# Final Report

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This report conveys the results of multiple studies conducted as requirements of the Penn State Architectural Engineering senior capstone project, formally AE481/AE482. Included within are proposed design modifications to Manassas Park Elementary School in Manassas Park, VA. Much of the background knowledge used to conduct these studies came from 500-level master's courses taken at the Pennsylvania State University, specifically AE 557 (Central Cooling), AE 558 (Central Heating), and involvements in the international ASHRAE Student Design Competition, a master's level independent study. This report was created for speculation only, and should not be used as a basis for changes to the current systems of Manassas Park Elementary School without consultation with a registered Professional Engineer.

**The Pennsylvania State University**
**Architectural Engineering: Mechanical**
**Advisor: Dr. Freihaut**
**April 7, 2010**

## Table of Contents

## List of Tables

## List of Figures

*Renderings Generously Provided by VMDO Architects. Special Thanks to Michael Smith for Abstract Inspiration.*

# Manassas Park Elementary School

Architect:

**VMDO Architects**

Contractor:

**Hess Construction**

Structural Engineer:

**Fox & Associates**

Civil Engineering:

**Bowman Consulting**

MEP Engineer:

**2rw Consulting Engineers**

Foodservice Consultant:

**EIS Incorporated**

Commissioning Authority:

**Sebesta Blomberg & Associates**

*Construction:*

*Proposal: October 2006*

*Overall Project Cost: $33 Million*

*Substantial Completion: March 2009*

*Project Delivery Method: Design-Bid-Build*

*Structure:*

*Foundation: CMU.*

*Support is provided by 4" slabs on composite decking, held in place by a 33' x 22' grid of steel columns supporting wide flange beams and open web steel joists of varying sizes*

*Mechanical Systems:*

*The buildings air is heated and cooled by multiple heat pumps, and is ventilated by 5 outside air units and a makeup unit. The heat pumps are connected to a 200-well geothermal system, where heat is either absorbed or rejected depending on seasonal needs.*

*Lighting:*

*The lighting systems consist mostly of pendant type dual lamp dimmable 32 Watt T-8 fixtures connected to both photocells and occupancy sensors. In the Gym and Library, light wells are used to distribute clean, natural daylight to the occupied spaces when artificial lighting is unnessary.*

*Cougar Upper Elementary School was designed to achieve an educationally productive and environmentally friendly space to enrich the lives of school children in grades three through five. The architecture of this building is focused on sustainability and constructability; it takes simple cubes and through extrusions and indentations creates visually pleasing forms that interact with humans and nature to achieve an aesthetically satisfying design.*

# Executive Summary:

The purpose of this report is to convey the results of multiple studies conducted as requirements of the Penn State Architectural Engineering senior capstone project. This report outlines existing and proposed designs relevant to Manassas Park Elementary School; a recently designed and built LEED® Gold elementary school in Manassas Park, VA. Integral points of engineering interest include a building design summary, an existing system analysis, mechanical system modification suggestions, two breadth topics, system schematics, and etcetera.

The system modification suggestions included within this report consist of:

- Connecting the existing Outdoor Air Units (OAUs) to the ground loop to remove the direct expansion coils and/or the direct fire reheat.
- Removing the sensible wheels from the OAUs to decrease associate pressure drop.
- Rerouting ductwork from the OAUs to the Ground Source Heat Pumps (GSHPs) such that the system goes from a series configuration to a parallel configuration, thus allowing the GSHP to be bypassed when applicable.
- Adding BACNET compatible people counters which manipulate added dampers on the Outdoor Air (OA) side of the GSHPs to ramp down the OAUs blowers when applicable.
- Manipulating ventilation operation modes to optimize building ventilation performance.
- Altering the buildings envelope to synergize with the aforementioned ventilation modifications.
- Adding an off-building photovoltaic (PV) array to decrease grid dependence.

Conclusions made within this report include:

- Connecting the existing Outdoor Air Units to the ground loop would require 21 additional wells to be drilled, costing $233,250 and having a simple payback of 10.7 years.
- Removing the sensible wheels from the OAUs reduces the capacity of the OAU supply and exhaust motors by 30%, and decreases the systems total thermal capacity[1] by over 4%.
- Putting the OAUs and the GSHPs in parallel allows the heat pumps to be de-energized whenever the OAUs can meet the thermal loads of the building, significantly decreasing annual GSHP fan energy consumption.
- People counters could be utilized to control the real-time ventilation requirements of intermittently used spaces.
- The optimal ventilation strategy does not include a natural ventilation mode.
- Replacing the operable windows with non-operable windows saves energy and decreases the chance for building occupants to be exposed to outdoor allergens.
- Adding an off-building PV array is ultimately cost-prohibitive.

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[1] System total thermal capacity refers to the combined OAU and GSHP capacity.

## Building Design Summary:

Manassas Park Elementary School is a 123,000 square foot building located in Manassas Park, Virginia. The school is served by some relatively efficient[2] heating and cooling systems that were allegedly chosen as the best combination of minimized first cost and an ability to provide a comfortable indoor environment to the buildings occupants. These systems were also chosen to help promote the school as an environmentally conscious building, as minimizing the overall energy and associated resource consumption of the school was important to both the township and its citizens.

Sustainability was a major consideration in the initial system selection of the design team because the building was pre-determined to be an example of growing environmental consciousness in the construction of educational facilities in northern Virginia. The school's design was planned with the overlying philosophy that a good school can be the catalyst for an evolving and maturing community; a philosophy that MPES ultimately proved robust[3]. Figure 1, below, is a rendering of the school provided by the architect of record, VMDO Architects.

Figure 1: Manassas Park Elementary School

Sustainable highlights of the building include a 75,000 gallon cistern used for grey water storage, light tubes that virtually eliminate artificial illumination requirements on a sunny day, floors made out of recycled airplane tires and a non-toxic adhesive, motion sensors with automatic light meters, and a non-automated natural ventilation system[4].

