 | 5 | 0.3 | | 382 | 1400 | 322 | 0.23 |
| 230 | Office | 729 | 4 | 5 | 0.3 | | 239 | 1000 | 184 | 0.18 |
| 231 | Office | 850 | 5 | 5 | 0.3 | | 280 | 800 | 230 | 0.29 |
| 310 | Office | 1084 | 6 | 5 | 0.3 | | 356 | 1800 | 413 | 0.23 |
| 320 | Office | 658 | 4 | 5 | 0.3 | | 218 | 1300 | 299 | 0.23 |

| | | | | |
|---|---|---|---|---|
| TOTALS: | 3577 | 13500 | 3103 | 0.23 |
| Max Zp: | | | | 0.29 |

**Table-19, ASHRAE 62.1 Ventilation Rates**

| FAN COMPLIANCE | | | | |
|---|---|---|---|---|
| UNIT | HP | CFM | CFM * 0.0015 | 90.1 COMPLIANCE |
| AHU-1 SUPPLY | 20 | 13500 | 20.25 | YES |
| AHU-1 RETURN | 20 | 13500 | 20.25 | YES |
| F-1 | 0.4 | 400 | 0.6 | YES |
| F-2 | 0.4 | 750 | 1.125 | YES |
| F-3 | 0.1 | 150 | 0.225 | YES |
| F-4 | 3 | 22500 | 33.75 | YES |
| F-5 | 3 | 22500 | 33.75 | YES |
| F-6 | 3 | 22500 | 33.75 | YES |
| F-7 | 3 | 22500 | 33.75 | YES |
| F-8 | 0.1 | 250 | 0.375 | YES |
| F-9 | 0.1 | 50 | 0.075 | YES |
| F-10 | 0.1 | 50 | 0.075 | YES |

**Table-20, Fan Compliance**

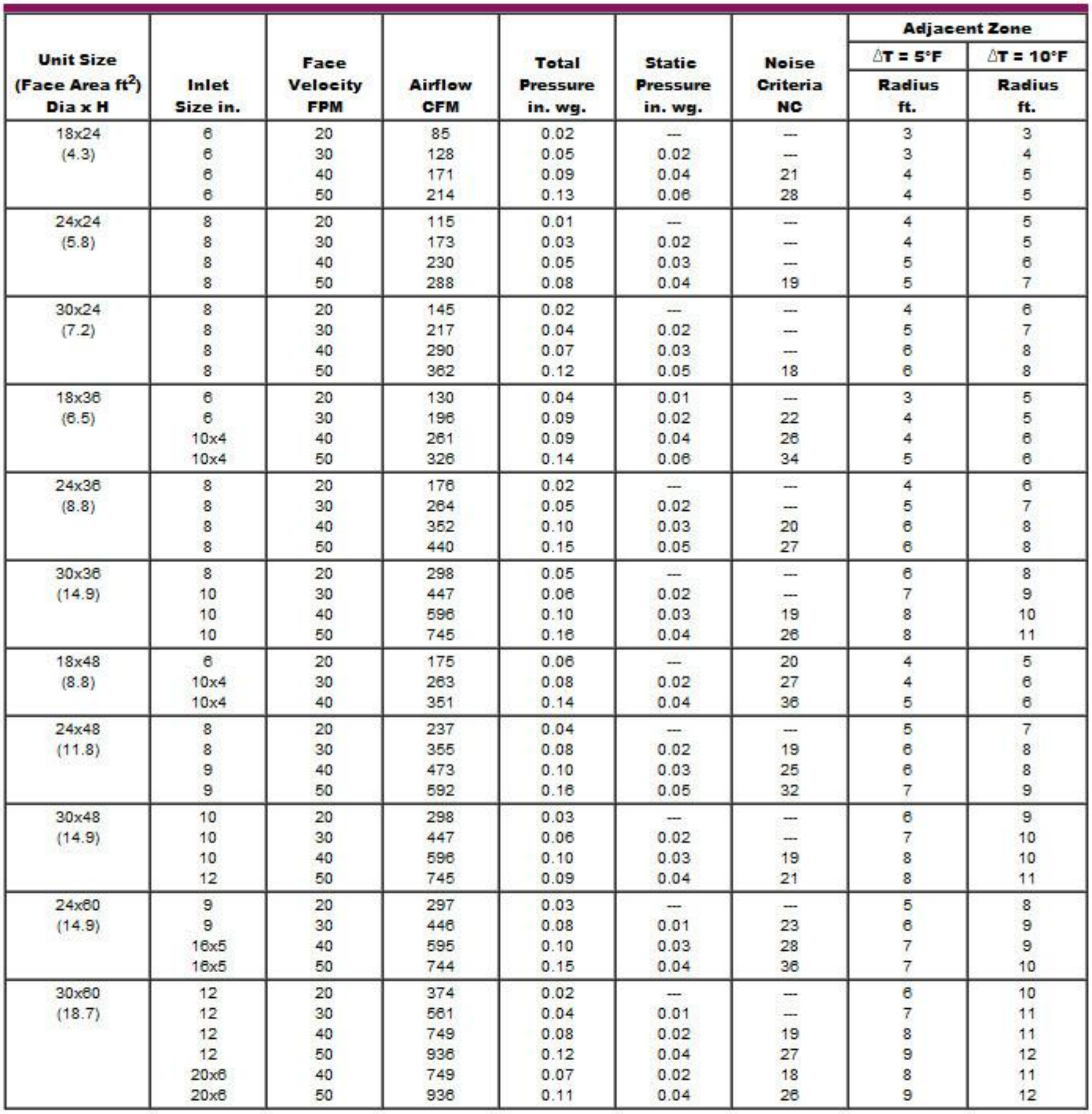
| EQUIPMENT COMPLIANCE | | | |
|---|---|---|---|
| UNIT | EER | 90.1 STANDARD | COMPLIANCE |
| HP-1 COOLING | 13.6 | 13.4 | YES |
| HP-2 COOLING | 13.6 | 13.4 | YES |
| | | | |
| UNIT | COP | 90.1 STANDARD | COMPLIANCE |
| HP-1 HEATING | 3.7 | 3.6 | YES |
| HP-2 HEATING | 3.7 | 3.6 | YES |

