Final Report

Application of Dedicated Outdoor Air System with Radiant Ceilings, Solar Hot Water System and Redesign of Building Envelope

Des Places Residence Hall

Duquesne University

Pittsburgh, PA

DUQUESNE UNIVERSITY

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Building Abstract

DES PLACES RESIDENCE HALL

PETER EDWARDS | MECHANICAL OPTION

Project Information

Location: Duquesne University, Pittsburgh, PA

Size: 131,438 ft^2

Number of Stories: 11 stories above grade

Total Cost: $ 27,535,000

Construction Dates: 5/1/2010— 8/7/2012

Project Team

Owner: Duquesne University

CM Agency: Regency Construction Services Inc.

Architect: WTW Architects

MEP Engineer: CJL Engineering

Structural Engineer: Barber and Hoffman Inc.

Civil Engineer: Gateway Engineers Inc.

Architecture

Des Places meshes well with the rest of Duquesne's campus through the use of brick in its exterior façade, while at the same time standing out as an eye-catching modern structure. The large continuous glass façade on the west elevation ties the interior design to the exterior architecture and gives the residents a clear view of the athletic field directly adjacent to the building. Des Places will also achieve a minimum of LEED certification by its completion.

Electrical and Lighting System

The main electrical feed is brought into the building through a 23 KV-277/480 V, 3 phase, 4 wire transformer. The transformer then feeds a 2000 A, 277/480 V switchboard which connects to 4 main panel boards. Emergency power is supplied by a 250 KW, 277/480 V diesel generator. This building uses high efficiency LED and T5 fixtures and occupancy sensors to save energy.

Mechanical System

Four-pipe vertical fan coil units serve the dormitory spaces and large conference room on the 12th Floor. A 100% outdoor air AHU with a heat recovery wheel provides conditioned outdoor air to all of the remaining spaces and unconditioned outdoor air to all of the rooms that require it. Two shell and tube heat exchangers supply hot water and the chilled water is delivered to the building from a chiller plant on campus.

Structural System

Foundation: Grade beams transfer reinforced concrete wall loads to drilled concrete piers spaced roughly 8 ft. apart.

Superstructure: Structural steel framing system made with ASTM A50 Carbon Steel and a 12" reinforced concrete shear wall around the central core of the building for additional lateral resistance.

Façade: Curtain wall system consisting of face brick and two-pane glazed glass.

Roof: 8" precast hollow-core plank with a white TPO roof system on top.

CPEP Web Address: http://www.engr.psu.edu/ae/thesis/portfolios/2011/pie5002/index.html

Executive Summary

Des Places Residence Hall is a 130,438 ft^2 building currently being constructed on the campus of Duquesne University in Pittsburgh, Pennsylvania. The building primarily consists of private dormitory rooms, with some office and conference space as well. The budget for Des Places is approximately $28,000,000 and Duquesne University required that the building achieve a minimum of LEED certification by its completion.

The existing mechanical system in Des Places Residence Hall is a dedicated outdoor air system with individual fan coil units in every conditioned room. One energy recovery unit in the penthouse delivers the required amount of outdoor air to the building and meets the latent loads of each space. The sensible heating and cooling loads of the building are met by Whalen fan coil units in each room.

In this report alternatives and additions to the existing mechanical system in Des Places were proposed and analyzed. The redesigned mechanical system for Des Places should not be viewed as superior or inferior to the existing design. The suggested changes are instead meant to examine the possible benefits and disadvantages of using alternative systems in Des Places. Many of the external requirements placed upon the mechanical design team such as a fixed budget and specific owner requirements were not considered in this report. The primary alterations analyzed in this report were the redesign of the existing DOAS system to a dedicated outdoor air system that uses radiant chilled ceilings and baseboard radiators, adding a solar hot water system and changing the building envelope.

The proposed dedicated outdoor air system ended up costing $186,528 less than the original system but it consumes more energy than the fan coil unit DOAS system, which would result in an approximate increase of $7,370 in yearly operational costs for the building. The DOAS system should increase the comfort and productivity of the students living in Des Places because it would eliminate fan noise and produce a more uniform temperature distribution in each room.

The solar hot water system designed for Des Places would save Duquesne's central steam plant approximately 2,350 therms of energy every year. The system has a relatively high initial cost of $94,500 but it still has a payback period under 10 years if federal and state financial incentives are factored into the life-cycle cost analysis.

The building envelope redesign involved doubling the size of every bedroom and living room window in Des Places Residence Hall. These larger windows are meant to allow more natural daylight into the student's rooms. A daylighting analysis showed that the windows did allow a good amount of additional light into each room throughout the year, but the redesigned building envelope cost $203,312 more than the original design and resulted in an increase of $2,137 in annual energy costs for the building.

Project Information

Introduction

Des Places Residence Hall is a 13 story, 131,000 square foot mixed use dormitory building for Duquesne University in Pittsburgh, Pennsylvania. The building primarily consists of student living space, with offices on the first and second floor, conference space on the twelfth floor and mechanical space on the first floor and thirteenth floor penthouse. The total estimated budget for the project is $27,535,000. Des Places was designed to provide comfortable and modern living space to its student occupants while at the same time minimizing its energy use. The building was designed to achieve a minimum of LEED certification upon its completion and it will achieve this through the implementation of efficient mechanical and electrical systems, energy saving controls, high efficiency lighting fixtures and sustainable construction practices.

Location

The site of Des Places is located on Duquesne University's campus in Pittsburgh, Pennsylvania. There is an existing dormitory building on the site that will need to be demolished before the construction of Des Places can begin. The site is along the eastern edge of Duquesne's campus with a busy urban street that acts as the dividing line between campus property and a residential area. Figure 1 below shows where the site is located on Duquesne's campus. Because of the urban environment surrounding Duquesne, the building was designed with security in mind. Certain precautions were made to ensure the safety of students living in the building, such as a limited amount of entrances, card access and security cameras. The building will get its steam for heating and chilled water for cooling from central plants that service all of the buildings on campus. The site is immediately adjacent to an athletic field to the west, academic buildings to the north and a smaller street that runs through campus on the south.

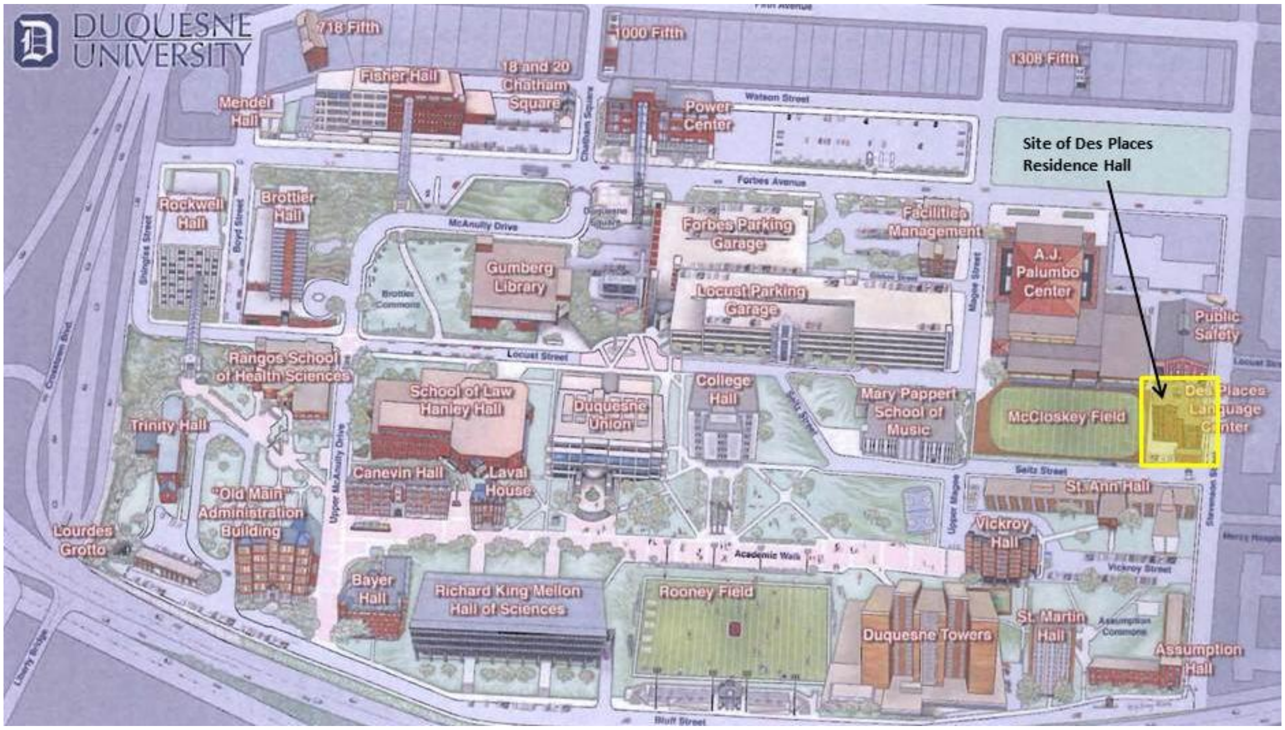


Figure 1: *Location of the Des Places Residence Hall site on Duquesne University's campus*

Project Team

- **Owner:** Duquesne University
- **Construction Management Agency:** Regency Construction Services Inc.
- **Architect:** WTW Architects (www.wtwarchitects.com)
- **Landscape Architect:** LaQuatra Bonci
- **Mechanical Engineer:** CJL Engineering
- **Electrical Engineer:** CJL Engineering
- **Structural Engineer:** Barber and Hoffman Inc.
- **Civil Engineer:** Gateway Engineers Inc.

Building Overview and Existing Conditions

Architecture

The exterior design of Des Places Residence Hall is largely influenced by the buildings that surround it and by the entire campus of Duquesne. Most of Duquesne University's buildings use brick and glass for their exterior facades and this is especially true for the buildings adjacent to the site of Des Places. The architects designing this building wanted it to stand out, but at the same time it needed to mesh well with its surroundings. The building blends in nicely with the rest of Duquesne's campus through the use of glass and brick for the exterior façade, but its modern design and the large continuous glass façade on its west elevation allow the residence hall to be an eye-catching structure as well. The glass wall that runs up the west side of the building also ties the interior design of the building into its exterior design. The common areas on floors three through eleven (which compose of the laundry room and student lounge) are all in the same area of each floor, which allow the glass wall on these floors to appear as one continuous and uniform vertical strip from the outside of the building. This glass strip then continues to the highest floor of the structure where it extends horizontally to surround the large conference room on Floor 12.

Figure 2: *Rendering of Des Places courtesy of WTW Architects*

The interior of the building is mostly private spaces, with the vast majority of public space on the ground level and highest level (Floor 12). The basement houses most of the storage and mechanical space for the building, and is intended only for the use of the maintenance crew that will keep the building operational. The ground floor consists mostly of residential units, but there are also entrance lobbies for the building and offices for employees of Duquesne University. Floors 3 through 11 are almost identical and are composed entirely of residential units and a common student lounge and laundry area that serve as a public gathering place for students living on each floor. Floor 12 is still dominated by private residential rooms, with the exception of one large conference space in the southwest corner of the building. There is a central service shaft in the middle of the building that runs through every floor. This shaft takes care of the buildings circulation by housing the stairwells and elevators for the structure and it provides storage and electrical rooms for all of the dormitory floors.

Every residential unit in the building is connected to a central hallway on each floor through one door. They consist of one to three bedrooms (depending on the intended use) and private bathrooms. Each unit will also be equipped with appropriate furniture to accommodate all residents, such as desks, chairs and beds. There are handicap accessible residential units on each floor of the residence hall as well.

Sustainability Features

The Des Places project has had an emphasis on sustainability throughout the design process and will continue this focus throughout all phases of construction. Duquesne University is requiring that the building achieve a LEED certification at the very minimum. During the design process, energy modeling and payback analysis has been performed for the building by CJL Engineering, using the program TRACE. For the plumbing, the building will save on water consumption by using low flow fixtures for the faucets, shower heads, sinks and toilets. Water use will also be minimized through the landscaping design by using plants that do not require any irrigation.

The HVAC and electrical systems have also been designed with sustainability in mind. There will be occupancy sensors installed throughout the building, so that lights will only be on in spaces where people are present and natural day lighting has been used to save on the amount of artificial lighting needed during the day. High efficiency fixtures will be used throughout the building as well. All of the exterior lighting will be done by LED fixtures and all of the dorm rooms will be lit by T5 high output fluorescent fixtures. The mechanical system will lower the building's energy consumption by using a desiccant wheel in the air handling unit. This wheel will rotate between the return air being exhausted to the outside and the outdoor air being introduced into the building and transfer some of the sensible and latent heat from the exhaust air to the incoming supply air. There will also be a small wind turbine placed in the outdoor air plenum for the air handling unit in the penthouse. The wind turbine will produce electricity while the AHU is pulling outdoor air through the plenum.

Duquesne will maintain their emphasis on LEED accreditation during the construction process by only hiring contractors and subcontractors who are committed to sustainable practices, such as the segregation and recycling of construction waste and protecting indoor environmental quality. One unique strategy that is being considered by the construction team to promote sustainability involves recycling the rubble created by the demolition of the existing dormitory on the future site of Des Places. When the building is destroyed the contractor can crush old building materials such as the brick and concrete masonry units into fine enough pieces to be used as infill underneath the slab on grade. This will drastically reduce the amount of stone infill that they will need to bring onto the site. The university will also make a strong effort to use local materials with a high recycled content as well as certified wood and low emitting building products.

Building Envelope

The exterior façade of Des Places is primarily a masonry wall, with some large storefront windows on the ground level and a glass façade running up the middle of the west wall in line with the student lounges and laundry rooms on floors three through twelve.

Structural System

The superstructure of Des Places consists of steel framing made with ASTM A50 carbon steel. The columns and beams are configured in an orthogonal and regular pattern on every floor above grade. There is also a 12 inch reinforced concrete shear wall around the central core of the building for additional lateral resistance. The floors above grade will be 8” precast hollow-core concrete planks nested within the webs of the wide flange beams. There will also be a 3” topping slab of concrete on each floor to provide a level finished floor surface and fill in any gaps between the concrete planks and structural steel. The structure of the roof will consist of an 8” precast hollow-core concrete plank with a white TPO roof system on top. The roof is also supported by the webs of steel beams. The exterior walls primarily consist of a masonry curtain wall system with openings for windows. There is also a glass curtain wall on the west elevation of Des Places. The foundation is supported by grade beams that transfer the loads from the reinforced concrete walls to drilled concrete piers spaced roughly 8 feet apart. The piers range in size from 30 in. to 60 in. in diameter, with the thicker shafts lying underneath the perimeter of the interior concrete shear wall. The foundation piers are drilled 8 feet to 10 feet into the bedrock below, depending on their location.

Construction

Des Places Residence Hall is a Design-Bid-Build project with an estimated cost of $27,535,000. Utility feeds have been relocated to appropriate locations and the existing building on site was demolished in February of 2011. The actual construction of Des Places began in March of 2011 and has a scheduled completion date of August 1, 2012.

Electrical System

The main electrical feed will be provided through an existing Duquesne Light manhole on the site, using a 23 KV cable. This cable will connect to a 23 KV Duquesne Light pad mount transformer, that will bring the power supply down to a 277/480 V, three phase, four wire cable. The transformer then feeds one 2000 A, 277/480 V switchboard in the basement that distributes power to panelboards located throughout the building. Five main panel boards distribute the power needed for receptacles and lighting on each floor. These panel boards are all 120/208 V and range in size from 400 to 800 A. Emergency power is supplied by 250 KW, 277/480 V diesel powered generator. The generator is located in a separate room in the basement that is equipped with an exhaust system that brings air from the room directly outside.

Lighting

The lighting for every space will be controlled separately and connected to occupancy sensors, so that fixtures are only turned on when there are people in the room. Des Places uses a variety of LED, T5 and TRT fixtures to save energy on lighting throughout the building. All fixture ballasts are pre-programmed and rated at 120 V. The lighting power density of Des Places is 0.74 W/ft^2. This is well below the acceptable limit of 1.0 W/ft^2 for dormitory buildings, as stated in section 9 of ASHRAE Standard 90.1. T5 ceiling mounted high output fixtures are used to light all of the private dormitory space in the building. T8 linear fluorescent fixtures are used for all of the mechanical space and recessed can TRT fixtures are used for the majority of the hallways and public areas.

Fire Protection System

The entire building is fully sprinklered in accordance with NFPA 13 and 14 standards and the requirements given by Duquesne University’s insurance underwriters. A 75 HP, 750 gpm pump will circulate the water through the fire suppression piping. Smoke detectors and signaling devices are provided in each dormitory room and the entire system is compatible with the university’s Simplex Command System.

Transportation and Circulation

All of the vertical circulation for Des Places is contained in the central service shaft that runs up the entire length of the building. This central shaft has three elevators and two stairwells that are surrounded by the proper fire-rated walls. The elevators and one of the stairwells stop on the twelfth floor so the penthouse above is only accessible by one set of stairs. The circulation space for each floor consists of a central hallway that wraps around the service shaft on the interior of the building. There are two different service entrances on the first floor of Des Places and only one main entrance on the ground floor for residents and visitors. The decision to only have one main entrance for the building was made for security purposes.

Telecommunications System

Des Places is wired with Category 6 cabling and patch panels that are connected to data and telephone outlets throughout the building. There is a data closet on each floor and these are all connected together at the basement level right before the service entrance. Telecommunications wiring is distributed throughout each floor with conduit or cable tray above the ceiling. Each dormitory bedroom is equipped with one data outlet and one cable television coax outlet.

Security System

Due to the urban environment surrounding the Duquesne campus, security was a large part of the design of Des Places. There is only one main entrance into the building, with a 24 hour front desk to monitor people entering and leaving. Both the student entrance and the two service entrances are equipped with card access and there are alarms on every perimeter door. The dormitory units are equipped with card or key access as well and there are individual deadbolt locks for all of the bedrooms within each unit. Camera surveillance is used to monitor the public areas of the building.

Existing Mechanical System Summary

Design Objectives and Requirements

There were several objectives that drove the design of the mechanical system for Des Places. Duquesne University wanted a system that could provide fast responding individual control for all of the occupied spaces in the building and the system had to meet the prescribed standards given by the 2009 edition of the National Mechanical Code and the National Plumbing Code. Des Places was designed in accordance with ASHRAE Standards 62.1 and 90.1 as well, and therefore the building is designed to meet all of the energy, ventilation, temperature and humidity requirements prescribed in these documents. The University also required that the building achieve a minimum of LEED certification upon its completion. After considering several alternatives, the mechanical engineers decided to use individual fan coil units to condition each room, and a dedicated OA air handling unit to deliver the required amount of ventilation to each space.

Initial Cost of System

The cost for the entire mechanical system of Des Places was estimated by Regency Construction Services to be $2,827,770 which is equivalent to $21.52 per square foot of floor area. The plumbing system was estimated to be $2,067,912 which comes out to approximately $15.74 per square foot. The mechanical system will account for about 10.2% of the buildings total cost and the plumbing will take up about 7.5% of the overall cost.

Energy Sources and Utility Rates

Des Places will receive steam and chilled water from central plants on campus. These two utilities are connected to the building through underground piping that enters the mechanical room on the first floor through penetrations in the foundation wall. The main electrical feed is provided through an existing Duquesne Light manhole on the site. A 23 KV cable delivers power to a pad mount transformer, which brings the power supply down to a 277/480 V, three phase, four wire cable. The average utility costs for Des Places were given to CJL Engineering by Duquesne University and are given in the table below.

Utility Costs	
Energy Type	**Cost**
Electricity	0.087 ($/KWh)
Natural Gas	1.282 ($/therm)

Table 1: *Duquesne University utility costs*

Lost Space

The lost space due to the mechanical and electrical systems is summarized in table 2 below. The mechanical system accounts for the large majority of the total square footage values given in the table. The electrical rooms, IDF rooms, mechanical rooms and the space taken up by the vertical duct risers were all accounted for in the square footage calculations. The mechanical and electrical space accounts for approximately 6.8% of the total square footage of Des Places.

Lost Space due to Mech/Elec Systems	
Floor	**Area (SF)**
1	3,216
2	239
11-3	2,511
12	279
Penthouse	2,706
TOTAL	8,951

Table 2: *Lost space due to mechanical and electrical systems in building*

Design Air Conditions

Des Places is located within the city limits of Pittsburgh, PA so the outdoor design conditions for Pittsburgh were used for the buildings energy model. This data was attained from ASHRAE Fundamentals 2005 and is given in Table 3.

Outdoor Air Design Conditions				
Summer Conditions		**Winter Conditions**	**Clearness Number**	**Ground Reflectance**
Dry Bulb	**Wet Bulb**	**Dry Bulb**		
86 F	71 F	5 F	0.97	0.2

Table 3: *Outdoor air design conditions used for Trace model*

The indoor design conditions for Des Places were obtained from CJL Engineering. These figures are shown in Table 4 below.

Indoor Design Conditions	
Cooling Dry Bulb Setpoint	75 F
Cooling Dry Bulb Driftpoint	78 F
Heating Dry Bulb Setpoint	72 F
Heating Dry Bulb Driftpoint	64 F
Relative Humidity	50%

Table 4: *Indoor air design conditions used for Trace model*

Mechanical Equipment Summaries

All of the rooms in Des Places except for the data rooms, electrical rooms and the conference room on the 12th floor will be fully conditioned by individual four-pipe fan coil units. There are 257 FCUs throughout the building that range in size from 300 CFM to 1200 CFM. All of these units are connected to separate hot water and chilled water pipes and are equipped with thermostats so that occupants can have direct control of the temperature in each space. They are also equipped with motion sensors so that they can change from occupied to unoccupied mode and automatically shut themselves off when the room is empty. Duquesne University required that Whalen fan coil units be used for Des Places, because they have had them installed in other buildings and have found that they are especially reliable and easy to maintain. This has caused many of the units to be oversized, because the heating and cooling capability of the smallest FCU that Whalen produces (FC-A in the schedule) is much larger than the demands of many spaces in the building. The fan coil unit schedule is given in Table 5 below.

Fan Coil Unit Schedule													
				Hot Water Coil				Chilled Water Coil					
								EAT				Total	Sensible
Mark	CFM	Motor HP	Max Amp	EA DB	EWT	LWT	Total MBH	DB	WB	EWT	LWT	MBH	MBH
FC-A	300	0.025	0.75	70	140	120	12	78	65	45	57	11.5	8.1
FC-B	400	0.03	0.9	70	140	120	17	78	65	45	57	13.5	9.5
FC-C	600	0.05	1.2	70	140	120	24	78	65	45	57	20.1	13.6
FC-D	800	0.08	1.5	70	140	120	27	78	65	45	57	28.2	21.8
FC-E	1200	0.16	2.3	70	140	120	34	78	65	45	57	34.6	27.3

Table 5: *Fan coil unit schedule*

The 12th floor conference space required the highest quality interior finishes in the building and the sound produced by the mechanical equipment serving the space had to be kept to a minimum. Because of these two factors, the architects decided that the Whalen fan coil units could not be used to condition this space. Instead two blower coils were placed above the ceiling to deliver conditioned air through diffusers. The technical information for these blower coils is given in the table below.

Blower Coil Schedule					
		Motor	Cooling Coil		Heating Coil
Mark	Airflow (cfm)	HP	MBH Total	MBH Sensible	MBH Total
BC-1	1600	1	60.3	44	58.9
BC-2	800	3/4	30.1	22	31.1

Table 6: *Blower coil schedule*

A one-hundred percent outdoor air, energy recovery unit provides all of the required ventilation needed for the building, in accordance with ASHRAE Standard 62.1. The ERU also exhausts all of the public and private bathrooms in the building and conditions the electrical rooms and data rooms. ERU-1 uses a desiccant energy wheel to transfer latent and sensible heat between the incoming outdoor air stream and the outgoing exhaust air from the bathrooms and data rooms. After passing through the energy wheel, the outdoor air goes through a preheat coil for freeze protection and then a cooling coil. After this stage of conditioning the air is split into two separate ducts. One duct sends air at 52 ^{o}F to the data rooms and the other duct has a reheat coil that brings the air back to a neutral temperature where it is delivered to all of the other rooms in the building for ventilation purposes. The fans in both the exhaust plenum and outdoor air plenum are equipped with variable frequency drives to reduce the energy consumption of the unit. The schedule for ERU-1 is given below.

Energy Recovery Unit Schedule											
						CHW Cooling Coil					
	Supply Air		Exhaust Air			EAT		LAT		HW Reheat Coil	
Mark	Airflow (cfm)	Motor HP	Airflow (CFM)	Motor HP	Net Efficiency	DB	WB	DB	WB	EAT DB	LAT DB
ERU-1	20,600	10	13,375	10	66.3	68.9	62.3	52	52	54	70

Table 7: *Energy Recovery Unit Schedule*

The laundry dryers and rooms that contain potentially harmful or odorous air were given their own dedicated exhaust systems. The air from these rooms and machines will be sent directly outside of the building by separate exhaust fans in accordance with ASHRAE Standard 62.1. Technical Report 1 gives a more detailed analysis of the buildings compliance with this standard. The exhaust fan schedule is shown in Table 8 below.

Exhaust Fan Schedule			
Mark	Serves	Airflow (cfm)	Motor HP
EF-1	Trash and Recycling	400	1/8
EF-2	Trash Chute	800	1/4
EF-3	Generator Room	150	1/4
EF-4	Dryer Vent Riser	6000	3

Table 8: *Exhaust fan schedule*

The large amount of air exhausted from the building by these four fans explains the difference between the exhaust air cfm and outdoor air cfm in ERU-1. When the exhaust air leaving through the energy recovery unit is combined with the exhaust air leaving through the four fans shown above the total cfm is roughly equivalent to the supply air cfm in ERU-1.

The heating source for Des Places comes from Duquesne University's central steam plant. Immediately after the main steam line enters Des Places it is converted into hot water by two steam to hot water convertors. The schedule for these two heat exchangers is shown below.

Steam to Hot Water Converter Schedule									
						Tubes			
Mark	Tube Length (in)	Diameter (in)	Fouling Factor	Lbs/Hr.	Shell Operating Pressure (psig)	Flow (GPM)	EWT	LWT	Passes
C-1	41	10	0.00086	2400	5	195	120	140	2
C-2	41	10	0.00086	2400	5	195	120	140	2

Table 9: *Steam to hot water converter schedule*

The pumps in Des Places are a major component of the buildings mechanical system. All of the pumps in the building are connected to a variable frequency drive with the exception of the condensate pump. A variable primary flow arrangement is used for the hot water, chilled water and domestic water pumps. The schedule for all of the pumps in Des Places is shown in table 10.

Pump Schedule							
Mark	Pump Duty	Type	Flow (GPM)	Head (ft)	Motor HP	Motor RPM	Impeller Size (in)
P-1	Chilled Water	Base Mounted	480	71	5	1760	8.5
P-2	Chilled Water	Base Mounted	480	71	5	1760	8.5
P-3	Hot Water	Base Mounted	180	71	5	1760	8.5
P-4	Hot Water	Base Mounted	180	71	5	1760	8.5
P-5	Chilled Water Booster	Base Mounted	120	60	5	1750	8
P-6	Domestic Hot/Chilled Water Booster	Base Mounted	175	60	5	1750	8.5
P-7	Hot Water Booster	Base Mounted	175	60	5	1750	8.5
P-8	Condensate Pump	Base Mounted	12	30 PSIG	0.75	3000	--

Table 10: *Pump schedule*

Operating History of System

Des Places Residence Hall is currently under construction and therefore there is no operating data for the designed mechanical system.

Design Heating and Cooling Loads

Trane Trace 700 was used to model the energy consumption of Des Places Residence Hall. This program provides an in depth analysis of a buildings energy consumption, design loads and performance. A combination of individual room and block loading was used to model this building. All of the information necessary to create this model was found in the drawings and specifications for Des Places.

The table below summarizes the total cooling load, heating load and supply airflow for the entire building and compares it to the heating capability, cooling capability, and total supply airflow of all the fan coil units in the building. This table also compares the total ventilation airflow calculated in Trace to the amount of outdoor air coming from the energy recovery unit.

Comparisons by System								
	Cooling		Heating		Supply Airflow		Ventilation Airflow	
	Design (MBh)	Modeled (MBh)	Design (MBh)	Modeled (MBh)	Design (CFM)	Modeled (CFM)	Design (CFM)	Modeled (CFM)
Fan Coil Units	2,421	1,452	3,624	1,200	92,100	51,266	20,600	17,667

Table 11: *Design vs. modeled load comparison by system*

Table 11 shows that the designed heating and cooling capability of the fan coil units in Des Places is much greater than the total designed heating and cooling loads. This large discrepancy gives the appearance of either a poor energy model or some significant errors made during the design process. However there is a justification for the fan coil units being so oversized in comparison to the loads. According to Tony Valenza, a mechanical engineer for CJL Engineering who worked on the Des Places project, Duquesne University specifically required the use of Whalen fan coil units to heat and cool the building. The owner wanted fan coil units in each room, so that the students could have personalized control of the temperature in the space they were occupying. Furthermore they specifically required Whalen units, because they had used them in other buildings and found that they were very reliable. The smallest fan coil unit that Whalen makes has a heating coil capacity of 12 MBh and a cooling coil capacity of 8.1 MBh. The vast majority of rooms in Des Places have calculated heating and cooling loads that are far less than these values, so all of these rooms have oversized equipment.

Annual Energy Use

The annual energy consumption of Des Places Residence Hall was calculated using the Trace model created for the building. Utility rates for chilled water, hot water and electricity were provided by Duquesne University. The energy model created by the engineers that worked on Des Places could not be attained. Therefore their energy model could not be compared to the one created for this report. The annual energy consumption for the entire building is broken down into major categories in Table 12.

Annual Energy Consumption		
System	Electrical Consumption (kWh)	Gas Consumption (kBTU)
Primary Heating	--	1,397,382
Heating Accessories	13,770	--
Primary Cooling	387,640	--
Cooling Accessories	3,854	--
Pumps	24,152	--
Supply Fans	201,090	--
Lighting	263,162	--

Table 12: *Annual energy consumption by system*

All of the primary systems in Des Places that require some form of energy are shown in relationship to one another in Figure 3. The entities that were measured in kWh were converted to kBTU, so that all of the systems could be accurately compared.

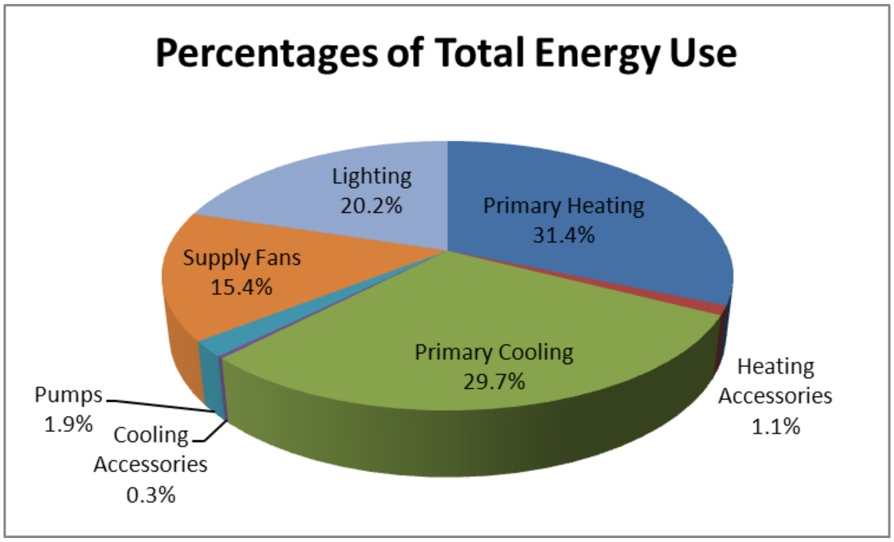


Figure 3: *Pie chart showing percentages of total energy use*

Evaluation of Existing Mechanical System

ASHRAE Standard 62.1-2007 Compliance

Section 5

The table below shows that Des Places Residence Hall complied with every applicable guideline given in Section 5 of ASHRAE Standard 62.1. Please refer to Technical Report 1 for a more detailed analysis of the buildings compliance with Section 5.

ASHRAE Standard 62.1, Section 5 Compliance	
Section	ASHRAE 62.1 Compliance
5.1-Natural Ventilation	N.A.
5.2-Ventilation Air Distribution	YES
5.3-Exhaust Duct Location	YES
5.4-Ventilation System Controls	YES
5.5-Airstream Surfaces	YES
5.6-Outdoor Air Intakes	YES
5.7-Local Capture of Contaminants	YES
5.8-Combustion Air	YES
5.9-Particulate Matter Removal	YES
5.10-Dehumidification Systems	YES
5.11-Drain Pans	YES
5.12-Finned-Tube Coils and Heat Exchangers	YES
5.13-Humidifiers and Water-Spray Systems	N.A.
5.14-Access For Inspection, Cleaning and Maintenance	YES
5.15-Building Evelope and Interior Surfaces	YES
5.16-Building with Attached Parking Garage	N.A.
5.17-Air Classification and Recirculation	YES
5.18-Requirements for Buildings Containing ETS Areas and ETS-Free Areas	N.A.

Table 13: *Summary of ASHRAE Standard 62.1, Section 5 compliance*

Section 6

In order to verify that the buildings dedicated outdoor air system provided adequate ventilation to its occupants, a ventilation rate calculation had to be performed in accordance with one of the suggested methods outlined in Section 6 of ASHRAE Standard 62.1. ERU-1 is a 100% outdoor air unit that provides fresh air to all of the required zones in the building. The amount of outdoor air entering the building from ERU-1 has to be compared to the total outdoor air needed in Des Places in order to see if the building has enough ventilation. The Ventilation Rate Procedure was chosen over the IAQ Procedure because the building does not utilize controls that remove air contaminants.

The table below shows the total outdoor air required by floor and the design outdoor air delivered to each floor by the supply registers and diffusers. The value for $\sum V_{oz}$ was found by summing the V_{oz} calculated for each room. The values in the column designated "Design OA" is the sum of the design outdoor air delivered to each room by all of the supply registers and diffusers on each floor.

OA Requirements By Floor

Floor	∑Voz	Vot	Design OA
1	769 cfm	769 cfm	1425 cfm
2	868 cfm	868 cfm	1615 cfm
3	897 cfm	897 cfm	1265 cfm
4	897 cfm	897 cfm	1265 cfm
5	897 cfm	897 cfm	1265 cfm
6	897 cfm	897 cfm	1265 cfm
7	897 cfm	897 cfm	1265 cfm
8	897 cfm	897 cfm	1265 cfm
9	897 cfm	897 cfm	1265 cfm
10	897 cfm	897 cfm	1265 cfm
11	897 cfm	897 cfm	1265 cfm
12	1145 cfm	1145 cfm	1470 cfm
Total:	10855 cfm	10855 cfm	15895 cfm

Table 14: *Total outdoor air required and delivered to each floor*

The next table is a summary of the building's compliance with the ASHRAE ventilation guidelines, given in section 6 of Standard 62.1.

Compliance Summary

AHU	Calculated Outdoor Air	Design OA Flow Into Rooms	Design OA Flow From Schedule	ASHRAE 62.1 Compliance
ERU-1	10855 cfm	15895 cfm	20600 cfm	YES

Table 15: *ASHRAE 62.1, Section 6 Compliance Summary for ERU-1*

The Energy Recovery Unit in the penthouse is the only system that delivers outdoor air to the building, so it was therefore the only piece of equipment that was examined for ventilation compliance. According to the schedule on drawing H0.1, ERU-1 can supply a maximum of 20,600 CFM of outside air. This is almost double the required amount for the building, as calculated in accordance with the procedures given in Section 6.2 of Standard 62.1. It is also

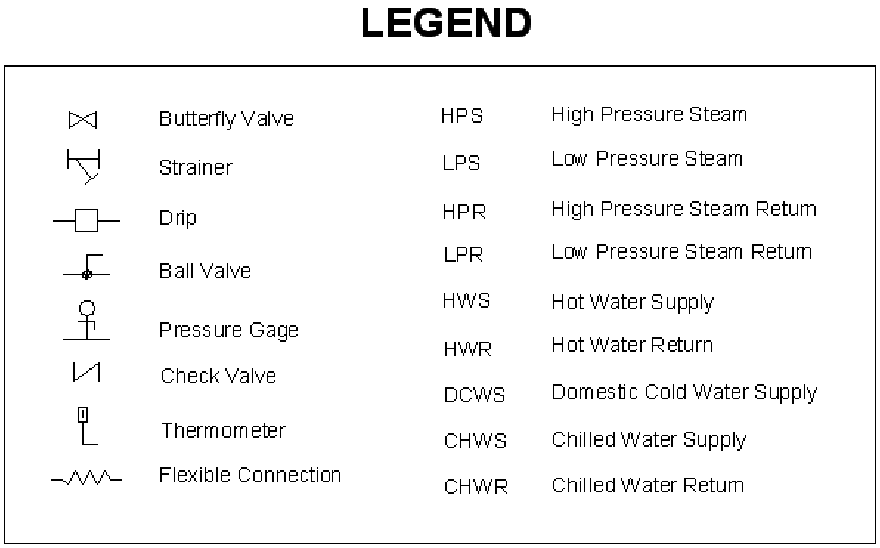
4,705 cfm more than the total design outdoor airflow into all of the spaces from the supply diffusers. Therefore it can be concluded that ERU-1 safely meets the ventilation requirements of ASHRAE Standard 62.1.

ASHRAE Standard 90.1-2007 Compliance

Des Places Residence Hall meets all of the requirements given in section 5 through 9 of Standard 90.1. Some of the requirements outlined in Standard 90.1, such as those given in the Service Water Heating section do not apply to this building and were therefore not examined. Refer to Technical Report 1 for a detailed analysis of the buildings compliance to ASHRAE Standard 90.1.

System Operation and Schematics

The waterside and airside system schematics are shown in Appendix B of this report. The waterside section has a schematic for the steam, hot water and chilled water systems and the airside section has one drawing, showing how the energy recovery unit distributes air throughout the building. A legend for the water side systems (shown below) explains what all of the abbreviations and symbols mean in the system schematic diagrams.


LEGEND

Butterfly Valve
Strainer
Drip
Ball Valve
Pressure Gage
Check Valve
Thermometer
Flexible Connection

HPS	High Pressure Steam
LPS	Low Pressure Steam
HPR	High Pressure Steam Return
LPR	Low Pressure Steam Return
HWS	Hot Water Supply
HWR	Hot Water Return
DCWS	Domestic Cold Water Supply
CHWS	Chilled Water Supply
CHWR	Chilled Water Return

Figure 4: *Legend for water side system schematics*

Steam

High pressure steam enters the building from the central steam plant through a foundation wall on the first floor in a 4" pipe at a pressure of 50 lbs and a velocity of 6,000 fpm. Immediately after the high pressure steam enters Des Places it goes through a pressure reducing valve station that brings the steam to a more manageable pressure. The pressure reducing valve is connected to a flash tank that takes care of any flashing steam and turns it into condensate. Some of the low pressure steam then branches off to the domestic water heater that services the entire building. After running through a temperature control valve station, the remaining low pressure steam enters two identical steam to hot water converters that act as heat exchangers between the steam and the return hot water for the building. These two converters are arranged in parallel and feed the hot water system that is responsible for heating the entire building. After making two passes through the converters the hot water temperature rises from 120 ^{o}F to 140^{o}F. The two heat exchangers turn all of the remaining steam into condensate. A condensate pump then pushes all of the condensate produced by the flash tank, domestic water heater, and heat exchangers out of the building and back into the district steam loop where it is brought back to Duquesne's central plant.

Hot Water

The hot water supply for the building starts at the two steam to hot water converters at 140^{o}F. Before the water reaches any of the pumps it passes through an air separator that removes any air bubbles from the water to avoid cavitation in the pumps. Cavitation can lead to inefficiency and damage to the equipment. A portion of the hot water supply branches off to serve all of the unit heaters in the building and the two heating coils in the energy recovery unit. The water in this branch is circulated by a single 5 HP, base mounted pump. This pump is equipped with a variable frequency drive that matches the load demand. The remaining majority of the hot water is delivered to the fan coil units on each floor of the building by two variable frequency pumps arranged in parallel. These two pumps are identical and work together as one package so that they are operating at the most efficient combination possible that will still meet the required load. A small amount of hot water is diverted from the fan coil loop in the first floor mechanical room, so that chemicals can be fed into the water and then recirculated into the loop through the return water. The chemicals injected into the hot water return keep the water from fouling and protect the pipes from corrosion. The pumps are arranged in a variable primary flow arrangement, so there are no secondary pumps in the building. After the hot water meets the load it is returned back to the two heat exchangers at 120 ^{o}F where it is heated back up again to 140 ^{o}F.

Chilled Water

The chilled water loop for the Des Places is designed in an almost identical arrangement as the hot water loop. The chilled water enters the building in the first floor mechanical room straight from Duquesne's central plant instead of from heat exchangers like the hot water. The chilled water comes in at 45 ^{o}F and is returned to the district cooling loop at 57 ^{o}F after running through the various loads in the building. Because the chilled water is not recirculated in the system like the hot water, chemical treatment is not necessary. The chilled water is broken into two loops. The smaller loop serves the cooling coil in ERU-1 and is circulated by a single pump, and the larger loop serves all of the buildings fan coil units and is circulated by two identical pumps arranged in parallel.

