2011 ASHRAE STUDENT DESIGN COMPETITION

SYSTEM SELECTION CATEGORY

Drake Well Oil Museum

Titusville, Pennsylvania

Prepared by:

Adam Bernardo
4th Year Architectural Engineering
Anticipated Graduation: May 2012
E-mail: asb5112@psu.edu

Current Address:
608 Vairo Blvd. Apt. 618
State College, PA 16803
(412) 760-9821

Permanent Address:
2801 Autumnwood Drive
Glenshaw, PA 15116
(412) 487-0731

Daniel Wiggans
4th Year Architectural Engineering
Anticipated Graduation: May 2012
E-mail: dlw5089@psu.edu

Current Address:
320 E. Beaver Ave Apt 309
State College, PA 16801
(856) 979-7783

Permanent Address:
49 Cove Road
Moorestown, NJ 08057
(856) 235-4592

Kayla Gavin
5th Year Architectural Engineering
Anticipated Graduation: May 2011
E-mail: krg5036@psu.edu

Current Address:
254 S. Burrowes St. Apt. 4
State College, PA 16801
(845) 235-4709

Permanent Address:
58 White Pond Road
Stormville, NY 12582
(845) 878-3770

William P. Bahnfleth, Ph.D., P.E.
E-Mail: WBahnfleth@psu.edu

Department of Architectural Engineering
The Pennsylvania State University
207 Engineering Unit A
University Park, PA 16802
(814) 863-2076

Submitted: May 4, 2011

Tables

Figures

1.0 Executive Summary

This report outlines and describes the HVAC system selection for the Drake Well Oil Museum in Titusville, Pennsylvania. The process of selection that follows was utilized in determining the most appropriate system for the museum based upon several significant design criteria.

The system design parameters and minimum criteria were determined using ASHRAE Standards and ASHRAE Handbooks. These references established clear heating, cooling, and dehumidification requirements that would need to be met by each proposed system.

To compare systems and determine which would meet all required design parameters, a weighted point matrix was created. An in-depth analysis of each proposed design solution followed, and each option was awarded a final point total, used to make the ultimate recommendation.

When comparing system energy use and determining economic feasibility, Appendix G of ASHRAE Standard 90.1, which prescribes a baseline system based on building size, was used to design a reference system to which all alternatives would be compared.

The report discusses and analyzes the following systems to determine their feasibility in the prescribed application:

- Baseline System: CAV air handling with a gas-fired furnace and chiller
- System 1-A: VAV air handling with chiller and boiler; desiccant wheel dehumidification
- System 1-B: Separate CAV and VAV air handling with chiller and boiler
- System 2-A: Heat pumps with ground-source loop; desiccant wheel dehumidification
- System 2-B: Fan coil units with chiller and boiler, desiccant wheel dehumidification
- System 3-A: Chilled beams with ground-source loop; desiccant wheel dehumidification
- System 3-B: Chilled beams with chiller and boiler; desiccant wheel dehumidification

Analyses of these systems provided the design team with a design matrix score for each option, which was used to make a final system recommendation of System 2-A: Ground Source Heat Pumps with Desiccant Wheel Dehumidification. This system was determined to have the lowest 25-year life-cycle cost with a relatively low payback period, for the owner of a museum, of just over 9 years. System 2-A was also determined to be very architecturally flexible and has the least harmful effect on the environment, based off of an energy-use and emissions analysis.

2.0 Introduction

The Drake Oil Well Museum is a state-owned museum with an adjacent park designated for recreation. The museum and the park are designed to be used by the community for education, learning the heritage of the area, and leisure. The museum will conceivably be in the ownership of the state for the life of the facility and the grounds. Thus, initial, operating, and life cycle costs will be important factors in the ultimate selection of the final system.

Being the birthplace of the modern oil industry, and with its ties to the energy industry, it is also a site that can become a local symbol of the efficient use of the resources and on-site energy available. This unique combination of owner, site, and use provide a wide range of options around which to formulate design alternatives.

The design opportunities associated with the museum, including the large gallery space and several public areas, provide a setting to push the envelope and maximize the options of the mechanical systems. This process led to the formulation of seven system alternatives.

3.0 Building and Site Description

3.1 Site Description

The 20,000 square foot Drake Oil Well Museum is located approximately a mile and a half outside of Titusville, PA, on the banks of Oil Creek. The museum stands on the Drake Well State Park, with opportunities for family recreation including hiking, biking, picnicking, fishing, and canoeing. All necessary utilities are already connected to the structure, including power, sewer and city water.

The total site area encompassed by the limit of contract is roughly 115,000 ft^2. Located to the west of the museum, just beyond the limit of contract, is Oil Creek, a cold water stream with a predominantly bass and trout population. To the east of the museum is an open plot of land about 18,000 ft^2 in area. Just beyond this land, past the limit of contract, is a small pond. A site plan can be seen in Figure 1.

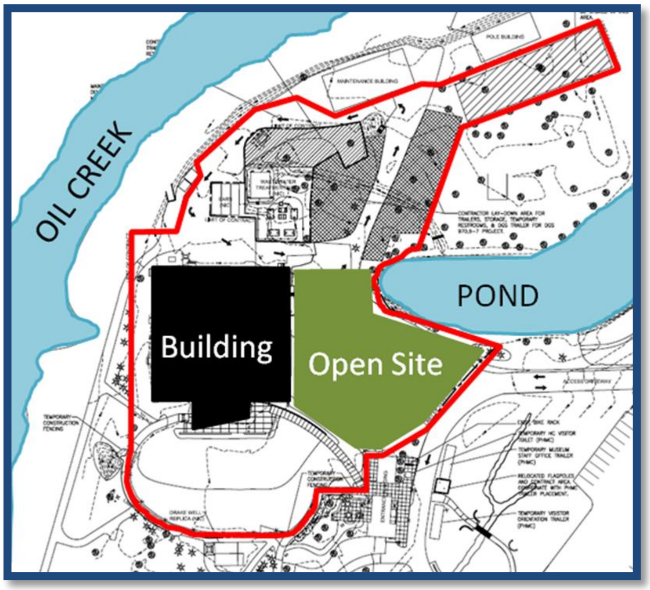

Figure 1 – Building and adjacent site features

3.2 Building Occupancy

The museum has four distinct occupancies: an exhibit gallery, collections maintenance area, administrative offices, and public education areas. These regions are highlighted in Figure 2 below. The exhibit spaces and the collections storage areas are required to meet the Pennsylvania Historical and Museum Commission's (PHMC) standards, as well as all ASHRAE standards.

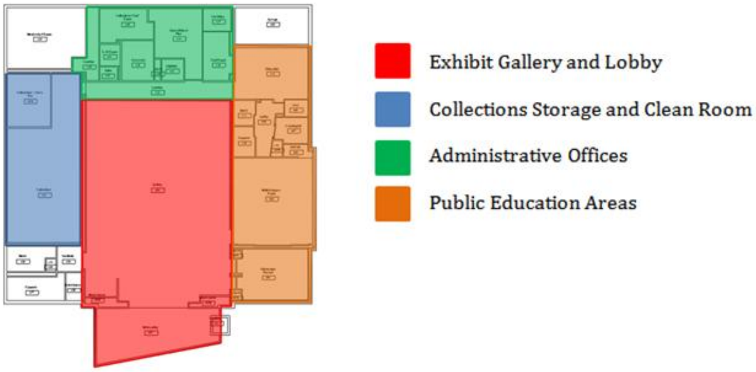

Figure 2– ***Building Occupancy Layout***

3.2.1 Exhibit Gallery and Lobby

The exhibit gallery houses all of the collections available to public viewing. It is the focal point of the building and requires strict temperature and humidity control for the preservation of the collections. This space has the potential for a wide variation in occupancy, which coincides with a large latent load. Thus, the selected system must be able to account for these large fluctuations in load while still maintaining the stringent temperature and humidity control required by the PHMC. The lobby area was included in an occupancy zone with the gallery because there is no physical barrier between the spaces. Different load requirements in the lobby could compromise the integrity of the collections if these two areas are not controlled together.

3.2.2 Collections Storage and Clean Room

Similar to the exhibit gallery, the collections storage room and the collections clean room must maintain minimal temperature fluctuations and a fairly constant relative humidity. These areas, however, are not available to the public during museum hours and are thus not as subject to the fluctuation in latent load as the gallery and lobby spaces. Because they have the same design parameters, the collections area will be included in the same zone as the exhibit gallery.

3.2.3 Administrative Offices

The office area contains smaller spaces and less stringent design parameters than the public gallery and collections storage, though they should still be maintained in accordance with ASHRAE Standard 62.1 to ensure a healthy comfortable work environment.

In these office spaces, there exists a possibility for chilled beams or radiant surfaces to heat and cool the space because the materials kept in this area do not require the strict humidity control.