### Existing Mechanical System:

Primary mechanical heating and cooling is supplied to the building at the zone level via a distributed

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[2] In reference to the average Virginia elementary education facility

[3] See Technical Report 3

[4] Teachers are expected to open and close windows as a corridor mounted green light turns on and off, respectively.

two-pipe ground source heat pump system. These heat pumps utilize a 5 acre, 200-well variable primary geothermal loop that is able to consistently supply water at 55 degrees Fahrenheit and has a maximum operating capacity of 4000 MBH. Air-side and water-side system schematics can be found in Appendix A.

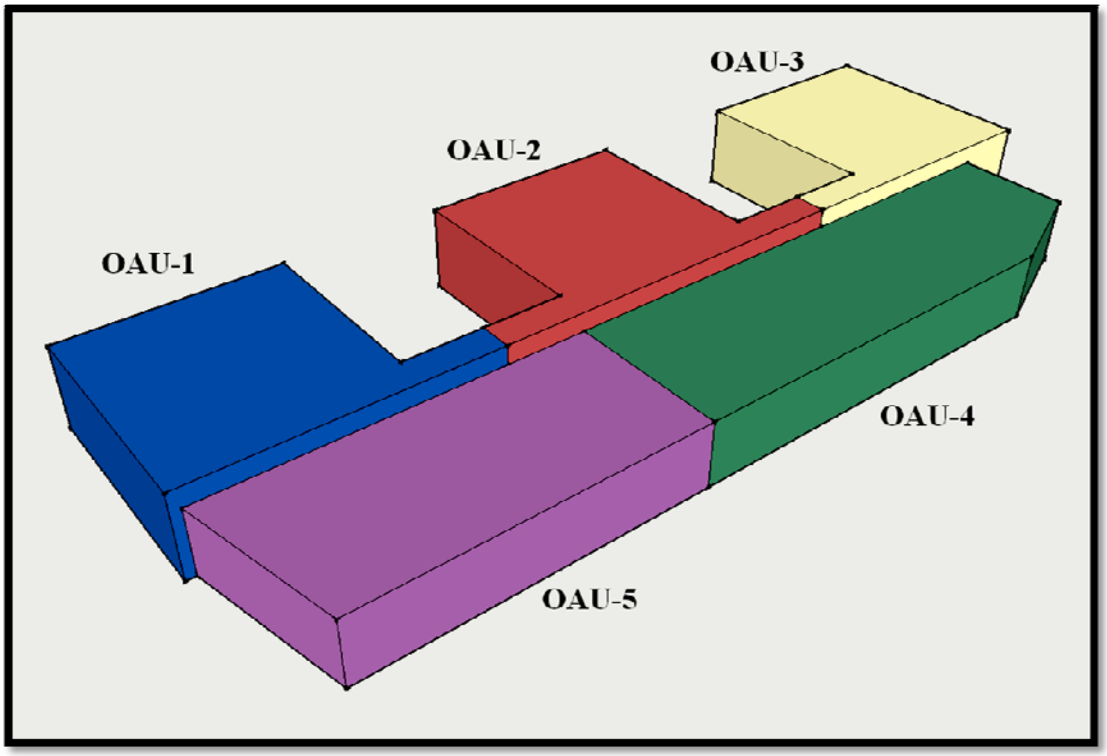
Before the supply air is supplied to the heat pumps, it goes through one of 5 outside air units[5]. Relevant specifications for the individual units can be seen in Table 1, below.

**Table 1: Outdoor Air Unit Schedule[6]**

| Mark | Supply Air (CFM) | Supply Fan Power (HP) | Exhaust Fan Power (HP) | Enthalpy Wheel Power (HP) | Sensible Wheel Power (HP) | Cooling Coil Cap (MBH) | Gas Fired Cap (MBH) | Pre-Filter Efficiency |
|---|---|---|---|---|---|---|---|---|
| OAU-1,2,3 | 3360 | 5 | 3 | 0.25 | 0.25 | 128.5 | 123 | 30% |
| OAU-4 | 9330 | 15 | 7.5 | 0.5 | 0.25 | 365.3 | 341 | 30% |
| OAU-5 | 4650 | 7.5 | 3 | 0.25 | 0.25 | 188.3 | 170 | 30% |

Figure 1 shows the relationships between the OAUs represented in Table 1 and the five main buildings zones[7]. Because of the similarities between the buildings “pods” (blue, red, and yellow zones in Figure 2), outside air units 1, 2, and 3 are identically designed and specified.

**Figure 2: OAU Zones**



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[5] See Appendix B for the Outside Air Unit Schematic taken directly from the construction documents as drawn by 2rw Consulting Engineers.

[6] The building ventilation requirements do not exceed 24,060 cubic feet per minute.

[7] Figure 2 was created using Google Sketchup 7 for the assistance of this system zone explanation.

In each one of the 5 OAUs, 100% ventilation air goes through an enthalpy wheel, an air-cooled direct expansion coil[8], a sensible wheel, and an optional direct-fire natural gas heater[9] to precondition the air to 72 degrees Fahrenheit and 50% relative humidity. From here, this 100% outside air is mixed with return air at the zone level, and is then delivered to the distributed ground source heat pumps. This mixed air is then conditioned to the supply temperature by the R-407c vapor compression cycle[10] within the heat pumps, rejecting heat to or absorbing heat from the ground loop water. Air is primarily exhausted[11] to the outside air units, where it provides supplemental conditioning to the intake air via the aforementioned sensible and enthalpy wheels.

The initial design for the ventilation portion of the system utilizes what is called a "green light" natural ventilation system. When the weather conditions fall into an acceptable range, a green light in the corridor turns on and teachers are expected to open all of the operable windows in their classrooms. Fan energy requirements are reduced as applicable OAUs are de-energized, and no mechanical ventilation is sent to the perimeter zones.