**Table-21, Equipment Compliance**

| LIGHTING COMPLIANCE | | | | | | |
|---|---|---|---|---|---|---|
| FIXTURE | BASEMENT | FIRST FLOOR | SECOND FLOOR | THIRD FLOOR | WATTS / FIXTURE | TOTAL WATTS |
| DPE/42 | - | 24 | 37 | 12 | 250 | 18250 |
| DFL/26 | - | - | 4 | 2 | 26 | 156 |
| RI/24 | 4 | 6 | 11 | 8 | 24 | 696 |
| RI/12 | 4 | 4 | 2 | 4 | 12 | 168 |
| SC/30 | - | 4 | 4 | 2 | 50 | 500 |
| WDI/80 | - | 1 | - | 6 | 70 | 490 |
| I/80 | 24 | 4 | - | 1 | 70 | 2030 |
| DPE/40 | - | 3 | - | - | 234 | 702 |
| DP/40 | - | 2 | - | - | 234 | 468 |
| DP/20 | - | 5 | - | - | 35 | 175 |
| CFVT/42 | 2 | - | - | - | 52 | 104 |
| DP/42 | - | 9 | - | - | 250 | 2250 |

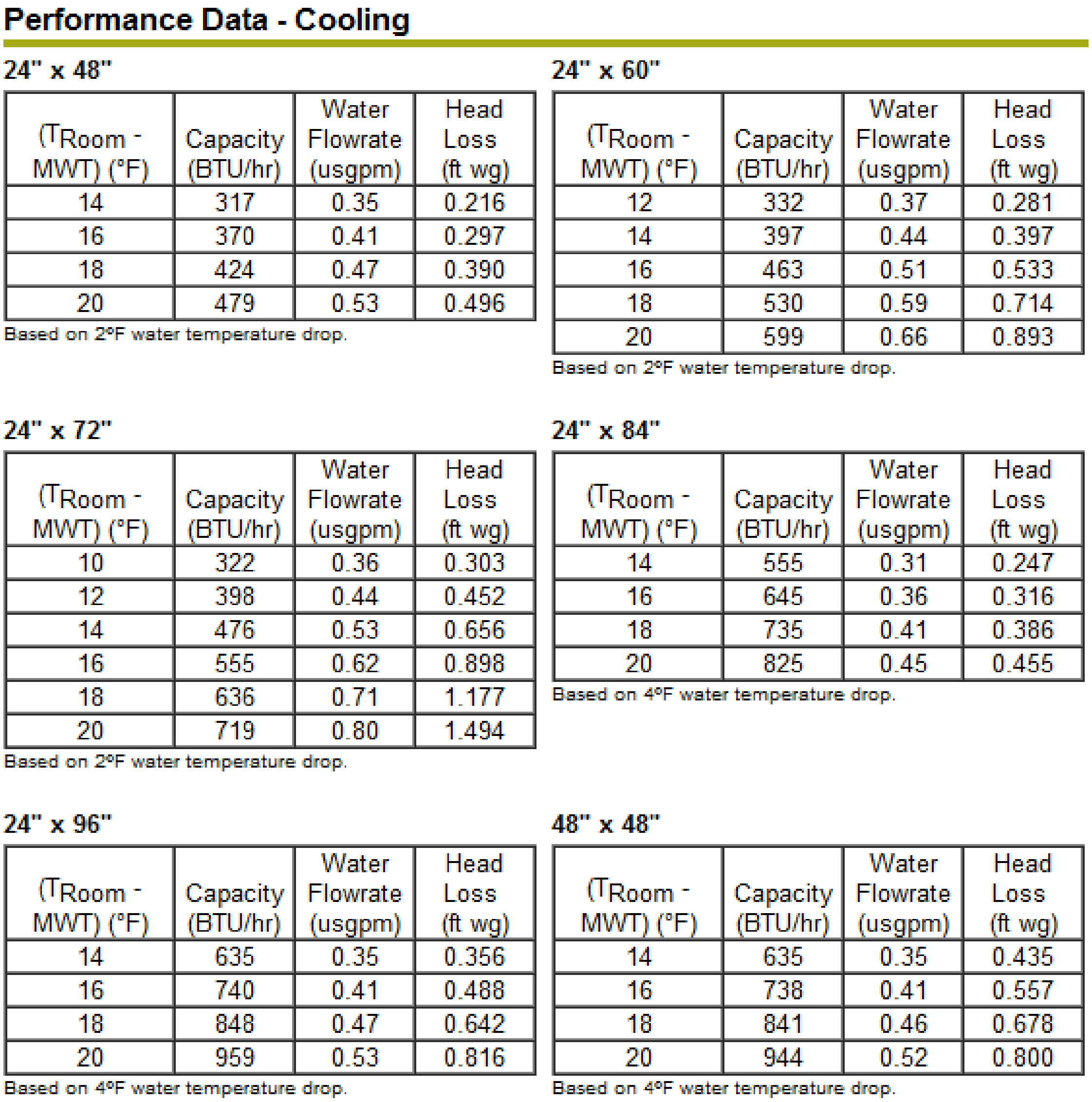
| | |
|---|---|
| TOTAL: | 25989 |
| S.F. | 24219 |
| LPD | 1.073083 |