Air System

The airside system for this building is limited to the large energy recovery unit in the penthouse and the associated ducts and diffusers that provide ventilation to the entire building and condition the IDF rooms. This unit is also responsible for exhausting all of the lavatories in the building as well. The ERU uses 100% outdoor air and exhausts all of its return air directly outside of the building. The unit is able to recover some of the latent and sensible heat from the exhaust air stream with a dessicant wheel. In the supply air plenum, the incoming air passes through a preheat coil for freeze protection and then a cooling coil. From there the energy recovery unit becomes a split system. A small amount of air is sent to the IDF rooms conditioned at 52 ^{o}F and the remaining air splits off into another duct to bring outdoor air at a neutral temperature into all of the rooms in the building that require ventilation. This air supply is braught back up to a neutral temperature by a second reheat coil in the ventilation air plenum. This coil brings the air from 52 ^{o}F to 70 ^{o}F. The supply air flow and the exhaust air flow are both pushed through the system by 10 HP fans in the energy recovery unit. These fans are run by variable frequency drives that use pressure sensors to determine their operating speed.

LEED Analysis

The Des Places project is projected to earn a minimum of 55 points on the LEED 3.0 checklist, which would give the building a LEED Silver Certification. There is also potential for the building to earn additional credits, which could move it into the range of points needed to earn a LEED Gold Certification. The 2009 LEED standard has two sections that are particularly influenced by the mechanical design of a building. These two sections are titled Energy and Atmosphere (EA) and Indoor Environmental Quality (IEQ). For the Energy and Atmosphere section, Des Places should receive 13 of the possible 35 points and for the Indoor Environmental Quality section it is anticipated that the building will receive 13 of the possible 15 points. A thorough analysis of the buildings compliance with all of the points given in these two sections is listed in Technical Report 3.

Proposed Redesign Overview

Dedicated Outdoor Air System with Radiant Ceilings

Dedicated outdoor air systems use 100% outside air to mechanically ventilate a building. In a typical DOAS system an energy recovery unit provides all of the ventilation air required at constant volume and meets the latent load of the outside air coming into the unit and the latent load of the spaces that it conditions. An entirely separate parallel system meets the sensible loads in the building. There are several different alternatives for the sensible system, such as fan coil units, radiant panels in the ceiling, chilled beams, or a more conventional VAV system. The two systems operate in parallel to adequately meet the designed heating and cooling loads of each space in the building. A properly designed DOAS system can save a considerable amount of energy over more conventional methods of air conditioning while supplying the correct amount of ventilation air, as prescribed in ASHRAE Standard 62.1. A DOAS system should specifically reduce the amount of energy a building consumes by lowering fan energy consumption, lowering the load on the cooling coil and reducing chiller energy consumption.

Des Places already uses a dedicated outdoor air system that is fairly efficient, especially when compared to the baseline building (Des Places consumes 22% less energy than the base building designed in accordance with Appendix G of ASHRAE Standard 90.1). Even though the existing mechanical system performs well it could possibly be improved by replacing the fan coil units with radiant ceiling panels and baseboard radiators. Energy modeling and economic analysis have shown that radiant cooling panels are the best choice for a parallel sensible system (Jeong, Mumma and Bahnfleth 627-636). This would be especially true for Des Places because 227 out of a total of 264 fan coil units used in the building are oversized. Most of the rooms in Des Places have a heating and cooling load that is far less than the heating and cooling capacity of the smallest available Whalen unit. Therefore these oversized units will almost always be running at part load, which will make them run less efficiently. If radiant ceilings and baseboard radiators were used as the parallel sensible system, they could be custom sized for each room so that their heating and cooling capacity closely matched the demands of the space. Then they would be running at or near one-hundred percent of their capacity where they are most efficient.

Radiant ceilings and radiators can also improve the occupants comfort level by creating a thermally uniform space while producing little to no mechanical noise in the room they are conditioning. This type of system takes advantage of the natural buoyancy effects of air by placing the heating source at the lowest vertical height of the room and the cooling source at the highest level in the room. Because cold air naturally sinks and hot air rises, the cooling effect from the chilled beams and the heating effect from the radiators would be naturally stratified throughout the room. In order for a fan coil unit to produce the same effect, it has to force hot or cold air out of the unit at a high enough flow rate to forcefully spread the conditioned air throughout the space. This method does not always create a uniform temperature in the space and the fan that is used to blow the air out of the fan coil unit consumes additional energy and can create enough noise in the space to be annoying to the occupants.

Solar Hot Water System

Solar hot water collection is a fairly recent technology that has gained more popularity over the last decade as an effective way to offset space heating energy use or domestic hot water heating in a building. Solar hot water heating is done by absorbing thermal energy from the sun and converting it into usable heat. The thermal heat is usually absorbed by water or a freeze resistant water mix. The figure below shows a basic schematic of this process. In the illustration shown below a closed loop solar hot water system is being used to offset the energy consumption of a boiler by preheating the domestic water in the tank.

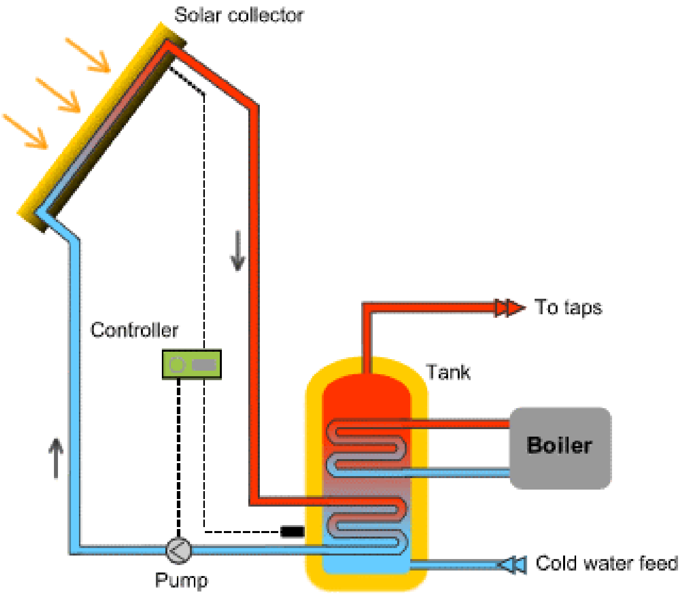


Figure 5: *Basic schematic of a solar hot water system*

Currently there is an array of photovoltaic direct current electricity panels on the roof of Des Places. These photovoltaic panels only provide 1% of the buildings total electrical use and are largely there for the purpose of earning one LEED point under EA Credit 2: On-Site Renewable Energy. This small PV array should be replaced by a larger solar hot water array that could provide most of the heating needed for the domestic hot water system in Des Places. Solar hot water systems are usually about three times more efficient than photovoltaic systems in harvesting energy from the sun and there is a lot more space on the roof of the 12th floor and mechanical penthouse that could be utilized.

Incorporating solar hot water heating into the mechanical system of Des Places will significantly improve upon the energy savings of the existing PV array and will reduce the amount of steam that the building requires from the central plant on campus.

Structural Breadth

The addition of a solar hot water array on the roof of Des Places will bring an additional load to the roof structure that was not factored into the original design. Therefore a new structural analysis is necessary to ensure that the existing roof can safely hold this additional load. The roof of Des Places is supported by three separate structures. Each structure will be analyzed to make sure that the metal roof deck and hollow core concrete plank underneath the solar collectors can handle the additional lb/ft^2 load. If they are found to be inadequate, then the metal decking or concrete plank will be resized. The steel beams that support the rows of collectors will also be analyzed to make sure that they can handle the new shear and moment loads applied to them. If these beams are found to be inadequate then the structure of the roof will be redesigned and the size of the steel members will be increased.

Redesign of Building Envelope

Each bedroom and private living room in Des Places has one window that is four feet wide and five feet tall. The smallest exterior wall for a bedroom in Des Places is nine feet wide and ten feet tall. Therefore every bedroom and living room window could be doubled in size. This change in the building envelope would allow more natural daylight into each private room. The increase in natural daylighting could eliminate or reduce the need for artificial light in the room during the day and create a more desirable environment for students occupying the spaces. Studies have shown that buildings with a large amount of natural daylight result in occupants that are more productive, more focused and are happier with their surroundings (Ella MacKenna). If all of the 4 ft. by 5 ft. windows were doubled in size to 8 ft. by 5 ft., this would greatly increase the solar heat gain on the building envelope which would increase the total cooling load for the building. It would also increase the heating load on the building during the colder months, because the windows have a smaller R-Value than the brick masonry wall. The increase in installation cost and annual energy costs could be justified by the many benefits that larger windows would bring, both for the building and for its occupants.

Daylighting Breadth

A qualitative analysis for the daylighting benefits of the building envelope redesign will be completed through the use of the lighting software AGI. Two models of the same typical bedroom will first be created in Revit Architecture. The first model will have the original 4 foot by 5 foot window and the second model will have the proposed 8 foot by 5 foot window. These two three-dimensional models will be exported into AGI and compared in two separate scenarios. The first scenario will model a typical east facing bedroom and the second scenario will model a typical north facing bedroom. The east and north facing rooms should have very different results, because the east facing side of the building receives a great deal of solar exposure, while the north facing side receives the least amount of exposure. Simulations for the two room models will be run at different days in the year and the resulting illuminance fields in the rooms will be compared and evaluated. These simulations will show how much additional daylight enters the east and north facing bedrooms with the larger windows. These results can then be used to ultimately decide if the additional daylighting in the bedrooms and living rooms is worth the extra cost of the building envelope redesign.

Dedicated Outdoor Air System with Radiant Ceilings – Mechanical Depth

Introduction

Des Places Residence Hall currently uses a dedicated outdoor air system with fan coil units to fully condition the building and deliver the required amount of outdoor air. This type of DOAS system was chosen for Des Places because the fan coil units can provide individual and responsive climate control for each room and they are also durable and easy to maintain. The durability and maintainability of the system was a big concern for Duquesne because Des Places is a college dormitory and damage to the system is a likely possibility. If the dedicated outdoor air system was redesigned so that it used radiant chilled ceilings and baseboard radiators instead of fan coil units, all of the original design goals could be adequately met and the redesigned mechanical system would be superior to the original design in several ways. The following analysis will show how a radiant ceiling DOAS system can be less expensive and produce a higher level of thermal comfort in the building, while still being just as rugged and responsive as the original dedicated outdoor air system.

System Design

Radiant chilled ceilings cool spaces primarily through radiation, so they are not dependent on air movement to transfer large heat loads. Therefore these systems do not require any fans for heating and cooling and will consequently save on fan energy consumption in comparison to a fan coil unit DOAS system. There will also be no fan noise in each room. This is an important factor to consider in a dormitory, where students need a quiet room to complete their schoolwork and sleep comfortably.

Radiant ceilings cool spaces in a fundamentally different way than fan coil units and they have proven that they deliver the highest level of thermal comfort out of any option for dedicated outdoor air systems. These systems use radiant cooling to condition buildings, which is based on the principle that bodies with varying temperatures exchange thermal radiation until equilibrium is achieved in the space. This means that the various heat sources in a given room will be naturally absorbed by the cool surface of the chilled ceiling panels. The placement of the cooling source at the highest surface in a space also increases its effectiveness by taking advantage of the natural buoyancy and density effects of air. Hot air rises and cold air sinks, therefore the cold radiation coming out of the chilled ceiling will naturally sink down to the floor, covering the entire room and creating a more uniform temperature throughout the space. The baseboard radiators will be placed at the floor of the rooms underneath the windows. This will allow the heat from the radiators to rise from the lowest point in the room to the highest point and spread throughout the entire space. The two figures below show the original design for a typical bedroom in Des Places and the proposed redesign for the same bedroom. Both figures show every element in the room that will consume energy and the heating and cooling capacity of the mechanical equipment in the room is labeled as well. The yellow figures in each model are lighting fixtures and the circle with a T in the middle signifies where the thermostat is placed in the room.

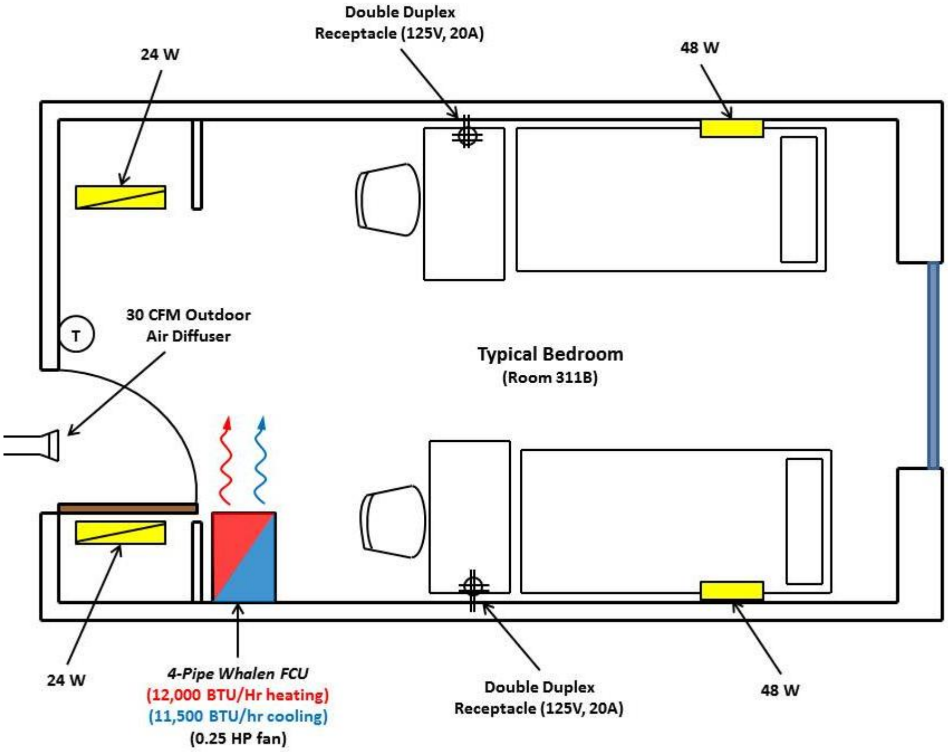


Figure 6: *Model of room 311B with a fan coil unit*

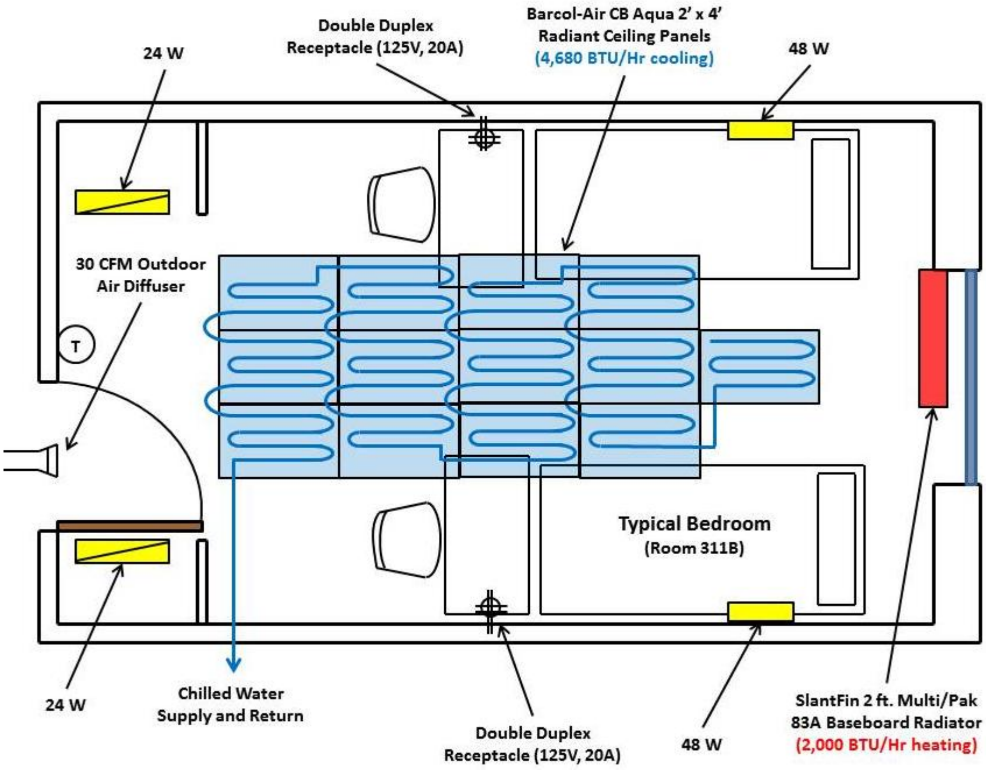


Figure 7: *Model of room 311B with a radiant ceiling and baseboard radiator*

The designed peak heating load for room 311B is 1411 btu/hr and the peak cooling load is 4533 btu/hr. The two figures above show how the radiant ceiling and baseboard radiator are closely matched to the peak loads of the space where as the fan coil unit is significantly oversized for the space. This is due to the fact that radiant ceilings and baseboard radiators are customizable for each space. This means that they can be sized individually to meet the demands of each room so that they are running at or near part load for the majority of their operation, which keeps them close to their maximum efficiency. The Whalen fan coil units selected for Des Places only come in a limited number of sizes, so as a result most of the fan coil units in the building are oversized for the spaces that they condition. Therefore they will always be running at part load and will consequently not operate anywhere near their maximum efficiency.

The actual dedicated outdoor air system for Des Places will remain the same. Only the parallel system that meets the sensible heating and cooling demands of the building will be replaced in the proposed redesign for Des Places. This means that ERU-1 will remain in the penthouse the way that it is currently designed and the outdoor air and exhaust ductwork will remain the same.

Slantfin Multi/Pak 83A baseboard radiators were chosen to take care of the heating load in Des Places because they are specifically designed for upscale residential buildings and they fit the needs of Des Places well. These radiators are simple and reliable and they come in a wide variety of sizes which allows them to be more customizable to each room. The 83A model produces approximately 1,000 btu/ft with the 140 ˚F hot water supply temperature in Des Places. Slantfin manufactures these radiators in 2 feet, 3 feet, 4 feet, 5 feet, 6 feet, 7 feet and 8 feet sizes so the models range from a capacity of 2,000 btu to 8,000 btu. Slantfin uses a low profile design with very little depth for the 83A model, so the radiator will barely be noticeable in any room. A picture of the Slantfin 83A baseboard radiator is shown in figure 8.

Figure 8: *Picture of a Slantfin Multi/Pak 83A baseboard radiator (courtesy of www.pexsupply.com)*

The Barcol-Air CB Aqua system was the best choice for the radiant ceilings in Des Places because of its flexibility, durability and customization. The system consists of metal ceiling panels, heat conduction rails, copper tubing, flexible hoses with quick connectors and metal nipples. The copper tubing and heat conduction rails are the pieces of the system that actually absorb the heat in a room. The flexible hoses connect each ceiling panel to one another and they also connect a loop of panels to the main chilled water supply and return piping. The nipples are placed at the actual connection of the flexible hoses to the chilled water supply and return piping. The metal panels are meant to enhance the radiation effect of the heat conduction rails and also protect the system from any possible damage. The metal panels are not actually produced by Barcol-Air but there are a variety of different suppliers that produce aluminum or steel panels custom-built for the CB Aqua system. Steel panels manufactured by Steel Ceilings Inc. were chosen for Des Places, because they are the most durable option. A diagram of the CB Aqua system is shown below.

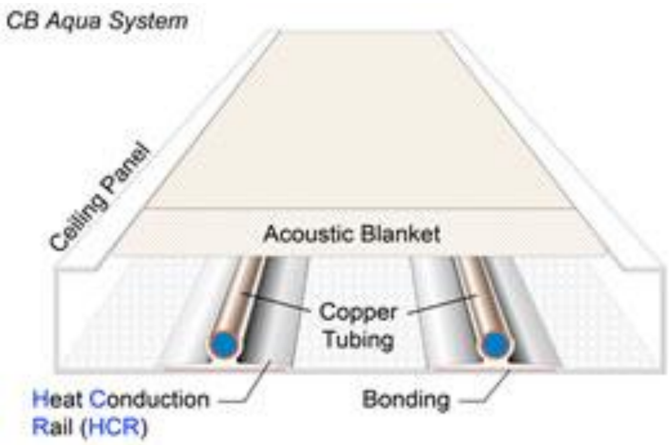


Figure 9: *Diagram of the CB Aqua System*

The radiant ceiling comes in standard 2 foot by 2 foot or 2 foot by 4 foot panels and each ceiling in a building is custom fit to the cooling loads of each room. A picture of a 2 foot by 2 foot ceiling panel is shown in the figure below. All of the ceiling panels used in Des Places will be 2 foot by 4 foot, to match the rectangular shape of the majority of the rooms in the building.

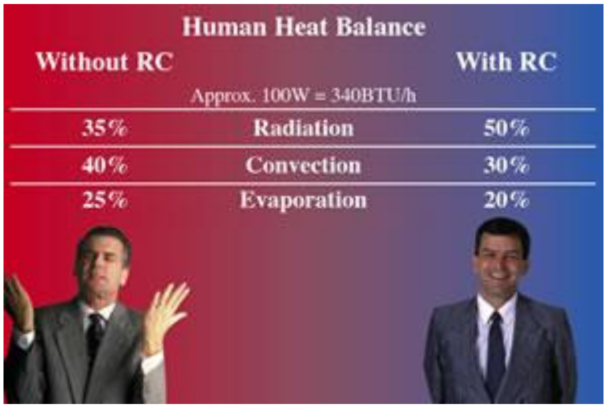
Figure 10: *Picture of a typical 2' x 2' CB Aqua ceiling panel*

Reliability and durability were major concerns for the mechanical system in Des Places and ended up being the primary reason why Whalen fan coil units were chosen to condition the building. Barcol-Air has designed the CB Aqua system to match or exceed the durability and reliability of any DOAS system, and it can be seen in the details of every component that makes up the system. The metal ceiling panels that act as the barrier between the radiant ceiling and the room are made of steel with a 24 gauge thickness. These panels are extremely durable and will last for a very long time. Barcol-Air also uses the highest quality copper tubing that has been thoroughly tested for flaws before installation. This ensures that absolutely no leakage will occur for the entire operating life of the tubing. Flexible hoses are used for every connection as well, so that the hose will bend and not break in the event that it is pushed or bumped. Even the nipples that connect the panel arrays to the chilled water supply and return piping are made of one piece, precision made brass. These nipples were custom designed by Barcol-Air to ensure that the connection is leak tight. All of these elements in the system combine to create a radiant ceiling that is completely leak-tight and unsurpassed in durability.

The CB Aqua radiant ceilings and baseboard radiators can be controlled by automated or manual thermostats in the same way as fan coil units. A thermostat in each room would be connected to control valves placed before the baseboard radiator piping and radiant ceiling coils. These control valves would dictate the flow of chilled water through the radiant ceiling coils and hot water through the radiator in order to maintain the desired temperature of the space. This system will be able to react quickly to a change in the heating or cooling loads in any space. One important control requirement of a chilled radiant ceiling is keeping the chilled water supply temperature above the dew point of the air in the room. This can be achieved by placing a dew point sensor in each room. The dew point sensor would control the flow of chilled water through the coils in the radiant ceiling, along with the thermostat so that the temperature of the chilled water in the coils was never below the dew point of the air in the room.

Thermal Performance Study

According to the Barcol-Air website the CB Aqua system delivers the highest level of thermal comfort by improving human heat balance, which refers to what percentage of cooling is done by radiation, convection and evaporation. Because the radiant ceiling uses less convection and evaporation to cool off the human occupants and more radiation, the people in the room will feel a higher sense of thermal comfort. According to Barcol-Air this change in human heat balance will even result in a perceived ambient air temperature 2 °F lower than the actual dry bulb temperature. The figure below compares the human heat balance in a room conditioned by a radiant ceiling to a room that uses another method of cooling, such as a fan coil unit.



Human Heat Balance

Approx. 100W = 340BTU/h

Without RC		With RC
35%	Radiation	50%
40%	Convection	30%
25%	Evaporation	20%

Figure 11: *Human heat balance with a radiant ceiling and without a radiant ceiling*

Thermal comfort should be a high priority for a dormitory like Des Places, where increased comfort can lead to more productive and successful students. In this report the cooling performance of a Whalen fan coil unit will be compared to the performance of a CB Aqua radiant ceiling in a typical bedroom in Des Places Residence Hall. The computational fluid dynamics software Phoenics will be used to compare the cooling effects of both systems in the same room with the same internal heat loads. The resulting temperature distribution in both CFD models will be evaluated and compared to see which system delivers a lower average temperature and a more uniform temperature distribution in the space.

Model Properties

Room 311B was chosen as the appropriate room in Des Places to model in Phoenics. It is a typical east facing bedroom on the third floor of the building. It has the same dimensions and furniture layout as most of the bedrooms in Des Places. The floor plan of this room is shown in figure 12 below.

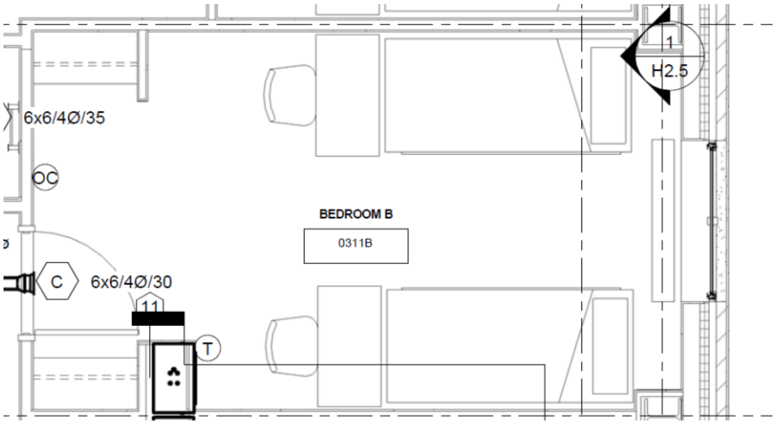


Figure 12: *Floor plan of room 311B*

Three alternative models of room 311B were created in Phoenics. The first model was of the room with internal heat sources only. This model had to be created and simulated correctly before the other two models could be made. Several simulations were run for this model until the mass residual was below 3%. The mass residual is the sum of the absolute residuals in each cell divided by the total mass inflow. The mass residual needs to be below 3% to ensure that the results of the CFD analysis are convergent and correct. After accurate results were attained for the first model, the room could be modeled with a fan coil unit and a radiant ceiling. The tables and figures below give the various properties of the three models created for this analysis.

The grid mesh across the x-plane and y-plane for the modeled room is shown in the two figures below. This grid mesh was altered slightly for the fan coil unit model but it was kept the same for the radiant ceiling model. The grid mesh was made as regular and square as possible and the grid was staggered near the walls of the room, so that the mesh became finer as it came closer to the walls.

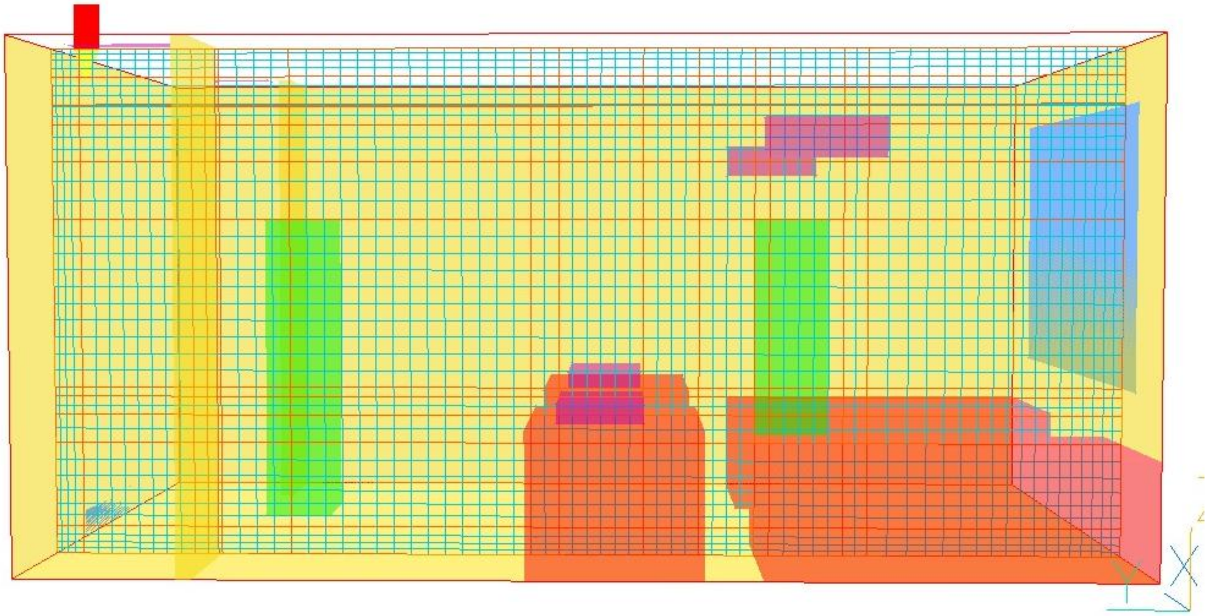


Figure 13: *Grid mesh in the y-plane*

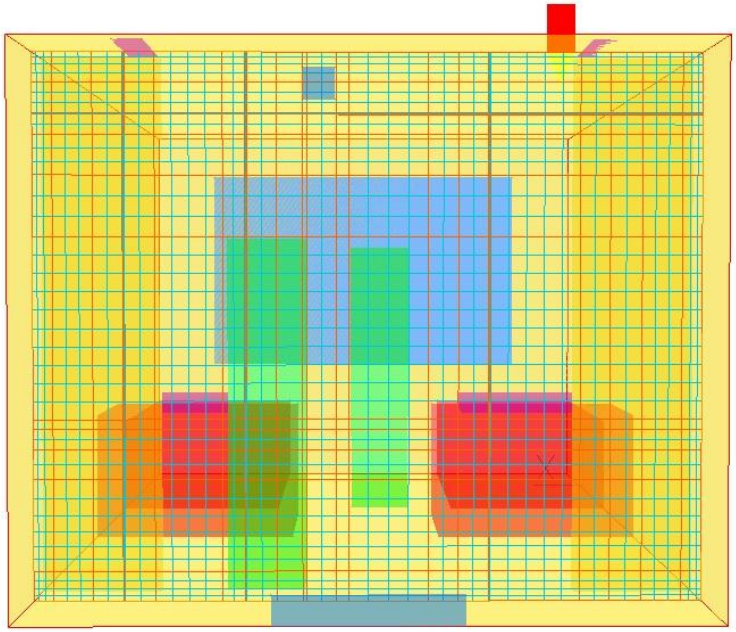


Figure 14: *Grid mesh in the x-plane*

Tables 16 and 17 list the size and location of all of the objects placed in the radiant ceiling model and fan coil unit model. The only difference between the objects in these two models is the fan coil unit inlet and outlet. The image below is the radiant ceiling model created in Phoenics. The green objects in the room are the two human occupants, the longer orange blocks in the room are the two beds and the smaller orange blocks are the two desks. The pink objects on the desks are each occupants personal computers and the four pink objects on the walls and ceiling are the different lighting fixtures in the space.

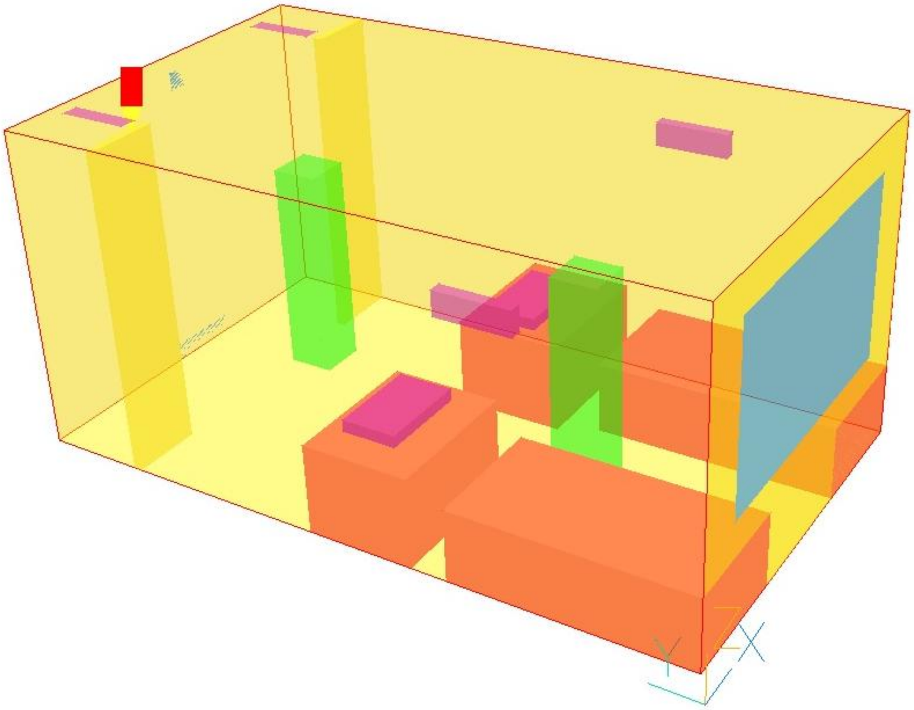


Figure 15: *Phoenics model of room 311B*

Dimensions and Positions of Objects

Fan Coil Unit Model

	Size			Location		
	ΔX (m)	ΔY (m)	ΔZ (m)	X(m)	Y(m)	Z(m)
Room	3.35	5.79	2.74	0	0	0
Floor	3.35	5.79	0	0	0	0
Ceiling	3.35	5.79	0	0	0	2.74
North Wall	0	5.79	2.74	3.35	0	0
South Wall	0	5.79	2.74	0	0	0
West Wall	3.35	0	2.74	0	5.79	0
East Wall	3.35	0	2.74	0	0	0
Window	2.44	0	1.52	0.46	0	0.91
Bed 1	1.07	1.98	0.61	0	0	0
Bed 2	1.07	1.98	0.61	2.28	0	0
Desk 1	1.22	0.91	0.76	0	2.28	0
Desk 2	1.22	0.91	0.76	2.13	2.28	0
North Closet Wall	0.61	0.076	2.74	0	4.88	0
South Closet Wall	0.61	0.076	2.74	2.74	4.88	0
Person 1	0.4	0.4	1.82	1.37	1.5	0
Person 2	0.4	0.4	1.82	2	4.5	0
Lighting Fixture DSK 1	0.1	0.61	0.2	0	1.37	2.13
Lighting Fixture DSK 2	0.1	0.61	0.2	3.25	1.37	2.13
Lighting Fixture SCL 1	0.15	0.61	0	0.46	5.03	2.74
Lighting Fixture SCL 2	0.15	0.61	0	2.74	5.03	2.74
OA Diffuser	0.15	0	0.15	1.83	5.79	2.44
Outlet	0.91	0	0.15	1.22	5.79	0
Computer 1	0.76	0.46	0.1	0.3	2.58	0.76
Computer 2	0.76	0.46	0.1	2.29	2.58	0.76
FCU Inlet	0	0.36	0.2	0	4.5	1.9
FCU Outlet	0	0.36	0.91	0	4.5	0.2

***Table 16:** Dimensions and positions of objects in the fan coil unit model*

Dimensions and Positions of Objects

Radiant Ceiling Model

	Size			Location		
	ΔX (m)	ΔY (m)	ΔZ (m)	X(m)	Y(m)	Z(m)
Room	3.35	5.79	2.74	0	0	0
Floor	3.35	5.79	0	0	0	0
Ceiling	3.35	5.79	0	0	0	2.74
North Wall	0	5.79	2.74	3.35	0	0
South Wall	0	5.79	2.74	0	0	0
West Wall	3.35	0	2.74	0	5.79	0
East Wall	3.35	0	2.74	0	0	0
Window	2.44	0	1.52	0.46	0	0.91
Bed 1	1.07	1.98	0.61	0	0	0
Bed 2	1.07	1.98	0.61	2.28	0	0
Desk 1	1.22	0.91	0.76	0	2.28	0
Desk 2	1.22	0.91	0.76	2.13	2.28	0
North Closet Wall	0.61	0.076	2.74	0	4.88	0
South Closet Wall	0.61	0.076	2.74	2.74	4.88	0
Person1	0.4	0.4	1.82	1.37	1.5	0
Person2	0.4	0.4	1.82	2	4.5	0
Lighting Fixture DSK 1	0.1	0.61	0.2	0	1.37	2.13
Lighting Fixture DSK 2	0.1	0.61	0.2	3.25	1.37	2.13
Lighting Fixture SCL 1	0.15	0.61	0	0.46	5.03	2.74
Lighting Fixture SCL 2	0.15	0.61	0	2.74	5.03	2.74
OA Diffuser	0.15	0	0.15	1.83	5.79	2.44
Outlet	0.91	0	0.15	1.22	5.79	0
Computer 1	0.76	0.46	0.1	0.3	2.58	0.76
Computer 2	0.76	0.46	0.1	2.29	2.58	0.76

Table 17: *Dimensions and positions of objects in the radiant ceiling model*

All three models used the same internal heat sources. The heat flux values for these sources were found from the results of a Trane TRACE model created for Des Places. The internal loads were given in the room checksums report for room 311B. Table 18 below gives the heat flux values for the various internal heat sources in room 311B.

Internal Heat Sources		
Heat Sources	**Btu/hr**	**W**
Person 1	175	51.3
Person 2	175	51.3
Computer 1	732	214.5
Computer 2	732	214.5
Solar Gain through Window	1620	474.8
Lighting Fixture DSK 1	64	18.8
Lighting Fixture DSK 2	64	18.8
Lighting Fixture SCL 1	64	18.8
Lighting Fixture SCL 2	64	18.8

Table 18: *Properties of the internal heat sources in room 311B*

In order for any CFD model to produce accurate and convergent results at least one inlet and one outlet must be assigned to the space. All three models used the 6 inch by 6 inch outdoor air diffuser as an inlet, but there are no return air diffusers in the bedrooms and living rooms of Des Places. Instead the design relied on air being drawn out of the positively pressurized bedrooms through the doorways and into the negatively pressurized lavatory space that is adjacent to all of the private bedrooms and living rooms. Every lavatory has multiple exhaust fans that bring stagnant air outside of the building. Because the air flow for the bedrooms is designed this way the outlet was modeled as a 6 inch tall by 3 foot long opening at the floor level on the same wall as the door to simulate air leaving the room through the cracks of a closed door.

The fan coil unit model had an additional inlet and outlet for the FCU in the room. The dimensions of the inlet and outlet were attained from technical specifications for a Whalen fan coil unit. These specifications can be seen in Appendix G. The WF-300-4P is the model used for room 311B. Tables 19 and 20 below give the modeling properties for the inlets in the fan coil unit model and the radiant ceiling model.

Inlet Boundary Conditions						
Fan Coil Unit Model						
Diffuser Type	Volume Flow Rate (m^3/s)	Gross Area (A_{gross})	Area Factor (A_o)	Σ (A_o/A_{gross})	Temp (˚C)	Temp (˚F)
Outdoor Air	0.014	0.15 m x 0.15 m	0.0225 m^2	100%	21	70
Fan Coil Unit	0.142	0.2 m x 0.36 m	0.0576 m^2	80%	12.8	55

Table 19: *Inlet boundary conditions for fan coil unit model*

Inlet Boundary Conditions						
Radiant Ceiling Model						
Diffuser Type	Volume Flow Rate (m^3/s)	Gross Area (A_{gross})	Area Factor (A_o)	Σ (A_o/A_{gross})	Temp (˚C)	Temp (˚F)
Outdoor Air	0.014	0.15 m x 0.15 m	0.0225 m^2	100%	21	70

Table 20: *Inlet boundary conditions for radiant ceiling model*

Table 21 lists the simulation properties of the three different models created for this analysis. Many simulations were run for each model before a mass residual lower than 3% was found. In the turbulence model column, LVEL stands for the low velocity generalized length-scale model and KEMODL stands for the classical two equation high Reynolds number K-E model. The KEMODL turbulence model was best suited for the room with the fan coil unit because the air was moving out of the FCU at a relatively high velocity, so there was more turbulence and a higher Reynolds number for the air flow in that area of the room. The LVEL model was better suited for the room with internal heat sources only and the room with a radiant ceiling because air moved at a low velocity throughout the space.

Properties of Different Phoenics Models								
	Turbulence Model	**Differencing Scheme**	**Iterations**	**Computation Time**	**Grid Size (X)**	**Grid Size (Y)**	**Grid Size (Z)**	**Mass Residual**
Room with Heat Sources Only	LVEL	Upwind	2000	2 hr, 1 min	66	75	44	2.70%
Room with Fan Coil Unit	KEMODL	Upwind	4000	3 hr, 15 min	48	63	47	0.30%
Room with Radiant Ceiling	LVEL	Upwind	8000	8hr, 10 min	66	75	44	1.26%

Table 21: *Properties of the three different Phoenics models*

Both the Whalen fan coil unit and the CB Aqua radiant ceiling were modeled in Phoenics in such a way that accurately represented the way that they would operate in reality. For the inlet of the fan coil unit the volume flow rate of air was 300 cubic feet per minute and the temperature of the air leaving the FCU was 60 °F. This is in accordance with the specifications for the fan coil unit used in room 311B, according to the fan coil unit schedule given in the mechanical plans for Des Places. The CB Aqua system was modeled as a ceiling with an assigned temperature of 50 °F. This temperature is slightly warmer than the supply temperature of the chilled water in Des Places, so it is reasonable to assume that the temperature of the radiant ceiling would be slightly higher than the temperature of the chilled water supply..