### Benefits of the existing GSHP system:

The ground loop utilized by the heat pump system at Manassas Park Elementary School provides a relatively constant temperature water stream to the buildings heat pumps[12]. This water stream is a reasonably easy media to absorb heat from or to reject heat to compared to ambient air for a variety of reasons. First off, absorbing heat from winter ambient air and rejecting heat to summer ambient air is very difficult. At these conditions (hot summer days, cold winter nights), there exists a very low temperature difference between the actual heat that the system is trying to absorb or reject and the media that it is absorbing it from or rejecting it to (the surrounding air). The reason that the constant temperature water stream can provide highly efficient heating and cooling is because of the greatly increased relative temperature difference between what the system is trying to absorb or reject and the media that it is absorbing from or rejecting to (the ground loop).

Another perk of a ground source heat pump system is that it uses water to transport heat as opposed to air. Water has a much higher thermal capacity than air, meaning that much less volume of water must be transported than air to have the same heat transportation effects. Because the transportation of heat is primarily accomplished via water pipes, the buildings mechanical area and volume allocations required to heat and/or cool each individual space are greatly decreased, saving energy, space, and money.

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[8] OAU-1,2,3 have individual remote 2-compressor air-cooled condensing units. OAU-4 has a packaged 4-compressor air-cooled condensing unit, and OAU-5 has a packaged 2-compressor air-cooled condensing.

[9] Equipment is listed in the order as seen by OA.

[10] Rooftop GSHP units utilize a 500W, 120V heater with a temperature stat set at 40 degrees Fahrenheit to precondition air. This is primarily used as freeze protection such that typical GSHP operation is possible.

[11] Areas including the mechanical rooms, penthouses, kitchens, data closets, and bathrooms are exhausted directly out of the building. A make-up air unit is used to balance the kitchen exhaust hood, and supplies a constant volume of air to the kitchen with optional direct fire heating.

[12] 55 degree Fahrenheit water is supplied from the ground to the building; not all GSHPs have a 55 degree entering water temperature.

## ASHRAE Standard 90.1-2007 Compliance of the Existing Building:

### ASHRAE Standard 90.1-2007 Section 5 – *Building Envelope*:

Manassas Park Elementary School is a nonresidential conditioned building located in climate zone 4a as specified by section 5.1.2.1 and Table B-1 of ASHRAE Standard 90.1-2007. The school has a 32% vertical fenestration area and a 3% skylight fenestration area. Because these areas are less than 40% and 5% respectively, the building was designed to follow the Prescriptive Building Envelope Compliance Path specified in section 5.5 of Standard 90.1.

The Standard specifies that the envelope system of a nonresidential conditioned space located in climate zone 4a is compliant based on the fulfillment of individual requirements outlined in sections 5.4, 5.5, 5.7, and 5.8. The explicit specifications stated within these sections are listed in Table 5.5-4 of the Standard, which is shown in Appendix C. Table 2, below, summarizes Manassas Park Elementary Schools compliance with the requirements of Table 5.5-4.

**Table 2: Section 5 Compliance Summary:**

| Value | Minimum Roof Insulation R-Value | Minimum Wall Insulation R-Value For Brick/CMU Walls | Non-Heated Slab on Grade Floor Minimum Insulation | Fenestration Assembly Maximum U-Value | Fenestration Maximum SHGC |
|---|---|---|---|---|---|
| Required | R-20 | R-9.5 | Not Required | 0.55 | 0.40 |
| Designed | R-30 | R-10 | Not Required | 0.40 | 0.30 |
| Compliance | Achieved | Achieved | Achieved | Achieved | Achieved |

### ASHRAE Standard 90.1-2007 Section 6 – *HVAC*:

Compliance with section 6 of ASHRAE Standard 90.1 was determined according to section 6.4, Mandatory Provisions, and section 6.5, Prescriptive Path. Section 6.3, Simplified Approach Option for HVAC Systems was neglected, as the school is over two stories in height and has a gross floor area over 25,000 ft$^2$.

The heat pump systems in the school were[13] originally designed to comply with Section 6 of the standard. MPES utilizes a myriad of different heat pump configurations manufactured by ClimateMaster, and the individual models of heat pumps used in the school can be reviewed in Table 3, below.

**Table 3: ClimateMaster Heat Pump Models Used in MPES:**

| Heat Pump Series | Model Number: |
|---|---|
| TSD | TSD018, TSD024, TSD030, TSD042, TSD048, TSD060 |
| TSV | TSV042, TSV018, TSV030, TSV036, TSV048, TSV024 |
| GLV | GLV200, GLV300 |
| RE | RE07, RE20 |

Appendix D shows energy efficiency tables for all TS-, GL-, and RE- models, from which Section 6 heat

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[13] Should have been.

pump compliance can be reviewed. All of the heat pump models specified in the MPES are compliant with ASHRAE Standard 90.1-2007 with the acception of the GLV300. There is only 1 GLV300 unit in the building, and it is shown by the manufacturer specifications to have an EER of 12.7 with a 77˚F entering water temperature. This does not meet the requirements set forth by the standard, which specifies that heat pumps must have an EER of 13.4 or better with an entering water temperature of 77˚F.

The 144,000 BTU/hr condensing units connected to OAU-1, OAU-2, and OAU-3 have EERs of 9.8, as is shown on the mechanical equipment schedule of the mechanical drawing set. ASHRAE Standard 90.1-2007 requires that condensing units of 135,000 BTU/h capacity or larger have an EER of 10.1 or better. These pieces of equipment were also not ASHRAE 90.1-2007 compliant.