3.2.4 Public Education Areas

The public education areas include a multi-purpose room, a classroom, and a small orientation theater. These spaces are subject to variations in occupancy, but do not house any particularly sensitive collections, thus have less stringent design parameters and could possibly use the chilled beam or radiant technology also used in the office area and will be included in the same zone as the office area.

3.3 Building Zone Layout

Using these analyses of the various building occupancies, a zone layout was constructed based on grouping spaces with similar design parameters and the possible types of equipment that may be used in those areas. This zone layout is shown below in Figure 3.

Figure 3 – *Building Zone Layout*

4.0 Design Considerations

4.1 Museum Design Requirements

The three most serious threats to all types of collections are light damage, improper environmental moisture content (EMC), and unsuitable temperature (ASHRAE HVAC Applications Handbook). When the EMC or relative humidity is too low or too high, or temperature is too high, physical and chemical damage could occur. The relative humidity and temperature of the gallery and collection spaces are directly controlled by the building's mechanical systems, so a system must be chosen to deliberately control these parameters to protect the collections. Temperature and relative humidity must be controlled in conjunction with one another for damage to the collections to be prevented.

4.2 Design Parameters and Data

4.2.1 Outdoor Design Conditions

The outdoor design conditions were assumed to be similar to those in Erie, PA, as shown in Table 1 below. The wide range of temperatures require a flexible, resilient system that is powerful enough to compensate for the wide temperature variation throughout the year, but also sensitive enough to make small modifications of the system to ensure a proper environment for the collections and the people in the space.

	Cooling Design			**Heating Design**
	ASHRAE 1% DB	**ASHRAE 1% MWB**	**Daily Range**	**ASHRAE 99%**
Titusville, PA	83.3°F	71.3°F	4.2°F	7.7°F

Table 1 – *Outdoor Design Conditions for Titusville, PA*

4.2.2 Collections/Gallery Zone

The Collections and Gallery spaces require the most stringent temperature and humidity control in the building. Both of these areas must be controlled to meet the Pennsylvania Historical and Museum Commission (PHMC) Category 1 Criteria. It is also important to note that the PHMC regulates the fluctuation of temperature and humidity for these areas, which means controllability and reliability of the system are particularly important for this zone. This zone will also be required to have a higher static pressure to limit the amount of infiltration from the exterior and the adjacent zones so that the careful regulation of temperature and humidity is not compromised. This zone's system must be available at all times to maintain this crucial control. A summary of this zone's set points are included in Table 2 below.

	Heating Design	Cooling Design
Temperature	68°F-72°F	68°F-72°F
Relative Humidity	45%	45%
24-Hour Fluctuation	2°F, 10% RH	2°F, 10% RH

Table 2 – *Collections, Gallery Design Parameter*

4.2.3 Office/Education Zone

The Office and Education zone includes all spaces other than collections and gallery areas. These areas require less stringent control of temperature and humidity. All of these spaces must be controlled to meet ASHRAE Standard 55-2007 (See section 4.3.2 of this report). This zone's system will be designed to be occupant-controlled. A summary of this zone's set points are included in Table 3 below.

	Heating Design	Cooling Design
Temperature	72°F	75°F
Relative Humidity	50%	50%

Table 3 – *Office/Education Design Parameter*

4.2.4 Heating and Cooling Loads

The proposed system must be designed to meet the peak heating and cooling loads of each space, which were calculated using TRANE Trace 700 software. Factors for the calculation of these loads included heat gain from occupants, lighting, and equipment for each space. Table 4 below shows the museum occupancy schedule according to the owner's project requirements; Table on the next page summarizes the lighting and power densities influencing heating and cooling loads.

	Monday - Friday	Saturday	Sunday
Employee-Occupied	8:00 AM – 5:00 PM	9:00 AM – 5:00 PM	Closed
Public Hours	9:00 AM – 4:00 PM	10:00 AM – 4:00 PM	

Table 4 – *Museum Occupancy Schedule*

Room	Lighting Power Density (W/ft^2)	Equipment Power Density (W/ft^2)
Lobby	1.94	N/A
Gallery	0.43	1.94
Collections Storage	N/A	0.43
Orientation Theater	0.55	0.55
Open Office Area	0.72	0.72
Conference Room	1.83	N/A
Mechanical Room	0.70	0.70

Table 5 – ***Lighting and Power Densities for spaces***

4.3 Referenced Standards and Codes

4.3.1 ASHRAE Standard 62.1 – 2010: Ventilation for Acceptable Indoor Air Quality

ASHRAE Standard 62.1 specifies minimum ventilation rates and related criteria needed to provide acceptable indoor air quality for human occupancy and to maintain air quality requirements for occupant health. Table 6-1 of the standard assigns minimum ventilation rates in breathing zones based on the space occupancy category. These rates were then used in conjunction with the occupancy density and schedule of each space to determine the total ventilation required for each area. A summary of these ventilation requirements is shown in Appendix A of this report.

Adhering to Standard 62.1 is of particular importance in a museum application because improper ventilation can result in damage to in-house artifacts. Particular attention must be paid to Section 5 of the standard, which governs systems and equipment, when designing an air distribution system in the collections and gallery space.

4.3.2 ASHRAE Standard 55 – 2007: Thermal Environmental Conditions for Human Occupancy

ASHRAE Standard 55 establishes guidelines for a thermally comfortable environment for human occupancy of a building. Factors considered within this standard include the activity or metabolic rate of the occupant population and the air distribution temperature and speed. The necessary range of operative temperature and humidity for all spaces falls into the recommended range for occupant comfort, as governed by Figure 5.2.1.1 of Standard 55 – 2007.

4.3.3 ASHRAE Standard 90.1 – 2007: Energy Standard for Buildings

ASHRAE Standard 90.1 provides minimum requirements for the design of energy-efficient, non-residential buildings. Specifically included within this standard are provisions for the building envelope, HVAC and service hot water equipment, electrical power distribution, and lighting power densities. All of these provisions are dependent on the specific climate conditions of the building's geographic location.

This standard addresses minimum equipment efficiencies in Tables 6.8.1A-J, which will be of particular importance when selecting equipment and developing system alternatives.

Section 5 of Standard 90.1 – 2007 discusses building envelope requirements and provisions, and will need to be considered when making improvements to the building envelope to be sure that it meets the requirement for the proper climate zone, which is discussed in the next section of this report.

4.3.4 Climate Data

The design of certain mechanical systems and certain design conditions relies heavily on the area's expected climate. The Drake Oil Well Museum, located in northwestern Pennsylvania, lies in Climate Zone 5A, as shown in Figure 4 below, which implies a cool, humid climate.

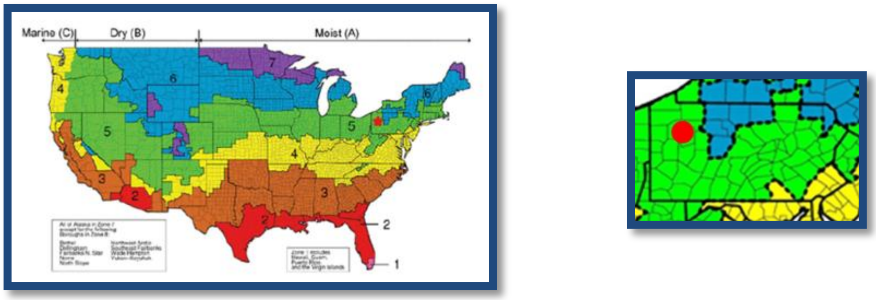

Figure 4 – *ASHRAE Climate Zones*

4.3.5 ASHRAE Standard 189.1 – 2009: Standard for the Design of High-Performance Buildings

ASHRAE Standard 189.1 establishes recommended standards for the design of high-performance green buildings. The standard has the goal of promoting environmental responsibility and maximizing resource efficiency by majorly addressing site sustainability, water use efficiency, energy efficiency, and indoor environmental quality.

4.4 Building Envelope Improvement

The Pennsylvania Historic Museum Commission has expressed interest in improving the existing building envelope insulation and vapor barrier. Utilizing WUFI-ORNL/IBP, moisture design software, the exterior walls were modeled and analyzed. The architectural drawings illustrate a typical wall section consisting of gypsum board, rigid insulation, batt insulation, and stone masonry. These components were input into the modeling software and their collective thermal and moisture transfer properties were investigated. Calculations taking place throughout the winter months yielded worrisome results: relative humidity reached 100%, forecasting condensation in the wall cavity. This was supported by the accompanying high water content values. By improving the building envelope, relative humidity can be kept within an acceptable range, and the water content can be minimized.

Several strategies, including the use of over insulation, double glazing façades, and low-emissivity glass, would successfully reduce the building loads, and create a more sustainable building envelope. Adding improved vapor barrier materials and air cavities significantly improves the building envelope, and would prove very affordable and within the $500,000 budget outlined in the owner project requirements.