Comparison of Models

The velocity field in the fan coil unit model differs greatly from the velocity field in the radiant ceiling model due to the 300 cfm of air being pushed into the space by the fan coil unit. Figures 16 and 17 below show the velocity profiles of both models cutting through the outdoor air diffuser in the x-plane.

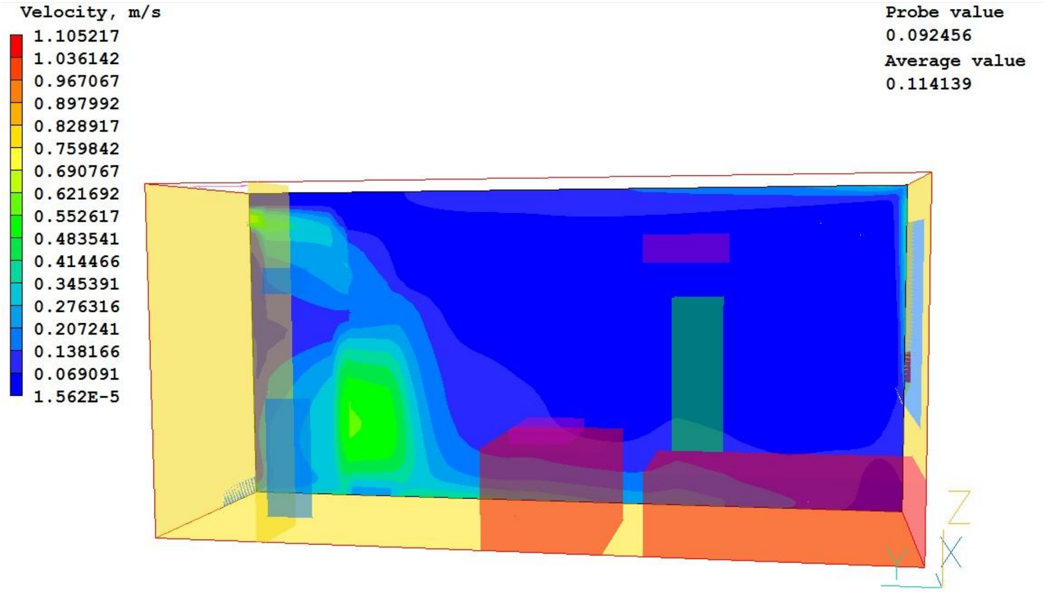


Figure 16: *Velocity profile cutting through the outdoor air diffuser in the fan coil unit model*

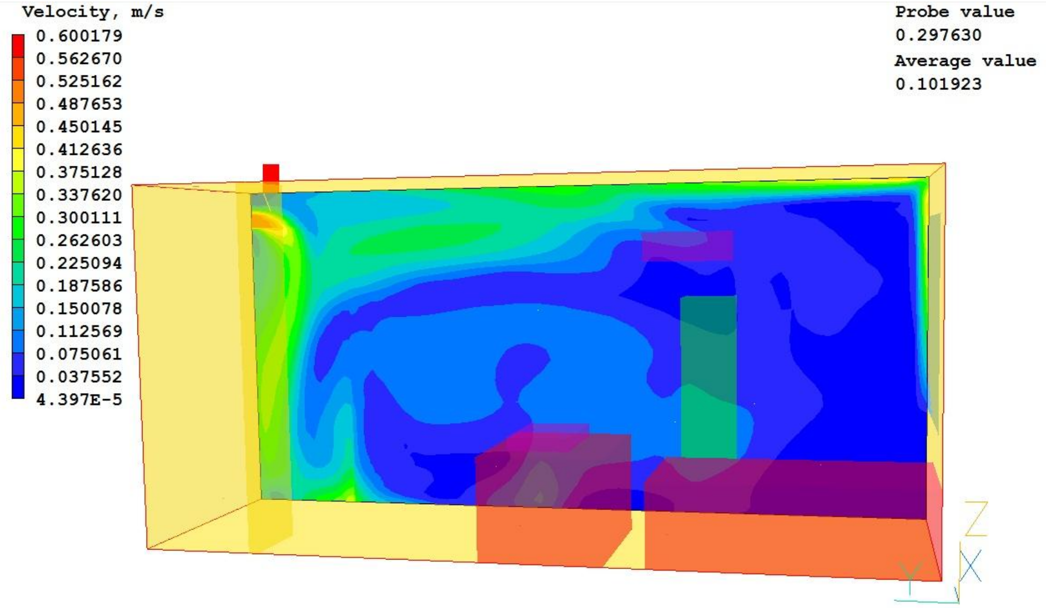


Figure 17: *Velocity profile cutting through the outdoor air diffuser in the radiant ceiling model*

These two velocity profiles are taken across the same plane in room 311B. The maximum velocity in the fan coil unit model is almost twice as much as the highest velocity found in the radiant ceiling model. The velocity profile for the fan coil unit shows how the FCU creates strong drafts in certain areas of the room, while the velocity field in the radiant ceiling model is influenced more by the buoyancy effects of hot and cold air. There are no strong air currents in the room with the radiant ceiling, which will make the space more comfortable for the occupants. The figure below shows a velocity profile in the fan coil unit model cut across the FCU inlet in the y-plane.

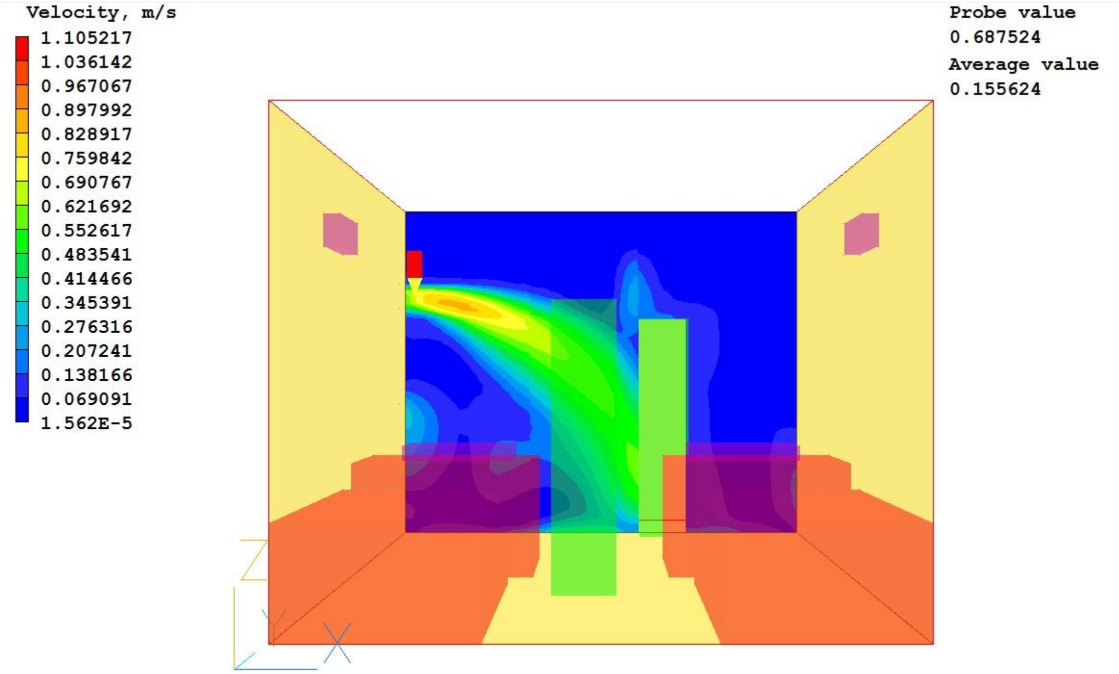


Figure 18: *Velocity profile cutting through the FCU inlet in the fan coil unit model*

The velocity profile above clearly demonstrates how the fan coil unit pushes most of its supply air into one general area in the room. This will create warm and cold pockets throughout the space. A radiant ceiling creates a uniform gradual movement of air throughout the entire room. The next two figures compare the temperature profiles for the two models at a plane cut across the outdoor air diffuser in the x-axis.

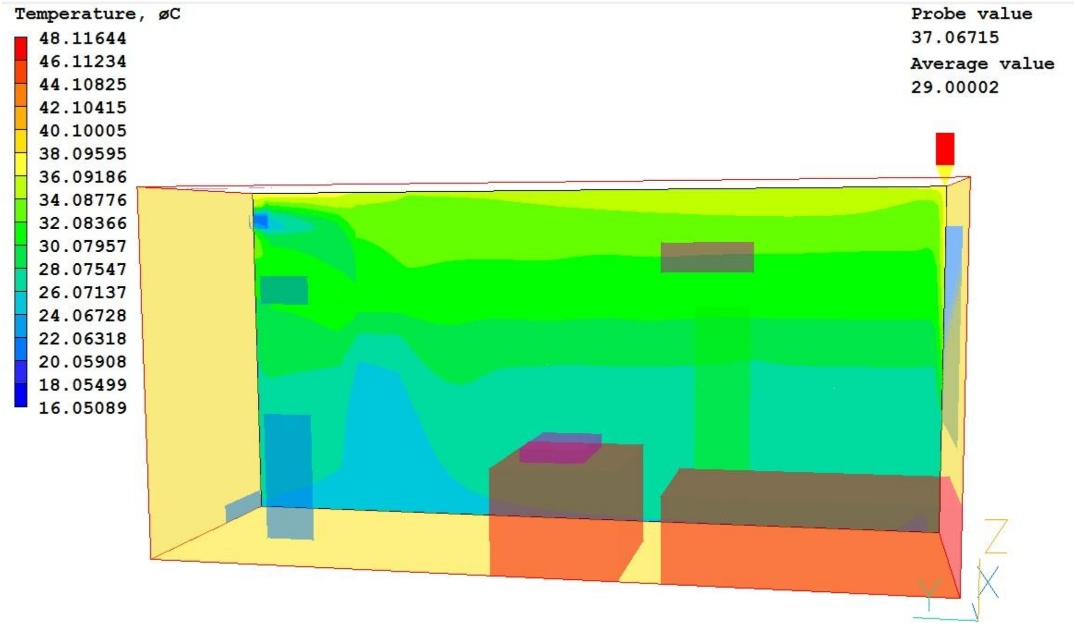


***Figure 19:** Temperature profile cutting through the outdoor air diffuser for the fan coil unit model*

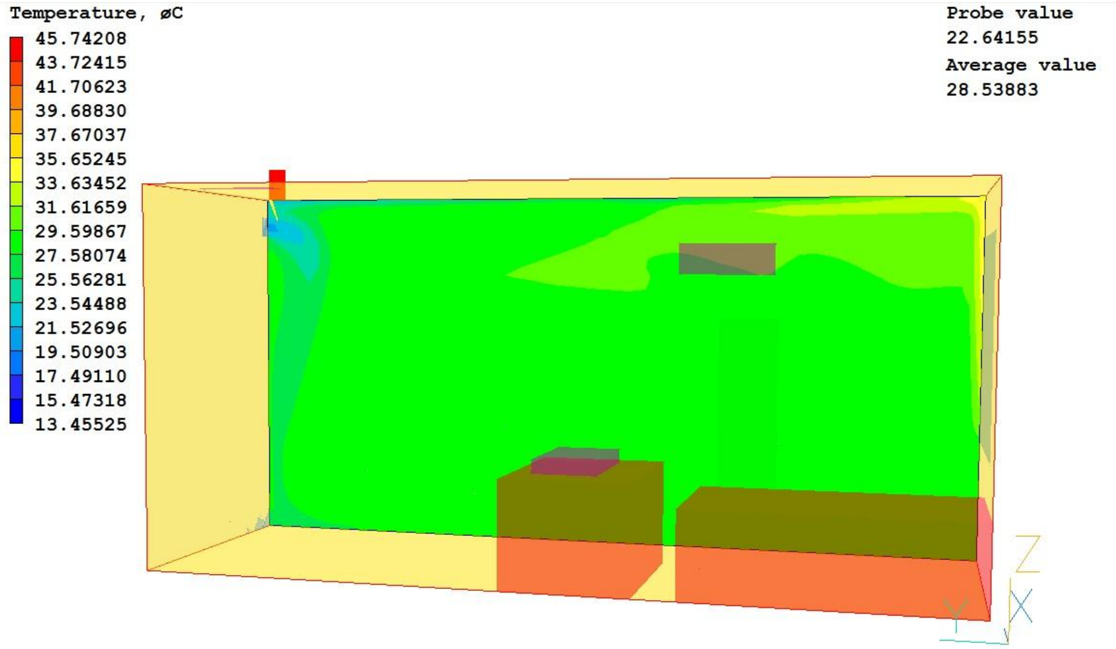


***Figure 20:** Temperature profile cutting through the outdoor air diffuser for the radiant ceiling model*

Figures 21 and 22 show the temperature profiles for both models at a plane cut through the z-axis four feet from the floor. This area is right in the middle of the occupied zone of the room, which ranges from the floor level to about 7 feet off of the floor.

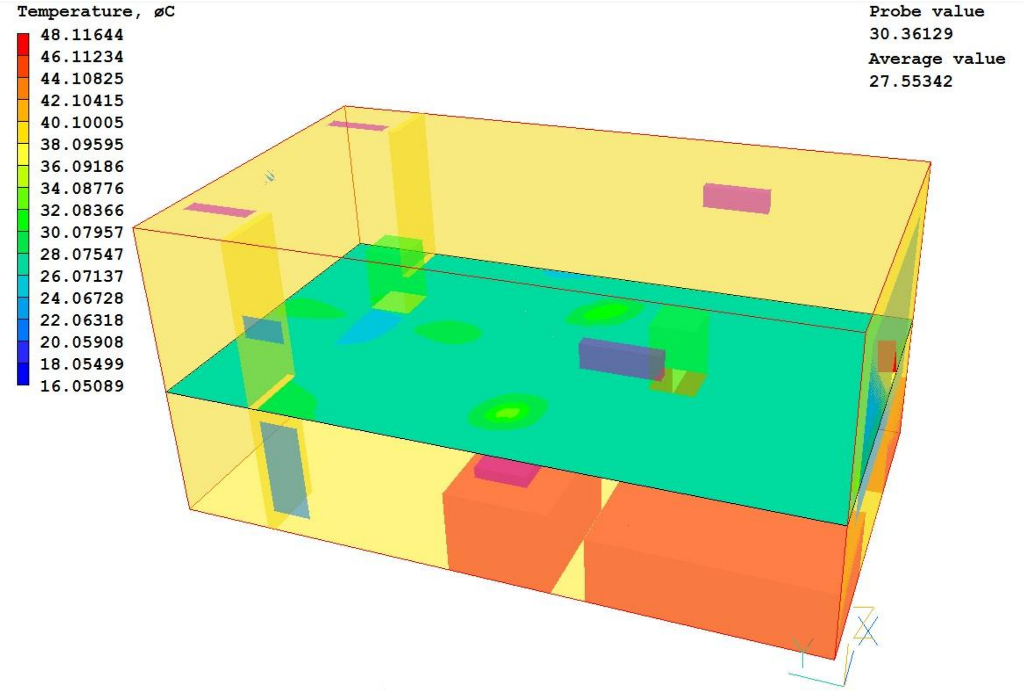


Figure 21: *Temperature profile at 4 ft. above the floor for the fan coil unit model*

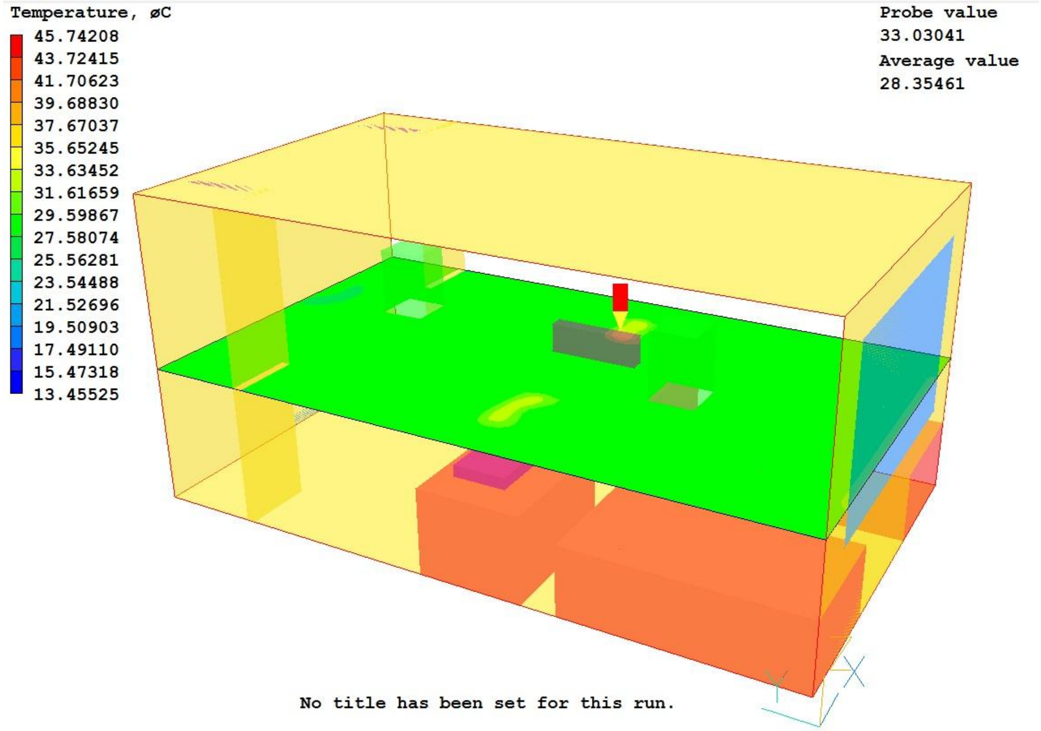


Figure 22: *Temperature profile at 4 ft. above the floor for the radiant ceiling model*

The four figures above prove that the temperature field in a room conditioned by a radiant ceiling is more uniform and constant than a room conditioned by a fan coil unit. Figure 19 illustrates how the temperature rises steadily in the vertical direction in the room with a fan coil unit. Layers of different temperatures are created in the room, with the coldest layer near the floor and the warmest layer near the ceiling. The radiant ceiling is able to create a uniform temperature in the entire occupied zone of the room. The only temperature change in the radiant ceiling model occurs in the top right corner of the room near the ceiling. This is at a height above the occupants head level, so they will feel the same temperature no matter where they are in the room. This thermal uniformity makes radiant ceilings more reliable and increases the comfort of the occupants.

Table 22 below compares the cooling ability of the Whalen fan coil unit to the cooling ability of the CB Aqua radiant ceiling by recording the average temperatures in each model at different heights in the room. The average temperature of the space is recorded at every foot, from 2 feet to 8 feet and then these numbers are all averaged together for one final temperature value. The temperature values in both models are abnormally high, because the internal heat sources in the room have higher heat flux values than they most likely would in reality. This was done to create a worst case scenario in the room. It is safe to assume that the actual temperature in room 311B would be much lower in reality.

Average Temperatures at Different Heights in Room 311B								
	Distance From Floor							
	2 ft	3 ft	4 ft	5 ft	6 ft	7 ft	8 ft	
	0.61 m	0.91 m	1.22 m	1.52 m	1.83 m	2.13 m	2.44 m	TOTAL
Room with Fan Coil Unit	79.2 °F	80.2 °F	81.6 °F	84.6 °F	86.9 °F	89.2 °F	91.8 °F	84.8 °F
Room with Radiant Ceiling	82.5 °F	82.9 °F	83.0 °F	83.5 °F	84.2 °F	84.9 °F	85.3 °F	83.8 °F

Table 22: *Average temperatures at different heights in room 311B for the fan coil unit model and the radiant ceiling model*

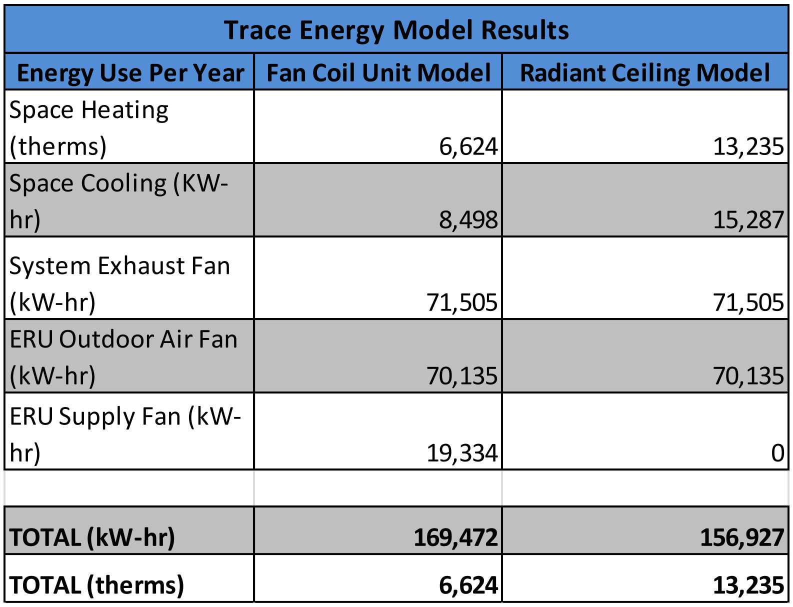
The average temperature readings show that the room with the radiant ceiling has a lower overall temperature and a much smaller temperature range than the room with the fan coil unit. This data further strengthens the argument for using a radiant ceiling over a fan coil unit. The average temperatures in the fan coil unit model range from 79.2 °F to 91.8 °F which is a difference of 12.6 °F. The average temperatures in the radiant ceiling model only range from 82.5 °F to 85.3 °F which is a difference of 2.8 °F. The overall temperature in the radiant ceiling model is 1 °F lower than the overall temperature in the fan coil unit model, but if Barcol-Air is correct the occupants of the space will feel that the temperature is actually 3 °F lower in the room, because of the change in human heat balance in the space due to the radiant cooling system.

Conclusion

After extensively comparing the two alternative Phoenics models for room 311B, the CB Aqua radiant ceiling system was proven to be superior to a Whalen fan coil unit in creating a higher level of thermal comfort for the occupants of room 311B. The fan coil unit created high velocity air currents and temperature differences throughout the space, while the radiant ceiling was able to create a constant temperature field in the room with no high velocity areas. Table 22 showed that the average temperature range for the radiant ceiling model was less than a fourth of the range found in the fan coil unit model. The overall average temperature of room 311B was lower in the radiant ceiling model as well. The CB Aqua system will provide the student occupants of Des Places with the highest level of thermal comfort available. This increased level of comfort should increase occupant satisfaction in the building and make the students living there more productive.

Energy Consumption Comparison

The annual energy consumption of the redesigned dedicated outdoor air system was compared to the original design, based on the results of Trace energy models constructed for both systems. A thorough Trace model for the fan coil unit DOAS system was created for Technical Assignment 2 and this model was used again to compare both DOAS alternatives. A new alternative Trace model was created for a radiant ceiling DOAS system in Des Places. The two models have identical rooms, the same cooling and heating loads and use the same central plants. The only difference in the two models was their system selection. For the new energy model, a system was chosen that used passive chilled beams for cooling, baseboard radiators for heating and a separate constant volume dedicated outdoor air system for ventilation. The resulting energy consumption figures for both models were examined and compared. The predicted annual energy use for both systems is given in table 23. This table only gives values for the energy consumption of the building that is directly attributed to the dedicated outdoor air system.



Trace Energy Model Results		
Energy Use Per Year	**Fan Coil Unit Model**	**Radiant Ceiling Model**
Space Heating (therms)	6,624	13,235
Space Cooling (KW-hr)	8,498	15,287
System Exhaust Fan (kW-hr)	71,505	71,505
ERU Outdoor Air Fan (kW-hr)	70,135	70,135
ERU Supply Fan (kW-hr)	19,334	0
TOTAL (kW-hr)	**169,472**	**156,927**
TOTAL (therms)	**6,624**	**13,235**

Table 23: *Trace energy model results for alternative DOAS systems*

The results showed that the radiant ceiling system will have a slightly smaller electricity demand than the fan coil unit system, despite the fact that it consumes 6,789 kW-hr more for cooling. This is due to the fact that radiant ceilings and baseboard radiators do not use fans to condition rooms like fan coil units. Therefore they will save approximately 19,334 kW-hr in supply fan energy in comparison to the fan coil unit system, which results in a net savings of 12,545 kW-hr.

Although the radiant ceiling DOAS system consumes less electricity than the fan coil unit system, it demands more than twice as much steam from Duquesne's central plant. The radiant ceilings and baseboard radiators require a significantly larger amount of energy for cooling and heating than the fan coil units. Some of this discrepancy is due to the differing air conditioning methods used by each system. The rest of the difference is due to the added load put on the heating and cooling coil in the energy recovery unit by the radiant ceilings. For both dedicated outdoor air systems, the energy recovery unit is relied upon to meet the latent loads of the building. This means that the energy recovery unit dehumidifies the air in Des Places. Dehumidification is necessary to ensure the comfort of the buildings occupants and to keep the indoor air conditions below the dew point so that condensate does not form inside the building. Radiant ceilings put a much higher dehumidification load on the dedicated outdoor air system than fan coil units. Therefore the heating coil in the energy recovery unit has to heat the incoming outdoor air more for a radiant ceiling system in order to dehumidify it to a satisfactory level. This results in a much higher heating demand for the radiant ceiling system and it indirectly increases the cooling demand for the system as well, because the outdoor air being delivered to each space is warmer for the building using radiant ceilings than for the same building using fan coil units.

The higher heating and cooling energy demands for the radiant ceiling system will result in a higher annual energy cost for Des Places. The annual energy consumption costs for both dedicated outdoor air systems are given in the table below. These numbers were determined by multiplying the annual energy consumption figures by the current utility rates for Duquesne University. These rates are given in Table 1 of this report.

Annual Energy Costs		
	Fan Coil Unit Model	**Radiant Ceiling Model**
Total Annual KW-hr Used	169, 472 kW-hr	156,927 kW-hr
Annual Cost of kW-hr Consumption	$14,744	$13,653
Total Annual therms used	6,624 therms	13,235 therms
Annual Cost of therm Consumption	$8,479	$16,941
Total Annual Energy Cost	**$23,223**	**$30,594**

Table 24: *Annual energy consumption costs for Des Places with different DOAS systems*

Based on the results found in the Trace energy models for both DOAS systems, the operational costs for Des Places will be approximately $7,370 more with a dedicated outdoor air system that uses radiant ceilings and baseboard radiators.

System Cost Comparison

In order to make a thorough comparison between the two DOAS systems, the initial cost of each system must be addressed. The prices for the Whalen fan coil units and the dedicated outdoor air system in the original design were attained from the initial construction estimate created by Regency Construction Services. The mechanical estimate for Des Places was approved by CJL Engineering and the cost figures used for this report are assumed to be accurate. Table 25 breaks down the cost for all of the various elements that make up the existing dedicated outdoor air system in Des Places and gives a final price for the entire system.

Fan Coil Unit Dedicated Outdoor Air System Cost

Component of System	Quantity	Unit	Cost/Unit	Total Cost
Energy Recovery Unit (20,000 cfm)	1	Each	$150,570	$150,570
Supply and Exhaust Ductwork	59,358	lb	$5.70	$338,341
Ductwork Insulation	35,162	ft^2	$3.61	$126,935
Constant Volume Supply Register	505	Each	$181	$91,405
Constant Volume Exhaust Register	387	Each	$135	$52,245
Fire and Smoke Damper and Access Door	400	Each	$194	$77,600
Steam to Hot Water Heat Exchanger (96 gpm)	2	Each	$10,300	$20,600
Steam Pressure Reducing Station	1	Each	$10,000	$10,000
Chilled Water and Hot Water Pump Package (Four 7.5 HP pumps)	1	Each	$61,200	$61,200
Water Shot Feeder (12 gal)	2	Each	$1,950	$3,900
Expansion Tank (31 gal)	2	Each	$2,775	$5,550
Condensate Pump (25 gpm)	1	Each	$8,900	$8,900
4-Pipe Whalen Fan Coil Unit	257	Each	$3,240	$832,680
			TOTAL:	**$1,779,926**

Table 25: *Total cost of dedicated outdoor air system with fan coil units*

The total cost of the dedicated outdoor air system with fan coil units came out to be $1,779,926. The cost of the entire system with the exclusion of the fan coil units was $947,246. This value will not change for the radiant ceiling DOAS system, because the sensible heating and cooling equipment was the only part of the system that was redesigned. The energy recovery unit, its associated ductwork and the supporting tanks, pumps, shot feeders and heat exchangers for the system will be unchanged. The total price for all of the required radiant ceiling panels and baseboard radiators was found by contacting the manufacturers and getting the thermal output and cost figures for the necessary equipment.

Before the cost of the new dedicated outdoor air system could be found, the system had to be resized to determine how many linear feet of baseboard radiators were needed to meet the heating demand and how many 2 foot by 4 foot radiant ceiling panels were needed to meet the cooling demand. The peak heating and cooling demand for every conditioned room in the building was determined from the results of the Trace energy model completed for Des Places. George Hoekstra, an engineer for Barcol-Air determined that the cooling capacity of the CB Aqua radiant ceiling designed for Des Places was approximately 45 (btu/hr)/ft^2. This value was determined with the following design parameters for Des Places:

- Target Room Temperature: 75 ˚F
- Chilled Water Supply Temperature: 57 ˚F
- Chilled Water Return Temperature: 60 ˚F

The chilled water in the ceiling coils has to be at or near 57 ˚F so that its temperature is higher than the dew point of the air in the room. Keeping the chilled water this warm will prevent condensation from occurring in the room. Based on the calculated thermal output of 45 (btu/hr)/ft^2 for the radiant ceiling, it was determined that each 2 foot by 4 foot panel could produce 360 btu/hr. This value was used to determine the number of panels needed in each room and in the entire building.

Slantfin was chosen as the manufacturer for the baseboard radiators. The multi/pak 83A model was chosen as the best fit for Des Places and it was determined that these radiators could produce approximately 1000 btu per linear foot with the 140 ˚F hot water supply temperature in Des Places. This value was used to determine the linear feet of radiator required in each room and in the whole building. The sizing information for the radiant ceiling panels and baseboard radiators in each room of Des Places is given in Table 26 below.

Radiant Ceiling and Radiator Sizing for Des Places Residence Hall

	Room	Peak Cooling Load (Btu/hr)	Barcol-Air Radiant Ceiling		Peak Heating Load (Btu/hr)	SlantFin Radiator	
			Btu/hr per Panel	Number of Panels Required		Btu/hr per Linear Foot	Length Required (ft)
Floor 1	102B-Switchgear	7900	360	22	14900	1000	15
	105-Generator Room	11200	360	31	3500	1000	4
	112-Maintenance	3300	360	9	5100	1000	6
	113-House Office	3700	360	10	2700	1000	3
	114-Grounds Office	3000	360	8	1400	1000	2
Floor 2	201A-Security Desk	2400	360	7	1300	1000	2
	202-FCC	2100	360	6	300	1000	1
	203A-Office	3500	360	10	3300	1000	4
	203-SEC	2900	360	8	2000	1000	2
	204-Lounge	26500	360	74	11200	1000	12
	206-Ministry Office	3100	360	9	2000	1000	2
	207A-Bedroom	4000	360	11	1400	1000	2
	207B-Bedroom	3900	360	11	1500	1000	2
	207C-Bedroom	4500	360	12	2600	1000	3

	208-RA ADA	4800	360	13	1500	1000	2
	210A-Bedroom	4000	360	11	1500	1000	2
	210B-Bedroom	4000	360	11	1500	1000	2
	211A-Bedroom	4100	360	11	1500	1000	2
	211B-Bedroom	3900	360	11	1500	1000	2
	211C-Bedroom	4700	360	13	2600	1000	3
	212-ADA Bedroom	5300	360	15	1500	1000	2
	214A-Bedroom	4500	360	13	1500	1000	2
	214B-Bedroom	4500	360	13	1500	1000	2
	215A-Bedroom	4000	360	11	1400	1000	2
	215B-Bedroom	3900	360	11	1500	1000	2
	215C-Bedroom	5000	360	14	2600	1000	3
	216A-Living Room	5900	360	16	2600	1000	3
	216B-Bedroom	5500	360	15	2400	1000	3
	216C-Bedroom	6000	360	17	2600	1000	3
Floor 3 - Floor 11	301A-1101A-Bedroom	35500	360	99	12600	1000	13
	301B-1101B-Bedroom	35500	360	99	12600	1000	13
	301C-1101C-Bedroom	40700	360	113	22300	1000	24
	302-1102-Lounge	249900	360	694	95900	1000	96
	303-1103-Laundry	240900	360	669	97300	1000	98
	304A-1104A-Bedroom	36300	360	101	12600	1000	13
	304B-1104B-Bedroom	35800	360	99	12600	1000	13
	304C-1104C-Bedroom	39400	360	109	22000	1000	22
	305-1105-Two Bed Suite	44600	360	124	13800	1000	14
	307A-1107A-Bedroom	36600	360	102	12700	1000	13
	307B-1107B-Bedroom	36600	360	102	12600	1000	13
	308A-1108A-Bedroom	36200	360	101	12600	1000	13
	308B-1108B-Bedroom	35800	360	99	12600	1000	13
	308C-1108C-Bedroom	41600	360	116	22100	1000	22
	309-1109-Two Bed Suite	48900	360	136	14000	1000	14
	311A-1111A-Bedroom	41900	360	116	13000	1000	13
	311B-1111B-Bedroom	40800	360	113	12700	1000	13

	312A-1112A-Bedroom	35700	360	99	12600	1000	13
	312B-1112B-Bedroom	35300	360	98	12600	1000	13
	312C-1112C-Bedroom	42600	360	118	20400	1000	21
	313A-1113A-Bedroom	37000	360	103	12800	1000	13
	313B-1113B-Bedroom	36900	360	103	12700	1000	13
	314-1114-RA Unit	43700	360	121	13700	1000	14
Floor 12	1201-Conference Room	33200	360	92	28700	1000	29
	1202-Lounge	26700	360	74	12400	1000	13
	1203-Laundry	31400	360	87	9200	1000	10
	1204A-Bedroom	3400	360	10	1600	1000	2
	1204B-Bedroom	3300	360	9	1700	1000	2
	1204C-Bedroom	4300	360	12	2600	1000	3
	1205-Two Bed Suite	4200	360	12	1800	1000	2
	1207A-Bedroom	3400	360	10	1700	1000	2
	1207B-Bedroom	3400	360	10	1700	1000	2
	1208A-Bedroom	3400	360	10	1700	1000	2
	1208B-Bedroom	3500	360	10	1700	1000	2
	1208C-Bedroom	4000	360	11	2600	1000	3
	1209-Two Bed Suite	4400	360	12	1800	1000	2
	1211A-Bedroom	4000	360	11	1700	1000	2
	1211B-Bedroom	3900	360	11	1700	1000	2
	1212A-Bedroom	3700	360	10	1700	1000	2
	1212B-Bedroom	3700	360	10	1700	1000	2
	1212C-Bedroom	4400	360	12	2800	1000	3
	1213-RA Unit	4300	360	12	1800	1000	2

TOTAL:	**4482 panels**	**TOTAL:**	**689 ft.**

Table 26: *Radiant ceiling and radiator sizing for Des Places Residence Hall*

Based on the cooling and heating demands of each room and the calculated thermal output of the radiant panels and baseboard radiators, it was determined that 4,482 2' by 4' radiant ceiling panels were required and 689 linear feet of radiators was required for the entire building. These figures were used to find the total cost of the redesigned dedicated outdoor air system.

The approximate cost per linear foot for the SlantFin radiators was provided online at www.pexsupply.com. The 83A model is about $18 per foot. Finding the total cost of the radiant ceiling was more complicated, because there are several pieces that make up the radiant ceiling system. The unit prices for all of the necessary pieces of the CB Aqua radiant ceiling was provided by George Hoekstra and these individual prices were used to determine the total cost. The cost per panel for the radiant cooling system itself is $86, but the panels are connected in loops and each panel is connected by flexible hoses with quick connectors that cost $18 each. Each loop is connected to a main chilled water line by flexible hoses and metal nipples, and these nipples cost $6 each. The last remaining piece of the CB Aqua system is the metal panels that cover the radiant cooling assembly and protect it from possible damage. Barcol-Air does not actually manufacture these panels but they work with a variety of different vendors that manufacture aluminum or steel panels custom-made for the CB Aqua system. Steel ceiling panels manufactured by Steel Ceilings Inc. were chosen for Des Places, because they are the most rugged and durable option. These metal ceiling panels are $31.25 each. The total estimate for the redesigned dedicated outdoor air system is given in the table below.

Radiant Ceiling Dedicated Outdoor Air System Cost

Component of System	Quantity	Unit	Cost/Unit	Total Cost
Energy Recovery Unit (20,000 cfm)	1	Each	$150,570	$150,570
Supply and Exhaust Ductwork	59,358	lb	$5.70	$338,341
Ductwork Insulation	35,162	ft^2	$3.61	$126,935
Constant Volume Supply Register	505	Each	$181	$91,405
Constant Volume Exhaust Register	387	Each	$135	$52,245
Fire and Smoke Damper and Access Door	400	Each	$194	$77,600
Steam to Hot Water Heat Exchanger (96 gpm)	2	Each	$10,300	$20,600
Steam Pressure Reducing Station	1	Each	$10,000	$10,000
Chilled Water and Hot Water Pump Package (Four 7.5 HP pumps)	1	Each	$61,200	$61,200
Water Shot Feeder (12 gal)	2	Each	$1,950	$3,900
Expansion Tank (31 gal)	2	Each	$2,775	$5,550
Condensate Pump (25 gpm)	1	Each	$8,900	$8,900
SlantFin Multi/Pak 83A Baseboard Radiator	689	Linear Foot	$18	$12,402
Barcol-Air CB Aqua 2' x 4' radiant ceilng panel	4482	Each	$86	$385,452
Setup cost of radiant ceiling	1	Each	$650	$650
Barcol-Air nipple connector	1794	Each	$6	$10,764
Barcol-Air flexible hose with quick connector	5379	Each	$18	$96,822
Steel Ceilings Inc. 2' x 4' steel ceiling panel	4482	Each	$31.25	$140,062
			TOTAL:	**$1,593,398**

Table 27: *Total cost of dedicated outdoor air system with radiant ceilings and baseboard radiators*

The total cost for the dedicated outdoor air system with radiant ceilings and baseboard radiators is $1,593,398. This system is actually $186,528 less than the original dedicated outdoor air system with fan coil units.

Conclusion

The existing dedicated outdoor air system in Des Places could be improved upon in several ways by replacing the fan coil units with radiant chilled ceilings and baseboard radiators. This alternative system could still provide responsive personalized control in each room, while improving the thermal comfort of the students living in Des Places. A computational fluid dynamics analysis of both systems proved that a radiant ceiling produces an overall lower temperature in a given room and creates a more thermally uniform temperature distribution in the space. The radiant ceiling DOAS system also costs approximately $186,000 less than the original fan coil unit DOAS system. The primary advantage of the fan coil unit alternative is that it consumes less energy than radiant ceilings and baseboard radiators, which results in the fan coil unit DOAS system costing $7,370 less to operate each year. Despite having a higher operating cost, the radiant ceiling alternative could be a better fit for Des Places. The increase in yearly energy costs is partially offset by the fact that the radiant ceiling alternative is cheaper to install. The most important advantage of the radiant ceiling dedicated outdoor air system is that it creates a higher level of comfort for the occupants of Des Places. There is no fan noise with radiant ceilings and baseboard radiators and they deliver a higher level of thermal comfort than fan coil units. Therefore if Duquesne University decides that the comfort and satisfaction of the students living in Des Places is one of the most important design goals for the building, they should choose radiant ceilings and baseboard radiators over fan coil units for the dedicated outdoor air system in Des Places.