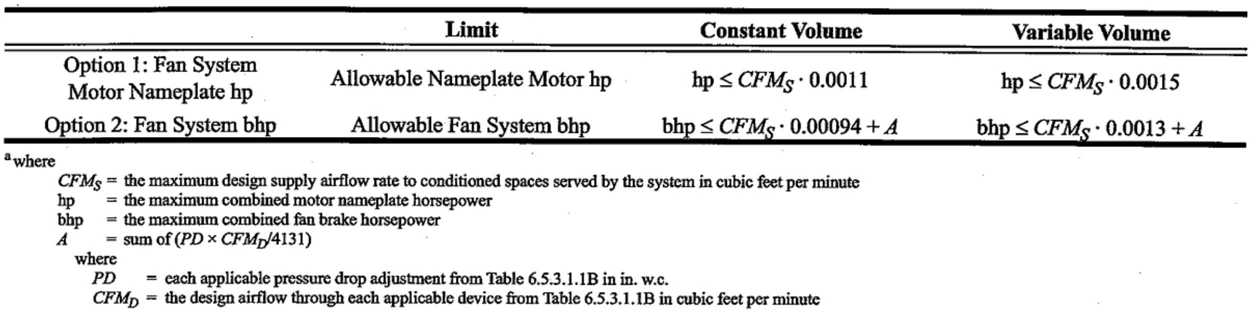
The mechanical equipment within MPES is covered by the U. S. National Appliance Energy Conservation Act of 1987, and thus does not need to have manufacturer installed labels stating that the given equipment complies with the requirements set forth in ASHRAE Standard 90.1. The equipment does, however, carry a perminant manufacturer installed label that shows specific equipment information from which ASHRAE Standard 90.1 compliance can be determined.

Section 6.5.1 of ASHRAE Standard 90.1 2007 specifies that “Each cooling system that has a fan shall include either an air or water economizer meeting the requirements of Sections 6.5.1.1 through 6.5.1.4”. Table 6.5.1 of the Standard specifies that there is no economizer requirement for systems located in climate zone 4a, and thus Manassas Park Elementary School is in compliance with Section 6.5.1.

Zone thermostatic controls in the building are capable of “operating in sequence the supply of heating and cooling energy to the zone”, which also complys with the standard (Section 6.5.2). This thermostatic control allows certain heat pumps to utilize reheat after air is dehumidified by the condensing units. In most cases, this section is irrellavant due to the fact that the air is dehumidified via dessicant wheels, and the associated cooling does not overcool the space (which would obviously require reheat).

Section 6.5.3.1, *Fan System Power Limitation*, specifies that system design conditions for supply fans, return/relief fans, and exhaust fans may not exceed the allowable fan system motor horsepower. The analysis conducted to verify compliance with this section was carried out in accordance with the calculations found within Table 6.5.4.1.1A of ASHRAE 90.1-2007, shown below as Table 4.

**Table 4: Fan Efficiency Limitation Calculations:**



|  | Limit | Constant Volume | Variable Volume |
|---|---|---|---|
| Option 1: Fan System Motor Nameplate hp | Allowable Nameplate Motor hp | $hp \le CFM_S \cdot 0.0011$ | $hp \le CFM_S \cdot 0.0015$ |
| Option 2: Fan System bhp | Allowable Fan System bhp | $bhp \le CFM_S \cdot 0.00094 + A$ | $bhp \le CFM_S \cdot 0.0013 + A$ |

[a] where

$CFM_S$ = the maximum design supply airflow rate to conditioned spaces served by the system in cubic feet per minute
hp = the maximum combined motor nameplate horsepower
bhp = the maximum combined fan brake horsepower
$A$ = sum of $(PD \times CFM_D/4131)$

where

$PD$ = each applicable pressure drop adjustment from Table 6.5.3.1.1B in in. w.c.
$CFM_D$ = the design airflow through each applicable device from Table 6.5.3.1.1B in cubic feet per minute

Through conducting the fan system power limitation analysis, it was determined that all of the fans except exhaust fan EF-7 were in compliance with Section 6.5.3.1. Sample calculations are shown in Table 5, below. This sample calculation set was chosen to specifically illustrate the non-compliant equipment.

**Table 5: Sample Calculations of Minimum Fan Efficiencies:**

| Mark | HP | W | CFM | CFM•0.0011 | Compliant? |
|---|---|---|---|---|---|
| EF-1 | 0.44 | 328 | 750 | 0.825 | Yes |
| EF-2 | 0.07 | 50 | 75 | 0.083 | Yes |
| EF-3 | 0.06 | 48 | 200 | 0.220 | Yes |
| EF-4 | 2.00 | 1491 | 12670 | 13.937 | Yes |
| EF-5 | 0.19 | 144 | 370 | 0.407 | Yes |
| EF-6 | 0.23 | 168 | 140 | 0.154 | No |
| EF-7* | 0.06 | 45 | 50 | 0.075 | Yes |
| EF-DW | 0.25 | 186 | 600 | 0.660 | Yes |
| EF-MAU-1 | 3.00 | 2237 | 5690 | 6.259 | Yes |

*Note: EF-7 is a variable speed motor, and compliance equations within this table have been modified to reflect such.

*VAV Fan Control (Including Systems Using Series Fan Power Boxes)* is discussed in Section 6.5.3.2 of ASHRAE Standard 90.1-2007. This section details variable air volume terminal box requirements within a building system. Manassas Park Elementary School does not utilize variable air volume terminal boxes, and thus is not subject to the requirements specified within Section 6.5.3.2.

Section 6.5.4 of the standard, *Hydronic System Design and Control*, specifies that "HVAC hydronic systems having a total *pump system power* exceeding 10hp shall meet provisions of Sections 6.5.4.1 through 6.5.4.4". Section 6.5.4.1, *Hydronic Variable Flow Systems*, states that "HVAC pumping systems that include control valves designed to modulate… shall be capable of reducing pump flow rates to 50% or less of the design flow rate". Table 8, below, shows that the MPES ground source heat pump motors are both over 50 hp, and thus are subject to the requirements set forth in Section 6.5.4.1. This information was taken directly from the mechancial schedules located on the mechancial drawings provided by 2rw Consulting Engineers.