5.0 System Selection Criteria

In order to evaluate the appropriateness of a system, a multitude of factors must be considered. Based on the design parameters and the use of the space, the following factors will be analyzed and applied to a custom-made, weighted decision matrix.

5.1 Economics (35%)

The cost of a system is often what the building owner is primarily concerned with, and should therefore be a crucial element of the system selection process. Capital cost is important for the building owner, as is the operating cost. In order for the commissioning owner to install a system that is more expensive than necessary, the simple payback period must be within a small enough range for the decision to make economic sense. Fuel and energy prices, as well as inflation rates and returns on investment, should be considered over the life-cycle of the system.

5.2 Energy Use and Efficiency (25%)

The energy used by a system is directly related to the economics of the system and in many cases is included into the economic analysis. For the purposes of the selection of this system, the energy analysis was kept separate to emphasize the importance of the life-cycle cost and yearly utility costs by keeping them separate from first costs and pay-back periods. The energy use for the systems in this report will be compared to an ASHRAE-prescribed baseline system to evaluate improvement over this baseline system.

5.3 Sustainability (15%)

As the price of energy continues to climb and the impact of the built environment on the earth becomes clearer, mechanical design considerations need to incorporate innovative designs that reduce energy use, lowering bills and reducing the building's impact on the environment. The United States Green Building Council (USGBC) has established itself as one of the foremost organizations on evaluating "green buildings." Their Leadership in Energy and Environmental Design (LEED) rating system evaluates the design of the building, location, and systems to determine its rating. The more points that a design accumulates above the minimum base requirements, the higher the building will be rated on the LEED point scale.

5.4 Maintainability and Reliability (15%)

The systems in the building should be easy and intuitive to maintain, and should work correctly every time and all of the time. Maintenance is a crucial part of the economic analysis as well as the system and equipment selection process. It is not practical for a building of this size to expect a full time facilities manager. Reliability is also vital to the design because not all of the equipment will be working all of the time. The owner of this building should never have to worry about a fan or pump starting, even if it has not been used in a long time. The artifacts that are in the museum are sensitive and irreplaceable; they should never be put at risk because of a maintenance or reliability issue with the equipment.

5.5 Architectural Synergy (10%)

For a public building such as a museum, aesthetics need to be considered when choosing a distribution system and layout in order to not negatively affect the public's perception of the artifacts and the rooms in which they are housed. Visual and audial environmental disturbances should be avoided to not distract from the purpose of the space. Thus, it is important to look at alternatives that allow for visually-appealing diffuser layouts and minimize intrusion to the space.

5.6 Weighted Decision Matrix

Based on these selection criteria, the following point system was established to aid in the selection of the most appropriate system:

Category	Points Possible
Economics	**35**
First Cost	*5*
Life-Cycle Cost	*20*
Payback Period	*10*
Energy Use and Efficiency	**25**
Meets Baseline Energy Use	*10*
Performs 20% Above Baseline	*5*
Additional Improvement Over Baseline	*10*
Sustainability	**15**
LEED Criteria	*10*
Emissions	*5*
Reliability and Maintainability	**15**
Architectural Synergy	**10**

Table 6 – *Decision Matrix*

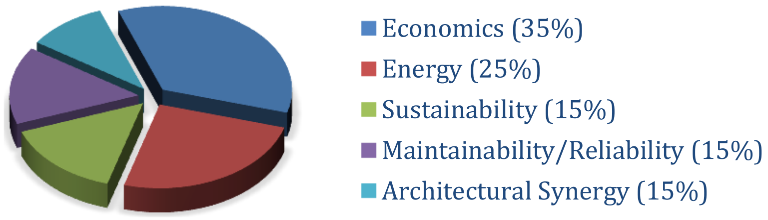

Figure 5 – *Selection Criteria*

6.0 Equipment Considered

6.1 Constant Air Volume (CAV) System

CAV systems only supply one air volume to a zone, and are thus easy to control, but very inefficient in terms of energy use. These systems are often used as an energy baseline, as is done in the following analysis, due to the low capital costs but high life-cycle costs. One benefit to a CAV system in this application is its ability to effectively control humidity without sophisticated controls.

6.2 Variable Air Volume (VAV) System

VAV systems are commonly used in place of CAV because of a relatively small additional capital investment with a noticeable improvement in energy efficiency and lower life-cycle costs. In such systems, fan speed is adjusted to provide varied flow rates to each zone, requiring fan-powered boxes before each space. Within a VAV system, the HVAC control structure becomes more advanced and the systems often require a specialized dehumidification system.

6.3 Dedicated Outdoor Air System (DOAS)

The Dedicated Outdoor System is sized and designed to meet the ventilation loads laid out in ASHRAE Standard 62.1. The DOAS will be coupled with other airside and waterside components to provide proper thermal comfort. The DOAS will handle the latent load and a portion of the sensible load, while the other components will handle the remainder of the sensible load. The system is designed to distribute only the required ventilation air, so the ducts and fans that are required can be sized much smaller due to the sensible load being handled closer to the spaces. The system also affords slower duct velocities, this will in turn lower the amount of vibration and therefore noise, which is especially important in the gallery spaces of the museum

6.4 Dry-Type Desiccant Wheel

A dry-type desiccant wheel is being considered for dehumidification of the gallery and collections spaces. This specialized dehumidification system works by passing dry desiccant, usually silica gel or a calcium chloride salt, alternately through incoming process air and regenerating air on a rotating wheel whenever dehumidification is necessary. The desiccant absorbs moisture from the incoming process air, thus dehumidifying the supply air to the space. The moisture in the desiccant is then absorbed via the hot regenerative air, and the moisture is expelled from the system with the exhaust air. This process is visually represented below in Figure 6.

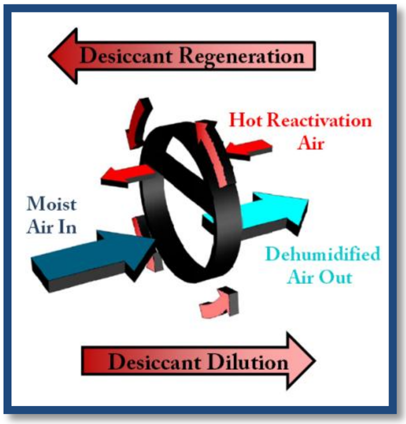

Figure 6 – *Desiccant Wheel Detail*

A dry-type desiccant dehumidification process was chosen over a liquid desiccant due to the exhibit space's vulnerability to moisture. Should there be a leak in the desiccant system, a dry-type reactant would cause less harm to the artifacts.

The major disadvantages to a desiccant dehumidification system are an increased capital and operating cost, and the need for more sophisticated control systems and maintenance personnel to properly regulate the amount of dehumidification occurring.

6.5 Boilers

The boiler used in our energy analysis is a high efficiency condensing boiler. They are different from standard boilers in the way it condenses the hot exhaust gasses and is able to recapture the heat from these gasses. This allows for especially high efficiencies for these types of boilers, while also limiting the amount of airborne emissions. All of the boilers used must comply with Table 6.8.1F of ASHRAE Standard 90.1 – 2007 by having higher than 82% efficiency. They do have a higher initial capital cost, but these higher costs are offset over the life of the boiler thorough efficiencies and lower operating costs.

6.6 Chillers

The chillers modeled for this analysis are air cooled screw chillers with an EER of over 10. The overall capital cost of the system will again increase but this increase is negated by the energy savings over the life span of the equipment and the system. The chillers will be used to supply the waterside equipment with cold water for sensible portion of the space load.

6.7 Fan Coils

A fan coil unit will work integrally to supply the zones with outdoor conditioned air. Fan coil units are attached to the ductwork before the outdoor air enters the space and, based on the input of the thermostat, the coils either cool or heat the air further than what ERV was able. The fan coils will provide further thermal comfort and further controllability of the space temperatures. This controllability will improve the comfort in the buildings and improve the environment in which the artifacts will be housed. The units will be supplied hot and cold water from a boiler and a chiller, respectively. The fan coil units, like the chilled beams, will be supplied by a three pipe hydronic system, a hot and cold supply and a common return.

6.8 Geothermal Wells

A ground coupled geothermal loop system will be examined. The area immediately adjacent to the building has an area large enough to support a vertical ground loop. The loop will consist of vertical bores spaced to allow the system to absorb and dissipate heat and not reject heat back to itself. In a geothermal loop the earth is used as a heat sink and source, depending on the time of the year. A water glycol solution is used to transport the heat from the building to the earth in the cooling season and, in the process, is reversed in the heating season. The ground source systems depend heavily on local site features and characteristics. When installed and implemented correctly the geothermal wells can greatly reduce the energy and emissions of a system.