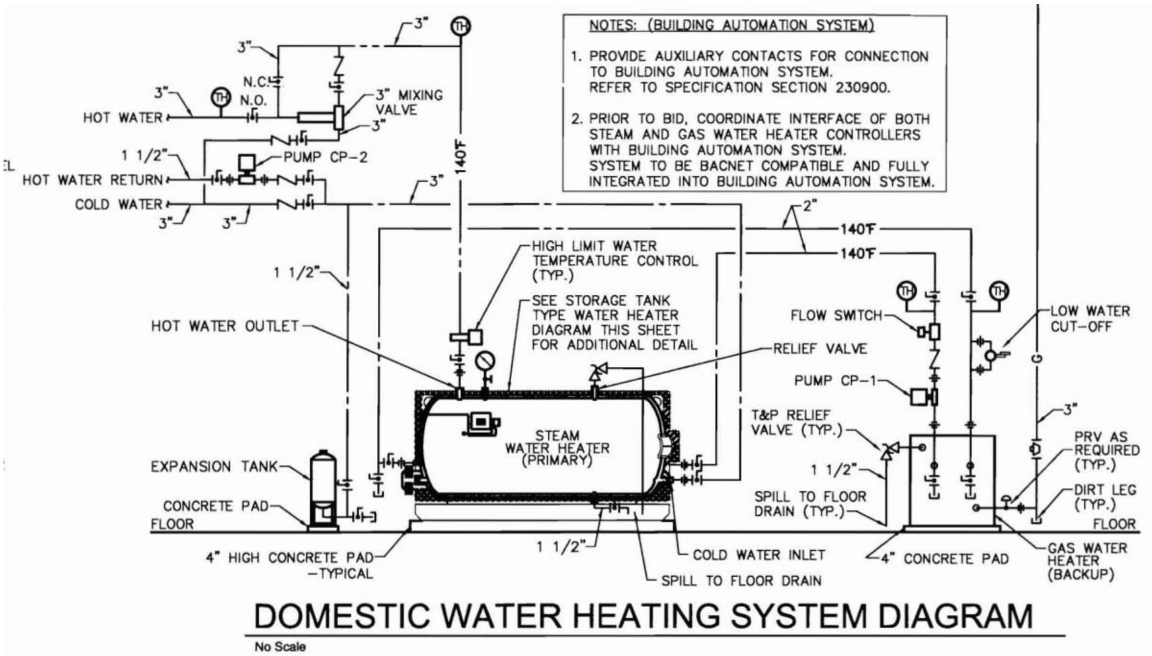
Solar Hot Water System – Mechanical Depth

Introduction

The addition of a solar hot water system on the roof of Des Places could save the building energy and money for years to come and make the building more sustainable. The current photovoltaic array on the roof is small and accounts for approximately 1% of the buildings total electrical demand. A solar hot water array would be more useful for the building because solar hot water panels are much more efficient than photovoltaic panels and Des Places has a large domestic hot water heating load that could be reduced by a solar thermal system. Federal and state governments have put a strong emphasis on encouraging the use of sustainable technology in buildings and there is consequently a great deal of government funding for new solar thermal systems. Government rebates and tax credits dramatically reduces the payback period for a solar thermal system and makes the technology more feasible and profitable than ever.

System Design

The domestic water for Des Places is stored in a large tank and heated by steam coming from Duquesne's central plant. There is also a gas fired backup heater that is only used if the steam water heater fails or is overloaded. A schematic for the domestic water heating system is shown in the figure below.



NOTES: (BUILDING AUTOMATION SYSTEM)

1. PROVIDE AUXILIARY CONTACTS FOR CONNECTION TO BUILDING AUTOMATION SYSTEM. REFER TO SPECIFICATION SECTION 230900.
2. PRIOR TO BID, COORDINATE INTERFACE OF BOTH STEAM AND GAS WATER HEATER CONTROLLERS WITH BUILDING AUTOMATION SYSTEM. SYSTEM TO BE BACNET COMPATIBLE AND FULLY INTEGRATED INTO BUILDING AUTOMATION SYSTEM.

Figure 23: *Domestic hot water heating system schematic (Courtesy of CJL Engineering)*

The steam water heater was sized based on the peak domestic water load for the building calculated by CJL Engineering. The peak domestic water load was sized for 390 occupants and was found to be 1,555 gallons per hour. Therefore a steam water heater with a capacity of 1,620 gallons per hour was chosen for the building. This water heater will be able to provide well over the anticipated maximum demand, so if a solar thermal array was added to the domestic hot water system its only purpose would be to reduce the steam demand for the primary heater. The schedules for the primary steam domestic water heater and the backup gas-fired heater are given in the tables below.

Primary Steam Domestic Hot Water Heater

Steam (psi)	Gallons per Hour*	Storage (Gallons)	Dimensions
15	1620	1890	84"ϕ x 96" L

*Gallons per hour is based on 100 °F ΔT

Table 28: *Primary domestic hot water heater schedule*

Backup Gas Fired Domestic Hot Water Heater

Input (Btu/hr)	Gallons per Hour*	Remarks
1,260,000	1298	Direct Vent

*Gallons per hour is based on 100 °F ΔT

Table 29: *Backup domestic hot water heater schedule*

The system would not rely on the solar thermal array to meet the anticipated heating loads, so the domestic water service to the building would be unaffected if the solar thermal system failed. There are many different arrangements to choose from with solar thermal systems. Different loop arrangements are better suited for different applications and situations, depending on the existing domestic hot water system. Four of the most common solar thermal systems are outlined in the figure below. This figure was found in the book “Solar Engineering of Thermal Processes”, by John A. Duffe and William A. Beckman.

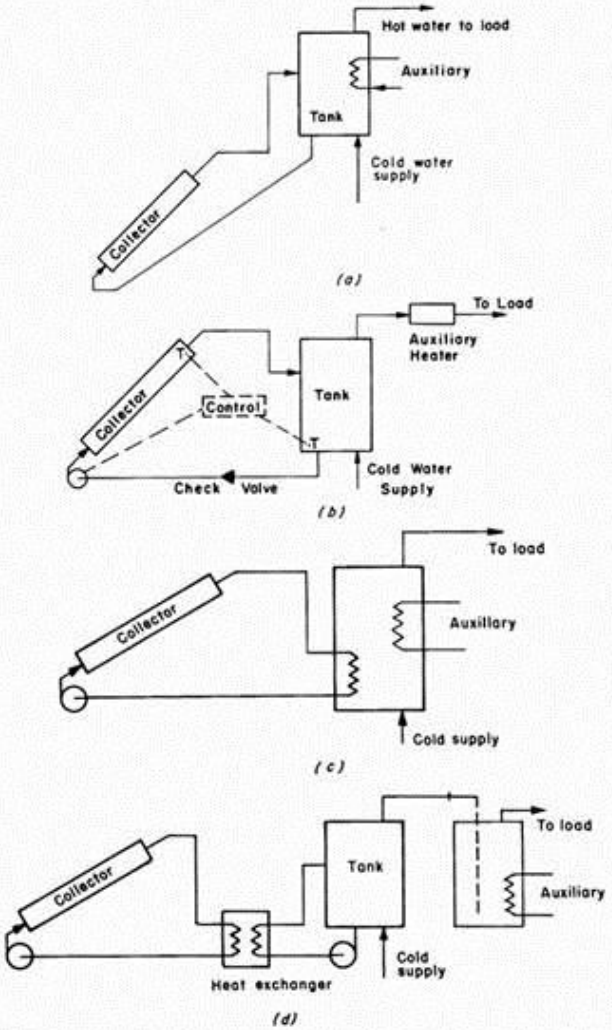


Figure 12.1.1 Schematic of common configurations of water heaters. (a) A natural-circulation system. (b) One-tank forced-circulation system. (c) System with antifreeze loop and internal heat exchanger. (d) System with antifreeze loop and external heat exchanger. Auxiliary is shown added in the tank, in a line heater, or in a second tank; any of these auxiliary methods can be used with any of the collector-tank arrangements.

***Figure 24:** Schematic diagrams of different solar thermal system arrangements (courtesy of "Solar Engineering of Thermal Processes")*

The best system option for Des Places is an antifreeze loop and internal heat exchanger in the existing domestic hot water tank (option C in figure 2). This loop arrangement is the best fit for the building for several reasons. Des Places is located in a climate that can reach very low temperatures in the winter. Therefore an antifreeze solution should be used in place of water to eliminate the risk of water freezing in the solar collectors. Because the solution will be antifreeze, it needs to be entirely separated from the domestic water loop, which creates the need for a heat exchanger arrangement as opposed to water from the solar hot water loop mixing in with water from the domestic water loop. This loop arrangement also keeps the system simple, which makes it cheaper and more reliable because there are fewer parts that can potentially fail. Placing the heat exchanger in the existing domestic water tank should yield the highest efficiency for the system. In this design the incoming cold domestic water will enter the bottom of the tank and be heated by the solar thermal loop and the steam loop in series. The water will cross the solar thermal loop first and be preheated before the rest of the heating load is met by the steam loop. This arrangement will allow the steam heating system to minimize its demand from the central plant by changing its steam flow rate based on how much heating energy is being delivered to the domestic water by the solar thermal system. A more detailed schematic diagram of the proposed domestic water heating system is shown in Figure 25 below.

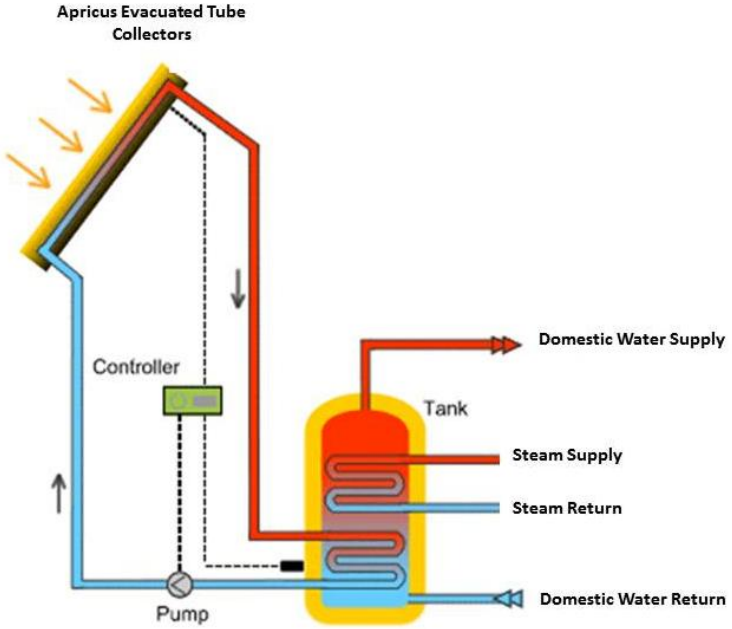


Figure 25: *Proposed domestic water heating system arrangement*

One of the most important factors in the design of a solar thermal system is the type of solar collectors that will be used. There are three main categories of solar collectors; evacuated tubes, flat plates and concentrating collectors. Evacuated tube collectors consist of parallel glass tubes that have the air withdrawn from them to create a vacuum that eliminates any conductive or convective heat losses. These collectors consequently perform very well in overcast and low temperature conditions. Flat plate collectors are insulated, weatherproof boxes that contain a dark absorber plate under one or more transparent or translucent covers. A heat conducting fluid passes through pipes located below the heat absorbing plate. This type of collector is inferior to evacuated tubes in many ways but it is still the most commonly used choice in the building industry, because the technology has been around longer than the other options, so it well known and reliable. Concentrating collectors are parabolic troughs that use mirrored surfaces to concentrate the radiation from the sun on an absorber tube filled with a heat conducting fluid. This type of collector is usually used for commercial power applications, because it is capable of producing very high temperatures in the working fluid. The biggest disadvantage to this technology is that it relies on direct sunlight and therefore it performs poorly in overcast conditions.

Evacuated tubes were chosen as the solar thermal collectors for Des Places primarily because of the buildings location. Pittsburgh typically has a lot of cloudy weather and cold winters and evacuated tubes perform better than the other options in both of these scenarios. Evacuated tubes are the ideal choice for domestic water heating because of their reliability and efficiency in all weather conditions. Apricus was chosen as the manufacturer for the evacuated tubes for several reasons. The main reason is their design which uses two glass tubes, a high efficiency heat pipe and metal fins to heat the circulating fluid in the system. A diagram of an Apricus solar collector is shown below.

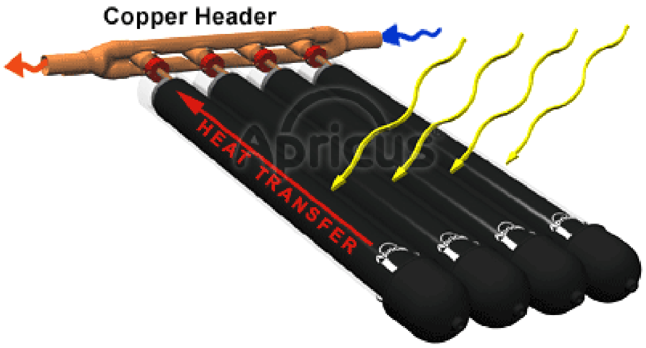


Figure 26: *Diagram of an Apricus solar collector (courtesy of www.apricus.com)*

The outer tube of the collector is transparent to allow sunlight onto the inner tube, which is made of black glass to maximize its heat absorption from the sun. Air is withdrawn from the space between the two tubes to create a vacuum. Because the two tubes are 100% glass and fused together at one end, the chances of the seal breaking between the two tubes and ruining the vacuum effect are greatly minimized. Instead of circulating the working fluid through the evacuated tubes, it stays in the copper headers at the top of the collectors and heat is transferred to the fluid by a high efficiency heat pipe and heat transfer fins. Specifications for the evacuated tubes used in Apricus solar collectors are given in table 30.

Apricus Evacuated Tube Specifications	
Length (nominal)	1500mm /1800mm
Outer tube diameter	58mm
Inner tube diameter	47mm
Glass thickness	1.6mm
Thermal expansion	3.3×10^{-6} °C
Material	Borosilicate Glass 3.3
Absorptive Coating	Graded Al-N/Al
Absorptance	>92% (AM1.5)
Emittance	<8% (80°C)
Vacuum	$P<5\times10^{-3}$ Pa
Stagnation Temperature	>200°C
Heat Loss	<0.8W/ (m2°C)
Maximum Strength	0.8 MPa

Table 30: *Apricus evacuated tube specifications*

Apricus evacuated tube collectors are also a good choice because they use materials that are corrosion resistant, so they have a very long operating life and are relatively maintenance free. Apricus is confident enough in the longevity of their products to offer a 10 year warranty on all of the collectors that they sell. The general specifications for Apricus solar collectors are given in Table 31 below.

Apricus Solar Collector General Specifications	
Manifold Casing Material	Aluminium (grade 3A21)
Frame Material	1.5mm 304 Stainless Steel
Header Pipe Material	99.93% pure Copper & lead free 45% silver brazing
Insulation	Compressed Glass Wool - K = 0.043W/mK
Rubber Seals and Rings	HTV grade silicone rubber
Optimal installation angle	20-70o Vertical, -5o to +5o Horizontal
Maximum Operating Pressure	8bar - 116psi
Optimal flow rate	0.1L/min/tube - 0.026G/min/tube
Performance Data (SPF)	Conversion Factor: ho = 0.717
	Loss Coefficients: a1 = 1.52, a2 = 0.0085

Table 31: *Apricus solar collector specifications*

Apricus only makes evacuated tube solar collectors, so another manufacturer had to be chosen to install the rest of the solar thermal system. Sunmaxx Solar is a quality company that has a great deal of experience in designing and installing solar thermal systems similar in size and function to the type of system proposed for Des Places. They can supply the piping, pump stations, accessories and controls necessary to complete the solar thermal system designed for Des Places.

In order to determine the energy output of the system the number of panels that could fit on the roof of Des Places had to be determined. A basic three dimensional model of Des Places was constructed in Google Sketch-Up using the dimensions of the building given in the architectural plans. The AP-30 model was chosen for the rooftop array of Des Places. It was chosen among Apricus' other options simply because it is the largest model available and the roof of Des Places had enough open space to use them effectively. The specifications for this model are given in the table below.

AP-30 Model Specifications	
Overall Length (mm/inch)	1980 / 77.9
Overall Width (mm/inch)	2196 / 86.4
Overall Height (mm/inch)	156 / 6.1
Absorber Area (m^2/ft^2)	2.4 / 25.8
Fluid Capacity (ml/ounces)	833 / 28.2
Gross Area (m^2/ft^2)	4.35 / 46.8
Dry Weight (kg/pounds)	95 / 209

Table 32: *AP-30 solar collector specifications*

The "30" in the name of the model refers to the number of evacuated tubes on the collector. Apricus provides a Google Sketch-Up block for the AP-30 solar collector. This block was used to find out how many AP-30 collectors could fit on the roof of Des Places. All of the collectors were placed at least 10 feet from the edge of the roof, in accordance with OSHA safety regulations. The two images below show the Google Sketch-Up model of Des Places with the designed solar array on the roof.

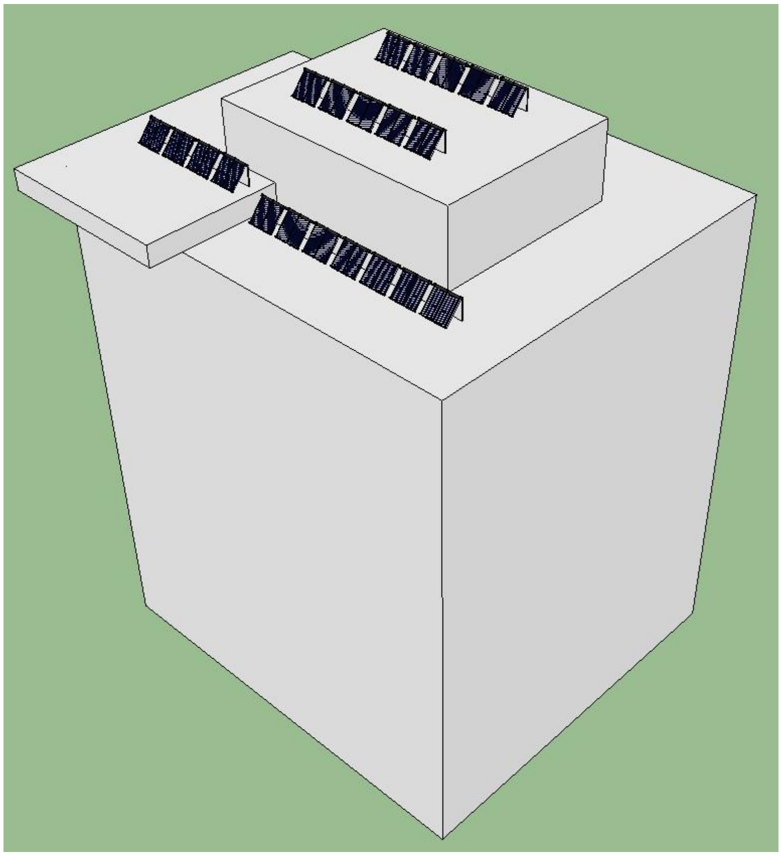


Figure 27: *Google Sketch-Up model of Des Places with solar thermal array*

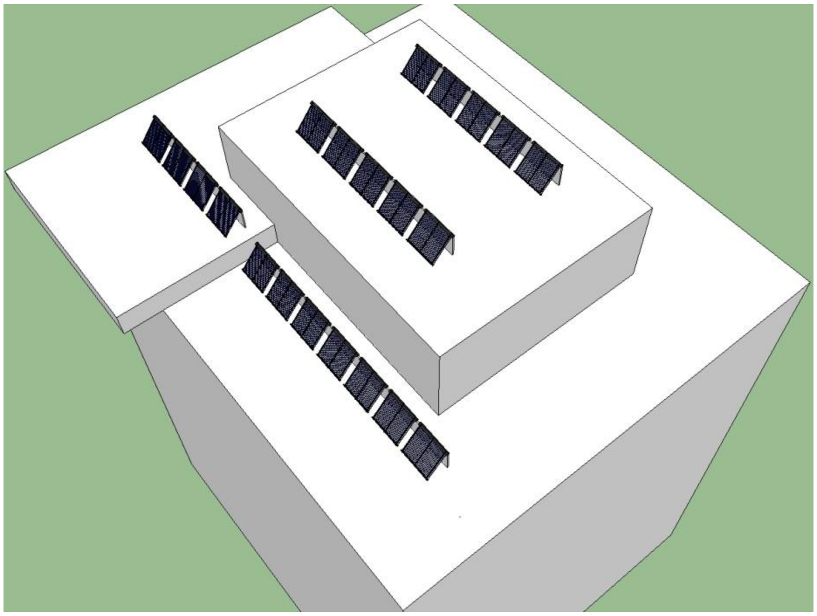


Figure 28: *Overhead view of solar thermal array in Google Sketch-Up*

The next figure shows a plan view of the roof of Des Places with dimensions for the placement of the solar thermal array. There are a total of 21 AP-30 evacuated tube collectors. The two rows of collectors that were placed on the penthouse roof were positioned far enough away from each other so that the front row did not cast a shadow on the back row until very late in the day. All of the collectors were positioned at 45 ° from horizontal and face east to maximize their solar gain.

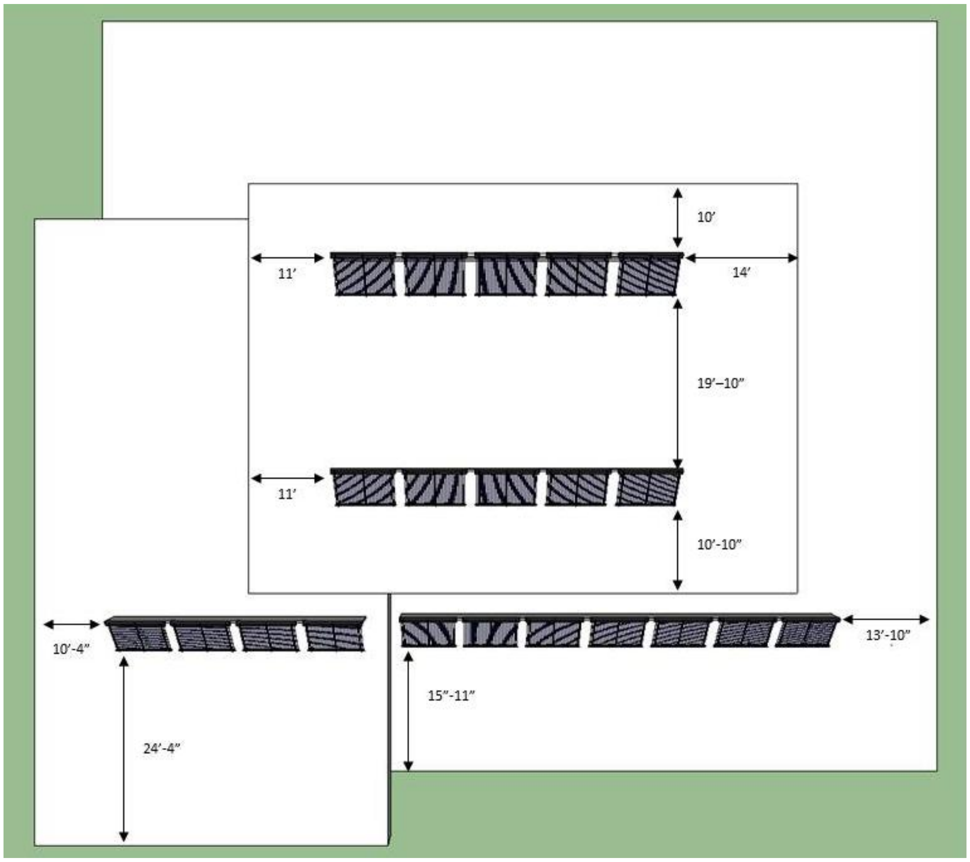


Figure 29: *Plan view of solar thermal array with dimensions*

Structural Analysis of Roof – Structural Breadth

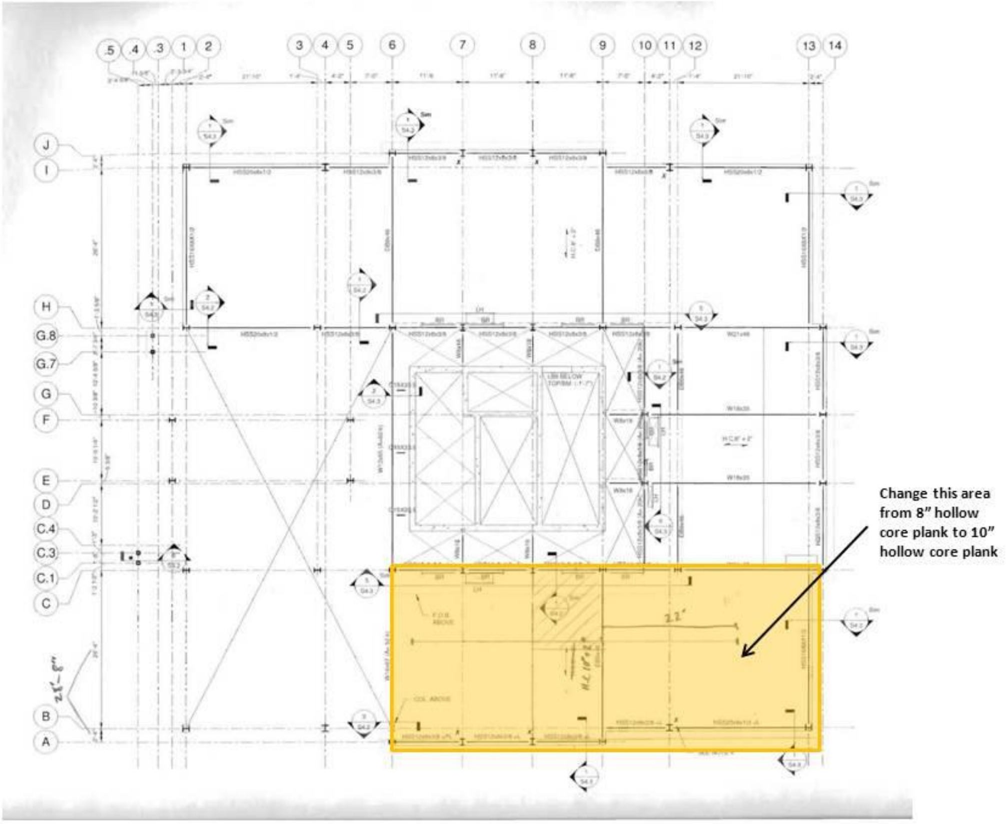
The addition of a solar thermal array created a new load on the roof structure of Des Places Residence Hall. In order to ensure that the roof could handle the additional weight, a structural analysis had to be performed. The roof of Des Places actually consists of three different structures. There is the main roof that holds 7 Apricus solar collectors, the penthouse roof that holds 10 collectors and the cantilevered roof that holds 4 collectors. The separation of these three roofs can be seen in figure 29. The structural plans for all three roofs are given in Appendix C.

For all three roof structures the metal decking or hollow core concrete plank underneath the solar collectors was analyzed to see if it could safely support the additional load. The next step in the process was to find the smallest beam in each roof structure that supported an array of panels and find the new shear and moment stresses on the beam. If the beam could handle the additional load then it was assumed that all of the larger beams on that particular roof that supported solar collectors could also handle the additional load. Hand calculations were performed for each roof in accordance with methods used in AE 404 to complete this structural analysis. The calculations performed for each floor can be seen in Appendix F.

Main Roof Structure

Eight inch hollow core concrete planks span between beams on the main roof of Des Places. The dead load and live load on this roof were determined and compared to the maximum allowable load for an 8 inch hollow core concrete plank manufactured by Nitterhouse Concrete Products. The dead load for one AP-30 solar collector was determined to be 29 lb/ft^2. This number is based on the weight and dimensions of these collectors (given in Table 32). There was also a dead load of 25 lb/ft^2 for the 2 inch concrete topping over the hollow core plank and a dead load of 12 lb/ft^2 for the roof. The roof load was determined from a table listing the weights of building materials, found in the AISC Steel Manual. A copy of this table can be found in Appendix E and the material that was used for this analysis is circled in red. The roof of Des Places consists of 6 inches of sprayed polyurethane foam with a white top coating. According to the information given in the AISC Steel Manual, 1 inch of poured insulation weighs approximately 2 lb/ft^2, so this value was multiplied by six to find the approximate dead load of the roof for Des Places. The only live load on the main roof was the snow load, which was assumed to be 25 lb/ft^2. This value was given in the structural design documents for Des Places.

After factoring the total live load and dead load, the total load on the roof came out to be 119.2 lbs/ft^2. This surpasses the maximum allowable load for an 8 inch hollow core concrete plank, which is listed at 107 lb/ft^2. Therefore the depth of the plank had to be increased to 10" in the area of the roof that supported the solar thermal panels. The rest of the main roof can still use 8" hollow core plank, because the loads did not change in these areas. The figure below highlights the area of the main roof that will need to be changed to a 10" hollow core concrete plank.



Change this area from 8" hollow core plank to 10" hollow core plank

Figure 30: *Proposed redesign of the hollow core concrete plank used in the main roof structure*

Changing the 8 inch hollow core plank to 10 inch plank in the proposed area will increase the cost of the roof structure but it will be a neglible increase in comparison to the total structural cost for the building.

The structural analysis for the beams supporting the solar thermal array was started by finding the load on the smallest beam in kips per linear foot. An HSS 12 x 8 x 3/8 beam was chosen for this analysis. The same loads that were used for the analysis of the hollow core concrete plank were used for the beam analysis with the addition of the dead load for the 10" hollow core concrete plank. The weight of the plank was given in its specifications, which are shown in Appendix D along with the specifications for 8" hollow core concrete plank. HSS beams are used for the main roof structure instead of the more typical wide flange beams, so a standard shear and moment analysis could not be used to determine if the beam could adequately support the given loads. Instead the yielding stress on the beam had to be determined and compared to the maximum allowable yielding stress. The formula used for finding the yielding stress placed on the beam is shown below:

$\sigma_{max} = (M_{max} * Y_{max}) / I$

The yielding stress (σmax) was determined to be 11.3 K/in^2 and the maximum allowable yielding stress for the type of steel used in Des Places (A500 Grade B steel) is 46 K/in^2. The maximum allowable stress is far greater than the actual stress being applied on the beam, so the HSS 12 x 8 x 3/8 beam will be able to withstand the applied loads easily. Because this beam is the smallest member supporting the solar thermal panels on the main roof it can be assumed that the larger members will also be able to safely withstand the increased load.

Penthouse Roof Structure

The penthouse roof uses 1.5 inch, 18 gauge, type B metal deck to span between the beams instead of hollow core concrete plank like the main roof structure. Metal deck has different properties than hollow core plank, but they are both sized based upon the maximum load they can carry in lb/ft^2. Therefore the total load on the penthouse roof was determined by the same method used for the main roof. The same dead loads and live loads were used for the penthouse roof as well with the exception the 2 inch concrete topping, because there is no concrete topping on the penthouse roof. The new load on penthouse roof was found to be 89.2 lb/ft^2 and 1.5 inch, 18 gauge metal decking can safely hold 96 lb/ft^2. Therefore the existing decking was determined to be sufficient for supporting the additional load of the solar thermal panels. Specifications for metal decking manufactured by Vulcraft were used to determine the maximum allowable load. These specifications are given in Appendix D.

Wide flange beams are used to support the penthouse roof, so a straightforward shear and moment analysis could be done to determine if the beams supporting the solar thermal panels could withstand the new load. A W 21 x 48 beam was analyzed because it is the smallest beam on the penthouse roof that will have to carry the additional load of the solar thermal panels. The maximum moment found on this beam was 90.5 foot-kips and the maximum allowable moment for the beam given in the AISC Steel Manual is 398 foot-kips. Therefore the W 21 x 48 member and all of the other beams of the same size or larger should easily be able to support the additional weight of the solar thermal array.

Cantilevered Roof Structure

The cantilevered roof uses the same type of metal decking as the penthouse roof. The live loads and dead loads for the cantilevered roof are also the same as the penthouse roof, because it does not have a 2” concrete topping. Therefore 89.2 lb/ft^2 was found to be the total load on the metal decking for the cantilevered roof, which was the same value found for the penthouse roof. The beams for the cantilevered roof are spaced much closer together than they are for the penthouse roof and the distance that the metal decking has to span from beam to beam is a large factor in determining the maximum load that it can withstand. Because the metal decking only spans 5 feet in the cantilevered roof, it can support a maximum load of 218 lb/ft^2. The maximum allowable load for the 1.5” metal decking is more than double the actual load that it will have to support, so the metal decking will be able to easily support the additional load of the solar thermal collectors.

The smallest beam in the cantilevered roof structure that supported solar collectors was a W 12 x 26 member. The maximum moment on this beam was found to be 29.4 foot-kips. A W 12 x 26 steel member can support a 140 foot-kip moment. Therefore this beam and every other beam that supports the solar thermal array on this roof should easily be able to support the additional load.

Conclusion

A thorough structural analysis for the roof of Des Places showed that the roof structure will be relatively unaffected by the addition of a solar thermal array. The only change that will need to be made is replacing 8 inch hollow core concrete plank with 10 inch plank for a portion of the main roof. This change will have very little impact on the design and the cost of the structural system for Des Places. The beams supporting the solar collectors could easily handle the additional load so all of the beams and girders supporting the roof will remain the same. Overall this structural analysis was successful in proving that the addition of a solar thermal system will have very little impact on the structure of Des Places.

Energy Savings

The solar thermal system will be able to produce a significant amount of energy for domestic water heating in Des Places, but the output of the system will vary with the weather of Pittsburgh. Because Des Places has a high domestic water demand, the solar thermal system will rarely be able to satisfy all or most of the heating load for the domestic water use in the building. The table below shows the variation in predicted thermal output of the system, broken down by month.

Monthly Energy Output for Solar Thermal Array		
Month	**Insolation Level ($KWh/m^2/day$)**	**Energy Output (therms)**
January	1.59	57.42
February	2.40	86.67
March	3.26	117.73
April	4.07	146.98
May	5.05	182.37
June	5.53	199.70
July	5.27	190.31
August	4.94	178.40
September	4.05	146.26
October	2.88	104.00
November	1.86	67.17
December	1.41	50.92

***Table 33:** Monthly energy output for solar thermal array*

The energy figures for Table 33 were found by an energy output calculator on Apricus' website (www.apricus.com) and were confirmed as accurate figures by Eric Skiba, an engineer for Apricus. The energy calculator took two major factors into consideration when calculating the monthly and yearly output of a given Apricus solar collector array. These two factors were the total absorber area of the system and the insolation level for the location of the system. The absorber area is given for every model of solar collector that Apricus produces, so this value was easy to find. The absorber area for each collector and for the entire array is given in Table 32. The solar insolation level is a measure of the amount of solar radiation incident on the surface of the earth, which basically means it is a measure of the amount of sunlight in a specific location. Solar insolation changes with location, time of year, weather conditions and other factors. The Apricus website lists insolation values provided by NASA for major cities all over the world. Each location has averaged insolation values for each month and for the entire year. The monthly solar insolation values for Pittsburgh, PA are listed in Table 33.

The energy output calculator provides a reasonable estimation of the monthly and yearly energy production for the solar thermal system designed for Des Places. Several safety factors were put into the calculations such as using 28 day months and average weather conditions to produce figures that will potentially underestimate the energy output of a given solar array rather than overestimate the capability of the system. Table 34 below gives the average energy output per day, average energy output per month and the energy production per year for the designed solar thermal system. It also gives the equivalent steam energy produced by the system, which is a measure of how much energy will be saved by the central steam plant per year. This figure was found by dividing the yearly energy output for the solar thermal system by the net efficiency of Duquesne's central steam plant and distribution network. According to Craig Duda of CJL Engineering, the net efficiency of Duquesne's central steam plant and distribution network is 66.3%.

Energy Output For Solar Thermal Array	
Insolation Level	3.53 kWh/m²/day
Absorber Area/Collector	2.4 m²
Number of Collectors	21
Total Absorber Area	50.4 m²
Average Energy Output Per Day	4.25 therms
Average Energy Output Per Month	127.5 therms
Energy Output Per Year	1551 therms
Equivalent Steam Energy Output per Year	**2350 therms**

Table 34: *Total energy output values for the solar thermal system*

When the efficiency of the central steam plant and distribution network are considered, the relative energy production of the solar collectors rises dramatically. The efficiency of the primary domestic water heater is an important factor to consider when finding the amount of energy and money that can be saved every year by a solar thermal system. This factor becomes especially important when evaluating the life cycle cost for the system.

Life Cycle Cost Analysis

Every additional cost to a buildings mechanical system has to be justified in some way. Usually the most compelling justification is monetary savings for the owner. A solar thermal system must pay for itself relatively quickly for it to be a justified expense for the owner. The life-cycle cost analysis for this solar thermal system will find approximately how many years it will take the system to pay for itself in energy savings for the building and how much money the system could ultimately save the building over a 25 year period.

The first step in any life cycle cost analysis is to find the cost of installing the new system. According to Eric Skiba, the MSRP value for one Apricus AP-30 solar collector is $1,500. This value was multiplied by 21 to find the cost for the entire array of collectors, which came out to be $31,500. It was difficult to find an exact price for the entire system, because it had not been designed in detail. The engineers at Apricus and Sunmaxx Solar both agreed that it is reasonable to assume that the price of any solar thermal system is about three times the cost of the solar collectors. This assumption was used to find the total cost of the system, which should be approximately $94,500.

The first life cycle cost analysis was done without factoring in any government rebates. The steam cost started at $1.28/therm for year one, which is the current rate Duquesne pays for steam energy. This cost was increased at an inflation rate of 3% every year, so that it ranged from $1.28/therm in year one to $2.60/therm in year twenty-five. The yearly equivalent steam energy produced by the solar thermal system, given in Table 34 was multiplied by the yearly steam cost to find the savings produced by the system. The preliminary life cycle cost analysis for the system without any government incentives is shown in Table 35 and Figure 31.

Life Cycle Cost Analysis with No Government Rebates			
Year	**Steam Cost**	**Savings**	**System Cost**
0	$1.28/therm	$0	($94,500)
1	$1.28/therm	$3,008	($91,492)
2	$1.32/therm	$3,102	($88,390)
3	$1.36/therm	$3,196	($85,194)
4	$1.40/therm	$3,290	($81,904)
5	$1.44/therm	$3,384	($78,520)
6	$1.48/therm	$3,478	($75,042)
7	$1.53/therm	$3,596	($71,446)
8	$1.57/therm	$3,690	($67,756)
9	$1.62/therm	$3,807	($63,949)
10	$1.67/therm	$3,925	($60,024)
11	$1.72/therm	$4,042	($55,982)
12	$1.77/therm	$4,160	($51,822)
13	$1.82/therm	$4,277	($47,545)
14	$1.88/therm	$4,418	($43,127)
15	$1.94/therm	$4,559	($38,568)
16	$1.99/therm	$4,677	($33,891)
17	$2.05/therm	$4,818	($29,073)
18	$2.11/therm	$4,959	($24,114)
19	$2.18/therm	$5,123	($18,991)
20	$2.24/therm	$5,264	($13,727)
21	$2.31/therm	$5,429	($8,298)
22	$2.38/therm	$5,593	($2,705)
23	$2.45/therm	$5,758	$3,053
24	$2.52/therm	$5,922	$8,975
25	$2.60/therm	$6,110	$15,085

Table 35: *Life cycle cost analysis with no government rebates*

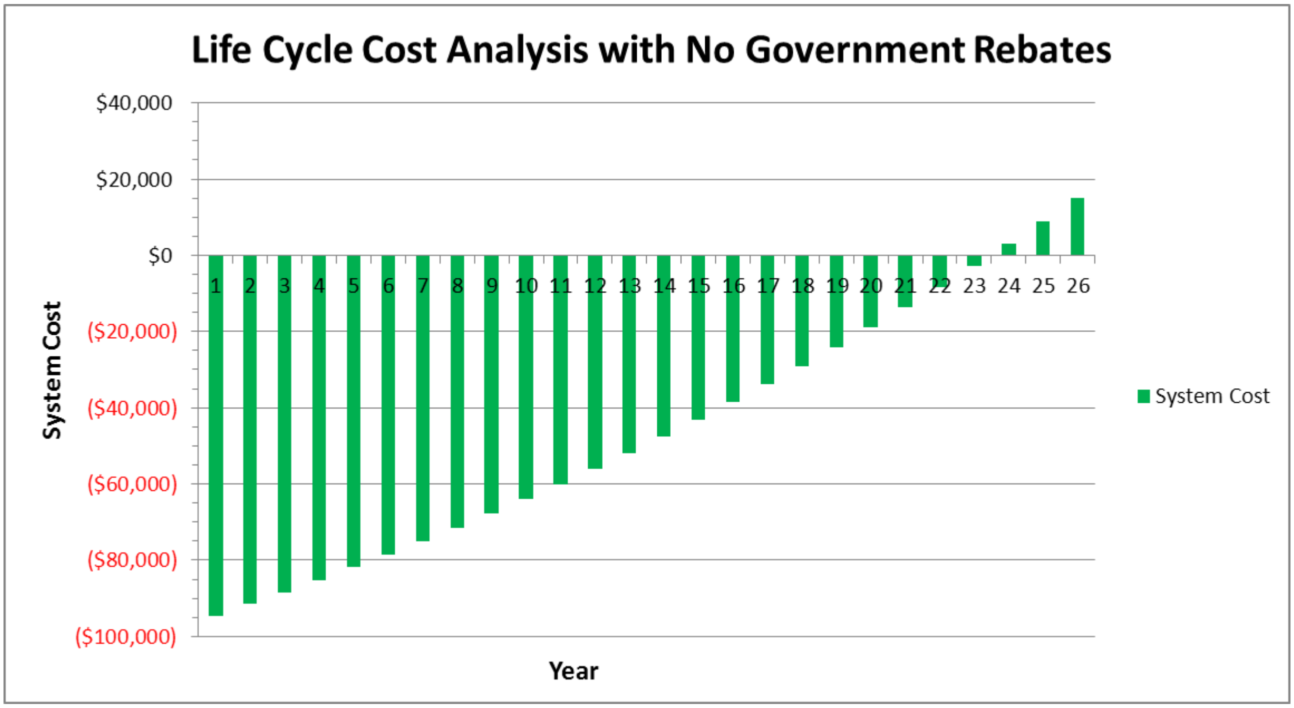


***Figure 31:** Bar graph for the life cycle cost analysis of the solar thermal system with no government rebates*

The table and graph above show that the solar thermal system is not very feasible by its energy savings alone. Solar thermal systems and all other types of renewable technologies have an expensive up front cost. This makes most renewable technology in buildings difficult to justify without financial incentives from the government, and this solar thermal system is no exception. It would take approximately 22 years for the system to pay for itself in energy savings alone and that long of a payback period would be unacceptable to any owner. The solar collectors only have a ten year warranty and 22 years is a long service life for any piece of mechanical equipment. There is a chance that the solar array could become too weathered and fail before the system payed for itself, which would result in a financial loss for Duquesne University.