**Table 6: Ground Loop Pump Motor Efficiencies:**

| Mark | Service | Efficiency | GPM | Head (ft) | HP |
|---|---|---|---|---|---|
| HLP-1 | Heat Pump Loop | 83.3% | 962 | 150 | 50 |
| HLP-2 | Heat Pump Loop | 83.3% | 962 | 150 | 50 |

Section 15265-2.1-D-23 of the MPES building specifications states that the variable frequency drive used by the heat pumps (HLP-1 & HLP-2) has a current limit adjustment of "0-100 percent of rated [amperage]". This meets relevant requirements specified in ASHRAE Standard 90.1-2007, including Section 6.5.4.1.

Section 6.5.4.2, *Pump Isolation* is only applicable if a building has more than one chiller. Because MPES does not have any chillers, it is exempt from the requirements of Section 6.5.4.2.

The standard aslo requires systems with a design capacity exceeding 300,000 BTU/hr to "include controls that automatically reset supply water temperatures by representative building loads or *outdoor air* temperature". Specification section 15730-2.3-A-4-i shows the heat pump control systems as having an automatic intelligent reset as one of the primary features. This reset feature was not ultimately required by Section 6.5.4.3 due to the following exception: "Hydronic systems… that used variable flow to reduce pumping energy [are exempt]".

Section 6.5.4.4, *Hydronic Heat Pump Systems*, specifies that "each hydronic heat pump shall have a two-position automatic valve interlocked to shut off water flow when the compressor is off". Specification section 15730-2.3-A-4-m states that a motorized water valve cycles wich the compressor such that water flow is shut off when the compressor is off, putting the system in compliance with the standard.

*Fan Speed Control* requirements in the standard state that "each fan powered by a motor of 7.5 hp or larger shall have the capability to operate that fan at two-thirds of full speed or less and shall have controls that automatically change the fan speed to control the leaving fluid temperature or condensing temperature/pressure of the heat rejection device". The heat pumps specified for Manassas Park Elementary School all have duel voltage capabilities, which puts them in compliance with this section.

Section 6.5.6.2 of Standard 90.1, *Heat Recovery for Service Water Heating,* states that "condenser heat recovery systems shall be installed for heating or preheating of service hot water" if the implied building has a specific set of charactoristics. Among these defined charactoristics is that the building must be a 24-hour facility. Because MPES is not open 24 hours a day, it is exempt from this section of the standard.

"Individual kitchen exhaust hoods larger than 5000 cfm [are required to] be provided with makeup air sized for at least 50% of exhaust air volume" as specified by Section 6.5.7.1, *Kitchen Exhaust Hoods*. EF-MAU-1 is a roof mounted upblast type kitchen exhaust fan that removes kitchen air at a rate of 5690 cfm, and because 5690 is greater than 5000, requirements specified in Section 6.5.7.1 apply. The elementary school utilizes a make-up air unit (MAU-1) to account for the air exhausted by EF-MAU-1. This unit provides 3985 cfm of constant volume make-up air via an energy efficient EPACT and NEMA 1210 compliant motor, more than satisfying the requirements set forth in Section 6.5.7.1 of Standard 90.1-2007.

Another kitchen requirement can be found in Section 6.5.7.2 of the standard. The *Fume Hoods* section applies to buildings with "fume hood systems having a total exhaust rate greater than 15,000 cfm". Manassas Park Elementary School is exempt from the requirements within this section, as the cumulative fume hood rate within the building is only 5,690 cfm.

Sections 6.5.8 (*Radiant Heating Systems*) and 6.5.9 (*Hot Gas Bypass Limitation*) are both irrelevant to the school, as it does not have radiant heating systems or equipment utilizing hot gas bypass.

## ASHRAE Standard 90.1-2007 Section 7 – *Water Heating*:

Domestic hot water in MPES is supplied by a variety of different heaters. These heater types include vertical storage gas fired heaters, vertical storage electric heaters, and electric instant heaters. The specific water heater types are listed in Table 7, below.

**Table 7: Water Heaters in Manassas Park Elementary School:**

| Mark | Type | Fuel | Input (btu/hr, kW) | Storage Capacity (Gal) | Compliance |
|---|---|---|---|---|---|
| DWH.1A, 1B | Vertical Storage | Natural Gas | 199000 | 100 | Achieved |
| DWH.2 | Vertical Storage | Electric | 24 | 80 | Achieved |
| DWH.3 | Instant | Electric | 10 | 0 | Achieved |
| DWH.4 | Vertical Storage | Electric | 9 | 80 | Achieved |
| DWH.5 | Vertical Storage | Electric | 18 | 80 | Achieved |
| DWH.6 | Instant | Electric | 3.5 | 0 | Achieved |

Section 7 of ASHRAE Standard 90.1-2007 specifies minimum efficiencies for water heating equipment as being 80%. The 199,000 BTU/hr natural gas fired vertical storage water heater is specified as being 98% efficient in the plumbing equipment schedule found on the plumbing drawings; this efficiency is well within the 80% requirement set forth by Standard 90.1. Because the direct efficiency of electrical heaters is assumed to be 100%, they were ignored from this analysis.

## ASHRAE Standard 90.1-2007 Section 8 – *Power*:

Section 8 of ASHRAE Standard 90.1-2007 specifies that feeder conductors must have a maximum voltage drop of 2% at the design load, and branch circuits most have a maximum voltage drop of 3% at the design load. The electrical designer used Standard 90.1-2004 as the design constraints for the building, and after cross-checking the 2004/2007 power requirements, it was determined that the requirements perscribed in Section 8 had also been met.

## ASHRAE Standard 90.1-2007 Section 9 – *Lighting*:

Section 9 of the standard, titled *Lighting*, applies to all interior and exterior lighting systems of the school.

Section 9.4.1.1, *Automatic Lighting Shutoff*, states that "[all] interior lighiting in buildings larger than 5000 ft$^2$ shall be controlled with an automatic control device to shut off building lighting in all spaces". Specification section 17030-3.9-A states that "the BAS shall control individual lighting circuits (as indicated on the plans) via relays with contacts rated for 20A at 277V. Each relay shall have its own operating schedule according to school programming. Exterior lighting shall be controlled by its own operating schedule and the BAS astronomical clock." This specification satisfies the requirements set forth in Section 9.4.1.1.