**Table-22, Lighting Compliance**



| Unit Size (Face Area ft$^2$) Dia x H | Inlet Size in. | Face Velocity FPM | Airflow CFM | Total Pressure in. wg. | Static Pressure in. wg. | Noise Criteria NC | Adjacent Zone | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | ΔT = 5°F | ΔT = 10°F |
| | | | | | | | Radius ft. | Radius ft. |
| 18x24<br>(4.3) | 6 | 20 | 85 | 0.02 | --- | --- | 3 | 3 |
| | 6 | 30 | 128 | 0.05 | 0.02 | --- | 3 | 4 |
| | 6 | 40 | 171 | 0.09 | 0.04 | 21 | 4 | 5 |
| | 6 | 50 | 214 | 0.13 | 0.06 | 28 | 4 | 5 |
| 24x24<br>(5.8) | 8 | 20 | 115 | 0.01 | --- | --- | 4 | 5 |
| | 8 | 30 | 173 | 0.03 | 0.02 | --- | 4 | 5 |
| | 8 | 40 | 230 | 0.05 | 0.03 | --- | 5 | 6 |
| | 8 | 50 | 288 | 0.08 | 0.04 | 19 | 5 | 7 |
| 30x24<br>(7.2) | 8 | 20 | 145 | 0.02 | --- | --- | 4 | 6 |
| | 8 | 30 | 217 | 0.04 | 0.02 | --- | 5 | 7 |
| | 8 | 40 | 290 | 0.07 | 0.03 | --- | 6 | 8 |
| | 8 | 50 | 362 | 0.12 | 0.05 | 18 | 6 | 8 |
| 18x36<br>(6.5) | 6 | 20 | 130 | 0.04 | 0.01 | --- | 3 | 5 |
| | 6 | 30 | 196 | 0.09 | 0.02 | 22 | 4 | 5 |
| | 10x4 | 40 | 261 | 0.09 | 0.04 | 26 | 4 | 6 |
| | 10x4 | 50 | 326 | 0.14 | 0.06 | 34 | 5 | 6 |
| 24x36<br>(8.8) | 8 | 20 | 176 | 0.02 | --- | --- | 4 | 6 |
| | 8 | 30 | 264 | 0.05 | 0.02 | --- | 5 | 7 |
| | 8 | 40 | 352 | 0.10 | 0.03 | 20 | 6 | 8 |
| | 8 | 50 | 440 | 0.15 | 0.05 | 27 | 6 | 8 |
| 30x36<br>(14.9) | 8 | 20 | 298 | 0.05 | --- | --- | 6 | 8 |
| | 10 | 30 | 447 | 0.06 | 0.02 | --- | 7 | 9 |
| | 10 | 40 | 596 | 0.10 | 0.03 | 19 | 8 | 10 |
| | 10 | 50 | 745 | 0.16 | 0.04 | 26 | 8 | 11 |
| 18x48<br>(8.8) | 6 | 20 | 175 | 0.06 | --- | 20 | 4 | 5 |
| | 10x4 | 30 | 263 | 0.08 | 0.02 | 27 | 4 | 6 |
| | 10x4 | 40 | 351 | 0.14 | 0.04 | 36 | 5 | 6 |
| 24x48<br>(11.8) | 8 | 20 | 237 | 0.04 | --- | --- | 5 | 7 |
| | 8 | 30 | 355 | 0.08 | 0.02 | 19 | 6 | 8 |
| | 9 | 40 | 473 | 0.10 | 0.03 | 25 | 6 | 8 |
| | 9 | 50 | 592 | 0.16 | 0.05 | 32 | 7 | 9 |
| 30x48<br>(14.9) | 10 | 20 | 298 | 0.03 | --- | --- | 6 | 9 |
| | 10 | 30 | 447 | 0.06 | 0.02 | --- | 7 | 10 |
| | 10 | 40 | 596 | 0.10 | 0.03 | 19 | 8 | 10 |
| | 12 | 50 | 745 | 0.09 | 0.04 | 21 | 8 | 11 |
| 24x60<br>(14.9) | 9 | 20 | 297 | 0.03 | --- | --- | 5 | 8 |
| | 9 | 30 | 446 | 0.08 | 0.01 | 23 | 6 | 9 |
| | 16x5 | 40 | 595 | 0.10 | 0.03 | 28 | 7 | 9 |
| | 16x5 | 50 | 744 | 0.15 | 0.04 | 36 | 7 | 10 |
| 30x60<br>(18.7) | 12 | 20 | 374 | 0.02 | --- | --- | 6 | 10 |
| | 12 | 30 | 561 | 0.04 | 0.01 | --- | 7 | 11 |
| | 12 | 40 | 749 | 0.08 | 0.02 | 19 | 8 | 11 |
| | 12 | 50 | 936 | 0.12 | 0.04 | 27 | 9 | 12 |
| | 20x6 | 40 | 749 | 0.07 | 0.02 | 18 | 8 | 11 |
| | 20x6 | 50 | 936 | 0.11 | 0.04 | 26 | 9 | 12 |

**Figure-9, PRICE DR180 performance data**



## Performance Data - Cooling

**24" x 48"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 14 | 317 | 0.35 | 0.216 |
| 16 | 370 | 0.41 | 0.297 |
| 18 | 424 | 0.47 | 0.390 |
| 20 | 479 | 0.53 | 0.496 |

Based on 2°F water temperature drop.