Fortunately there are many government incentives on the state and federal levels to promote the installation of sustainable technologies in buildings. Every financial incentive offered by state governments and the federal government is listed and described on the website www.dsireusa.org. This website listed two financial incentive programs that apply to the installation of any new solar thermal system. One incentive is a federal program called the Business Energy Investment Tax Credit. This program gives a tax credit to any private company installing a new renewable energy system that is worth 30% of the total cost of the system. The other financial incentive is provided by the state of Pennsylvania, as part of their Sunshine Solar Rebate Program. This program only applies to new photovoltaic and solar hot water systems and gives private companies installing these systems a rebate worth 35% of the systems total cost. Duquesne is a private university, so they would qualify for both the federal tax credit and the state rebate. A modified life cycle cost analysis that factors in both of the government incentive programs is shown in the table and figure below.

Life Cycle Cost Analysis with Government Rebates					
Year	**Steam Cost**	**Savings**	**Federal Government Rebates**	**State Government Rebates**	**System Cost**
0	$1.28/therm	$0	$28,350	$33,075	($33,075)
1	$1.28/therm	$3,008	$0	$0	($30,067)
2	$1.32/therm	$3,102	$0	$0	($26,965)
3	$1.36/therm	$3,196	$0	$0	($23,769)
4	$1.40/therm	$3,290	$0	$0	($20,479)
5	$1.44/therm	$3,384	$0	$0	($17,095)
6	$1.48/therm	$3,478	$0	$0	($13,617)
7	$1.53/therm	$3,596	$0	$0	($10,021)
8	$1.57/therm	$3,690	$0	$0	($6,331)
9	$1.62/therm	$3,807	$0	$0	($2,524)
10	$1.67/therm	$3,925	$0	$0	$1,401
11	$1.72/therm	$4,042	$0	$0	$5,443
12	$1.77/therm	$4,160	$0	$0	$9,603
13	$1.82/therm	$4,277	$0	$0	$13,880
14	$1.88/therm	$4,418	$0	$0	$18,298
15	$1.94/therm	$4,559	$0	$0	$22,857
16	$1.99/therm	$4,677	$0	$0	$27,534
17	$2.05/therm	$4,818	$0	$0	$32,352
18	$2.11/therm	$4,959	$0	$0	$37,311
19	$2.18/therm	$5,123	$0	$0	$42,434
20	$2.24/therm	$5,264	$0	$0	$47,698
21	$2.31/therm	$5,429	$0	$0	$53,127
22	$2.38/therm	$5,593	$0	$0	$58,720
23	$2.45/therm	$5,758	$0	$0	$64,478
24	$2.52/therm	$5,922	$0	$0	$70,400
25	$2.60/therm	$6,110	$0	$0	$76,510

Table 36: *Life cycle cost analysis with government rebates*

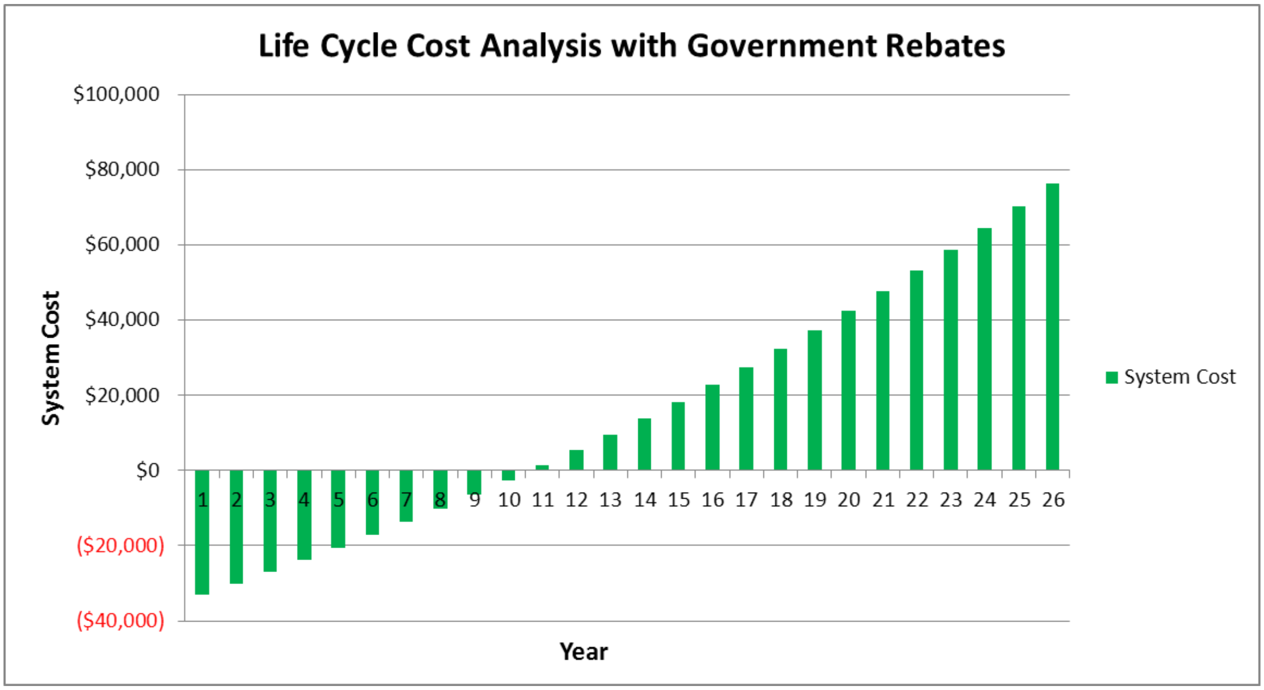


Figure 32: *Bar graph for the life cycle cost analysis of the solar thermal system with government rebates*

Table 36 shows the dramatic effect that the federal tax credit and state rebate has on the payback period for the solar thermal system. These two government incentives decrease the upfront cost of the solar thermal system by 65% and change the payback period from 22 years to 9 years. If the original system lasts for 25 years it will save Duquesne over $70,000 and the payback period is within the 10 year warranty for the solar collectors. Therefore if the solar collectors last longer than 10 years the system will net a positive cash flow and if they fail before 10 years they will be replaced for free and the system will still net a positive cash flow.

Conclusion

A solar thermal system with an antifreeze loop and an internal heat exchanger could tie in very easily with the current domestic water heating system for Des Places. The system that has been designed for Des Places would be reliable, nearly maintenance free and could consistently reduce the steam demand of Des Places. The system would produce an average of 1,551 therms per year, which is equivalent to 2,350 therms of energy coming from the central steam plant. The most compelling reason for installing the proposed solar thermal system is the fact that it will pay for itself within 10 years with the help of government incentives and save Duquesne money every year for as long as the equipment lasts. Duquesne University should secure the federal tax credit and the state funded rebate before they commit to installing this system, but they should easily receive both of these incentives. After the government money is secured there is no reason why Duquesne should not invest in this additional system for Des Places. This solar thermal system will make the building more sustainable and can guarantee financial savings over the duration of its service life.

Redesign of Building Envelope – Mechanical Depth

Introduction

In order to qualitatively analyze the benefits of doubling the size of every window in the private bedrooms and living rooms, a daylighting analysis was performed to find how much natural daylight entered a typical bedroom in different orientations and times throughout the year. Students living in Des Places will need a space that can accommodate every type of activity they will be doing while in their bedroom or living room. If these spaces let in enough natural light during the daytime, the students will be able to do everything they need to do without turning on any lights in the room. This will save energy over the entire life of the building and it will create a more desirable space to live in, because a space lit entirely by daylight naturally feels more comfortable than a space lit by artificial light. This increased comfort should result in students that are more productive and more satisfied with the dormitory space that Duquesne has provided for them. According to the ninth edition of the IESNA Lighting Handbook, written by the Illuminating Engineering Society of North America, 30 footcandles of light is needed for "handwritten tasks with a number two pencil". It is important that each bedroom can adequately accommodate this type of task, so that students can study for exams or complete their homework comfortably in their own rooms. In the residential section of the Lighting Handbook, the activity that required the most light was "dressing evaluation in the mirror". This activity also required at least 30 footcandles of light. Therefore, according to the recommendations of the IESNA Lighting Handbook, each bedroom and living room should have at least 30 footcandles of light throughout the space.

Daylighting Analysis – Daylighting Breadth

The lighting software AGI was used to complete a daylighting analysis of two typical bedrooms in Des Places Residence Hall. Two models were first created in Revit Architecture, using the dimensions and furniture layout given in the architectural floor plans for Des Places. The floor plan of a typical bedroom in Des Places is shown below.

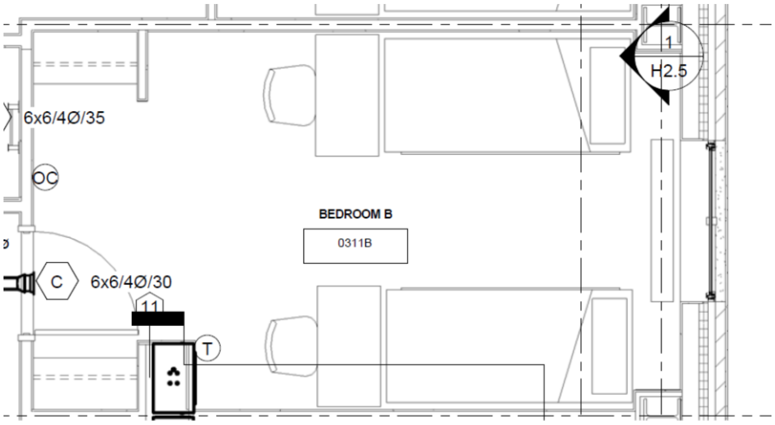


Figure 33: *Floor plan of room 311B, a typical bedroom (courtesy of WTW Architects)*

The first model created was for a typical bedroom with the existing 4 ft. by 5 ft. window and the second model was for the proposed redesign of the bedrooms, with an 8 ft. by 5 ft. window. After both models were created in Revit, they were first imported into AutoCAD 3D and then imported into AGI. For the purposes of this study, room 311B and room 307B were chosen as the typical bedrooms to model. A 3D rendering of both room models in AGI is shown in the figures below.

Figure 34: *3D rendering in AGI of room 311B with a 4' x 5' window*

Figure 35: *3D rendering in AGI of room 311B with an 8' x 5' window*

Room 311B is a typical east facing bedroom and room 307B is a typical north facing bedroom. Des Places faces almost exactly due north and has four sides with an east facing side, south facing side and west facing side. For a building with this type of orientation and shape, the south facing side will have the most solar exposure, followed by the east and west facing sides, which should receive a similar amount of daylight. The north side of the building will receive the least amount of daylight, so the rooms on this side of the building will see the biggest difference in the amount of natural light that they receive by doubling the size of their windows.

Analysis of a Typical East Facing Bedroom

Room 311B was analyzed at 10 AM on the summer solstice, fall equinox and winter solstice. These three dates were chosen because they show the range of natural daylight that will enter the space throughout the year. The summer solstice will show the upper extreme of natural daylight and the winter solstice will show the lower extreme. The fall equinox lies right in the middle of the two solstices, so it will show more average values of daylight. The table below shows the maximum, minimum and average illuminance values for room 311B with the smaller window and larger window on the three days mentioned above. These illuminance values were measured at 2.5 feet above the floor. This height was chosen because it is on the working plane of the two desks in the room and they have the highest priority for illumination in the space.

Illuminance Values For Room 311B									
	June 21, 10 AM			September 23, 10 AM			December 22, 10 AM		
	Average (fc)	Max. (fc)	Min. (fc)	Average (fc)	Max. (fc)	Min. (fc)	Average (fc)	Max. (fc)	Min. (fc)
4 ft. x 5 ft. Window	227.9	3971	19.2	157.64	2994	13.8	100.9	1768	15.2
8 ft. x 5 ft. Window	460	4096	30.4	304.5	3430	25.5	193.57	1936	23.9

Table 37: *Illuminance values for Room 311B on the summer solstice, fall equinox and winter solstice*

The data in Table 37 shows that the average illuminance level in the room was already well above the 30 footcandles needed, but the minimum illuminance in the room was below 20 fc for all three days. These minimum values were found in areas of the room that were not important to the occupants. The most important area in the room to illuminate properly is the two desks, because this is where the students will be doing most of their schoolwork. If there is well over 30 footcandles of daylight over the two desks then students can complete their work during the day without turning on the lights. AGI is able to accurately show the level of illuminance throughout a modeled room by various means. The images given below show floor plans of room 311B with illuminance contours and three dimensional pseudo-color renderings of the room.

The two figures below compare the illuminance contours for room 311B with the smaller window and the bigger window on June 21 at 10 AM. Illuminance contours are lines in the floor plan of the room that show how bright the space is in certain areas. For example, in figure 4 the green line shows where the illuminance drops below 50 footcandles in the room. The space to the left of the green line is darker than 50 fc and the space to the right of the green line is 50 fc or brighter.

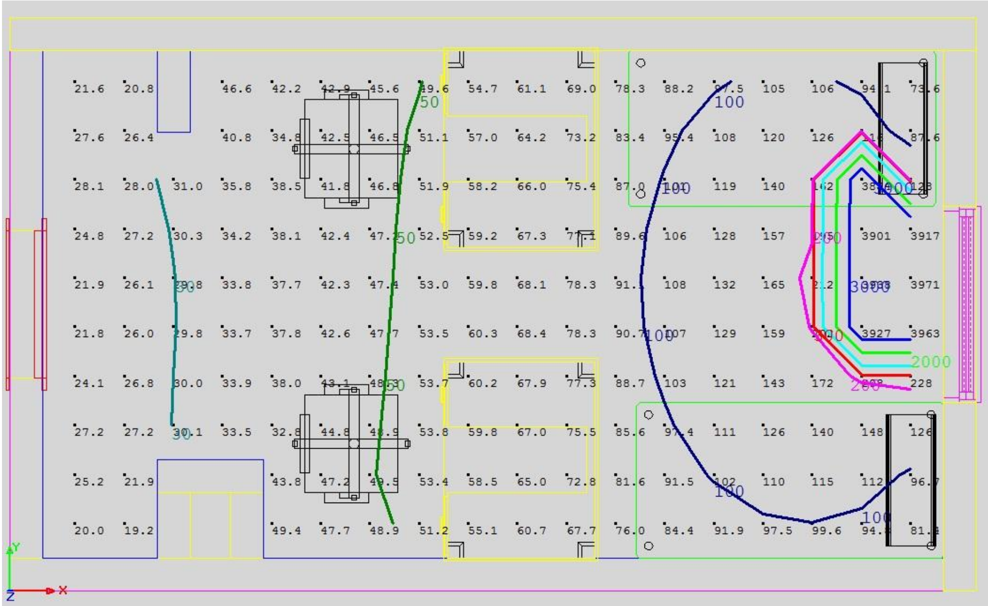


Figure 36: *Illuminance contours for Room 311B with a 4' x 5' window on June 21, 10 AM*

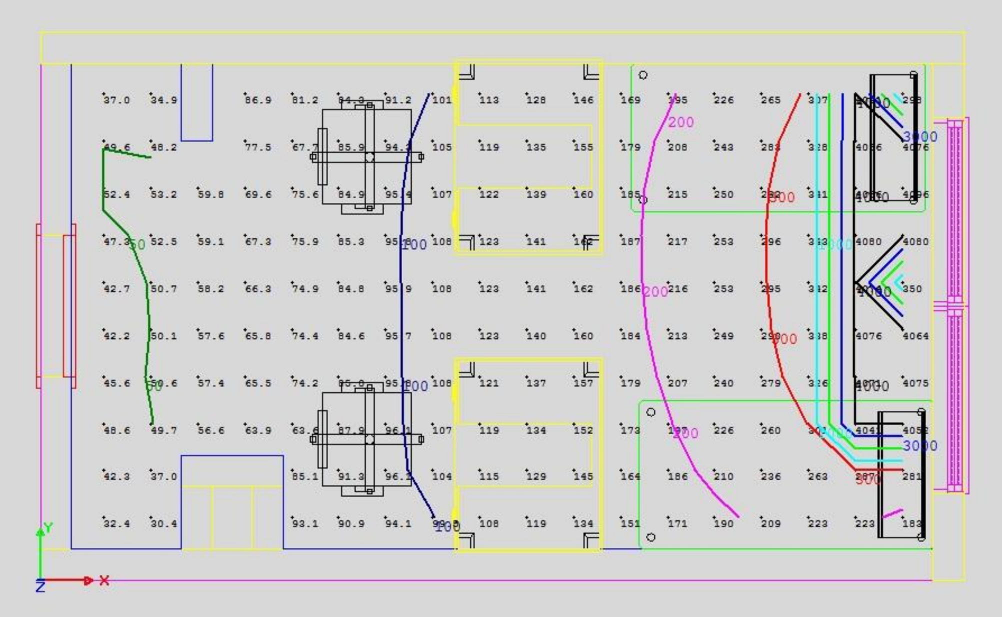


Figure 37: *Illuminance contours for Room 311B with an 8' x 5' window on June 21, 10 AM*

Figures 38 and 39 compare the two alternatives for room 311B on June 21 at 10 AM with pseudo-color renderings. These figures are three dimensional renderings of the room that assign colors to everything in the room based on its illuminance value. For all of the pseudo-color renderings in this daylighting analysis, 50 footcandles was set as the maximum illuminance value on the color scale. Therefore everything red in the room has at least 50 fc of light on it. Fifty footcandles was chosen, because this value is safely over 30 fc, which is the minimum amount of light needed for the occupants to do everything they need to do in their dorm rooms.

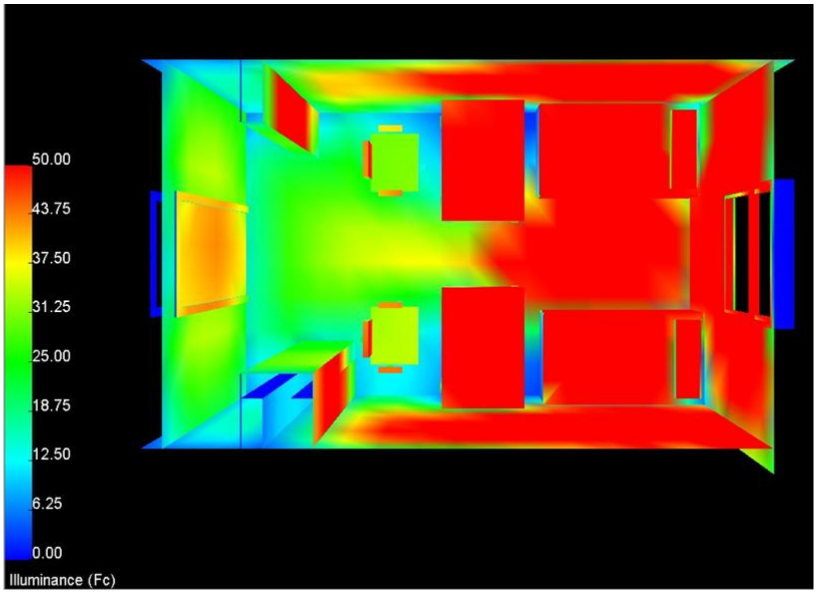


Figure 38: *Pseudo-color rendering of room 311B with a 4' x 5' window on June 21, 10 AM*

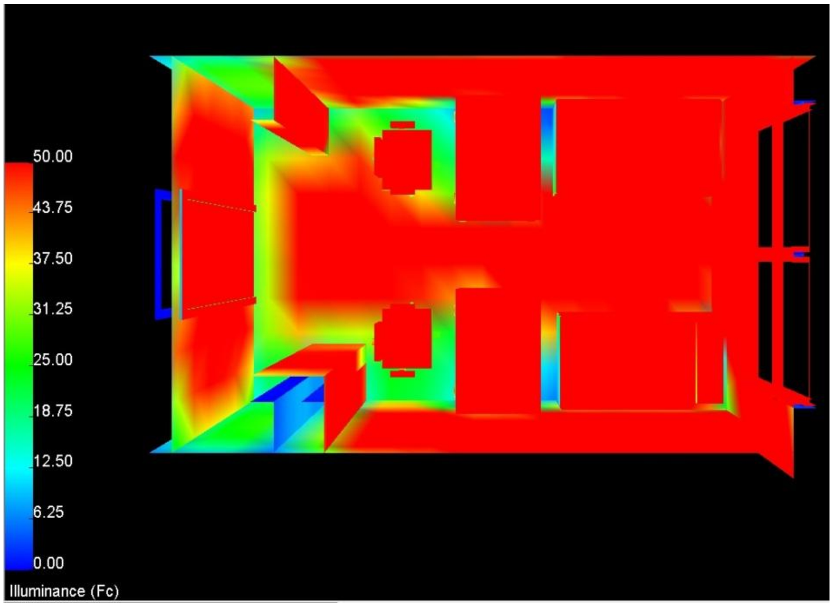


Figure 39: *Pseudo-color rendering of room 311B with an 8' x 5' window on June 21, 10 AM*

The two figures below compare the illuminance contours for room 311B with a 4 ft. by 5 ft. window and an 8 ft. by 5 ft. window on September 23 at 10 AM. Both desks in the room still receive at least 30 fc of natural light with the smaller window but they both get more than 50 fc of light with the larger window.

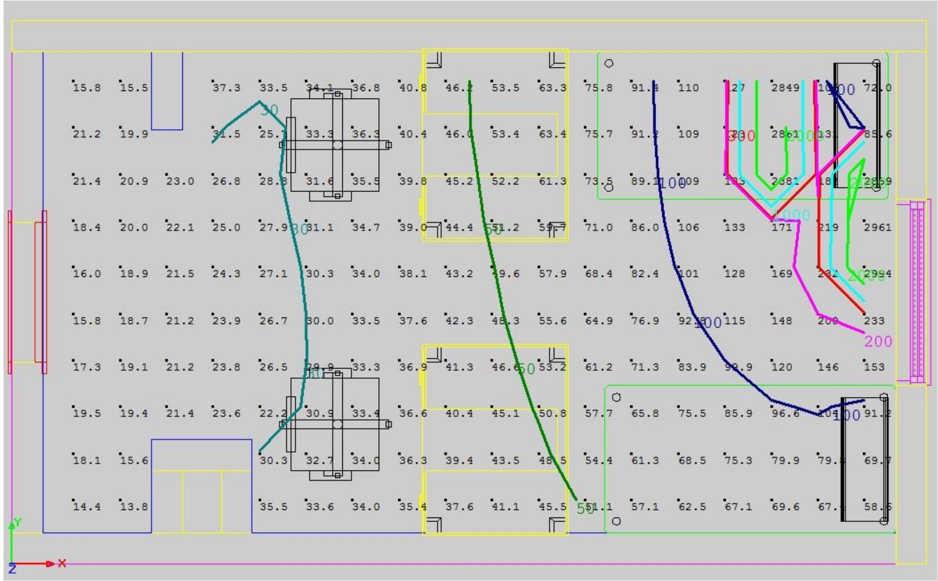


Figure 40: *Illuminance contours for Room 311B with a 4' x 5' window on September 23, 10 AM*

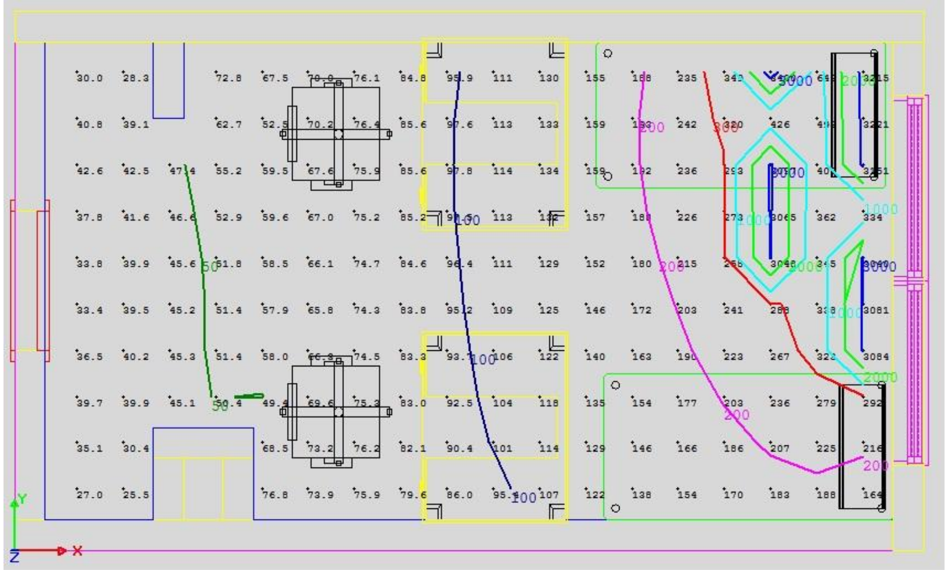


Figure 41: *Illuminance contours for Room 311B with an 8' x 5' window on September 23, 10 AM*

The next two figures show the pseudo-color renderings of the two alternatives for room 311B on September 23 at 10 AM.

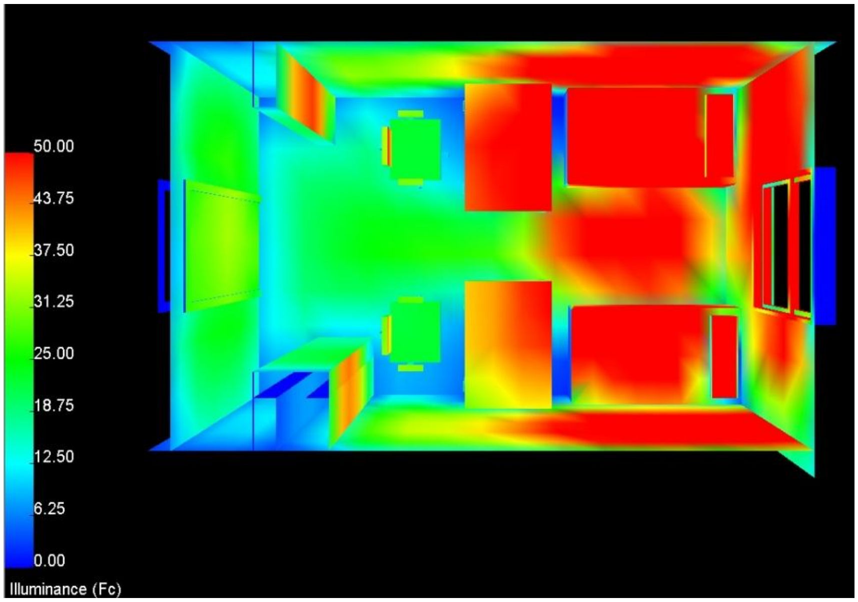


Figure 42: *Pseudo-color rendering of room 311B with a 4' x 5' window on September 23, 10 AM*

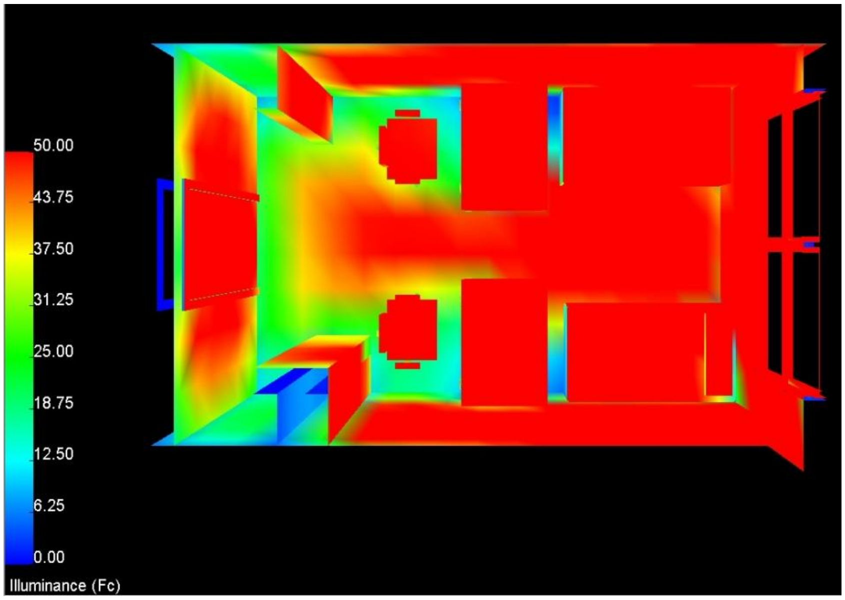


Figure 43: *Pseudo-color rendering of room 311B with an 8' x 5' window on September 23, 10 AM*

Figures 44 and 45 compare the illuminance contours of the two alternatives for room 311B on December 22 at 10 AM. This is the winter solstice, so the building will receive the least amount of sunlight on this day.

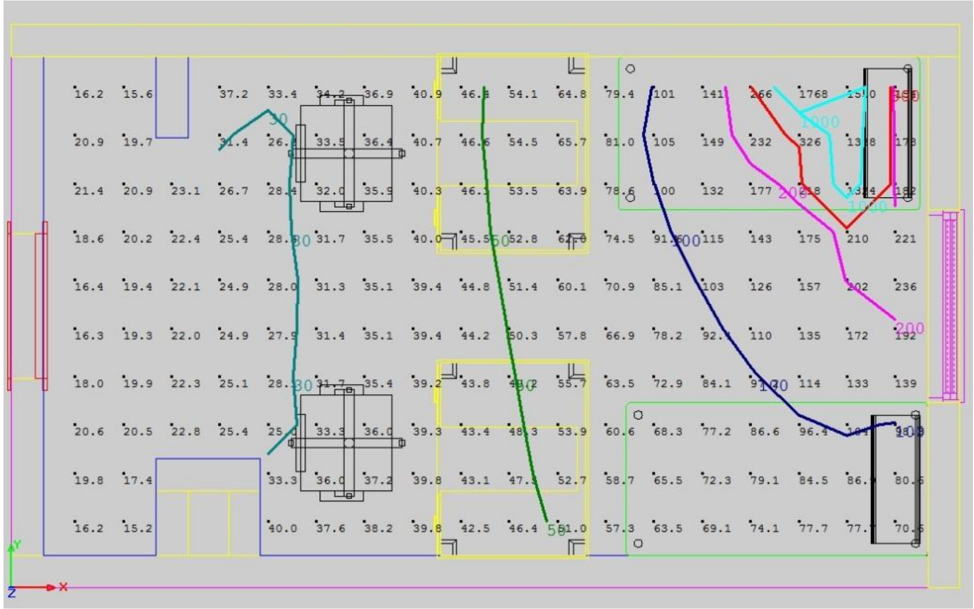


Figure 44: *Illuminance contours for Room 311B with a 4' x 5' window on December 22, 10 AM*

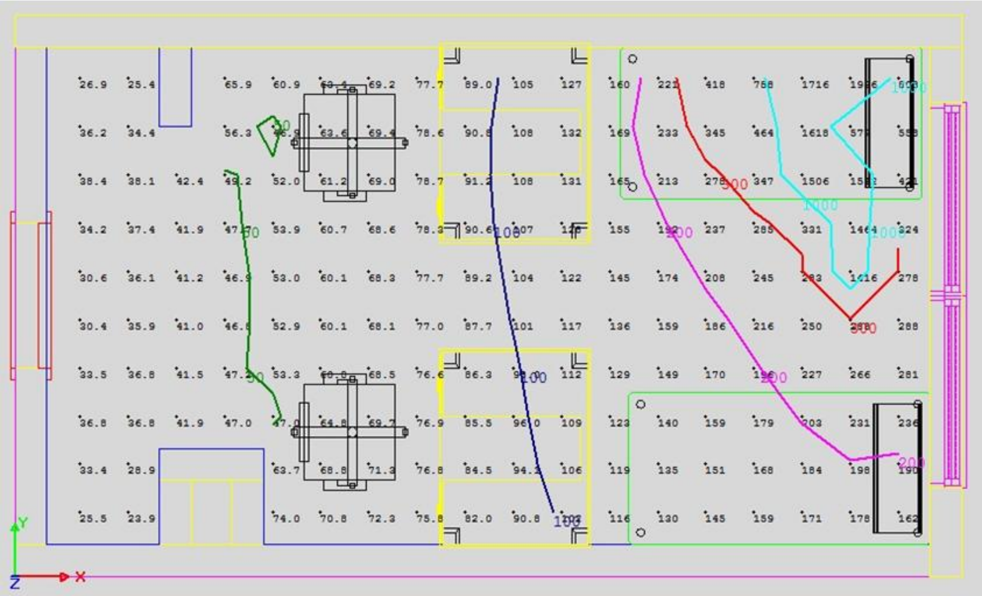


Figure 45: *Illuminance contours for Room 311B with an 8' x 5' window on December 22, 10 AM*

The next two figures compare the pseudo-color renderings of room 311B with the smaller window and with the larger window on December 22 at 10 AM.

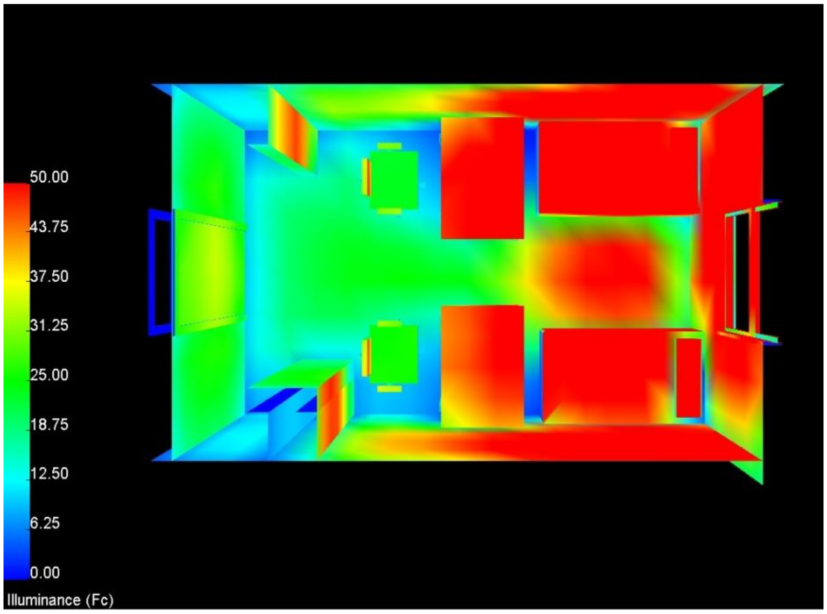


***Figure 46:** Pseudo-color rendering of room 311B with a 4' x 5' window on December 22, 10 AM*

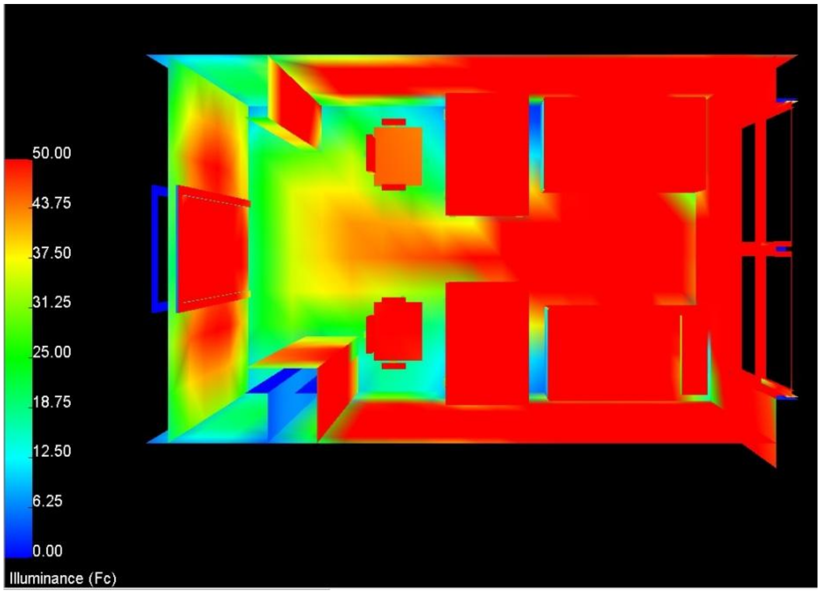


***Figure 47:** Pseudo-color rendering of room 311B with an 8' x 5' window on December 22, 10 AM*

The illuminance contours and pseudo-color renderings of room 311B show that a strong amount of natural light already enters the space with the smaller 4 foot by 5 foot window. There is already enough natural daylight in the room to illuminate the desks at or near 50 footcandles, which is more than enough light required for students to do their schoolwork. Although the level of daylight in the east facing rooms would be greatly increased by doubling the size of the window to 8 feet by 5 feet window, the increase would be unnecessary for the space. Therefore doubling the size of the windows in the east and west facing rooms is not entirely necessary.

Analysis of a Typical North Facing Bedroom

Room 307B was analyzed at 1 PM on the same three dates as room 311B. These three dates will show the entire range of the amount of sunlight that enters the room throughout the year. Room 307B is a typical north facing room, so doubling the size of the window will show much stronger results than room 311B, which is a typical east facing bedroom. The table below shows the average, maximum and minimum illuminance values in the room for the two alternatives on the summer solstice, fall equinox and winter solstice. The illuminance values for this room are drastically less than those for room 311B. On all three simulated days, the average illuminance in the room is less than 50 fc with a 4 foot by 5 foot window. When the window size is increased to 8 feet by 5 feet the average illuminance in the room increases to over 50 fc on two of the days and close to 50 fc on the winter solstice.

Illuminance Values For Room 307B									
	June 21, 1 PM			September 23, 1 PM			December 22, 1 PM		
	Average (fc)	Max. (fc)	Min. (fc)	Average (fc)	Max. (fc)	Min. (fc)	Average (fc)	Max. (fc)	Min. (fc)
4 ft. x 5 ft. Window	41.75	128	10.9	34	91.7	9.4	24.5	66	7.2
8 ft. x 5 ft. Window	73.2	170	15.5	58.5	127	13.2	42.5	91.5	10.2

Table 38: *Illuminance values for Room 307B on the summer solstice, fall equinox and winter solstice*

The illuminance contours and three dimensional pseudo-color renderings produced by AGI give a clearer image of where the daylight is dispersed throughout room 307B. These images are shown below for both building envelope alternatives on all three simulated days. Figures 48 and 49 compare the illuminance contours of the two alternatives for room 307B on June 21 at 1 PM.