The section of the standard addressing *Space Control* states that "Each space enclosed by ceiling-height partitions shall have at least one control device to independently control the general lighting within the space. Each manual device shall be readily accessible and located so that the occupants can see the controlled lighting". The spaces within Manassas Park Elementary School are all compliant with this section. Most of the systems in the school consist of pendant type dual lamp dimmable 32 Watt T-8 fixtures connected to both photocells and occupancy sensors. The occupancy sensors turn the lights off after no motion is detected for 10 minutes; however, occupants have the ability to manually shut the lights off at their discretion. The photocells allow the pendant fixtures to provide no more than the required amount of light to each space. When a large amount of natural light illuminates the building from the exterior, artificial lights are automatically dimmed to provide the appropriate amount of light to each space. All of these controls are clearly visible and in an obvious location, with the exception of the photocells, which are not designed for occupant manipulation[14].

To provide natural lighting to interior spaces including the gymnasium and the library, the school utilizes light tunnels with motorized dimming controls which are accessible by the occupants. These switches are intuitively designed and placed such that both teachers and students can manipulate lighting levels to meet the needs of specific activities. When the light from these tunnels is insufficient, the gym and library are illuminated on a secondary basis by halogen and fluorescent lamps. Light tunnels are located in the buildings largest spaces, which drastically reduces the as designed interior lighting power density of the school. Exterior zone lighting power density is also minimized due to a design that incorporates maximum natural daylight. Most of the building's exterior rooms have a ceiling height of 11 feet at the exterior wall and 9 feet at the interior partition. This peculiar ceiling arrangement was designed specifically to magnify the effects of ceiling reflection of natural daylight. Because of the phenomenal daylighting strategies utilized in both exterior and interior spaces, Manassas Park Elementary School is well within the compliant region of ASHRAE Standard 90.1-2007, Section 9.

### ASHRAE Standard 90.1-2007 Conclusion:

The original design for Manassas Park Elementary School was largely compliant with Standard 90.1-2007. The non-compliant systems make up a very small portion of the entire building, virtually rendering their effects negligible to the entire efficiency of the integrated building system. The reasons for non-compliance are most likely due to calculation errors and/or equipment specification errors. There is also a possibility that the methodologies conducted within this analysis differed from the strategies used for the initial system design preformed by the engineers of record, and that both methods are acceptable.

The MPES design team had a goal of achieving LEED® Gold certification, and the cumulative modeled energy use of the system is much less than that of a comparable school. Specifically, the use of light wells and natural daylighting practically eliminated the dependence on artificial light in most of the perimeter zones as well as select interior zones, and the base mechanical system used minimal energy to meet the needs of the occupants. An in-depth LEED analysis of the existing building can be reviewed in the section below.

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[14] The photocells are required to be intermittently checked by the building operation staff to confirm that minimum illumination levels are consistently being met.

## Mechanical Sustainability Assessment - LEED® v2.2

The United States Green Building Council (USGBC) has famously developed the Leadership in Energy and Environmental Design green building certification program (LEED®). Although there have been criticisms on the individual category weightings in the LEED rating system[15], it has proven to be a robust and comprehensive assessment of a sustainable building. Specific levels of LEED certification are currently required in many local building codes throughout the country, and LEED certification requirements have also been included in some United States federal mandates. The LEED rating system is currently the most widely used green building certification program in the country.

The LEED rating system "addresses all building types and emphasizes state-of-the-art strategies in five areas: *sustainable site development, water savings, energy efficiency, materials and resources selection, and indoor environmental quality*" (http://www.usgbc.org/). Of these five categories, a buildings credit score in *energy efficiency* and *indoor environmental quality* are most dependant on that buildings mechanical system. The LEED analysis that follows was performed with specific focus on these two categories.

### Energy & Atmosphere

In the energy efficiency category[16] of the LEED rating system, Manassas Park Elementary School achieved all three of the required prerequisites, as well as 8 out of the 17 possible credits.

The intent of E&A Prerequisite 1, *Fundamental Commissioning of the Building Energy Systems*, is to "verify that the buildings energy related systems are installed, calibrated, and perform according to the owner's project requirements, basis of design, and construction documents"[17]. This intent was achieved through a contract with Sebesta Blomberg[18], who provided the commissioning services on the project.

The intent of E&A Prerequisite 2, *Minimum Energy Performance*, is to "establish the minimum level of energy efficiency for the proposed building and systems". To satisfy this intent, the engineer of record designed the building to comply with all mandatory provisions[19] as well as the prescriptive requirements[20] of ASHRAE Standard 90.1-2004 (without amendments).

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[15] In the past, the LEED rating system has had controversial category weightings that have not "sufficiently stressed the importance of energy efficiency", claim some environmental critics. Newer versions of the LEED rating system have reconsidered category weightings, and have put a higher importance on the energy efficiency and overall conservation of an applicable building.

[16] The energy efficiency category of the LEED rating system is officially titled *Energy & Atmosphere* (E&A).

[17] The intents of individual prerequisites and credits that are shown in quotations were taken directly from the LEED-NC Version 2.2 Reference Guide.

[18] Sebesta Blomberg is a Minneapolis, MN based company with an extensive history of commissioning building systems. The design team worked directly with the Alrington, VA office to achieve many of the commissioning related credits in the LEED rating system.

[19] Mandatory provisions of ASHRAE Standard 90.1-2004 can be found in Sections 5.4, 6.4, 7.4, 8.4, 9.4, and 10.4 of the standard.

[20] Prescriptive requirements of ASHRAE Standard 90.1-2004 can be found in Sections 5.5, 6.5, 7.5, and 9.5.