**24" x 60"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 12 | 332 | 0.37 | 0.281 |
| 14 | 397 | 0.44 | 0.397 |
| 16 | 463 | 0.51 | 0.533 |
| 18 | 530 | 0.59 | 0.714 |
| 20 | 599 | 0.66 | 0.893 |

Based on 2°F water temperature drop.

**24" x 72"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 10 | 322 | 0.36 | 0.303 |
| 12 | 398 | 0.44 | 0.452 |
| 14 | 476 | 0.53 | 0.656 |
| 16 | 555 | 0.62 | 0.898 |
| 18 | 636 | 0.71 | 1.177 |
| 20 | 719 | 0.80 | 1.494 |

Based on 2°F water temperature drop.

**24" x 84"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 14 | 555 | 0.31 | 0.247 |
| 16 | 645 | 0.36 | 0.316 |
| 18 | 735 | 0.41 | 0.386 |
| 20 | 825 | 0.45 | 0.455 |

Based on 4°F water temperature drop.

**24" x 96"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 14 | 635 | 0.35 | 0.356 |
| 16 | 740 | 0.41 | 0.488 |
| 18 | 848 | 0.47 | 0.642 |
| 20 | 959 | 0.53 | 0.816 |

Based on 4°F water temperature drop.

**48" x 48"**

| (TRoom - MWT) (°F) | Capacity (BTU/hr) | Water Flowrate (usgpm) | Head Loss (ft wg) |
|---|---|---|---|
| 14 | 635 | 0.35 | 0.435 |
| 16 | 738 | 0.41 | 0.557 |
| 18 | 841 | 0.46 | 0.678 |
| 20 | 944 | 0.52 | 0.800 |

Based on 4°F water temperature drop.

**Figure-10, PRICE Chilled Sail Performance Data**

# APPENDIX B

## STRUCTURAL BREADTH

The following figures are intended to give context to the loading of each of the members looked at in the structural breadth analysis.