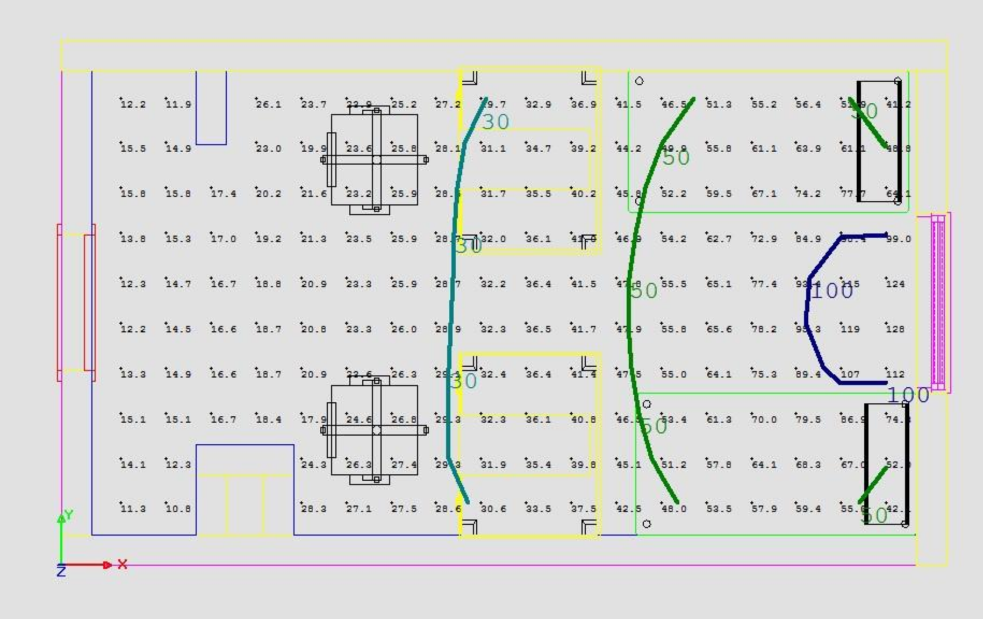


Figure 48: *Illuminance contours for Room 307B with a 4' x 5' window on June 21, 1 PM*

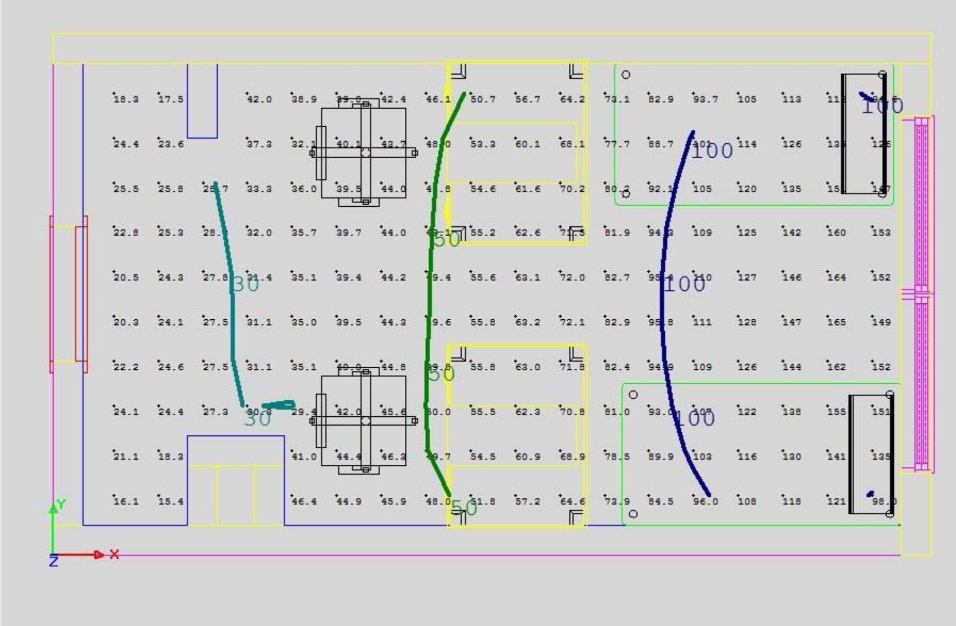


Figure 49: *Illuminance contours for Room 307B with an 8' x 5' window on June 21, 1 PM*

The following two images compare the pseudo-color renderings of room 307B with the smaller window and the larger window on June 21 at 1 PM. These two renderings clearly show how increasing the size of the window in the room allows enough light into the space to illuminate the desks to an adequate level.

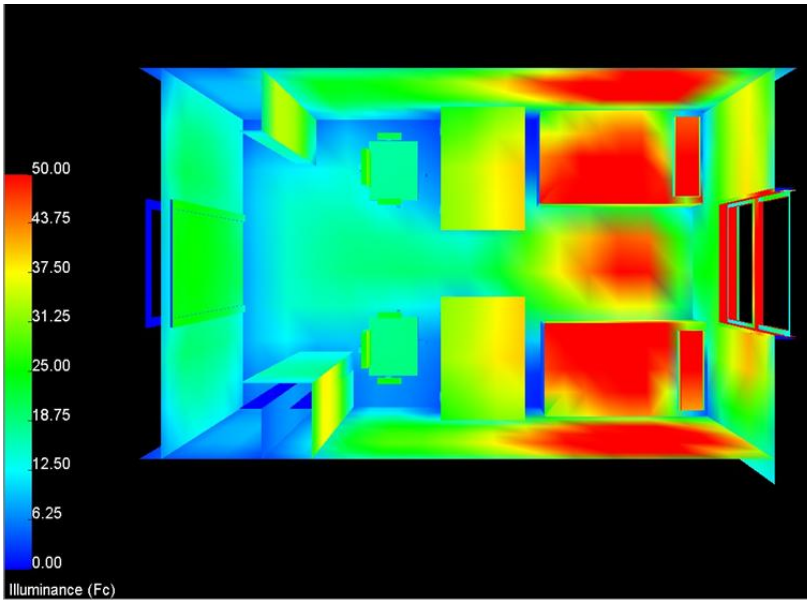


Figure 50: *Pseudo-color rendering of room 307B with a 4' x 5' window on June 21, 1 PM*

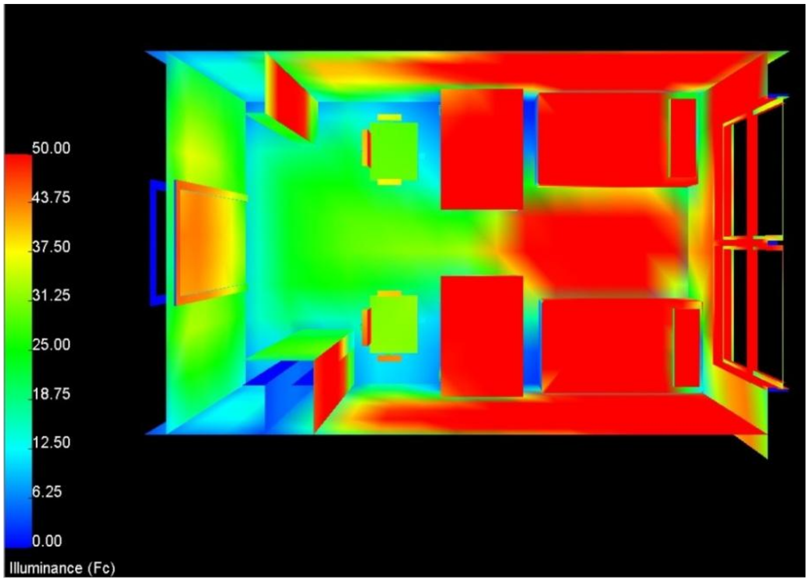


Figure 51: *Pseudo-color rendering of room 307B with an 8' x 5' window on June 21, 1 PM*

The two figures below show the illuminance contours of both alternatives for room 307B on September 23 at 1 PM. The area around the desks does not receive the minimum amount of daylight needed for students to do their schoolwork with the 4 foot by 5 foot window. With that level of daylight in the space the occupants would most likely need to turn on all of the lights in their room to comfortably perform necessary tasks. When the window is doubled in size, the illuminance around the desks is between 30 fc and 60 fc. With this level of daylight in the room, the students would not need to have any lights on to be comfortable in the space.

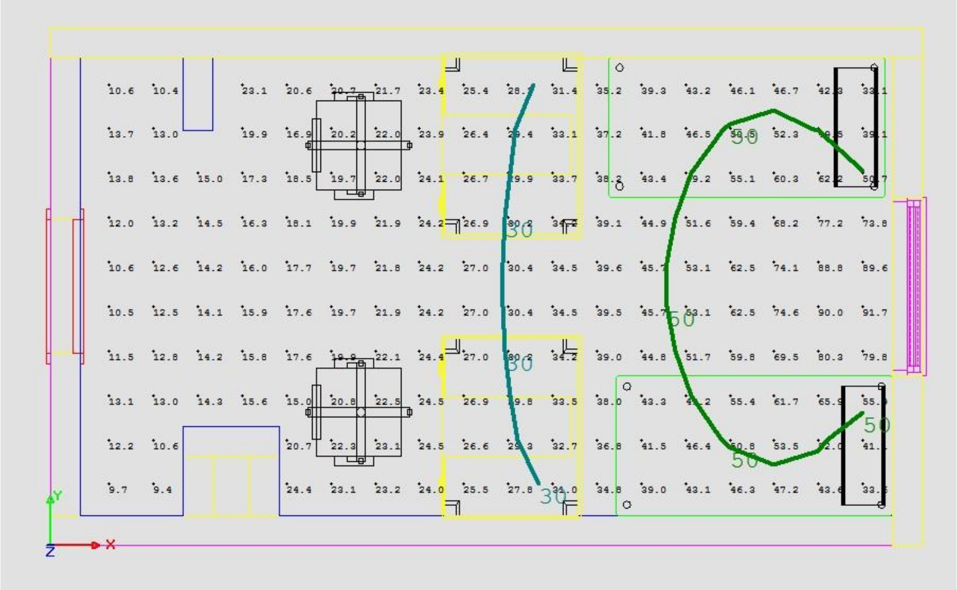


***Figure 52:** Illuminance contours for Room 307B with a 4' x 5' window on September 23, 1 PM*

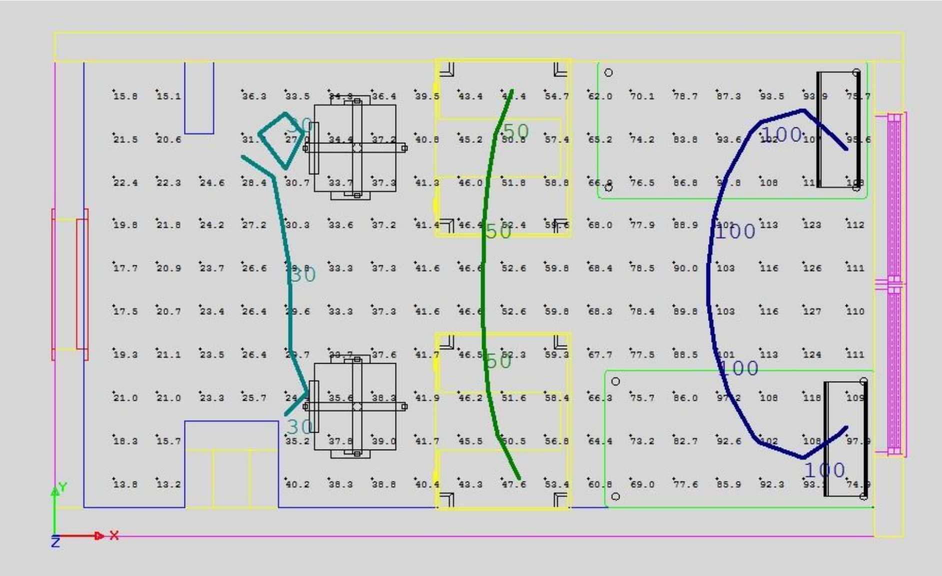


***Figure 53:** Illuminance contours for Room 307B with an 8' x 5' window on September 23, 1 PM*

The next two figures compare the pseudo-color renderings of the two alternatives for room 307B on September 23 at 1 PM. These two images further illustrate how the illuminance throughout the room is increased to a more acceptable level by increasing the size of the window.

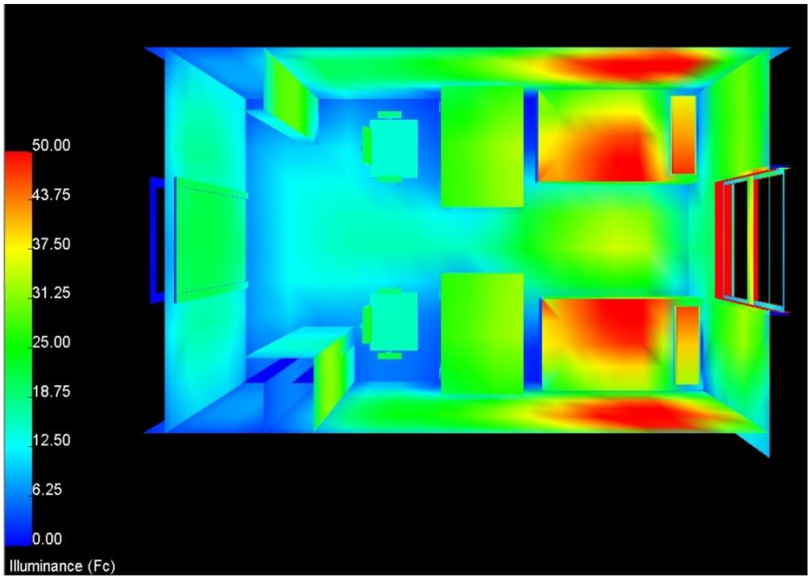


Figure 54: *Pseudo-color rendering of room 307B with a 4' x 5' window on September 23, 1 PM*

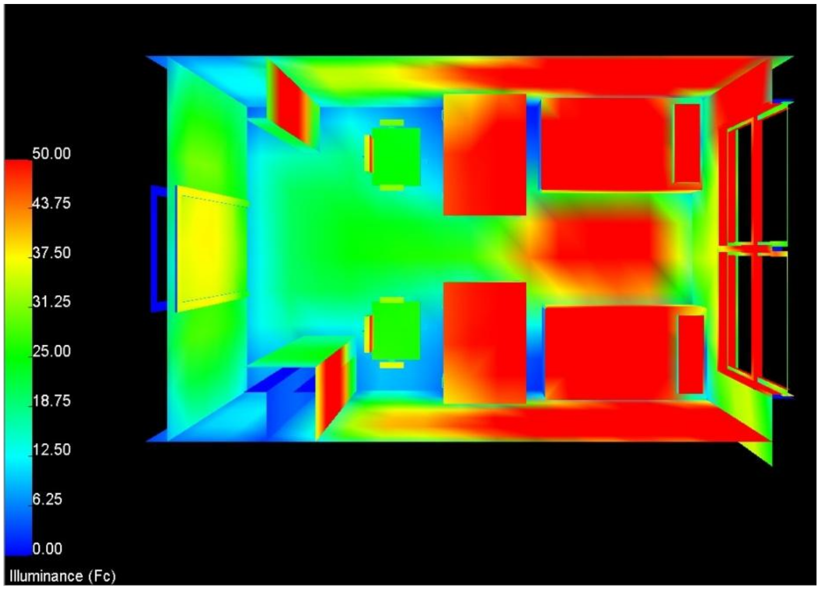


Figure 55: *Pseudo-color rendering of room 307B with an 8' x 5' window on September 23, 1 PM*

The following two figures compare the illuminance contours of the two alternatives for room 307B on December 22 at 1 PM. On this day the 4 foot by 5 foot window only lets in enough daylight to keep the front of the room illuminated above 30 fc. The rest of the room is far too dark to keep the lights off in the room. The 8 foot by 5 foot window lets in enough light for both desks to receive over 30 fc of natural light, allowing the students to work in their rooms during the day without any lights on.

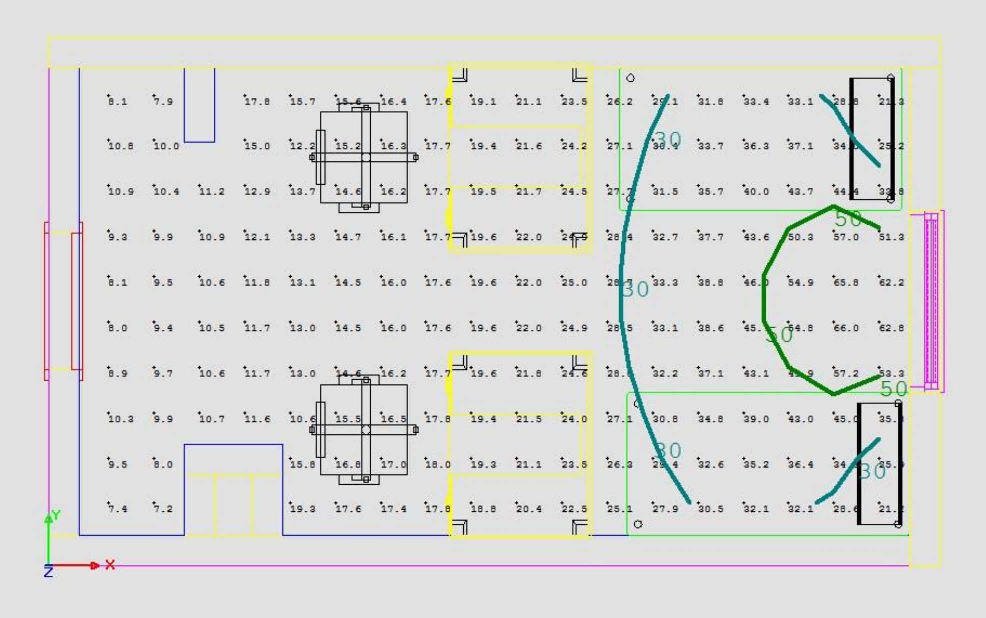


Figure 56: *Illuminance contours for Room 307B with a 4' x 5' window on December 22, 1 PM*

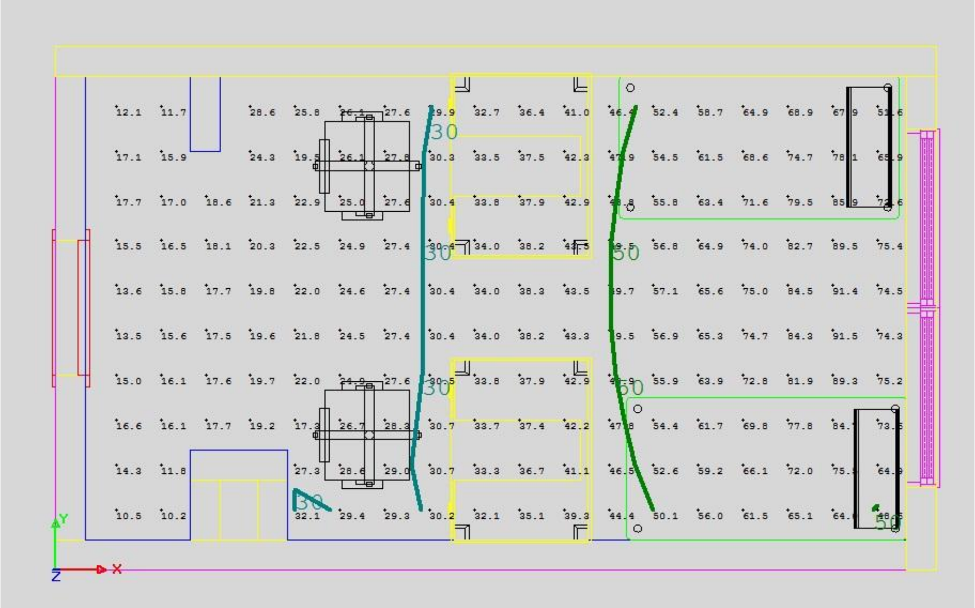


Figure 57: *Illuminance contours for Room 307B with an 8' x 5' window on December 22, 1 PM*

The next two figures show the pseudo-color renderings of both alternatives for room 307B on December 22 at 1 PM.

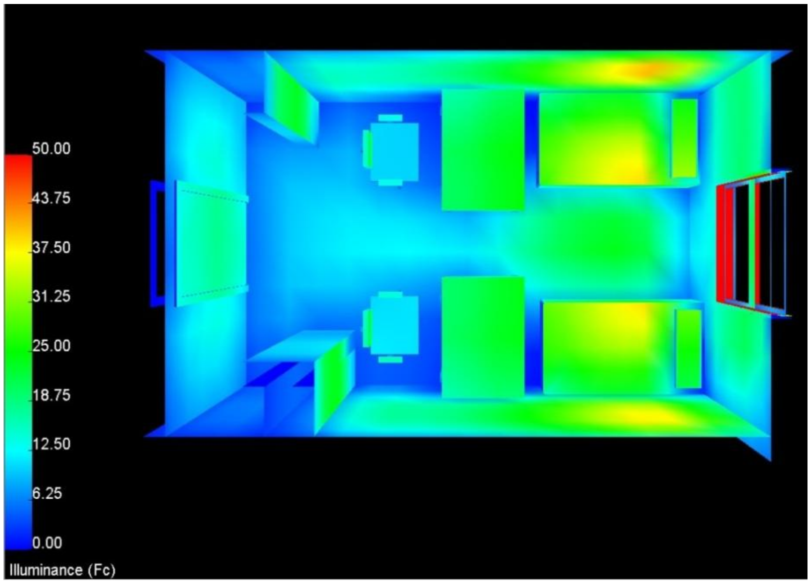


Figure 58: *Pseudo-color rendering of room 307B with a 4' x 5' window on December 22, 1 PM*

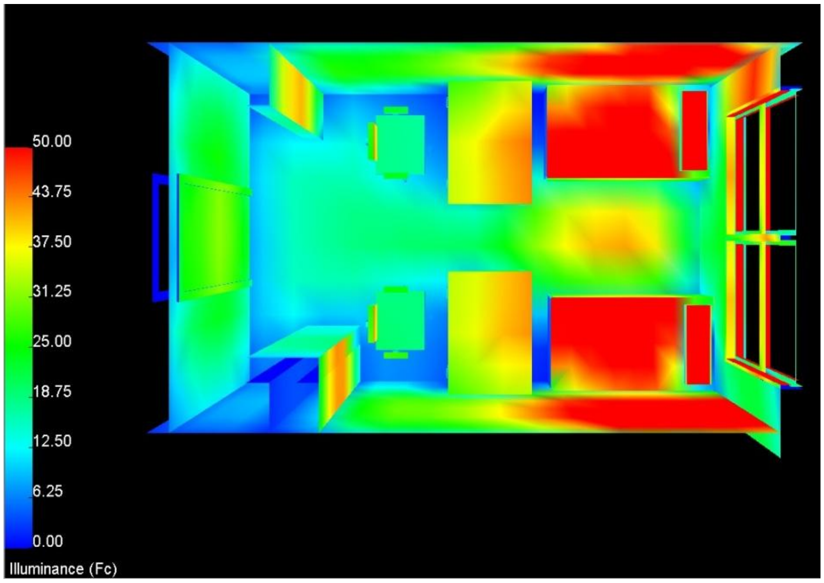


Figure 59: *Pseudo-color rendering of room 307B with an 8' x 5' window on December 22, 1 PM*

The daylighting analysis for room 307B yielded stronger results than room 311B in favor of doubling the size of the windows for each bedroom and living room. The level of daylight in room 307B would be inadequate for most of the year with a 4 foot by 5 foot window. The students would most likely have to turn on the lights in their room for most of the year to comfortably live in the space. If each room had 8 foot by 5 foot windows, the students would not need to turn on the lights during the day throughout the entire year, because there would be enough natural daylight in every bedroom and living room. This could save the building energy over the entire year and create a more desirable space to live in for the students.

Economic Analysis

Increasing the size of every bedroom and living room window in Des Places has noticeable daylighting benefits but it also brings an added cost to the building, both in its construction and in its yearly maintenance. The glazing for Des Places is much more expensive than the brick exterior wall so increasing the size of most of the windows in the building will result in a higher cost for the building envelope. Table 39 breaks down the additional cost of the building envelope by floor and material. The cost information for the glazing and the masonry wall was found in the original cost estimate for Des Places, done by Regency Construction Services.

Installation Cost of Building Envelope Redesign						
			Floor 2	Floors 3-11	Floor 12	**TOTAL**
Item Description	Cost/SF	Cost/Unit	Cost	Cost	Cost	Cost
PPG Solarban 60 window w/ NX-3500 aluminum frame		$1,211	$21,798	$272,475	$23,009	$317,282
Brick wall w/ 6" metal stud back-up	$21.75		($7,830)	($97,875)	($8,265)	($113,970)
TOTAL			$13,968	$174,600	$14,744	**$203,312**

Table 39: *Additional installation cost for building envelope redesign*

The additional cost for the entire building envelope would be approximately $203,312. This increase is less than 1% of the total projected cost of building Des Places, but it is still a considerable price to pay. In addition to the higher cost for the building envelope, the larger windows would also raise the yearly operational costs for Des Places because the building would have a higher solar heat gain in the warmer months and a higher rate of heat loss during the colder months. This increased energy cost must be addressed as well in order to fully understand the economic impact that the envelope redesign will have on the building. In order to find the increase in yearly energy costs two Trane trace models of Des Places were compared to one another. The first model was for Des Places with the redesigned dedicated outdoor air system that used passive chilled beams for cooling and baseboard radiators for heating. The second model was exactly the same as the first one, except for the building envelope, which had 8 foot by 5 foot windows in every bedroom and living room instead of the original 4 foot by 5 foot windows. After the energy calculations were run for both models their yearly gas and electric consumptions were compared to see how much additional energy Des Places would consume with the larger windows. The differences between both models are recorded in Table 40 and this energy consumption difference was converted into an increase in cost by using the current prices that Duquesne pays for natural gas and electricity. The university currently pays $1.28 per therm for natural gas and $0.087 per kilowatt-hour for electricity.

Yearly Energy Cost For Des Places Residence Hall					
	Yearly Gas Consumption (therms)	Gas Cost	Yearly Electricity Consumption (KW-Hr)	Electricity Cost	**Total Cost**
Building with 4 x 5 windows	10,988	$14,099	622,456	$54,153	$68,252
Building with 8 x 5 windows	12,467	$15,983	625,360	$54,406	$70,389
Difference	1,479	$1,884	2,904	$253	**$2,137**

***Table 40:** Increase in yearly energy cost for Des Places due to building envelope redesign*

The increase in energy costs per year at the current rates that Duquesne is paying for natural gas and electricity is $2,137. This increase in energy consumption will negatively affect the building over its entire existence and it will also offset any energy savings that would result from making the windows larger, such as the reduced use of interior lights during the day. The increase could also result in less LEED points for Des Places in the Energy and Atmosphere section of LEED Version 3.

Conclusion

After analyzing all of the advantages and disadvantages of doubling the size of the bedroom and living room windows in Des Places, it is difficult to justify making this change in the building envelope. The increased window size had the most effect on the north facing rooms, where the daylight levels were inadequate for most of the year with the 4 foot by 5 foot windows. The daylighting analysis of room 311B showed that there was already enough natural daylight entering the east facing rooms for most of the year with the smaller windows. The larger windows certainly let in more daylight to these rooms, but most of the time it was unnecessary because the occupants already had enough natural light to live comfortably without the lights being turned on. After seeing the results from the analysis of a typical east facing room it is safe to assume that having larger windows in the west and south facing rooms would be unnecessary for most of the year as well, because these two sides of the building receive the same or more sunlight than the east side. It is also difficult to predict how much energy would actually be saved by the increase in natural daylight that larger windows would bring to the building. Although it is reasonable to assume that students would not turn on the lights in their room if there was more than enough natural daylight this may not always be the case. Some occupants may use blinds to cover their windows for privacy purposes and would then have to turn on the lights or they might just leave the lights on accidently during the day. A daylight sensor in each room could make up for this human element, but they are expensive and having one in each bedroom and living room would most likely not be feasible. According to RS Means, the total cost of buying and installing a daylight level sensor is $212. There would need to be over 200 of these sensors installed if they were put in every bedroom and living room, which could cost over $42,000.

The daylighting and energy saving benefits of having larger windows are somewhat difficult to quantify, but the additional cost that they would bring to the building envelope and yearly energy costs are not difficult to put into tangible terms. This would make it even more difficult to convince Duquesne University that doubling the size of the windows is a worthwhile investment. The larger windows would increase the cost of the building envelope by $203,312 and they would increase the yearly energy costs for the building by $2,137. Therefore the proposed building envelope could not be justified economically. The strongest argument in favor of the larger windows would be that they increase the comfort of the occupants by allowing more natural light into their rooms which could consequently result in happier and more productive students. This argument would most likely not be convincing enough to justify the additional costs for Duquesne University.

Final Conclusion and Recommendations

Several alterations and additions were proposed and analyzed for the mechanical system of Des Places. The dedicated outdoor air system was redesigned to use radiant chilled ceilings and baseboard radiators instead of fan coil units to meet the sensible heating and cooling loads of the building. The alternative system cost $186,528 less than the original fan coil unit DOAS system and the radiant ceilings and baseboard radiators can provide a higher level of comfort for the occupants of Des Places. This is primarily due to the fact that the fan noise in each room is eliminated and that radiant ceilings are superior to fan coil units in creating a uniform temperature distribution throughout a given room. The biggest disadvantage to the proposed DOAS system is the fact that it consumes more energy than the original design, which would result in a predicted annual increase of $7,370 in operational costs for the building. Despite this drawback the radiant ceilings and baseboard radiators could still be the best choice for the dedicated outdoor air system in Des Places, if Duquesne places the comfort and productivity of the students as one of the principle design goals for the building.

The addition of a solar hot water system was also proposed and designed for Des Places. The solar thermal loop would heat the domestic water in the building in series with the existing steam water heater. A structural analysis for the roof of Des Places was also done to ensure that the roof structure could safely hold the additional load of the solar collector array. This analysis showed that the existing structure was basically unaffected by the solar thermal array, with the exception of replacing 8” hollow-core concrete plank with 10” plank in one area. The solar thermal system designed for Des Places would have an initial cost of $94,500, but it can save the central steam plant approximately 2,350 therms of energy per year. The most important aspect of the system is the fact that it’s payback period is less than 10 years with appropriate federal and state financial incentives. The analysis of this solar hot water system has shown that it would be a great addition to the mechanical system for Des Places. The proposed system has a short payback period and will save the building energy over the entire life of the solar collectors.

A change to the building envelope of Des Places was also proposed and analyzed in this report. The proposed change was to double the size of the existing bedroom and living room windows, from 4 feet by 5 feet to 8 feet by 5 feet. The primary goal of this alteration was to increase the amount of natural daylight that entered each room during the day, so that the students could live comfortably in their rooms without having to turn on the lights. A daylighting analysis was completed for a typical east facing bedroom and a typical north facing bedroom to assess the actual increase in lighting that resulted in each room by doubling the size of the windows. The analysis showed that the larger windows did let in much more light, but for most of the year it was an unnecessary increase because the smaller 4 ft. by 5 ft. windows already let in a good amount of natural light. The building envelope redesign also increased the cost of the building by $203,312 and it increased the yearly energy consumption cost for Des Places by $2,137. The analysis showed that the resulting increase in the cost of the building envelope and the increase in the operational costs of Des Places was not worth the limited daylighting benefits of doubling the size of every bedroom and living room window in the building.

MAE Course Related Study

In order to fulfill the requirements for the integrated Masters of Architectural Engineering program, material from various 500 level courses must be incorporated into the senior thesis design process. Information from AE 557 (Centralized Cooling), AE 558 (Centralized Heating) and AE 559 (Computational Fluid Dynamics in Building Design) was utilized to complete this report and satisfy the given MAE requirements.

Material from AE 558 was used several times during the re-design of Des Places. Investment analysis and life-cycle cost strategies presented in this class were used to determine the payback period for the solar thermal system. This material was used again when completing the life-cycle cost analysis for the redesigned dedicated outdoor air system. Information learned in AE 558 about hot water systems and steam systems was used in the design and selection of the solar thermal system for Des Places. It was also used to determine how the solar hot water loop would tie in with the existing steam domestic water heater.

Material from both AE 557 and AE 558 was used in selecting and redesigning the parallel cooling and heating systems for the dedicated outdoor air system. AE 557 covers all aspects of a centralized cooling system, such as the different types of refrigeration processes, the various components of a given system, different pumping and piping options, instrumentation and controls. This thorough background knowledge of the various components in a centralized cooling system was instrumental in understanding and interpreting energy model results for the original and re-designed dedicated outdoor air systems.

AE 559 covers the principles and theories behind computational fluid dynamics analysis and teaches students how to use a CFD software package effectively to get reliable and accurate results for any type of simulation. Phoenics was chosen by Professor Jelena Srebric as the CFD software that would be used for AE 559. The same software was also used for this report to conduct a CFD analysis that compared the cooling performance of an existing Whalen fan coil unit to the cooling performance of the proposed alternative system, a radiant ceiling. Both systems were tested in the same bedroom in Des Places with the same internal loads. The temperature and velocity fields produced in the room by each system were compared to see which option created a more thermally comfortable space. Knowledge learned in AE 559 was crucial in creating an accurate model of the bedroom, with the correct boundary conditions and internal heat loads. The correct turbulence models and simulation characteristics for both models were also chosen based on material covered in AE 559. Results from the CFD analysis proved that the radiant ceiling produced an overall lower temperature in the room and made the temperature distribution throughout the room more uniform than with a fan coil unit. These results show that a radiant ceiling can produce a more thermally comfortable space for the students living in Des Places. This theory could not have been proven without accurate results from the Phoenics models, and these models could not have been constructed without the knowledge learned in AE 559.

Credits and Acknowledgements

I would like to thank everyone that helped me throughout my yearlong study of Des Places Residence Hall. Without the support of everyone that assisted me along the way, I would not have been able to complete my Senior Thesis. I would like to give a special thanks to the following people:

- CJL Engineering – Thank you to the following people for always answering my phone calls and providing me with all the information that I needed
    - Craig Duda – Lead engineer for the design of the mechanical system of Des Places Residence Hall
    - Harry Hoover – Mechanical Engineer
    - Tony Valenza – Mechanical Engineer
    - Brad Allis – Mechanical Engineer and Drafting
- Adam Stadt – Architect for WTW Architecture
- Duquesne University – Thank you for allowing me to use Des Places Residence Hall as my senior thesis building
- Regency Construction Services
- George Hoekstra – Engineer for Barcol-Air
- Eric Skiba – Engineer for Apricus Solar Collectors
- Jason Brognano – Thank you for teaching me how to do a daylighting study in AGI
- Carl Hubben – Thank you for helping me with my structural breadth
- Bob Holland and Kevin Parfitt – Professors for Senior Thesis
- Dustin Eplee – Thank you for stepping in as my senior thesis advisor and giving me great feedback and advice throughout the year.

I would also like to thank all of the professors in the Architectural Engineering department that have helped me or instructed me during my five years at Penn State. Thank you to my family and friends that have supported me during my time at Penn State and throughout my entire life.

Lastly I would like to give a special thanks to my mom and dad, who have always supported me unconditionally and given me everything I needed to be successful in school.

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Appendix A: List of Tables and Figures

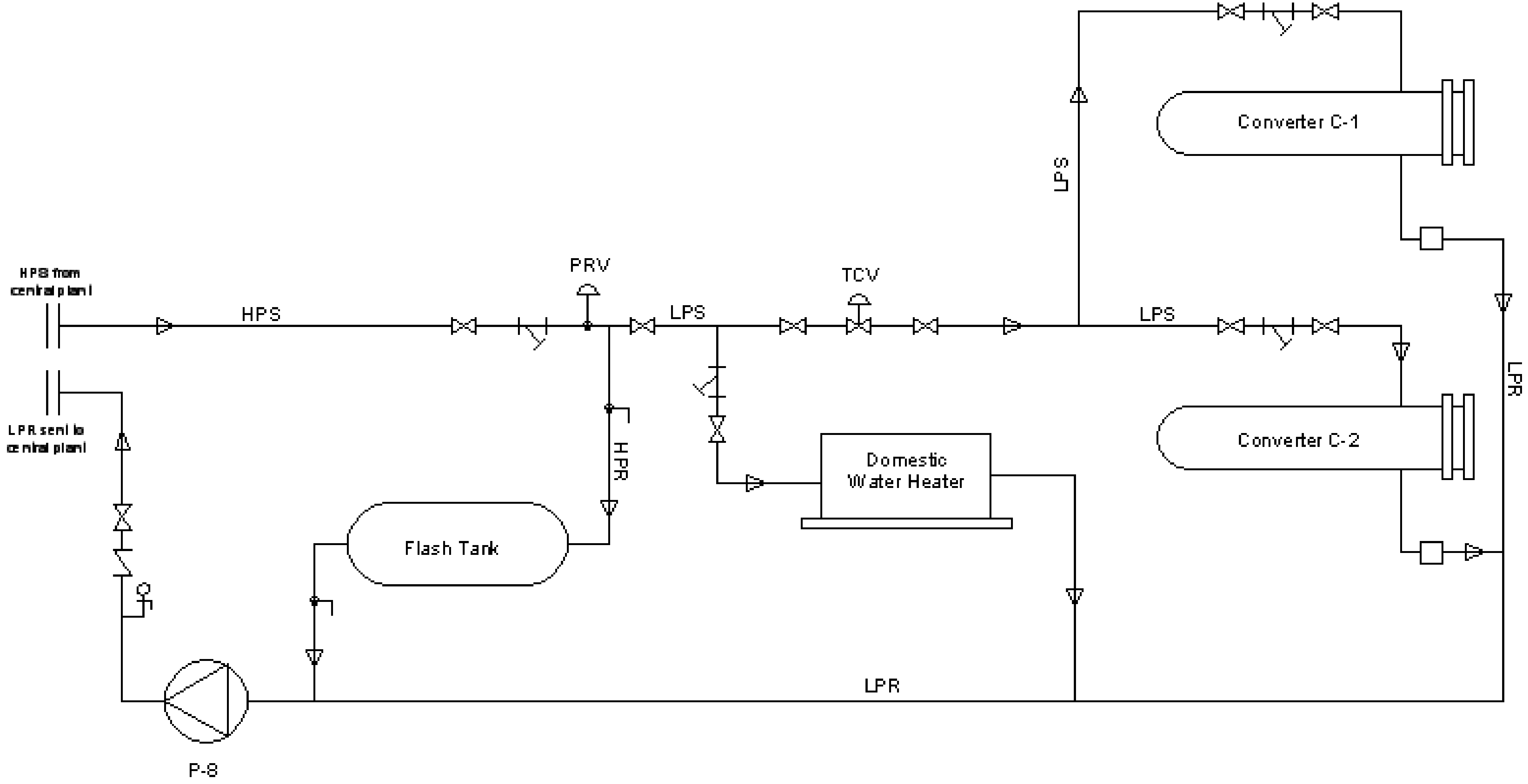
Tables

Figures

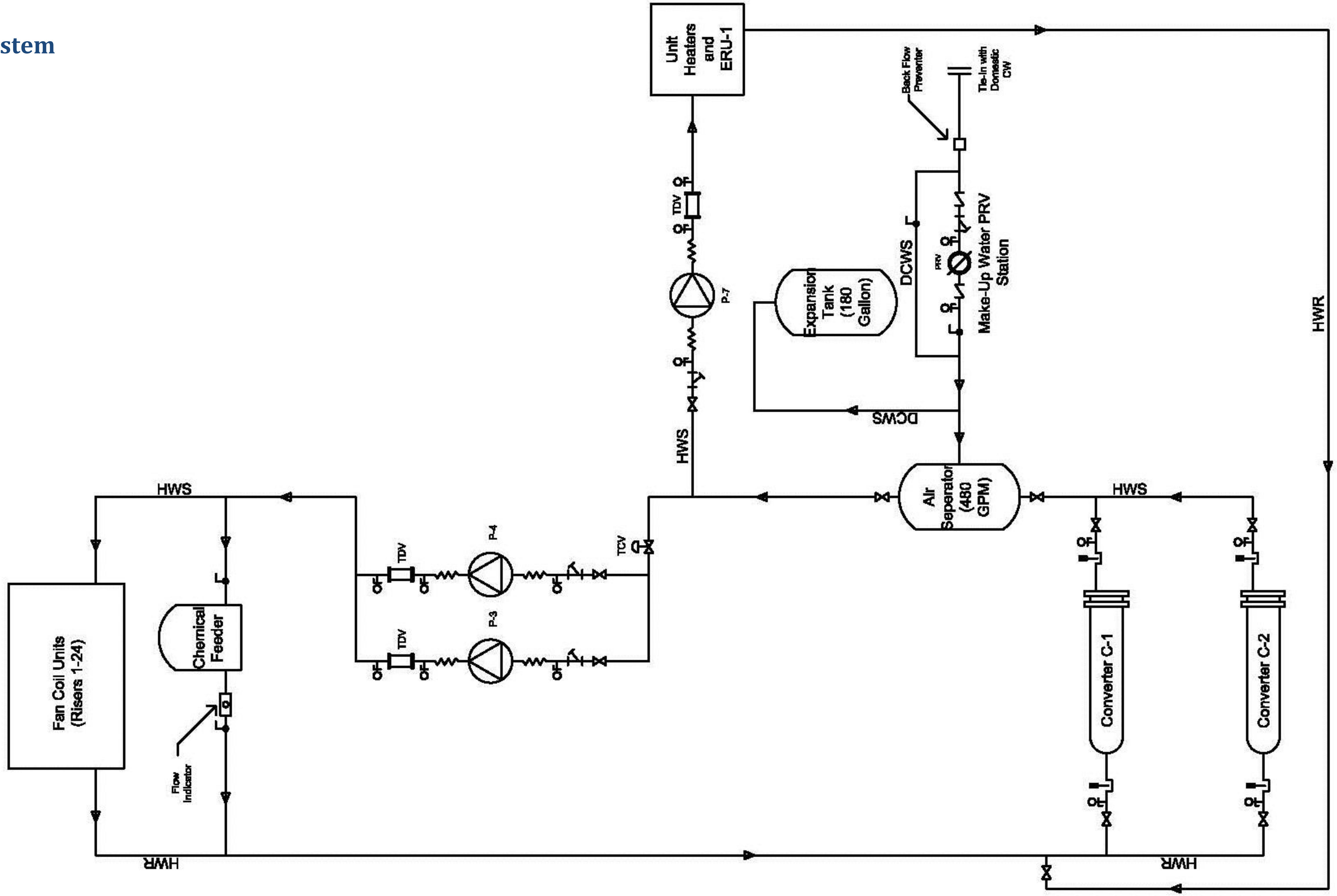
- ***Figure 59:*** *Pseudo-color rendering of room 307B with an 8’ x 5’ window on December 22, 1 PM*