6.9 Heat Pumps

The high coefficients of performance of heat pumps make them a very attractive alternative especially for high energy efficacies and long term cost savings. Heat pumps typically have a higher price tag than a conventional boiler and chiller system. The heat pumps can provide a higher level of controllability of the space temperatures by having a thermostat and a humidistat in each zone. The controllability can be a crucial because of the sensitivity of the artifacts in the gallery and collections storage spaces. The heat pumps used in the design of any system will need to comply with the minimum 3.1 COP efficiency requirement, as prescribed by Table 6.8.1B of ASHRAE Standard 90.1-2007.

6.10 Chilled Beams

As chilled beams continue to grow in popularity in the United States, more projects are considering them as an alternative to previously typical systems. There are two varieties: active and passive chilled beams. Active chilled beams use air forced through nozzles to provide heating and cooling. Passive chilled beams can only supply cooling to the space because they depend on the buoyancy of warmer air to rise, meet the beam and then fall after it cools. The beams in the various spaces will be connected to the supply cold and hot with a common return. This will prevent some beams from heating and cooling in the same zone. Careful monitoring of the wet bulb temperature in the space is crucial to the success of the system and to prevent any condensation from forming on the beam and then dripping. This is especially crucial in the gallery and storage spaces to protect the artifacts from damage.

7.0 System Alternatives

7.1 Baseline System

The baseline system was chosen in accordance with Tables G3.1.1A-B in Appendix G of ASHRAE Standard 90.1 – 2007. The system, a packaged, CAV rooftop air conditioner with direct expansion cooling and fossil fuel furnace heating, was used as an absolute minimum energy requirement. All future system alternatives were compared to this system to determine life-cycle cost and energy-use improvement percentages.

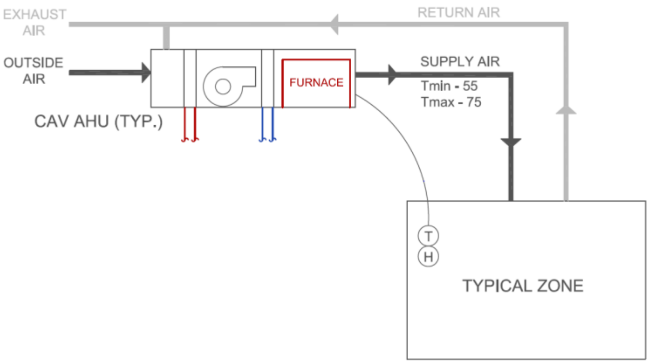

Figure 8 – *Baseline Airside Schematic*

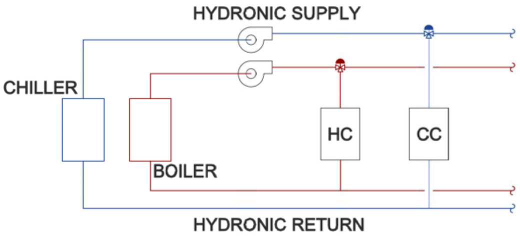

Figure 7 – *Baseline Hydronic Schematic*

7.2 Option 1

Option 1 is designed around a VAV alternative, evaluating the feasibility of a variable air volume flow in both building zones to investigate the trade-off between additional capital investment and improvement in life-cycle cost associated with this type of system. The following system alternatives include a VAV system for both building zones and upgrading to VAV in only less-sensitive spaces.

7.2.1 Option 1-A

This option utilizes the adjustable fan speed to control the air flow in all zones of the building per the heating and cooling requirements of each controlled space. This requires fan-powered boxes before each space and a more sophisticated control structure to ensure the proper amount of heating and cooling is obtained. A distinct disadvantage to this configuration is that humidity control will be significantly decreased in the collections and gallery spaces, prompting the need for additional dehumidification in the form of a dry-type desiccant wheel. Schematics of this system can be seen in Figures 9 and 10 on the next page.

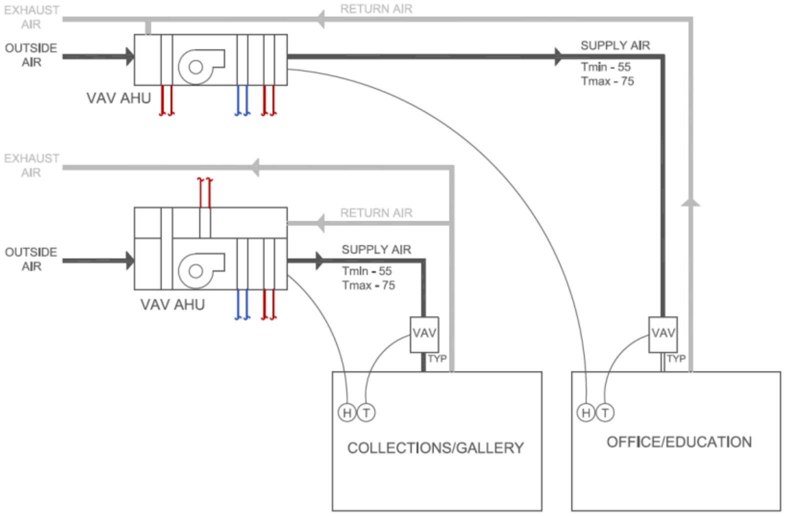

Figure 9 – *Option 1-A Airside Schematic*

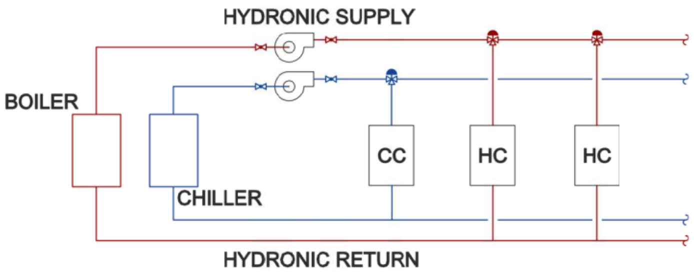

Figure 10 – *Option 1-A Hydronic Schematic*

7.2.2 Option 1-B

Option 1-B includes VAV control for non-critical spaces, such as the office and education zone while utilizing CAV fan control for the gallery and collections areas. This allows the critical zones of the building to be easily controlled and maintained, and to eliminate the need for additional dehumidification in these areas. The office and education areas, however, still reap the benefits of the increased energy efficiency of a variable air volume system. The hydronic schematic for this option is identical to that of Option 1-A, seen in Figure 10 above.

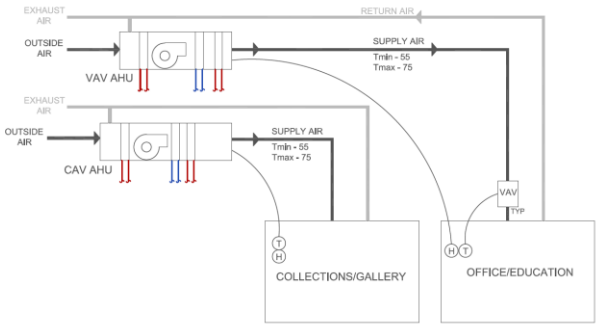

Figure 11 – *Option 1-B Airside Schematic*

7.3 Option 2

Option 2 is designed to decouple the ventilation loads and the cooling and heating loads. Heat pumps are used to ensure that the spaces are at the proper thermal comfort levels mentioned above. The difference between systems 2-A and 2-B will be how the water in the hydronic system will be heated or cooled.

7.3.1 Option 2-A

This option will utilize a 100% Ground Coupled Closed Loop to cool and heat the primary fluid for the heat pumps, as seen in the schematic in Figure 13 below. The building will require about 18 heat pumps located throughout the building. This will allow for increased controlling of the zones and spaces; this will become important in the winter and summer when the exterior spaces will be cooler and warmer, respectively, than the interior spaces. The site will provide enough area for the system. Assuming that a geotechnical report will allow for vertical bores, 40 will be needed spaced approximately 20 feet on center and extends 300 feet into the earth for a total length of about 12,000 feet.