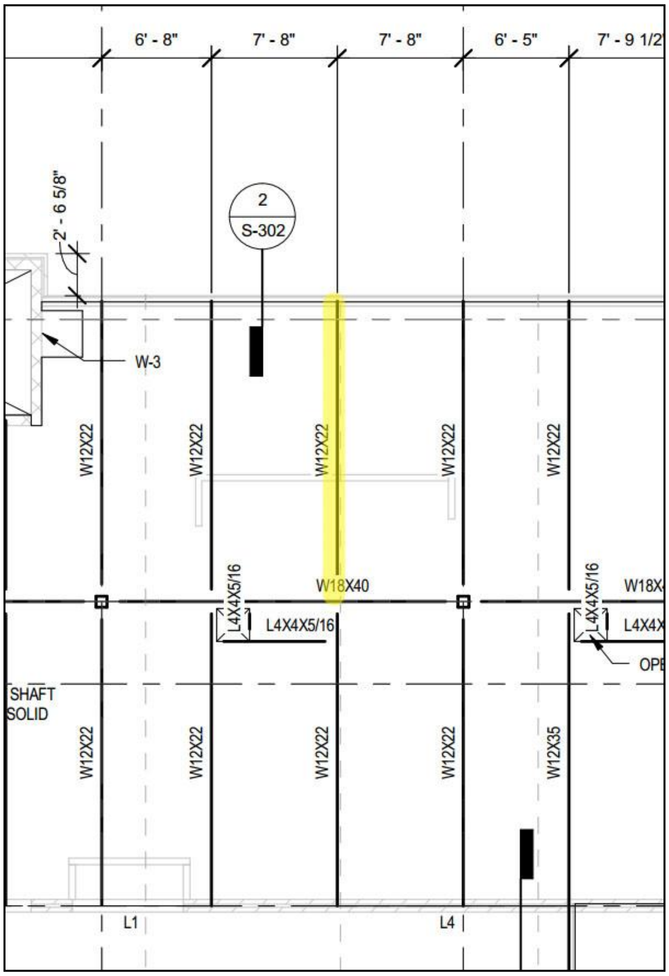


**Figure-11, Beam 1**

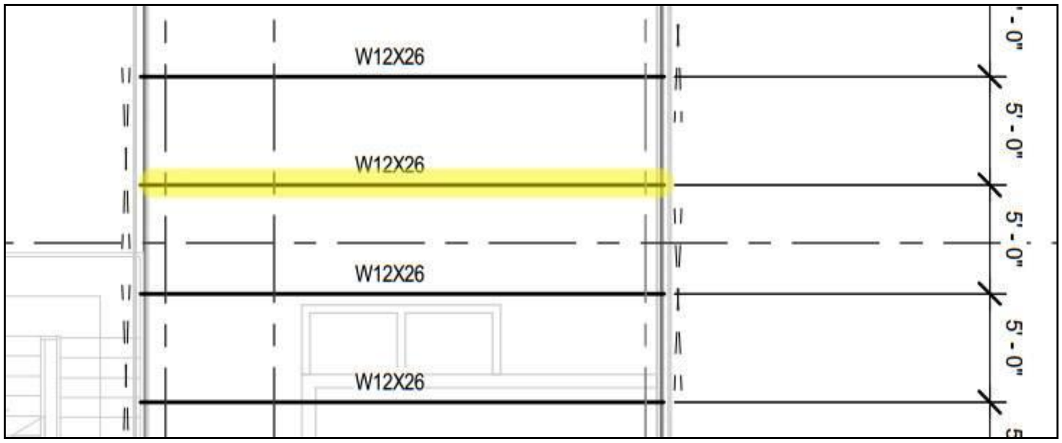