Appendix B: Existing System Schematics

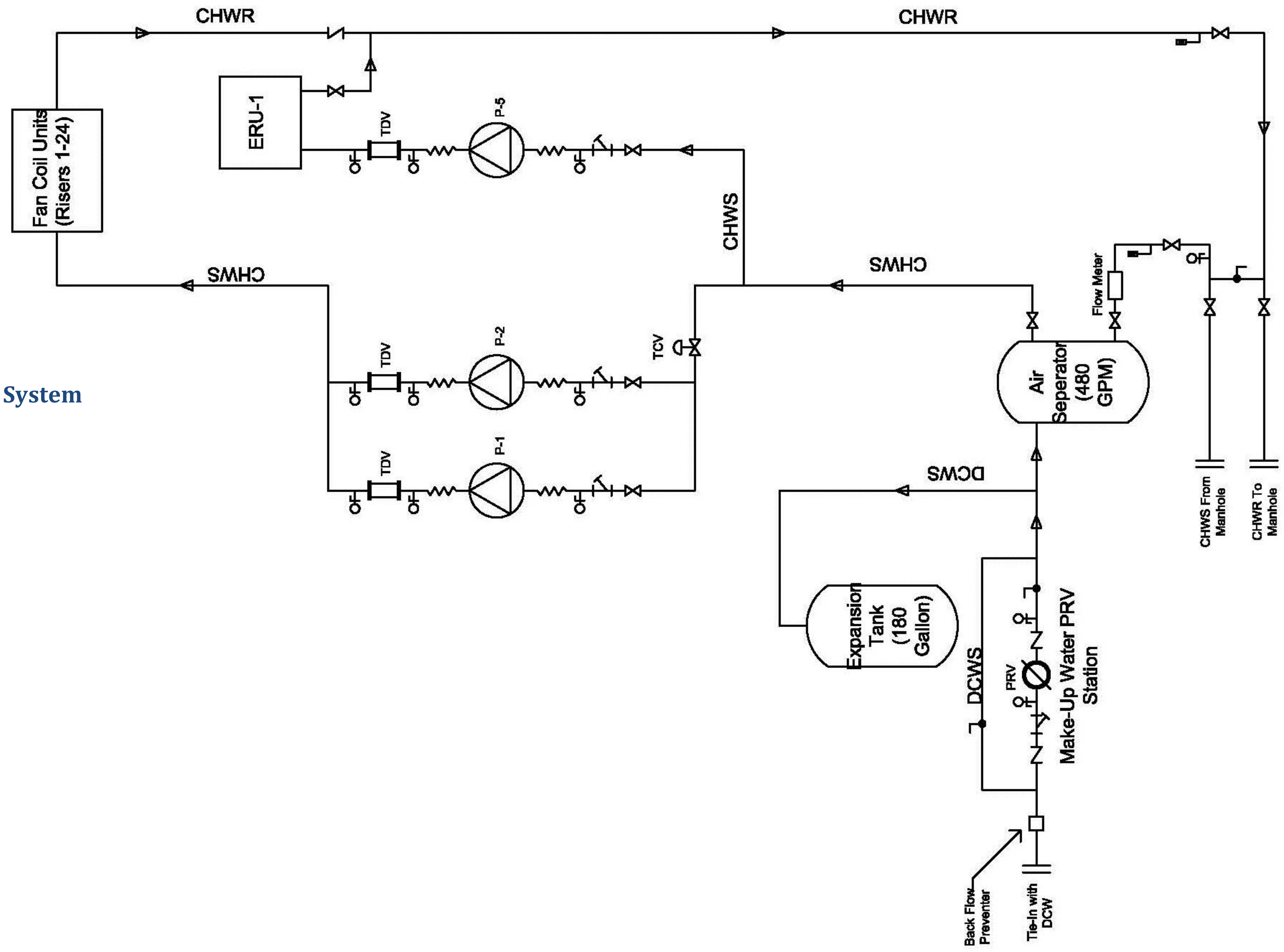
Steam System



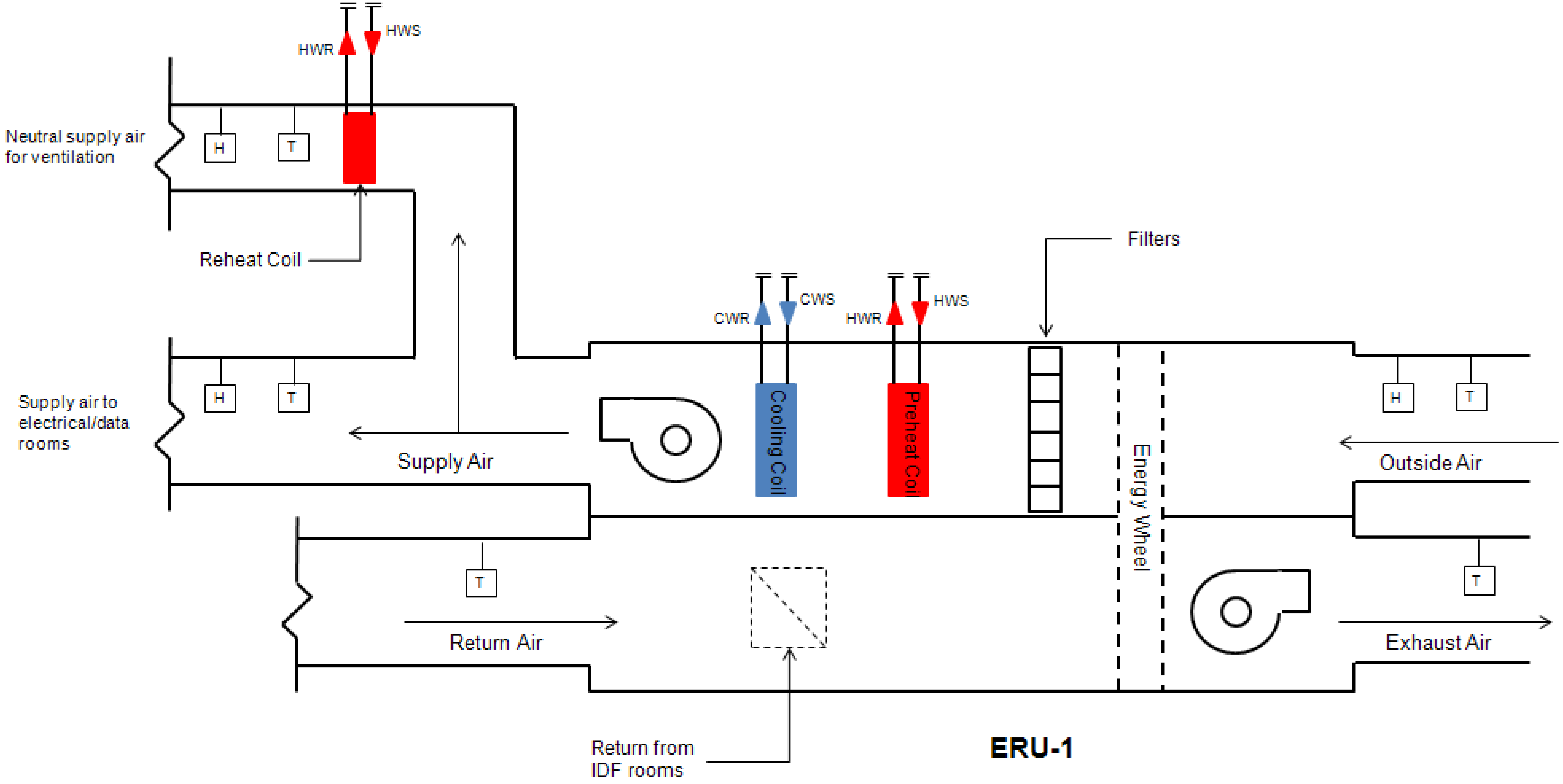
Hot Water System



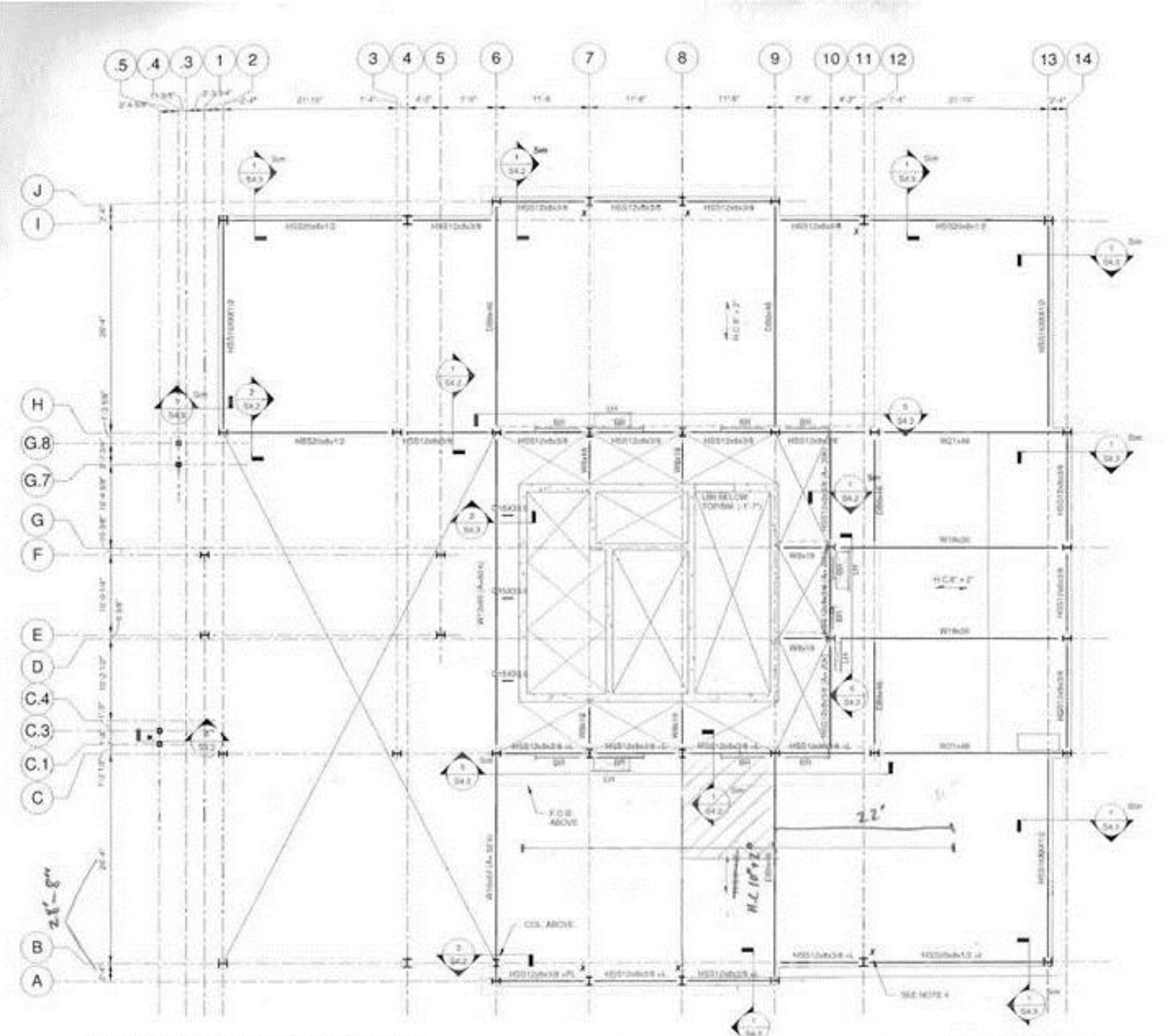
Chilled Water System



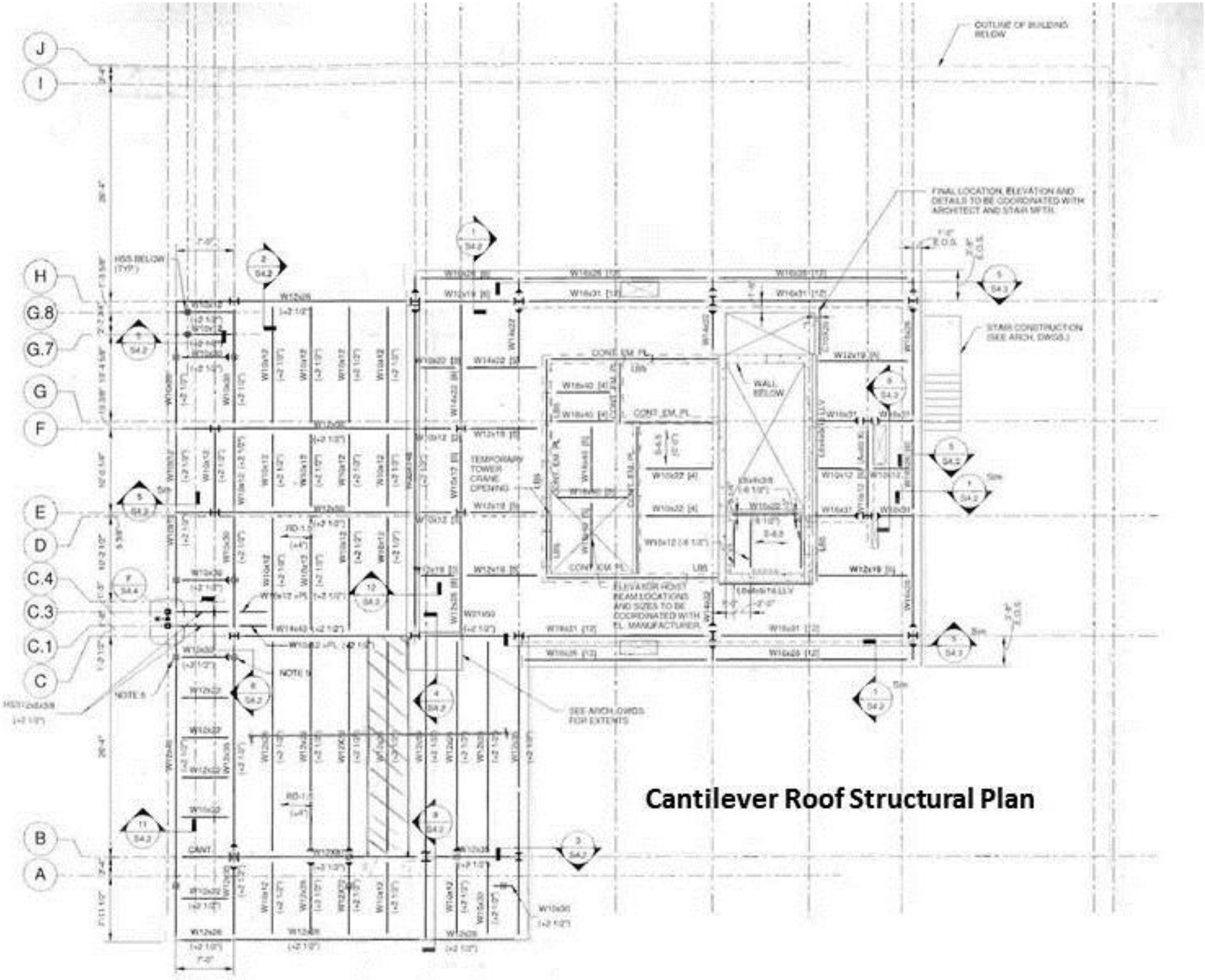
Dedicated Outdoor Air System



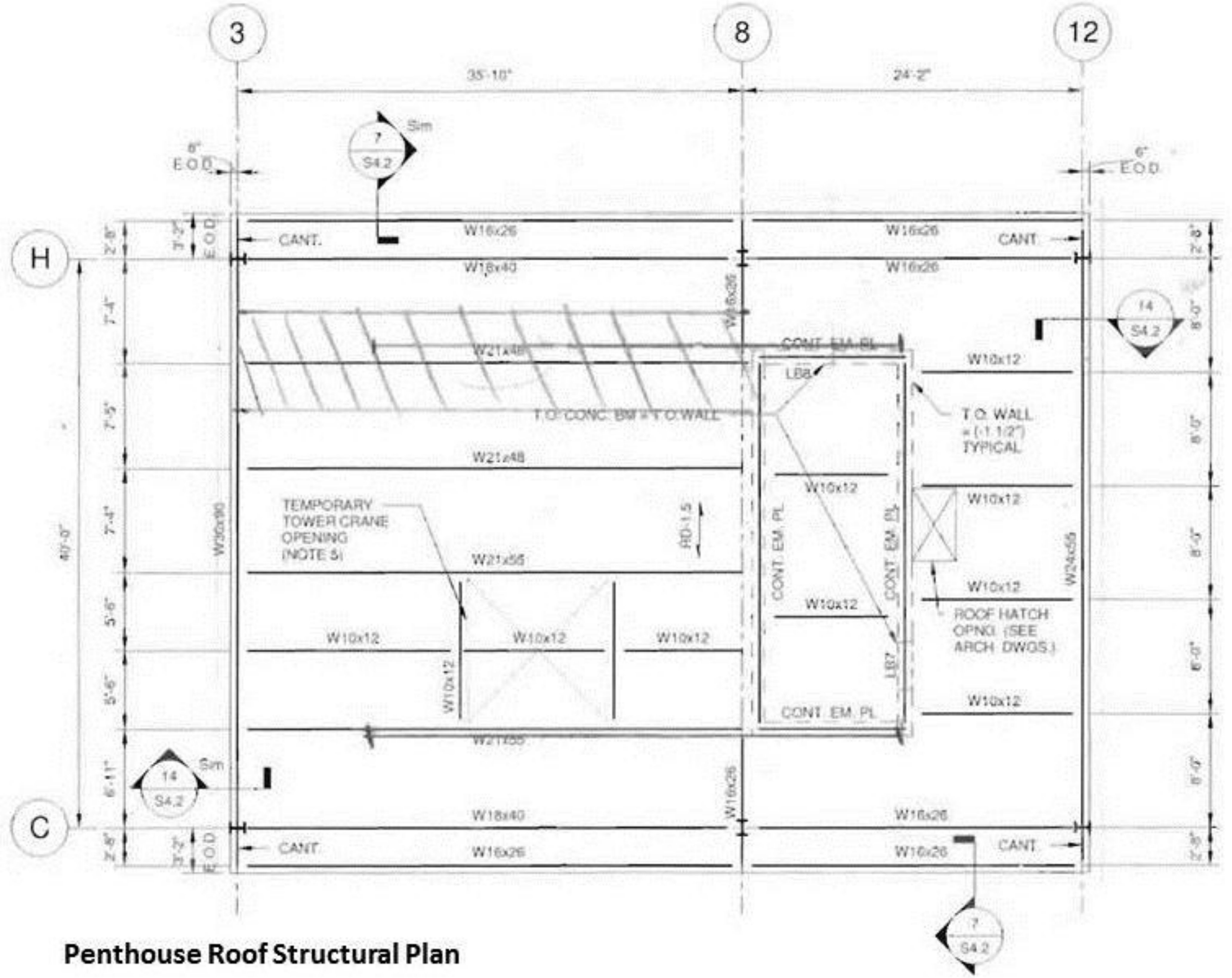
Appendix C: Roof Structural Plans



Main Roof Structural Plan

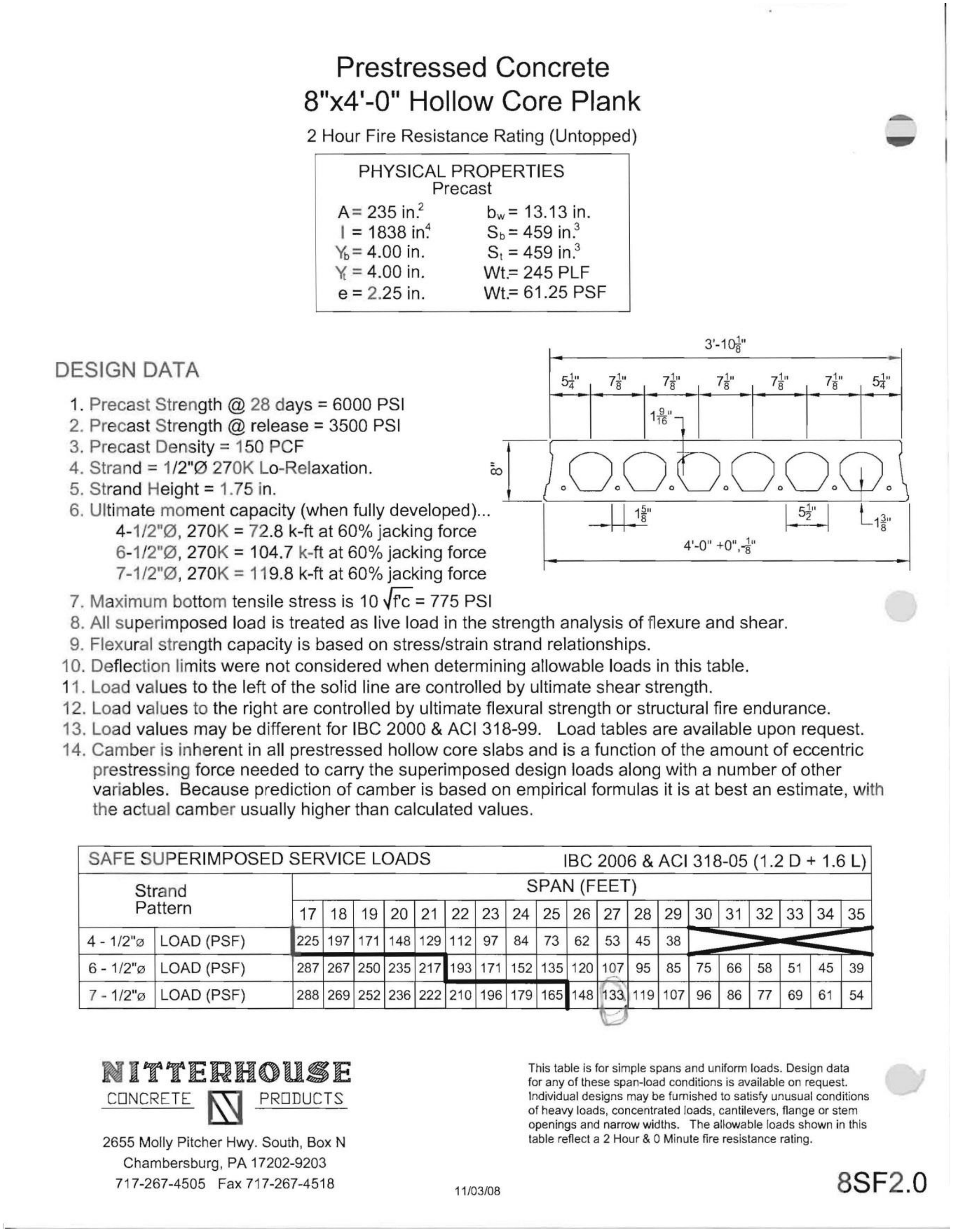


Cantilever Roof Structural Plan



Penthouse Roof Structural Plan

Appendix D: Hollow Core Plank and Metal Decking Specifications



Prestressed Concrete
8"x4'-0" Hollow Core Plank

2 Hour Fire Resistance Rating (Untopped)

PHYSICAL PROPERTIES
Precast

A = 235 in.^{2}	b_w = 13.13 in.
I = 1838 in.^{4}	S_b = 459 in.^{3}
Y_b = 4.00 in.	S_t = 459 in.^{3}
Y_t = 4.00 in.	Wt.= 245 PLF
e = 2.25 in.	Wt.= 61.25 PSF

DESIGN DATA

1. Precast Strength @ 28 days = 6000 PSI
2. Precast Strength @ release = 3500 PSI
3. Precast Density = 150 PCF
4. Strand = 1/2"Ø 270K Lo-Relaxation.
5. Strand Height = 1.75 in.
6. Ultimate moment capacity (when fully developed)...
   4-1/2"Ø, 270K = 72.8 k-ft at 60% jacking force
   6-1/2"Ø, 270K = 104.7 k-ft at 60% jacking force
   7-1/2"Ø, 270K = 119.8 k-ft at 60% jacking force
7. Maximum bottom tensile stress is $10\sqrt{f'c}$ = 775 PSI
8. All superimposed load is treated as live load in the strength analysis of flexure and shear.
9. Flexural strength capacity is based on stress/strain strand relationships.
10. Deflection limits were not considered when determining allowable loads in this table.
11. Load values to the left of the solid line are controlled by ultimate shear strength.
12. Load values to the right are controlled by ultimate flexural strength or structural fire endurance.
13. Load values may be different for IBC 2000 & ACI 318-99. Load tables are available upon request.
14. Camber is inherent in all prestressed hollow core slabs and is a function of the amount of eccentric prestressing force needed to carry the superimposed design loads along with a number of other variables. Because prediction of camber is based on empirical formulas it is at best an estimate, with the actual camber usually higher than calculated values.

SAFE SUPERIMPOSED SERVICE LOADS — IBC 2006 & ACI 318-05 (1.2 D + 1.6 L)

Strand Pattern		SPAN (FEET)																		
		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
4 - 1/2"ø	LOAD (PSF)	225	197	171	148	129	112	97	84	73	62	53	45	38						
6 - 1/2"ø	LOAD (PSF)	287	267	250	235	217	193	171	152	135	120	107	95	85	75	66	58	51	45	39
7 - 1/2"ø	LOAD (PSF)	288	269	252	236	222	210	196	179	165	148	133	119	107	96	86	77	69	61	54

NITTERHOUSE
CONCRETE PRODUCTS

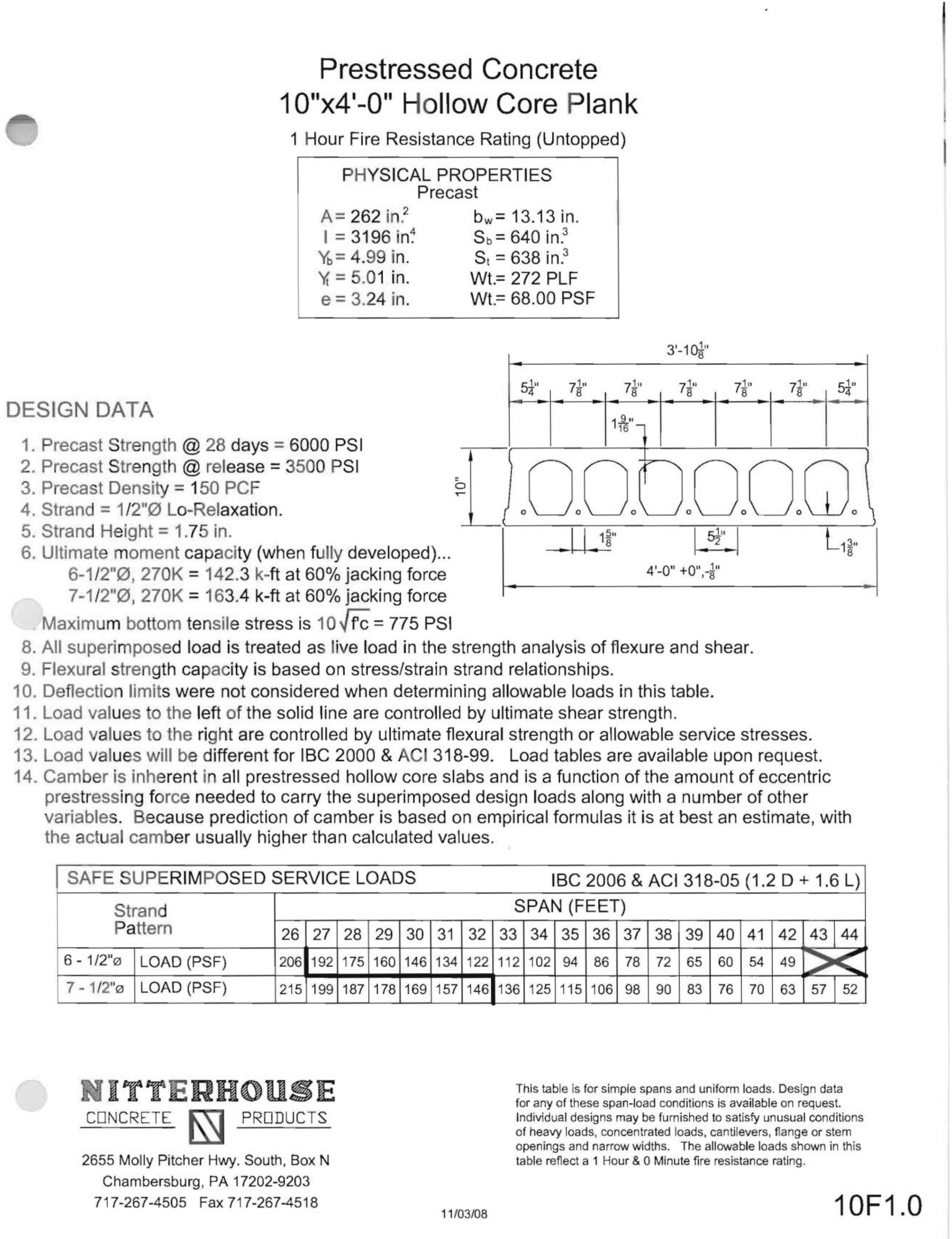
2655 Molly Pitcher Hwy. South, Box N
Chambersburg, PA 17202-9203
717-267-4505 Fax 717-267-4518

This table is for simple spans and uniform loads. Design data for any of these span-load conditions is available on request. Individual designs may be furnished to satisfy unusual conditions of heavy loads, concentrated loads, cantilevers, flange or stem openings and narrow widths. The allowable loads shown in this table reflect a 2 Hour & 0 Minute fire resistance rating.

11/03/08

8SF2.0

Specifications for 8” Hollow Core Plank



Prestressed Concrete
10"x4'-0" Hollow Core Plank

1 Hour Fire Resistance Rating (Untopped)

PHYSICAL PROPERTIES
Precast

$A = 262$ in.^{2}
$I = 3196$ in.^{4}
$Y_b = 4.99$ in.
$Y_t = 5.01$ in.
$e = 3.24$ in.
$b_w = 13.13$ in.
$S_b = 640$ in.^{3}
$S_t = 638$ in.^{3}
Wt.= 272 PLF
Wt.= 68.00 PSF

DESIGN DATA

1. Precast Strength @ 28 days = 6000 PSI
2. Precast Strength @ release = 3500 PSI
3. Precast Density = 150 PCF
4. Strand = 1/2"Ø Lo-Relaxation.
5. Strand Height = 1.75 in.
6. Ultimate moment capacity (when fully developed)...
   6-1/2"Ø, 270K = 142.3 k-ft at 60% jacking force
   7-1/2"Ø, 270K = 163.4 k-ft at 60% jacking force

Maximum bottom tensile stress is $10\sqrt{f'c}$ = 775 PSI

8. All superimposed load is treated as live load in the strength analysis of flexure and shear.
9. Flexural strength capacity is based on stress/strain strand relationships.
10. Deflection limits were not considered when determining allowable loads in this table.
11. Load values to the left of the solid line are controlled by ultimate shear strength.
12. Load values to the right are controlled by ultimate flexural strength or allowable service stresses.
13. Load values will be different for IBC 2000 & ACI 318-99. Load tables are available upon request.
14. Camber is inherent in all prestressed hollow core slabs and is a function of the amount of eccentric prestressing force needed to carry the superimposed design loads along with a number of other variables. Because prediction of camber is based on empirical formulas it is at best an estimate, with the actual camber usually higher than calculated values.

SAFE SUPERIMPOSED SERVICE LOADS — IBC 2006 & ACI 318-05 (1.2 D + 1.6 L)

Strand Pattern		SPAN (FEET)																	
		26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
6 - 1/2"ø	LOAD (PSF)	206	192	175	160	146	134	122	112	102	94	86	78	72	65	60	54	49		
7 - 1/2"ø	LOAD (PSF)	215	199	187	178	169	157	146	136	125	115	106	98	90	83	76	70	63	57	52

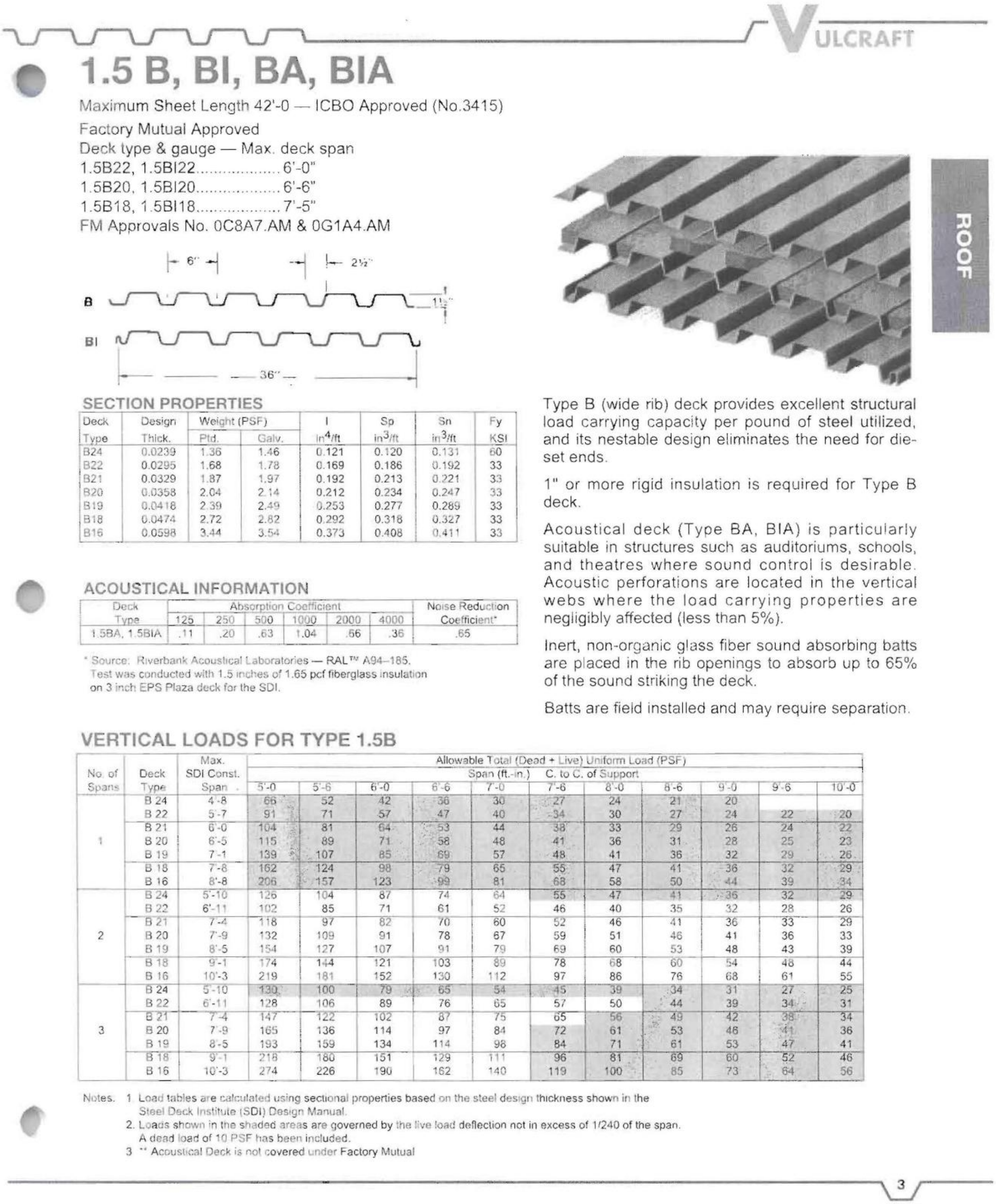
NITTERHOUSE
CONCRETE PRODUCTS
2655 Molly Pitcher Hwy. South, Box N
Chambersburg, PA 17202-9203
717-267-4505 Fax 717-267-4518

This table is for simple spans and uniform loads. Design data for any of these span-load conditions is available on request. Individual designs may be furnished to satisfy unusual conditions of heavy loads, concentrated loads, cantilevers, flange or stem openings and narrow widths. The allowable loads shown in this table reflect a 1 Hour & 0 Minute fire resistance rating.

11/03/08

10F1.0

Specifications for 10” Hollow Core Plank



VULCRAFT

1.5 B, BI, BA, BIA

Maximum Sheet Length 42'-0 — ICBO Approved (No.3415)
Factory Mutual Approved
Deck type & gauge — Max. deck span
1.5B22, 1.5BI22.................. 6'-0"
1.5B20, 1.5BI20.................. 6'-6"
1.5B18, 1.5BI18.................. 7'-5"
FM Approvals No. 0C8A7.AM & 0G1A4.AM

SECTION PROPERTIES

Deck Type	Design Thick.	Weight (PSF) Ptd.	Weight (PSF) Galv.	I In^4/ft	Sp in^3/ft	Sn in^3/ft	Fy KSI
B24	0.0239	1.36	1.46	0.121	0.120	0.131	60
B22	0.0295	1.68	1.78	0.169	0.186	0.192	33
B21	0.0329	1.87	1.97	0.192	0.213	0.221	33
B20	0.0358	2.04	2.14	0.212	0.234	0.247	33
B19	0.0418	2.39	2.49	0.253	0.277	0.289	33
B18	0.0474	2.72	2.82	0.292	0.318	0.327	33
B16	0.0598	3.44	3.54	0.373	0.408	0.411	33

ACOUSTICAL INFORMATION

Deck Type	Absorption Coefficient 125	250	500	1000	2000	4000	Noise Reduction Coefficient*
1.5BA, 1.5BIA	.11	.20	.63	1.04	.66	.36	.65

* Source: Riverbank Acoustical Laboratories — RAL™ A94–185. Test was conducted with 1.5 inches of 1.65 pcf fiberglass insulation on 3 inch EPS Plaza deck for the SDI.

Type B (wide rib) deck provides excellent structural load carrying capacity per pound of steel utilized, and its nestable design eliminates the need for die-set ends.

1" or more rigid insulation is required for Type B deck.

Acoustical deck (Type BA, BIA) is particularly suitable in structures such as auditoriums, schools, and theatres where sound control is desirable. Acoustic perforations are located in the vertical webs where the load carrying properties are negligibly affected (less than 5%).

Inert, non-organic glass fiber sound absorbing batts are placed in the rib openings to absorb up to 65% of the sound striking the deck.

Batts are field installed and may require separation.