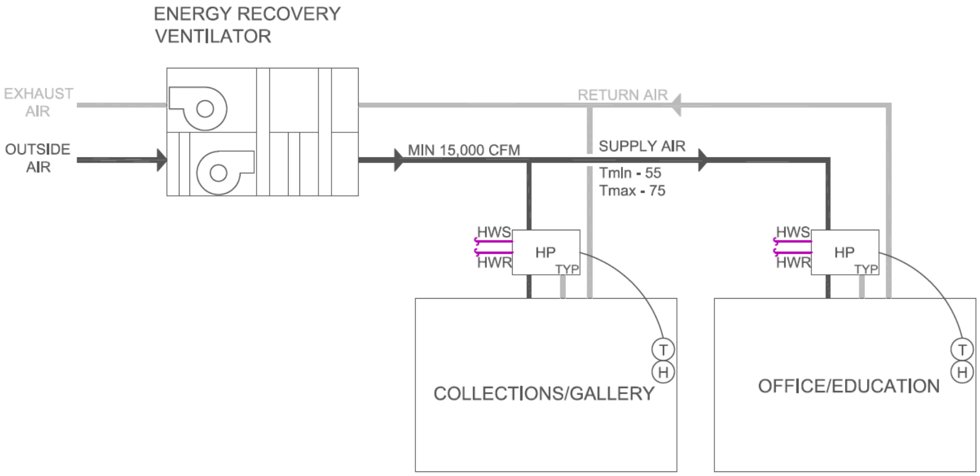

Figure 12 – *Option 2-A Airside Schematic*

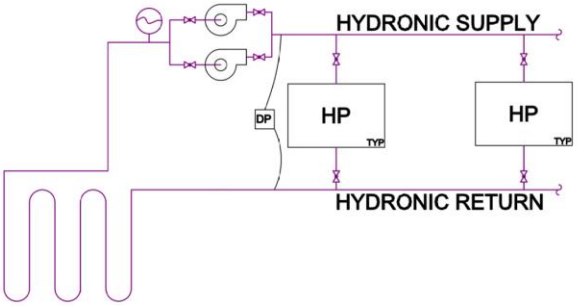

Figure 13 – *Option 2-A Hydronic Schematic*

7.3.2 Option 2-B

Option 2-B will utilize a boiler and a chiller to heat and cool the hydronic system and use fan coil units to push the cooled or heated air through the space. This system looks and acts similar to option 2-A, and should have similar performance characteristics. The cost and efficiency are compared to Option 2-A later in this report in Section 8 - Analysis of Systems. This is a more typical system, and this system is expected to use more energy but to cost less than the previous system, mainly due to the deletion of the geothermal wells.

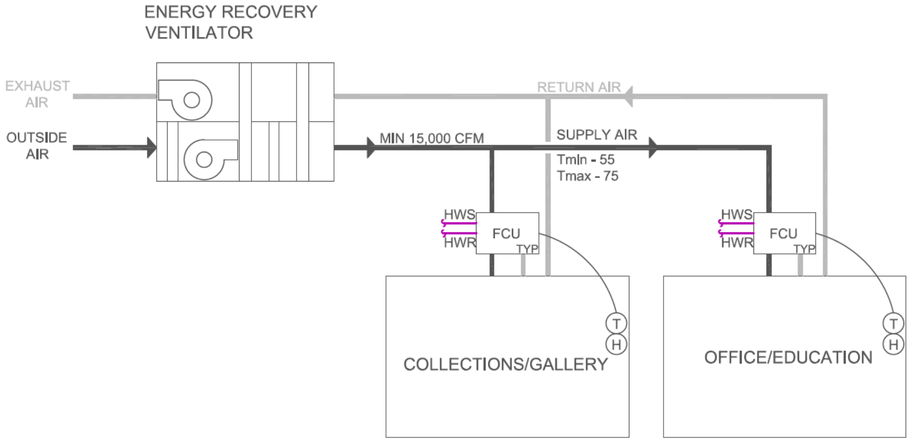

Figure 14 – *Option 2-B Airside Schematic*

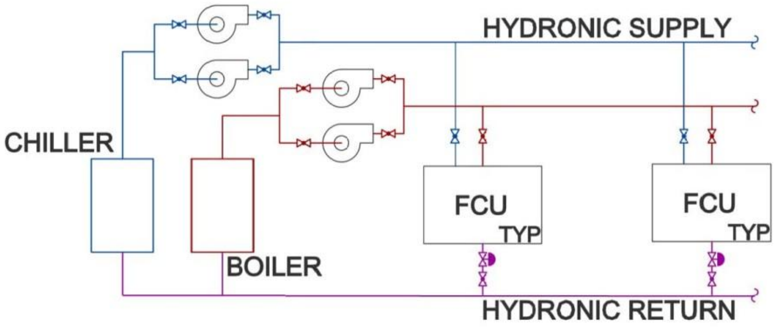

Figure 5 – *Option 2-B Hydronic Schematic*

7.4 Option 3

Option 3 is based around a similar airside ERV while replacing the heat pumps with active chilled/heated beams. The chilled beams are being considered because they supply a temperature that can be easily monitored and regulated within the space. As stated above the wet bulb temperature is critical to the success of the system. The two systems investigated in Option 3 are described in the next pages.

7.4.1 Option 3-A

This system will utilize a ground source loop that will preheat or precool the fluid then pass it through a small boiler or chiller if needed. The main advantage of this system is that the chiller and boiler will only be used on the hottest and the coldest days, while the ground loop is designed to be able to handle the lost most of the other days.

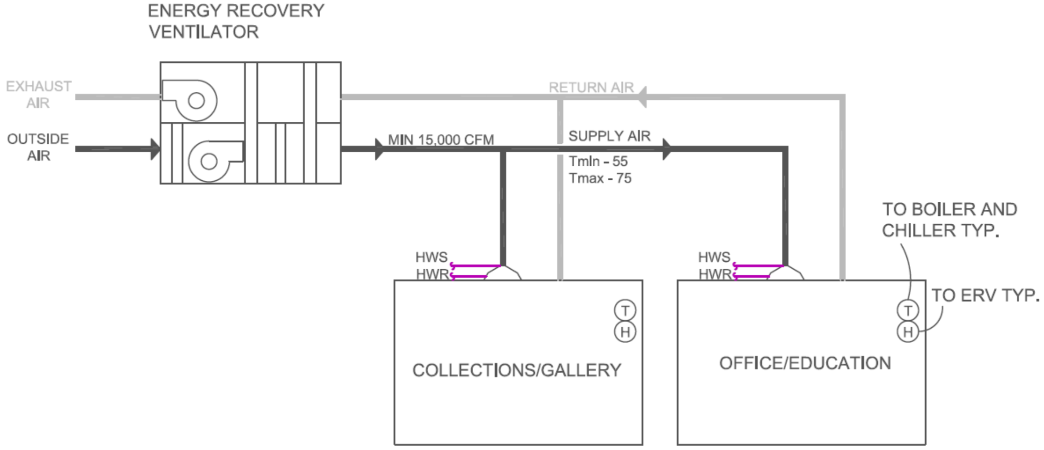

Figure 15 – *Option 3-A Airside Schematic*

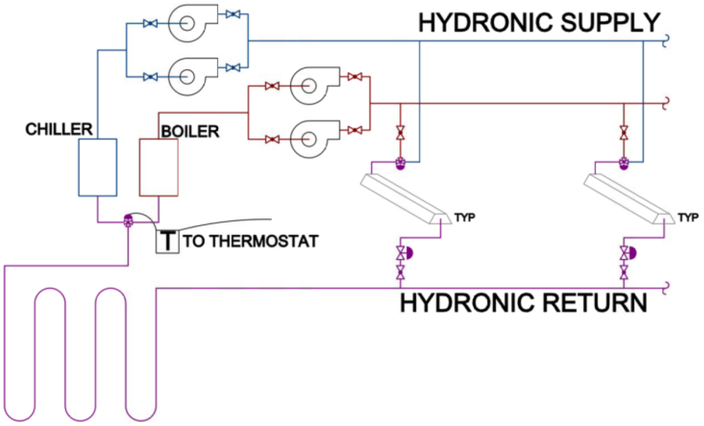

Figure 16 – *Option 3-A Hydronic Schematic*

7.4.2 Option 3-B

Option 3-B will be the same as above but will have only a boiler and a chiller. This design, like design 2-B, is mostly done for cost reasons. With the deletion of the ground source loop the cost is anticipated to fall but, due to the larger sizing of the boiler and chiller, these cost savings will only be a portion of the investment in the ground source loop. The efficiency of the system is expected to fall from system 3-A, this is discussed further below, in the analysis of systems section. Schematics of system 3-B can be seen in Figures 17 and 18 on the following page.