The intent of E&A Prerequisite 3, *Fundamental Refrigerant Management*, is to "reduce ozone depletion". To satisfy this intent, the engineer of record specified heating, ventilating, air-conditioning and refrigeration equipment that did not use any chlorofluorocarbon-based refrigerants.

Manassas Park Elementary School achieved 7 out of the 10 possible credits for E&A Credit 1, *Optimize Energy Performance*. The intent of this credit is to "achieve increasing levels of energy performance above the baseline in the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use". To satisfy this intent, the design team worked as an integrated entity to create a building that had a designed energy consumption equaling less than 68.5% of the energy that a comparable baseline building would consume. The comparable baseline energy consumption used in this analysis was calculated in accordance to the Building Performance Rating Method in Appendix G of ASHRAE Standard 90.1-2004. To reiterate, the major factors that contributed to this buildings energy use reduction include (but are not limited to) an efficient daylighting design that minimizes artificial illumination requirements, hydronic thermal transport between conditioning systems and the spaces being conditioned, and the use of a variable primary geothermal system to produce an approximately constant temperature heat source/sync for efficient space conditioning via a series of decentralized heat pumps.

The school was also able to achieve E&A Credit 5, *Measurement & Verification*. The intent of Credit 5 is to "provide for the ongoing accountability of building energy consumption over time". Achieving this credit is imperative for a publically owned building, as it can be used to *prove* substantial energy savings[21] that may or may not be the result of an increased first cost, financed by the paying public[22].

## Indoor Environmental Quality

In the indoor environmental quality (IEQ) category of the LEED rating system, Manassas Park Elementary School achieved both of the required prerequisites, as well as 11 out of the 15 possible credits.

The intent of IEQ Prerequisite 1, *Minimum IAQ Performance*, is to "establish minimum indoor air quality performance to enhance indoor air quality in buildings, thus contributing to the comfort and well-being of the occupants". To satisfy this intent, the engineer of record designed the building to comply with Sections 4 through 7 of ASHRAE Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality*.

The intent of IEQ Prerequisite 2, *Environmental Tobacco Smoke (ETS) Control*, is to "minimize exposure of building occupants, indoor surfaces, and ventilation air distribution systems to Environmental Tobacco Smoke". To satisfy this intent, the entire building site was designated as a tobacco free school

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[21] Without achieving E&A Credit 5, *Measurement & Verification*, a design team could potentially manipulate energy modeling results (knowingly or not) to obtain values indicative of a high performance building. These results could be used to undeservingly receive credit for an energy efficient building, as the energy efficiency of the constructed building could potentially be less than what was shown in the respective energy model.

[22] A group of Manassas Park township residents have been known to argue against energy saving measures in public buildings due to the potentially increased first costs of design (which is usually passed on to the respective tax payers).

zone. This virtually eliminates[23] all traceable amounts of environmental tobacco smoke from the building's interior and exterior air.

IEQ Credit 2, *Increased Ventilation*, was not attempted or achieved by the MPES design team. Discussion on other non-achieved credits has been neglected from this analysis; however, due to the controversial nature of this credit, a short insight has been included. ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*, has been under development for over 100 years. It is based on the results from experiments conducted by numerous design professionals and accredited institutions that have become famous within the industry as leading sources of experimentally proven information. The standard provides specific ventilation rates for different area types, with final ventilation values dependant on the affiliated amount of area and the occupancy levels of those areas. The USGBC has created IEQ Credit 2, which rewards a design team for specifying ventilation values that are 30% above the suggested values of ASHRAE Standard 62.1. This increased ventilation comes at a premium energy cost, and does not provide any proven advantages over a typical system that is compliant with ASHRAE Standard 62.1. According to Joseph Lstiburek[24], design teams should strive to "Build tight, ventilate right. Tight is [defined as] 0.39 cfm/ft2 [(or less) airflow when the building is pressurized to] 0.3 inches of water column. Right is [a design that is compliant with] Standard 62.1" (J. Lstiburek, *Why Green Can Be Wash*, ASHARE Journal, November 2008). IEQ Credit 2 directly opposes this philosophy. According to Dr. Lstriburek and like minded professionals, it was a technically vigorous decision on the part of the mechanical designers of Manassas Park Elementary School not to attempt this credit.

The intent of IEQ Credit 3.1, *Construction IAQ Management Plan, During Construction*, is to "reduce indoor air quality problems resulting from the construction/renovation process in order to help sustain the comfort and well-being of construction workers and building occupants". To achieve the intent of this credit, the General Contractor implemented an indoor air quality management plan for the construction and pre-occupancy phases of the project. This plan helped to ensure that absorptive material stored or installed on site was protected from moisture damage, and that filtration media with a MERV rating of 8 or higher was used at each return air grille of the AHU's that were operated during the construction phase of the project (among other things).

IEQ Credit's 4.1 through 4.4 were all achieved for this project. These credits all reference the installation or use of low-emitting materials in the building; more specifically: adhesives & sealants, paints & coatings, carpet systems, and composite wood & agrifiber products, respectively. The generalized intent of these credits is to minimize the "quantity of indoor air contaminants that are odorous, irritating, and/or harmful to the comfort and well-being of installers and occupants". This intent was achieved by specifying all products that can be classified within the aforementioned categories to have Volatile Organic Compound (VOC) emission rate less than or equal to the maximum emission rate specified in

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[23] Exterior air that is in close proximity to the tobacco free school zones boundaries may contain noticeable traces of ETS.

[24] Joseph W. Lstiburek, Ph. D., P.Eng., is a principal of Building Science Corporation in Westford, MA, as well as an ASHRAE Fellow. He has twenty-five years of experience in building science research, design, and construction, and is considered by many to be an international authority on indoor air quality, moisture, and condensation in buildings.

the LEED-NC Version 2.2 Reference Guide. The successful achievement of these credits is especially imperative for an elementary school project, as young children may be more susceptible to the negative effects of VOC emissions than adults.