Figure-12, Beam 2

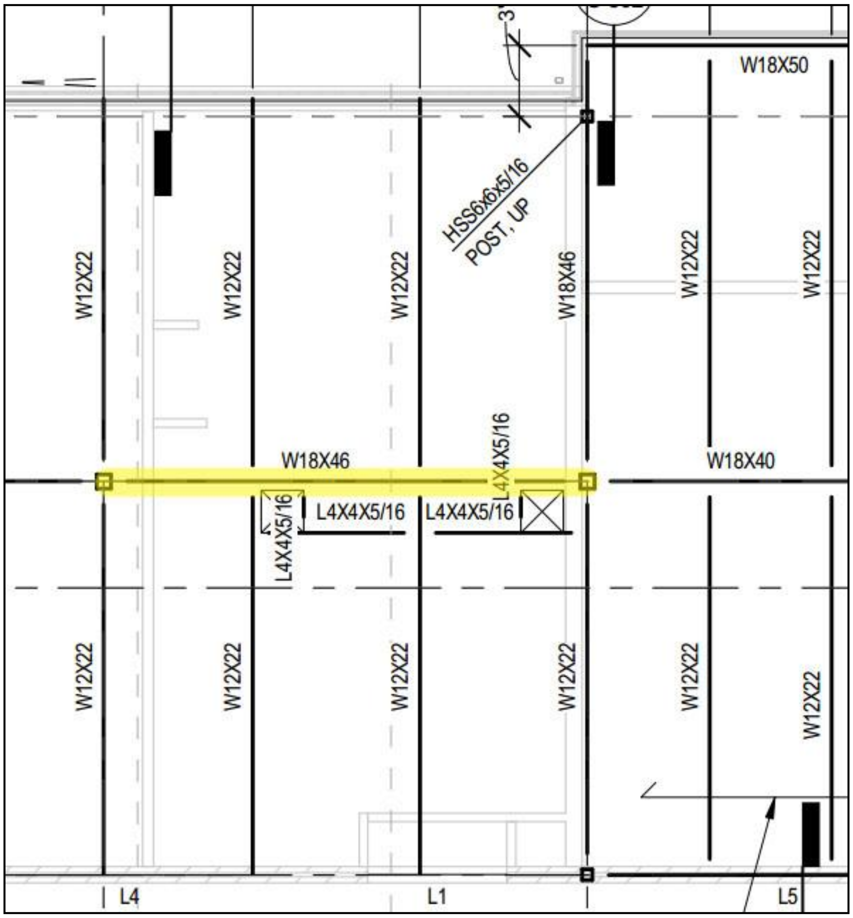


Figure-13, Girder 1