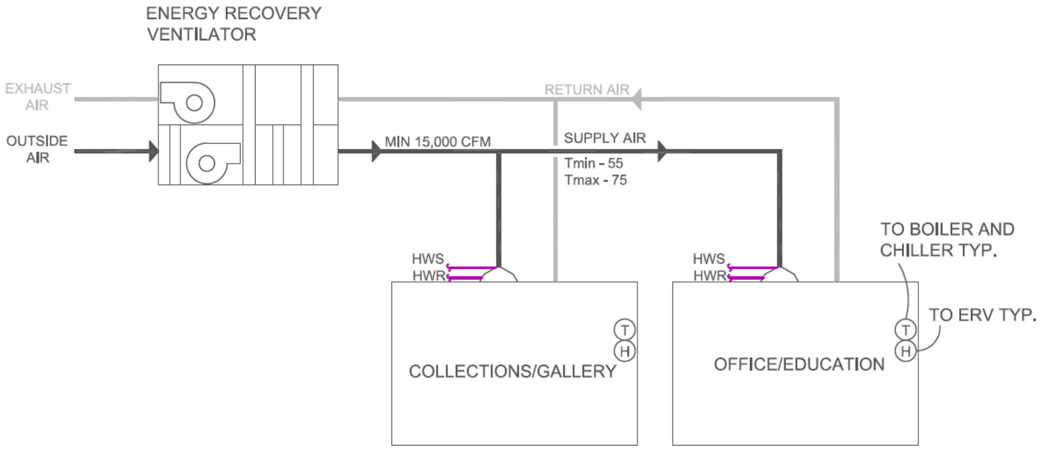

Figure 17 – *Option 3-B Airside Schematic*

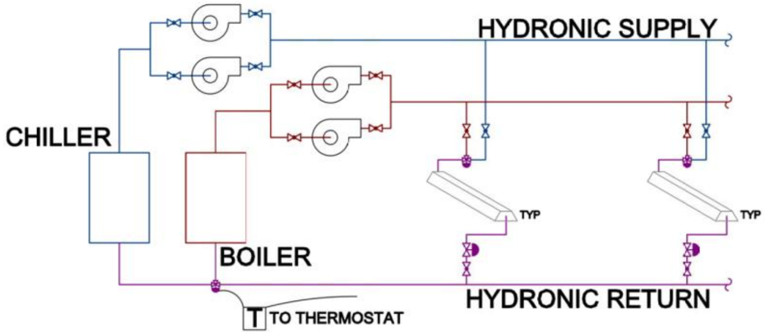

Figure 18 – *Option 3-B Hydronic Schematic*

8.0 Analysis of Systems

8.1 System Energy Use

The energy-use analysis is based solely on the yearly energy use associated with each system alternative, obtained from the Trane Trace 700 energy model. These energy and electrical consumption analyses were compared to one another, as shown in Figures 22 and 23 on the following page. As expected, the baseline system has the poorest energy performance and has the highest yearly electrical consumption. The VAV systems in Option 1 not surprisingly result in significantly decreased pumping and fan energy with a slight decrease in heating and cooling energy consumption as well. The geothermal systems in Options 2-A and 3-A have the lowest overall energy consumption due to their use of the earth as a heat source and sink.

A particular point of interest in this analysis is the heating energy required for Option 3-B, which utilizes active chilled beams with a chiller and boiler as the main heating and cooling supply. This system actually requires more energy to meet the heating load than the baseline system because of the distribution method used in active chilled beams. Because the air volume supplied to the space is much lower than in a standard VAV or heat pump system, this air is required to be heated much more than in the other alternatives.

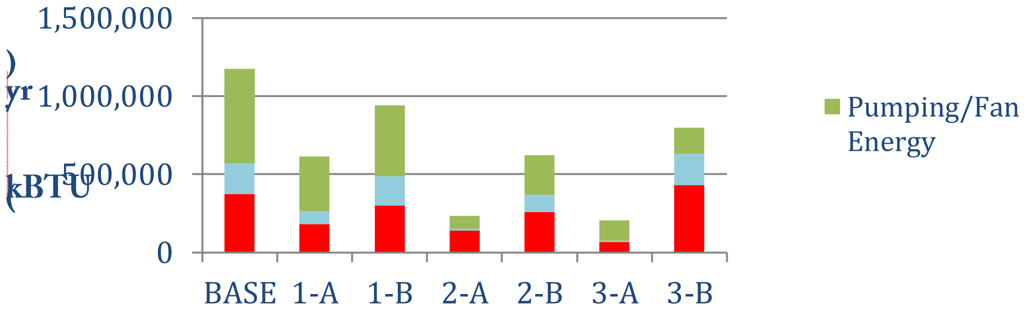

Figure 19 – *Yearly System Energy Consumption*

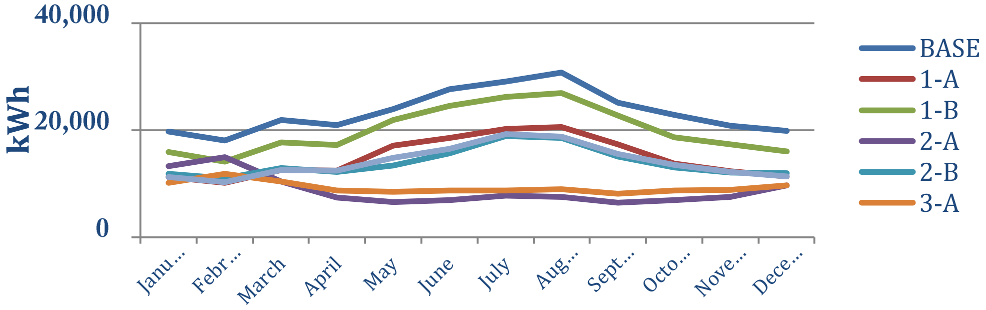

Figure 20 – *Monthly Electrical Consumption*

Each system's energy consumption was then compared to the baseline to determine a percent improvement from the baseline system, as summarized in Figure 24.

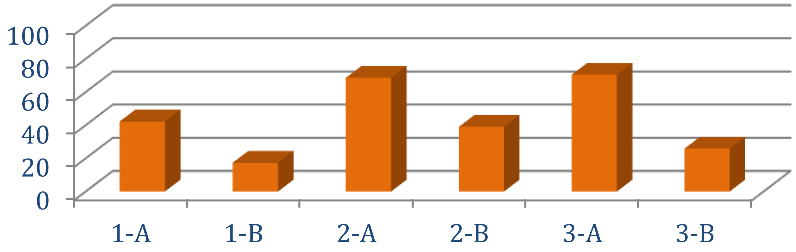

Figure 21 – *Percent Improvement from Baseline Energy*

8.2 Economic Analysis

As seen previously in Table 6, the system economic analysis will consider three main components: first cost, life-cycle cost, and simple pay-back period.

8.2.1 First Cost (5%)

The initial capital cost of the system, while important in the owner's system selection, is not the largest cost to the owner when considering the entire life of the building. This analysis will consider the first cost into the system recommendation, and more importantly, will use the initial capital required to determine each system's simple payback period in Section 8.1.3 of this report. A summary of each system's required capital is shown below, and a breakdown of system equipment costs is shown in Appendix B of this report.

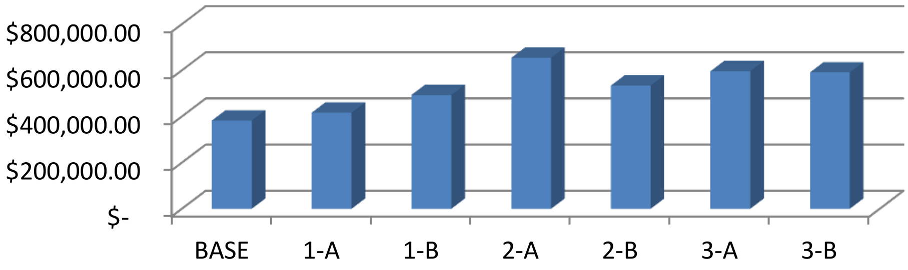

Figure 22 – ***First Cost Summary***

8.2.2 Life-Cycle Cost (15%)

A 25-year life-cycle analysis was conducted for each system, using the results from the energy analysis described in Section 8.1 of this report. The life-cycle cost of each system took into account maintenance costs and yearly energy costs, calculated with a utility rate structure taken from a U.S. Energy Information Administration data study. Factored into this life-cycle cost is a 7% return on investment and a yearly inflation rate of 3%.

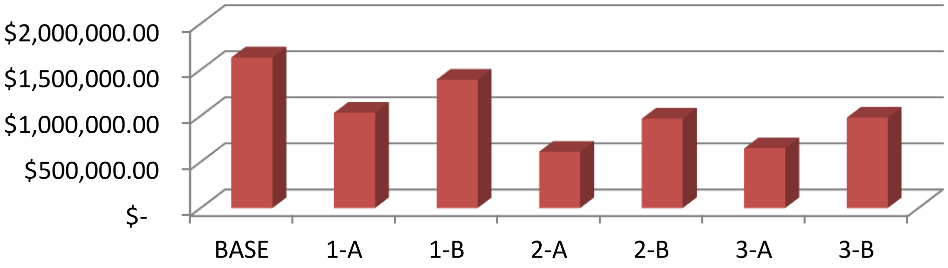

Figure 23 – ***Life Cycle Cost Summary***

8.2.3 Payback Period (15%)

The simple pay-back period is the timespan in which the additional initial capital investment for a system will be offset due to a lower annual energy cost. Typically, a system with a smaller first cost will have a higher operating and life-cycle cost, so the trade-off between these two investments must be evaluated and the proper compromise between the two will often result in the most appropriate system. In this analysis, Options 2-A and 3-A, those options utilizing the geothermal system, provide the best combination of low life-cycle cost with relatively short payback periods of less than 10 years. These results are seen in Figure 21 on the following page.