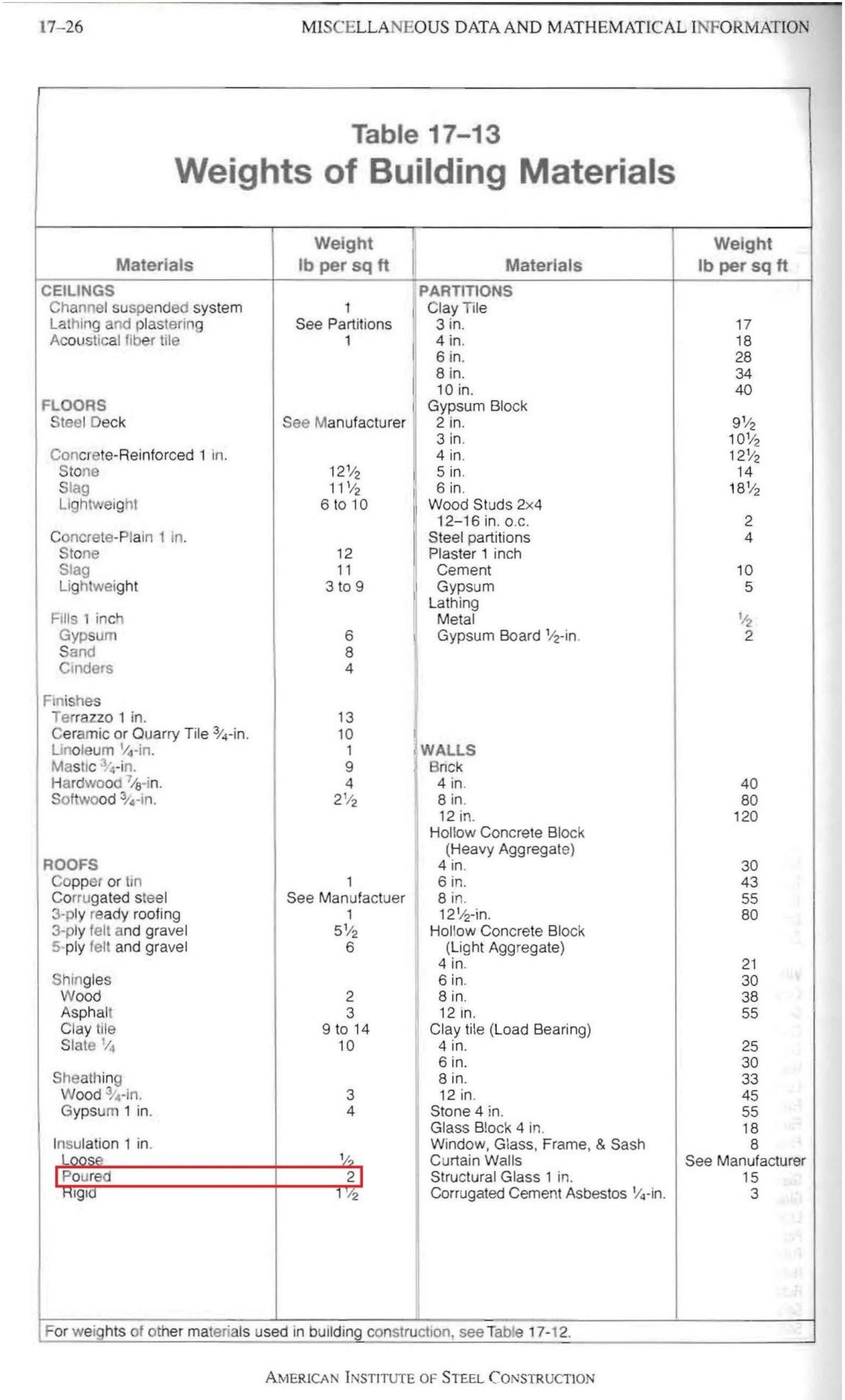
VERTICAL LOADS FOR TYPE 1.5B

No. of Spans	Deck Type	Max. SDI Const. Span	Allowable Total (Dead + Live) Uniform Load (PSF) Span (ft.-in.) C. to C. of Support 5'-0	5'-6	6'-0	6'-6	7'-0	7'-6	8'-0	8'-6	9'-0	9'-6	10'-0
1	B 24	4'-8	66	52	42	36	30	27	24	21	20		
	B 22	5'-7	91	71	57	47	40	34	30	27	24	22	20
	B 21	6'-0	104	81	64	53	44	38	33	29	26	24	22
	B 20	6'-5	115	89	71	58	48	41	36	31	28	25	23
	B 19	7'-1	139	107	85	69	57	48	41	36	32	29	26
	B 18	7'-8	162	124	98	79	65	55	47	41	36	32	29
	B 16	8'-8	206	157	123	99	81	68	58	50	44	39	34
2	B 24	5'-10	126	104	87	74	64	55	47	41	36	32	29
	B 22	6'-11	102	85	71	61	52	46	40	35	32	28	26
	B 21	7'-4	118	97	82	70	60	52	46	41	36	33	29
	B 20	7'-9	132	109	91	78	67	59	51	46	41	36	33
	B 19	8'-5	154	127	107	91	79	69	60	53	48	43	39
	B 18	9'-1	174	144	121	103	89	78	68	60	54	48	44
	B 16	10'-3	219	181	152	130	112	97	86	76	68	61	55
3	B 24	5'-10	130	100	79	65	54	45	39	34	31	27	25
	B 22	6'-11	128	106	89	76	65	57	50	44	39	34	31
	B 21	7'-4	147	122	102	87	75	65	56	49	42	38	34
	B 20	7'-9	165	136	114	97	84	72	61	53	46	41	36
	B 19	8'-5	193	159	134	114	98	84	71	61	53	47	41
	B 18	9'-1	218	180	151	129	111	96	81	69	60	52	46
	B 16	10'-3	274	226	190	162	140	119	100	85	73	64	56

Notes. 1. Load tables are calculated using sectional properties based on the steel design thickness shown in the Steel Deck Institute (SDI) Design Manual.
2. Loads shown in the shaded areas are governed by the live load deflection not in excess of 1/240 of the span. A dead load of 10 PSF has been included.
3 ** Acoustical Deck is not covered under Factory Mutual

3

Specifications for 1.5" Metal Deck



17–26 MISCELLANEOUS DATA AND MATHEMATICAL INFORMATION

Table 17–13
Weights of Building Materials

Materials	Weight lb per sq ft	Materials	Weight lb per sq ft
CEILINGS		PARTITIONS	
Channel suspended system	1	Clay Tile	
Lathing and plastering	See Partitions	3 in.	17
Acoustical fiber tile	1	4 in.	18
		6 in.	28
		8 in.	34
		10 in.	40
FLOORS		Gypsum Block	
Steel Deck	See Manufacturer	2 in.	9½
		3 in.	10½
Concrete-Reinforced 1 in.		4 in.	12½
Stone	12½	5 in.	14
Slag	11½	6 in.	18½
Lightweight	6 to 10	Wood Studs 2×4	
		12–16 in. o.c.	2
Concrete-Plain 1 in.		Steel partitions	4
Stone	12	Plaster 1 inch	
Slag	11	Cement	10
Lightweight	3 to 9	Gypsum	5
		Lathing	
Fills 1 inch		Metal	½
Gypsum	6	Gypsum Board ½-in.	2
Sand	8		
Cinders	4		
Finishes			
Terrazzo 1 in.	13		
Ceramic or Quarry Tile ¾-in.	10		
Linoleum ¼-in.	1	WALLS	
Mastic ¾-in.	9	Brick	
Hardwood ⅞-in.	4	4 in.	40
Softwood ¾-in.	2½	8 in.	80
		12 in.	120
		Hollow Concrete Block	
		(Heavy Aggregate)	
ROOFS		4 in.	30
Copper or tin	1	6 in.	43
Corrugated steel	See Manufactuer	8 in.	55
3-ply ready roofing	1	12½-in.	80
3-ply felt and gravel	5½	Hollow Concrete Block	
5-ply felt and gravel	6	(Light Aggregate)	
		4 in.	21
Shingles		6 in.	30
Wood	2	8 in.	38
Asphalt	3	12 in.	55
Clay tile	9 to 14	Clay tile (Load Bearing)	
Slate ¼	10	4 in.	25
		6 in.	30
Sheathing		8 in.	33
Wood ¾-in.	3	12 in.	45
Gypsum 1 in.	4	Stone 4 in.	55
		Glass Block 4 in.	18
Insulation 1 in.		Window, Glass, Frame, & Sash	8
Loose	½	Curtain Walls	See Manufacturer
Poured	2	Structural Glass 1 in.	15
Rigid	1½	Corrugated Cement Asbestos ¼-in.	3

For weights of other materials used in building construction, see Table 17-12.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION

Weights of Building Materials given in AISC Steel Manual

Appendix E: Weights of Building Materials

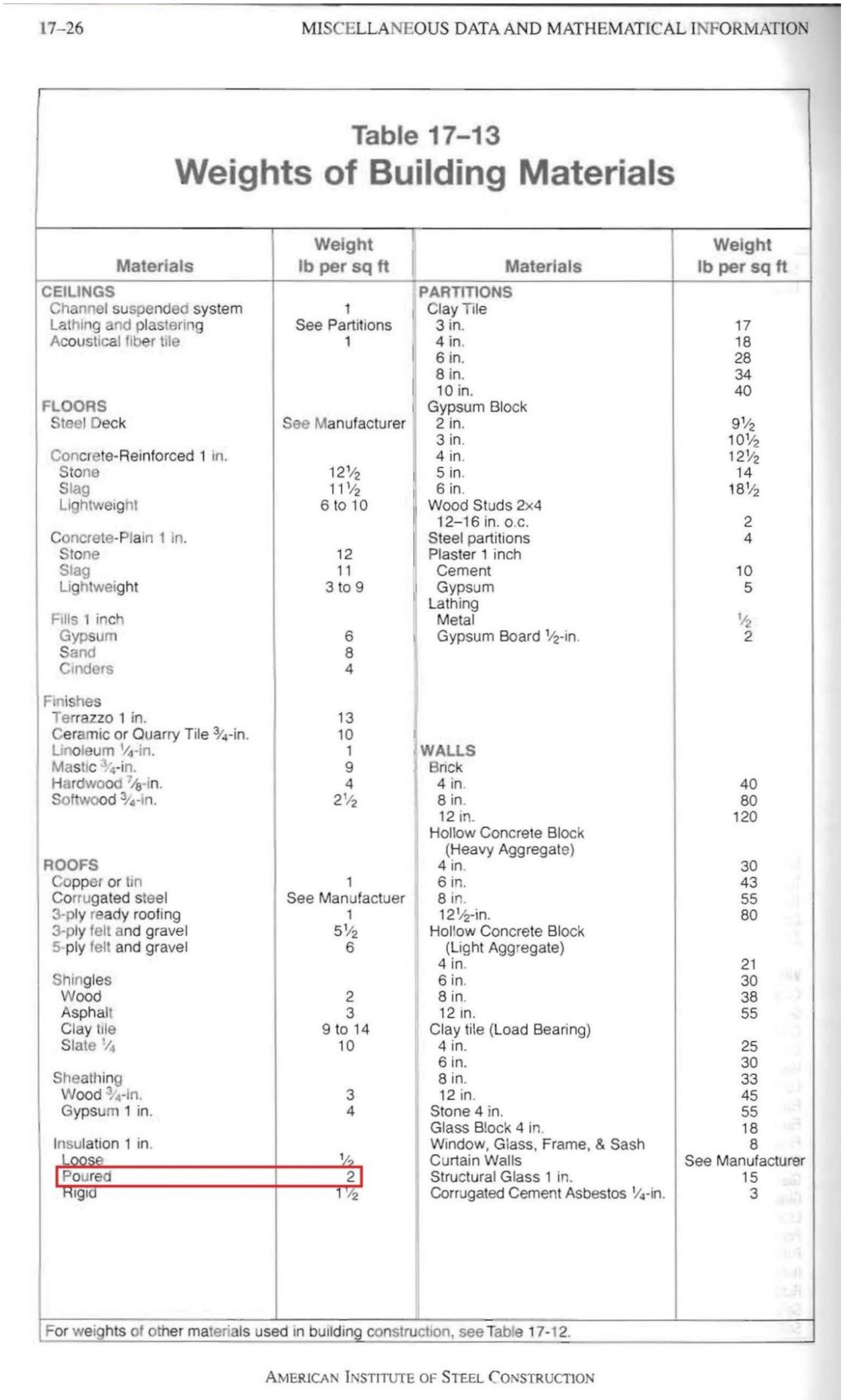


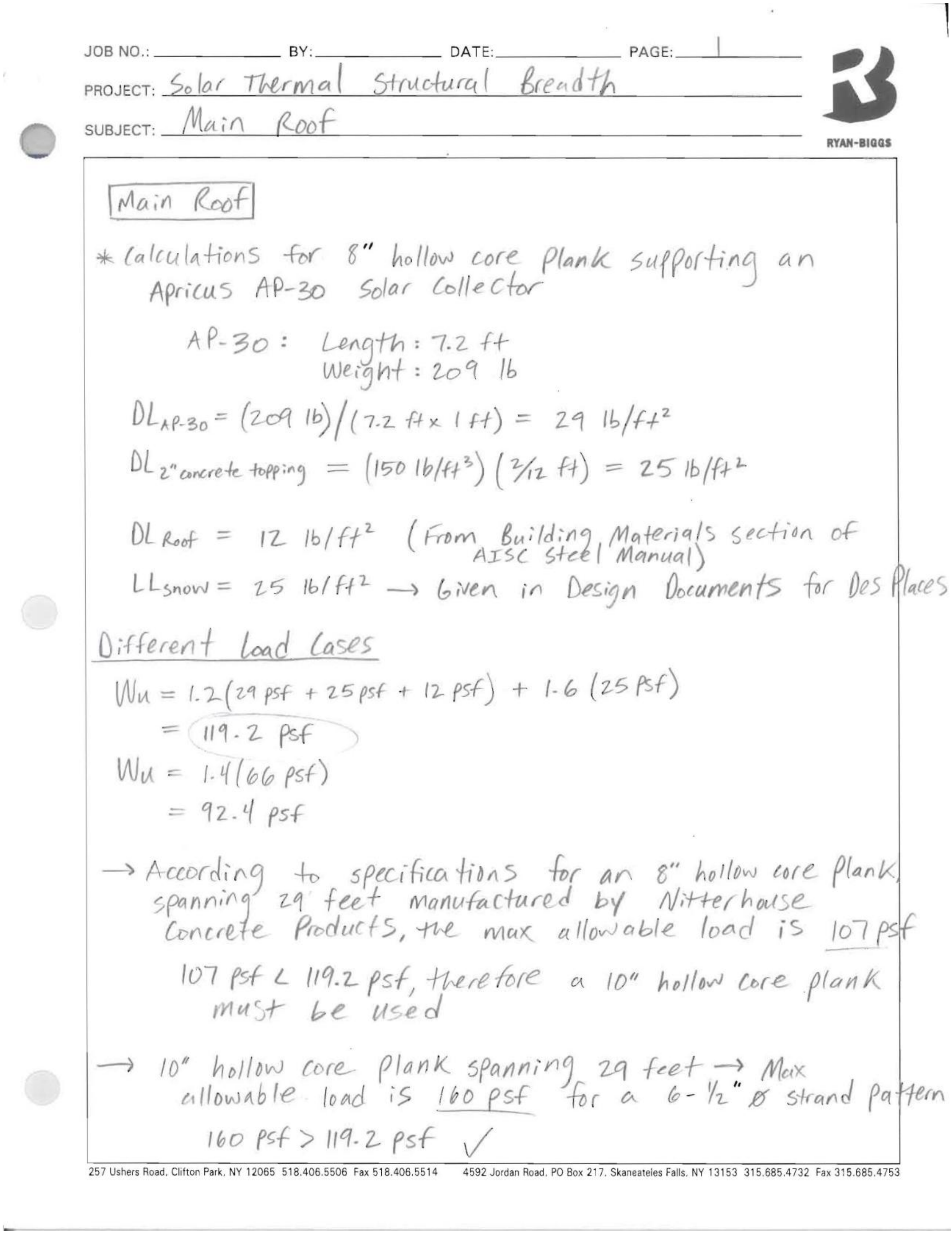
Table 17–13
Weights of Building Materials

Materials	Weight lb per sq ft	Materials	Weight lb per sq ft
CEILINGS		PARTITIONS	
Channel suspended system	1	Clay Tile	
Lathing and plastering	See Partitions	3 in.	17
Acoustical fiber tile	1	4 in.	18
		6 in.	28
		8 in.	34
		10 in.	40
FLOORS		Gypsum Block	
Steel Deck	See Manufacturer	2 in.	9½
		3 in.	10½
Concrete-Reinforced 1 in.		4 in.	12½
Stone	12½	5 in.	14
Slag	11½	6 in.	18½
Lightweight	6 to 10	Wood Studs 2×4	
		12–16 in. o.c.	2
Concrete-Plain 1 in.		Steel partitions	4
Stone	12	Plaster 1 inch	
Slag	11	Cement	10
Lightweight	3 to 9	Gypsum	5
		Lathing	
Fills 1 inch		Metal	½
Gypsum	6	Gypsum Board ½-in.	2
Sand	8		
Cinders	4		
Finishes			
Terrazzo 1 in.	13		
Ceramic or Quarry Tile ¾-in.	10		
Linoleum ¼-in.	1	WALLS	
Mastic ¾-in.	9	Brick	
Hardwood ⅞-in.	4	4 in.	40
Softwood ¾-in.	2½	8 in.	80
		12 in.	120
		Hollow Concrete Block	
		(Heavy Aggregate)	
ROOFS		4 in.	30
Copper or tin	1	6 in.	43
Corrugated steel	See Manufactuer	8 in.	55
3-ply ready roofing	1	12½-in.	80
3-ply felt and gravel	5½	Hollow Concrete Block	
5-ply felt and gravel	6	(Light Aggregate)	
		4 in.	21
Shingles		6 in.	30
Wood	2	8 in.	38
Asphalt	3	12 in.	55
Clay tile	9 to 14	Clay tile (Load Bearing)	
Slate ¼	10	4 in.	25
		6 in.	30
Sheathing		8 in.	33
Wood ¾-in.	3	12 in.	45
Gypsum 1 in.	4	Stone 4 in.	55
		Glass Block 4 in.	18
Insulation 1 in.		Window, Glass, Frame, & Sash	8
Loose	½	Curtain Walls	See Manufacturer
Poured	2	Structural Glass 1 in.	15
Rigid	1½	Corrugated Cement Asbestos ¼-in.	3

For weights of other materials used in building construction, see Table 17-12.

Weights of Building Materials given in AISC Steel Manual

Appendix F: Hand Calculations for Structural Breadth



JOB NO.: BY: DATE: PAGE: 1

PROJECT: Solar Thermal Structural Breadth

SUBJECT: Main Roof

RYAN-BIGGS

Main Roof

* Calculations for 8" hollow core Plank supporting an Apricus AP-30 Solar Collector

AP-30: Length: 7.2 ft
Weight: 209 lb

$DL_{AP\text{-}30} = (209\ \text{lb})/(7.2\ \text{ft} \times 1\ \text{ft}) = 29\ \text{lb/ft}^2$

$DL_{2''\ \text{concrete topping}} = (150\ \text{lb/ft}^3)(2/12\ \text{ft}) = 25\ \text{lb/ft}^2$

$DL_{Roof} = 12\ \text{lb/ft}^2$ (From Building Materials section of AISC Steel Manual)

$LL_{snow} = 25\ \text{lb/ft}^2$ → Given in Design Documents for Des Places

Different Load Cases

$W_u = 1.2(29\ \text{psf} + 25\ \text{psf} + 12\ \text{psf}) + 1.6(25\ \text{psf})$

$= 119.2\ \text{psf}$

$W_u = 1.4(66\ \text{psf})$

$= 92.4\ \text{psf}$

→ According to specifications for an 8" hollow core Plank, spanning 29 feet manufactured by Nitterhouse Concrete Products, the max allowable load is 107 psf

107 psf < 119.2 psf, therefore a 10" hollow core plank must be used

→ 10" hollow core plank spanning 29 feet → Max allowable load is 160 psf for a 6-½" ø strand Pattern

160 psf > 119.2 psf ✓

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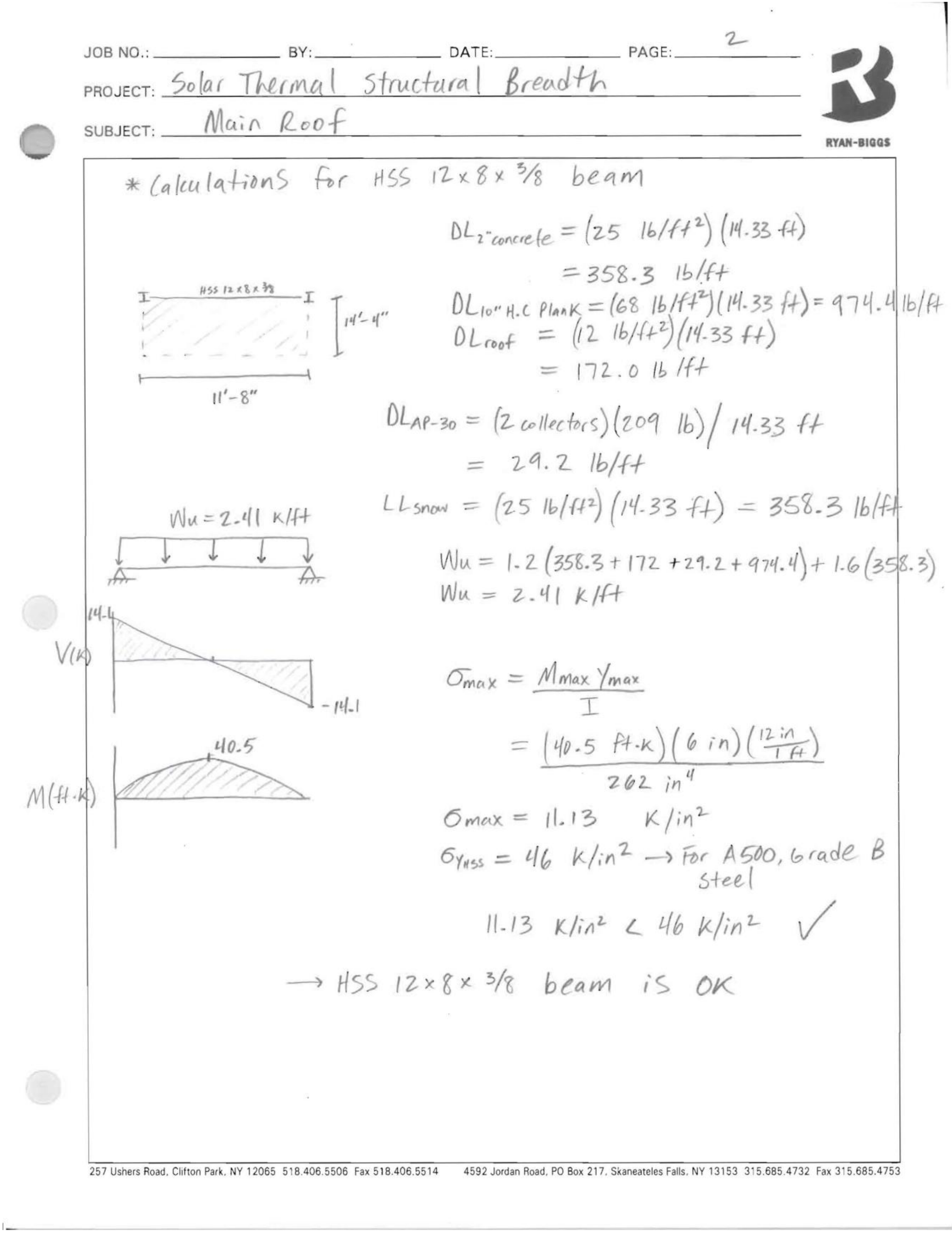

JOB NO.: BY: DATE: PAGE: 2

PROJECT: Solar Thermal Structural Breadth

SUBJECT: Main Roof

RYAN-BIGGS

* Calculations for HSS 12 x 8 x 3/8 beam

$DL_{2''\,concrete} = (25\ lb/ft^2)(14.33\ ft)$

$= 358.3\ lb/ft$

$DL_{10''\,H.C\,Plank} = (68\ lb/ft^2)(14.33\ ft) = 974.4\ lb/ft$

$DL_{roof} = (12\ lb/ft^2)(14.33\ ft)$

$= 172.0\ lb/ft$

$DL_{AP\text{-}30} = (2\ collectors)(209\ lb) / 14.33\ ft$

$= 29.2\ lb/ft$

$LL_{snow} = (25\ lb/ft^2)(14.33\ ft) = 358.3\ lb/ft$

$W_u = 1.2(358.3 + 172 + 29.2 + 974.4) + 1.6(358.3)$

$W_u = 2.41\ k/ft$

$$\sigma_{max} = \frac{M_{max}\, y_{max}}{I}$$

$$= \frac{(40.5\ ft\cdot k)(6\ in)\left(\frac{12\ in}{1\ ft}\right)}{262\ in^4}$$

$\sigma_{max} = 11.13\ k/in^2$

$\sigma_{y_{HSS}} = 46\ k/in^2$ → For A500, Grade B Steel

$11.13\ k/in^2 < 46\ k/in^2$ ✓

→ HSS 12 x 8 x 3/8 beam is OK

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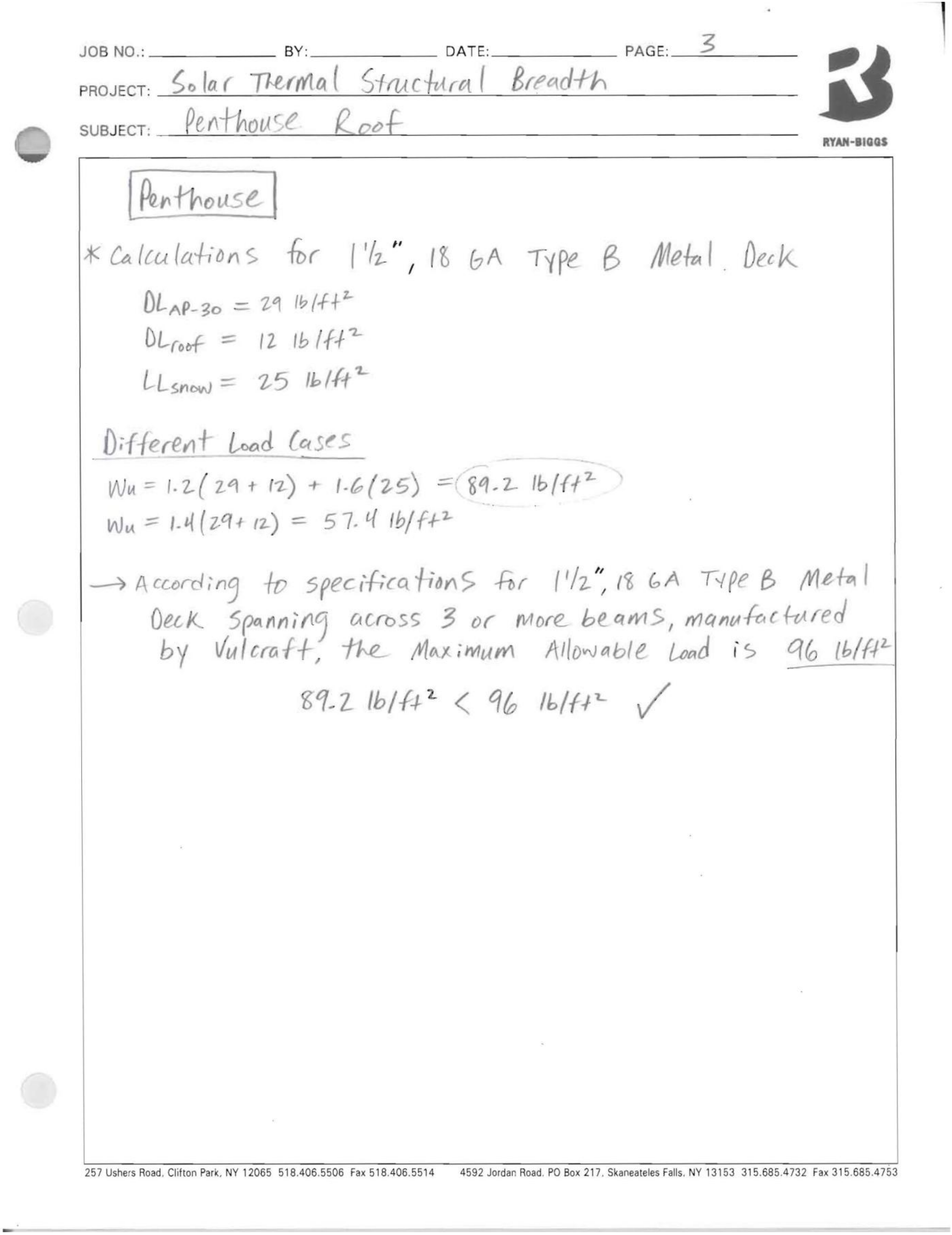

JOB NO.: BY: DATE: PAGE: 3

PROJECT: Solar Thermal Structural Breadth

SUBJECT: Penthouse Roof

RYAN-BIGGS

Penthouse

* Calculations for 1½", 18 GA Type B Metal Deck

$DL_{AP-30} = 29\ lb/ft^2$

$DL_{roof} = 12\ lb/ft^2$

$LL_{snow} = 25\ lb/ft^2$

Different Load Cases

$W_u = 1.2(29 + 12) + 1.6(25) = \boxed{89.2\ lb/ft^2}$

$W_u = 1.4(29 + 12) = 57.4\ lb/ft^2$

→ According to specifications for 1½", 18 GA Type B Metal Deck spanning across 3 or more beams, manufactured by Vulcraft, the Maximum Allowable Load is 96 lb/ft²

$89.2\ lb/ft^2 < 96\ lb/ft^2$ ✓

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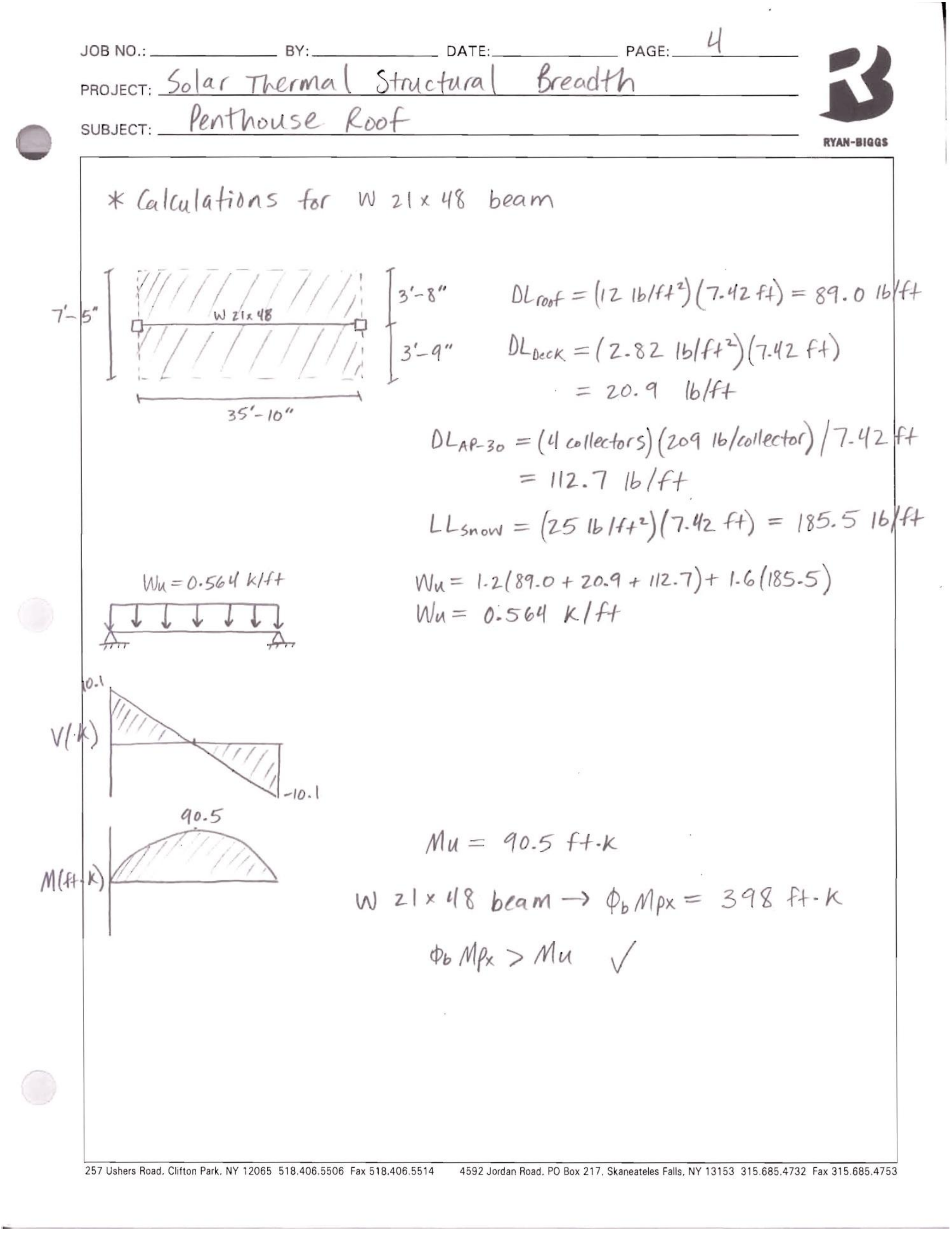


JOB NO.: BY: DATE: PAGE: 4
PROJECT: Solar Thermal Structural Breadth
SUBJECT: Penthouse Roof

RYAN-BIGGS

* Calculations for W 21 x 48 beam

$DL_{roof} = (12\ lb/ft^2)(7.42\ ft) = 89.0\ lb/ft$

$DL_{Deck} = (2.82\ lb/ft^2)(7.42\ ft)$
$= 20.9\ lb/ft$

$DL_{AP\text{-}30} = (4\ collectors)(209\ lb/collector)/7.42\ ft$
$= 112.7\ lb/ft$

$LL_{snow} = (25\ lb/ft^2)(7.42\ ft) = 185.5\ lb/ft$

$W_u = 1.2(89.0 + 20.9 + 112.7) + 1.6(185.5)$
$W_u = 0.564\ k/ft$

$M_u = 90.5\ ft \cdot k$

W 21 x 48 beam → $\phi_b M_{px} = 398\ ft \cdot k$

$\phi_b M_{px} > M_u$ ✓

JOB NO.: BY: DATE: PAGE: 5
PROJECT: Solar Thermal Structural Breadth
SUBJECT: Cantilever Roof

RYAN-BIGGS

Cantilever Roof

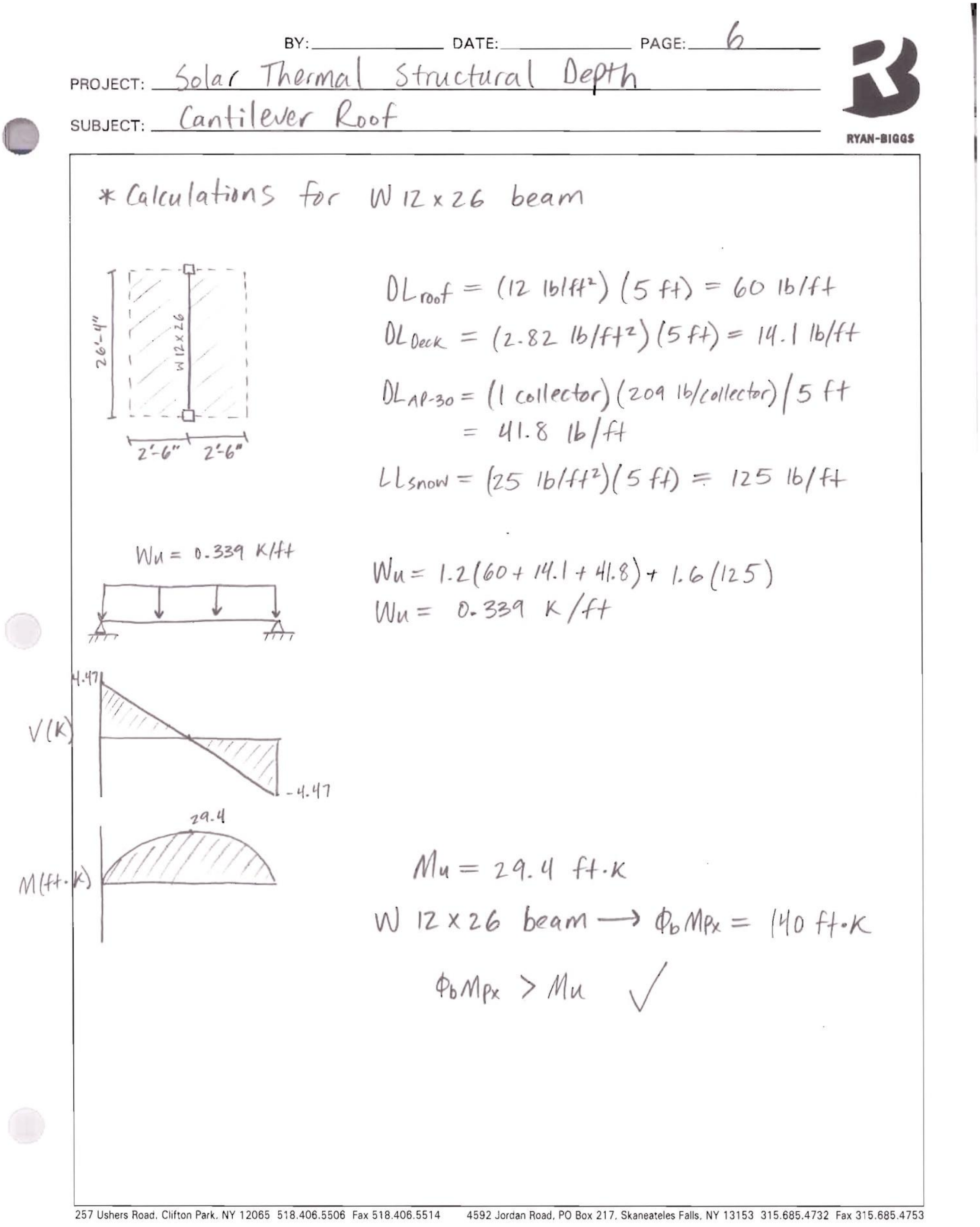
*Calculations for 1½", 18 GA Type B Metal Deck

$DL_{AP\text{-}30} = 29\ lb/ft^2$
$DL_{roof} = 12\ lb/ft^2$
$LL_{snow} = 25\ lb/ft^2$

$W_u = 89.2\ lb/ft^2$

→ 1½" 18 GA Type B Metal Deck spanning across 3 or more beams manufactured by Vulcraft
↳ Max Allowable Load (For 5' span) = 218 lb/ft²

$89.2\ lb/ft^2 < 218\ lb/ft^2$ ✓



BY: ______ DATE: ______ PAGE: 6

PROJECT: Solar Thermal Structural Depth

SUBJECT: Cantilever Roof

RYAN-BIGGS

* Calculations for W 12 x 26 beam

$DL_{roof} = (12\ lb/ft^2)(5\ ft) = 60\ lb/ft$

$DL_{Deck} = (2.82\ lb/ft^2)(5\ ft) = 14.1\ lb/ft$

$DL_{AP\text{-}30} = (1\ collector)(209\ lb/collector)/5\ ft$

$= 41.8\ lb/ft$

$LL_{snow} = (25\ lb/ft^2)(5\ ft) = 125\ lb/ft$

$W_u = 1.2(60 + 14.1 + 41.8) + 1.6(125)$

$W_u = 0.339\ K/ft$

$M_u = 29.4\ ft\cdot K$

W 12 x 26 beam $\longrightarrow \phi_b M_{px} = 140\ ft\cdot K$

$\phi_b M_{px} > M_u$ ✓

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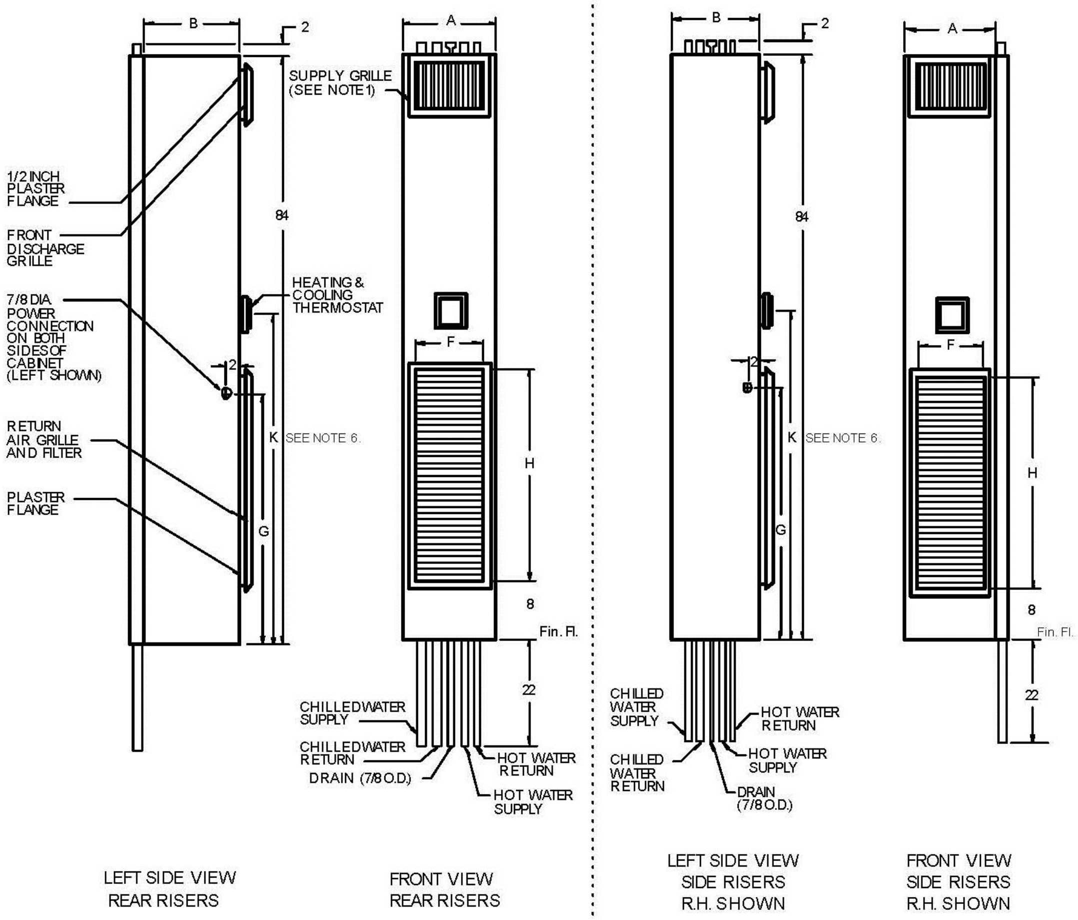
Appendix G: Specifications for a Whalen Fan Coil Unit



NOTES:

1. See drawing number 411 for supply grille or register options. The return air grille is always on the front of the unit.
2. Cabinet is continuous galvanized steel, suitable for direct application of "drywall" plaster board.
3. Return air grille is clear anodized aluminum.
4. Supply, return and drain risers are type M copper, standard or type L, optional. Riser assemblies include four ball valves inside the cabinet.
5. See drawing number 409-PT for detailed riser dimensions and plan views.
6. 48" thermostat height is standard on WF* 300 units. Remote thermostat is required on WF* 400 - 800 units for 48" thermostat height.

UNIT MODEL	NOMINAL CFM	A	B	F	H	G	K
WF*-300-4P	300	16	18	14	36	38	48
WF*-400-4P	400	16	18	14	40	42	52
WF*-600-4P	600	18	18	14	44	45	56
WF*-800-4P	800	18	18	14	48	49	60

*C = 3 ROW
*D = 4 ROW

All dimensions in inches.

VERTICAL FAN-COIL UNITS

THE WHALEN COMPANY
EASTON, MARYLAND

FAN COIL UNITS-4 PIPE
WITH INTERNAL DRAIN PAN
3 OR 4 ROW COOLING COILS

DRAWING NUMBER 403C-PT