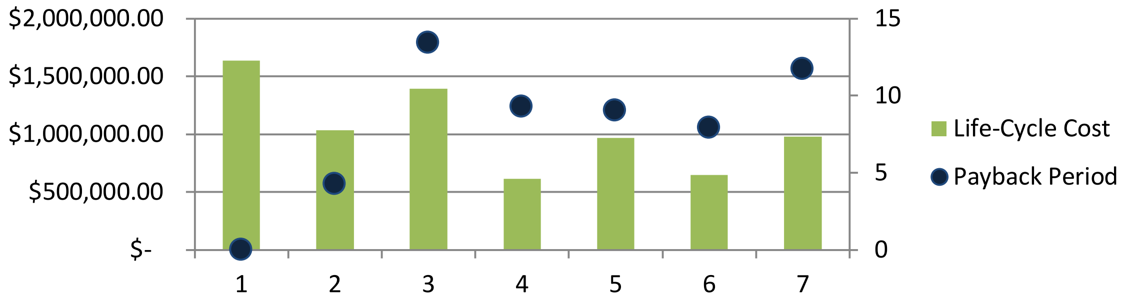

Figure 24 – *Payback Period vs. Capital Cost*

8.3 Sustainability and Emissions

8.3.1 LEED Evaluation (10%)

LEED (Leadership in Energy and Environmental Design) is a green building certification system that provides guidelines for high performance building strategies. The Drake Well Museum shall be designed to meet LEED Silver Certification and the mechanical system design and selection is a very important component to reaching the required number of points for this accreditation. Using the updated LEED Checklist from 2011, six particularly important categories were chosen as a guideline for the purpose of selecting a 'green' design, and full or partial credit was given to the system's matrix score if it met the requirements to get LEED Points in that category.

Category	BASE	1-A	1-B	2-A	2-B	3-A	3-B
Stormwater Design, Quantity Control	1	2	2	1	2	1	2
Optimize Energy Performance	0	1	0	2	1	2	1
On-Site Renewable Energy	0	0	0	2	0	2	0
Outdoor Air Delivery Monitoring	0	1	1	2	2	2	2
Controllability of Systems	2	1	1	0	1	0	1
Thermal Comfort Design	2	2	2	2	2	1	1
Totals	**5**	**7**	**6**	**9**	**8**	**8**	**7**

Table 7 – *Selected LEED Category Scores*

Certain categories listed are similar to other categories considered in this system selection, but these design elements will also be considered in the sustainability category due to their importance in an energy-efficient and environmentally-conscious system design.

8.3.2 System Emissions (5%)

The environmentally harmful emissions of a proposed system should also be evaluated when considering sustainability. Figures 25 and 26 on the following page provide summaries of the CO_2, SO_2, and NOX emissions of each proposed system. These values were obtained using the Trane TRACE energy model.

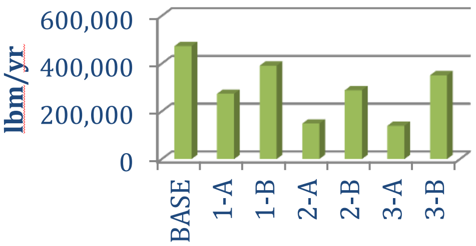

Figure 25 – *System CO_2 Emissions*

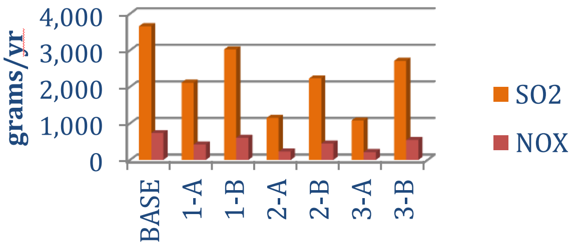

Figure 26 – *Other System Emissions*

8.4 Reliability and Maintainability

The reliability and maintainability of each system was assessed qualitatively based on the equipment used for each system. A standard CAV system requires the least amount of maintenance, and is most reliable due to a simple control structure. The more sophisticated controls of a VAV system require a higher maintenance cost, but the system still functions fairly reliably. The dry-type desiccant wheel was chosen for dehumidification in all systems where additional dehumidification is required due to its small impact on the collections in the event of a system failure.

The geothermal wells are slightly more complicated to maintain due to a more sophisticated control structure and because they are not seen as often as CAV and VAV systems and may be unfamiliar to maintenance personnel.

Chilled beams were deemed the most difficult to maintain and the least reliable in terms of preservation of the collections. Increased piping and sophisticated controls make maintenance difficult for most owners. Chilled beams also require more dehumidification than the other systems considered and could be harmful to the artifacts in the event of a leak or system fail.

8.5 Architectural Synergy

Each system was also evaluated from an aesthetic and acoustic perspective based on the air distribution methods and terminal units for each option. Standard diffusers and ductwork used for Options utilizing a CAV system, VAV system, and Fan Coil Units were deemed poor in terms of equipment noise because of the high volume of air being circulated, and poor in terms of aesthetic value in the gallery space.

Ground source heat pumps were considered the most effective in terms of minimizing equipment noise and for flexibility of the layout of ductwork and piping. The heat pumps can be located around the perimeter of the gallery and ductwork and piping can be hidden above the drop ceiling, as shown in the Navisworks model in Figure 27 on the next page.

Chilled beams, though similar to the heat pumps in terms of flexibility of layout, were considered to have slightly more interference with architectural elements in the gallery space due to the high ceiling height. The layout of the chilled beams could be even and aesthetically pleasing, as seen in Figure 28, but the interference with the gallery's ceiling may cause architectural issues. The chilled beams may also create a distracting noise because of the high velocity air leaving the nozzle.

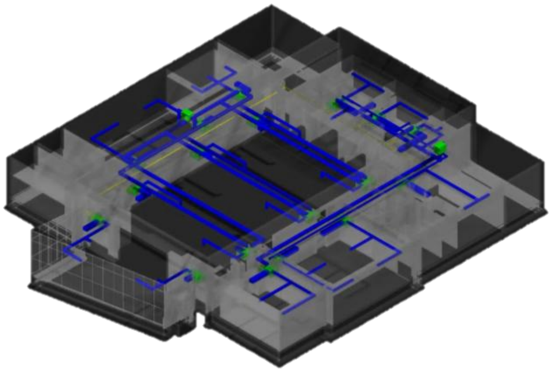

Figure 27 – *Heat Pump Layout*

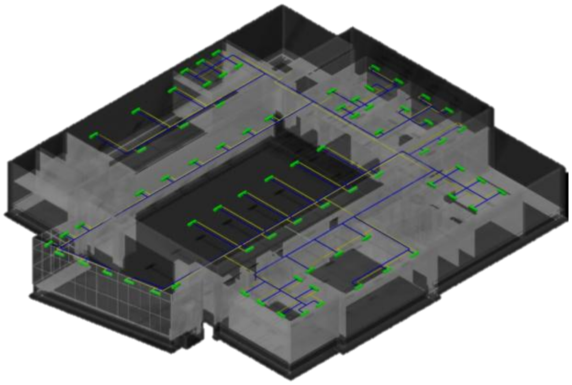

Figure 28 – *Chilled Beam Layout*

8.6 Decision Matrix

The analysis of systems that was just discussed is shown in Table 8 below and on the following page for ease of reference and comparison. Scores are then assigned to the matrix in Table 9, which immediately follows.

Table 8 – *Qualitative Decision Criteria Matrix*

	Baseline System	**Design 1-A**	**Design 1-B**
Description	CAV AHU with gas-fired furnace, chiller, boiler for pre-heat	Both zones VAV Controlled, chiller/boiler, desiccant wheel dehumidification	Zones CAV or VAV controlled, chiller/boiler, desiccant wheel dehumidification
Economics	Lowest first cost, highest life-cycle cost	Low first cost, medium-high life-cycle cost, short pay-back	Medium-low first cost, high life-cycle cost, long pay-back
Energy	Very high energy use; not energy-efficient	Energy-use reduced from baseline due to variable air flow	Energy-use only slightly reduced; not energy-efficient
Sustainability	Low LEED score, high volume of harmful emissions	Average LEED score, low volume of harmful emissions	Average LEED score, high volume of harmful emissions
Reliability/ Maintainability	Very reliable due to a simple system, low maintenance cost	Fairly reliable due to a slightly complex system, medium maintenance cost	Fairly reliable due to a slightly complex system, medium maintenance cost
Architectural Synergy	Relatively poor acoustical performance, rigid distribution layout	Relatively poor acoustical performance, semi-rigid distribution layout	Relatively poor acoustical performance, semi-rigid distribution layout

	Design 2-A	Design 2-B
Description	Heat Pumps with ground source loop, desiccant wheel dehumidification	Fan coil units with boiler/chiller and desiccant wheel dehumidification
Economics	Highest first-cost, lowest life-cycle cost, medium payback period	Medium-high first cost, medium-high life-cycle cost, medium payback period
Energy	Highly reduced heating, cooling, and fan and pumping energy. Very energy-efficient	Significantly reduced heating, cooling, and fan and pumping energy. Fairly energy-efficient
Sustainability	High LEED score, low volume of harmful emissions	High LEED score, average volume of harmful emissions
Reliability/ Maintainability	Fairly reliable due to a slightly complex system, medium to high maintenance cost	Fairly reliable due to a slightly complex system, medium to high maintenance cost
Architectural Synergy	Good acoustical performance, flexible distribution layout	Relatively poor acoustical performance, fairly flexible distribution layout

	Design 3-A	Design 3-B
Description	Chilled beams with ground source loop, back-up boiler/chiller, desiccant wheel dehumidification	Chilled beams with boiler/chiller, desiccant wheel dehumidification
Economics	High first cost, low life-cycle cost, medium-short payback period	High first cost, medium-high life-cycle cost, long payback period
Energy	Highly reduced heating, cooling, and fan and pumping energy. Very energy-efficient	Energy-use only slightly reduced; not energy-efficient
Sustainability	High LEED score, low volume of harmful emissions	Average LEED score, average volume of harmful emissions
Reliability/ Maintainability	Somewhat reliable due to a more complex system, medium to high maintenance cost	Somewhat reliable due to a more complex system, medium to high maintenance cost
Architectural Synergy	Satisfactory acoustical performance, flexible diffuser layout, could be disruptive to ceiling	Satisfactory acoustical performance, flexible diffuser layout, could be disruptive to ceiling

Table 9 – *Quantitative Decision Criteria Matrix*

	BASE	1-A	1-B	2-A	2-B	3-A	3-B
Economics	5	23	12	24	20	25	18
Energy	10	17	10	20	17	20	16
Sustainability	6	11	8	14	11	13	10
Reliability/ Maintainability	15	12	12	10	12	6	8
Architectural Synergy	4	5	5	9	5	7	7
TOTAL	**40**	**68**	**47**	**77**	**65**	**71**	**59**

9.0 Recommendation

After reviewing all design criteria for each system and assessing their relative importance with the custom-made decision matrix, design solution 2-A was selected as the most appropriate system, of those considered, for the Drake Well Oil Museum.

This system consists of 18 heat pumps, with heating or cooling fluid provided by a 100% ground-coupled closed loop, and an energy recovery ventilation system. The presence of these heat pumps allows the zones to be maintained at the necessary set points, even in the strictly-controlled gallery and collections spaces. The heat pumps, because of high coefficients of performance, are much more energy-efficient than a fan coil unit design.

The vertical geothermal loop will utilize the earth's natural temperature as a renewable source or an available heat sink, depending on the system requirements and the time of year. These geothermal bores not only provide the owner with energy cost savings, but also reduce the harmful emissions of the system.

The energy recovery ventilators effectively use the air that would normally be exhausted from the building to precondition the outdoor ventilation air. This addition to the system allows for energy savings and the opportunity to scale down equipment.

These benefits have shown through in our analysis of the investigated systems, as is shown by System 2-A having the highest decision matrix score, and is ultimately the system recommendation for the Drake Well Oil Museum.

10.0 Additional Considerations

A ground-source heat pump system was chosen as the best system out of those investigated, but there are obviously other system components or changes that could be made to this recommendation to potentially improve energy and economic performance. If proposed System 2-A was to be used as a design solution, it would be beneficial to investigate the benefits of replacing the ERV with a fan economizer. With this addition, there would likely be increased pre-heating and pre-cooling, but at the cost of a higher required fan energy. The heat pumps could also be improved upon by adding solar thermal collectors, if this was deemed feasible in this northwestern Pennsylvania climate. In addition to the building envelope improvements discussed, a reflective roof system could be considered in an attempt to control solar radiation into the building spaces.

Appendix A – Ventilation Requirements

Room #	Name	Area (SF)	Occupants	Ventilation (Peop. & Area)		Exhaust (cfm/SF)
101	Vestibule	28	502	-	-	-
102	Main Lobby	1164		5	0.06	-
103	Gallery	6324		7.5	0.06	-
104	Orientation Theater	752	35	10	0.12	-
105	Multi-Purpose Room	1485	213	5	2.5	-
106	Storage	75		-	0.12	-
107	Catering Kit	177		7.5	0.18	0.3
108	Vest	84		-	-	-
109	Lobby	236		7.5	0.06	-
110	Women's	138		140 CFM		140 CFM
111	Men's	112		140 CFM		140 CFM
112	Education	825	40	-	0.06	-
113	Corridor	568		-	0.06	-
114	Open Office and Files	605	21	5	0.06	-
115	Kit/Print	103		5	0.06	0.3
116	Conf Room	295		5	0.06	-
117	Dir Office	137		5	0.06	-
118	Research	281		10	0.18	0.5
119	Corridor	231		-	0.06	-
120	Collections Work Room	351		10	0.18	0.5
121	Dark Room	95		5	2.5	1
122	Toilet	52		50 CFM		50 CFM
123	Mechanical Room	1001	6	-	-	-
124	Collections	2221	9	7.5	0.06	-
125	Vestibule	136		-	-	-
126	Men's	235		210 CFM		210 CFM
127	Women's	308		280 CFM		280 CFM
128	Exist Unisex	93		50 CFM		50 CFM
129	Jan	26		-	0.12	1
103A	Mech Closet	64		-	-	-
103B	Mech Closet	69		-	-	-
104A	Closet	15		-	0.12	
107A	Jan	39		-	0.12	1
130	Garage	592	2	-	0.75	0.75
115A	Closet	27		-	0.12	-
124A	Collections - Clean Room	500		10	0.18	1
104B	Closet	25		-	0.12	-

Table A-1 – Ventilation Requirements

Appendix B – Economic Breakdown

Option	Air Handling/ Dehumidification	Heating/ Cooling	Air and Water Distribution	Total Capital
Base	$ 189,000.00	$ 123,900.00	$ 69,477.28	$ 382,377.28
1-A	$ 233,200.00	$ 88,300.00	$ 94,724.74	$ 416,224.74
1-B	$ 229,000.00	$ 170,000.00	$ 94,191.68	$ 493,191.68
2-A	$ 335,500.00	$ 254,000.00	$ 64,477.28	$ 653,977.28
2-B	$ 335,500.00	$ 133,900.00	$ 64,428.80	$ 533,828.80
3-A	$ 250,000.00	$ 272,000.00	$ 74,053.28	$ 596,053.28
3-B	$ 250,000.00	$ 266,900.00	$ 74,053.28	$ 590,953.28

Table B-1 – Equipment Capital Costs

	Capital ($)	Yearly Energy Use (kBTU)	Yearly Energy Cost ($)	Discount Rate	25-Year Life-Cycle Cost ($)	Simple Payback Period (Years)
BASELINE	328,377.28	280,553	56,110.60	7%	$1,634,221.23	-
OPTION 1-A	416,224.74	177,323	35,464.60	7%	1,032,906.48	4.25
OPTION 1-B	439,191.68	239,213	47,842.60	7%	1,393,415.73	13.40
OPTION 2-A	653,977.28	104,993	20,998.60	7%	611,584.23	9.27
OPTION 2-B	533,828.80	166,498	33,299.60	7%	969,850.85	9.01
OPTION 3-A	596,053.28	111,255	22,251.00	7%	648,060.38	7.91
OPTION 3-B	590,953.28	168,305	33,661.00	7%	980,376.63	11.70

Table B-2 – Payback Period Calculation

References

- ANSI/ASHRAE (2007). Standard 55-2004, Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.
- ANSI/ASHRAE (2010). Standard 62.1 - 2004, Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.
- ANSI/ASHRAE (2010). Standard 90.1 - 2004, Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.
- ANSI/ASHRAE (2010). Standard 189.1 - 2010, Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.
- ASHRAE (2008). 2004 ASHRAE Handbook - Systems & Equipment. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers.
- ASHRAE (2009). 2005 ASHRAE Handbook - Fundamentals. Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.
- ASHRAE (2007). 2007 ASHRAE Handbook - HVAC Applications. Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.
- ASHRAE. 1992. Gravimetric and dust-spot procedures for testing air-cleaning devices used in general ventilation for removing particulate matter. Standard 52.1-1992.
- International Energy Agency Heat Pump Centre. 1992. Heat Pump Centre Newsletter 10(1).
- ISO. 2003. Cleanrooms and associated controlled environments—Biocontamination control, part 1: General principles and methods. Standard 14698-1. International Organization for Standardization, Geneva, Switzerland.
- RS Means (2007). RS Means – Mechanical Cost Data. Kingston, MA.
- Trane Trace 700 v.6.2.6.5 (2010) Tyler, TX, United States of America.
- United States Energy Information Administration. September, 2008. CBECS. Commercial Energy Use & Costs.
- WUFI-ORNL/IBP v3.0 Software. Oak Ridge National Laboratory.