IEQ Credits 6.1 and 6.2 reference a building occupant’s ability to control the lighting and thermal comfort systems of occupied spaces, respectively. The generalized intent of these credits is to provide a high level of indoor environmental control “to promote the productivity, comfort, and well-being of building occupants”. The intent of these credits was achieved by the design team, who provided individual lighting controls for over 90% of the building occupants and individual comfort controls for over 50% of the building occupants. The design team also provided individual lighting and comfort system controllability in all shared multi-occupant spaces, assuring that each individual could manipulate their indoor environment to achieve comfort.

The design for Manassas Park Elementary School also achieved IEQ Credits 7.1 and 7.2. These credits reference the design and verification of a thermally comfortable environment for building occupants. The generalized intent of these credits is similar to that of Credit 6.2 (detailed above); however, Credit 7.2 specifically requires an occupant assessment of the thermal conditions of the building after a specified period of time (6-18 months after occupancy) to ensure that the buildings thermal systems are operating as designed. To achieve the intent of these credits, the engineer of record complied with ASHRAE Standard 55-2004, *Thermal Comfort Conditions for Human Occupancy*, and the building owner agreed to administer a thermal comfort survey within the required time period[25].

IEQ Credits 8.1 and 8.2, *Daylight and Views*, were both achieved for this project. The generalized intent of these credits is to “provide for the building occupants a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building”. The intent of these credits was achieved by the architectural team, who completed a glazing factor calculation that proved that the required glazing factor of 2% was exceeded for over 75% of the buildings regularly occupied areas. Figure 1, below, shows the methodology for completing glazing factor calculations. The architectural design team also provided a direct line of sight to the outdoors to over 90% of the building occupants to further solidify their daily connection with nature.

Figure 3: Glazing Factor Calculation Methodology

$$\text{Glazing Factor} = \frac{\text{Window Area [SF]}}{\text{Floor Area [SF]}} \times \text{Window Geometry Factor} \times \frac{\text{Actual } T_{vis}}{\text{Minimum } T_{vis}} \times \text{Window Height Factor}$$

The last mechanical design and/or energy consumption related credit that the design team was able to achieve cannot be found in the Energy & Atmosphere or the Indoor Environmental Quality categories of

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[25] The required thermal comfort survey has not yet been administered to the building occupants; however, the building owner reports minimal occupant dissatisfaction with the thermal quality of the indoor environment.

the LEED rating system, but rather in the Innovation & Design Process category[26]. Credit was given to the design team for their efforts to educate the buildings occupants on *how* the building was able to achieve the fundamental space and program requirements of an elementary school while decreasing the associated environmental toll. The design team discusses many of the design decisions through an easily comprehendible language on many plaques, placed throughout the building. These plaques discuss the effects of building orientation, daylight utilization, mechanical system design, material choice (and etcetera) on the overall stress that the building imposes on the environment. It was thought that if students learned and became accustomed to the technologies and methodologies implemented by the Manassas Park Elementary School design team, they would grow to appreciate the applied technologies, and even request similar technologies on future building designs over which they had influence.

To defend the design team's decision to spend the extra time, effort, and money[27] on educating the building occupants, let's theorize the potential results of the successful communication of these building traits to just one student who becomes a successful property manager. The school holds over 500 students every year. If just 10% of these students are positively influenced by the sustainable traits of this building each year, than that means around 50 students each year will feel some sort of connection with the sustainable built environment. If after 10 years, only 1 out of the 500 influenced students becomes a successful property owner/manager, then the added time, effort, and money spent on educating the building's occupants will become negligible compared to the end result; perhaps hundreds of thousands of square feet of building area, built in an environmentally conscious manor and thus saving inconceivable amounts of energy and primary resources.

## Mechanical System Direct Cost Breakdown

The mechanical system in Manassas Park Elementary School was designed at a financial primum in comparison to the average Virginia elementary school. An individual cost breakdown can be reviewed in Table 8, below.

**Table 8: Financial Breakdown of the Mechanical Systems**

| Description of Work | Scheduled Value |
|---|---|
| Mobilization | $ 66,000.00 |
| Bond | $ 133,000.00 |
| Submittals | $ 66,000.00 |
| Coordination Drawings | $ 60,000.00 |
| U/G Sanitary & Storm - Material | $ 163,000.00 |
| U/G Sanitary & Storm - Labor | $ 270,000.00 |
| Sleeving -Materials | $ 5,000.00 |
| SIeeving - Labor | $ 20,000.00 |
| A/G Sanitary & Storm - Material | $ 210,000.00 |
| A/G Sanitary & Storm - Labor | $ 225,500.00 |
| Plumbing Piping -Material | $ 20,000.00 |
| Plumbing Piping - Labor | $ 29,000.00 |
| HVAC Piping -Material | $ 19,000.00 |
| HVAC Piping - Labor | $ 27,000.00 |
| HVAC Ductwork - Material | $ 92,000.00 |
| HVAC Ductwork - Labor | $ 138,000.00 |
| Submittals & Mobilization | $ 25,000.00 |
| Sheet Metal Coordination Drawings | $ 65,500.00 |
| Pre-K Duct Work - Furnish | $ 92,000.00 |
| Pre-K Duct Work - Install | $ 50,000.00 |

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[26] This category was not included in the initial breakdown of the LEED rating system because it is designed to give credit to ambiguous sustainable design traits of a project that do not fit within the traditional 5 categories.

[27] The educational signs were completely financed by a $50,000 sustainability grant.

| | |
|---|---|
| Domestic & NPW Water Piping - Material | $ 232,000.00 |
| Domestic & NPW Water Piping - Labor | $ 193,000.00 |
| Gas Piping - Materials | $ 20,000.00 |
| Gas Piping - Labor | $ 15,000.00 |
| Plumbing Fixtures - Materials | $ 176,500.00 |
| Plumbing Fixtures - Labor | $ 48,000.00 |
| Domestic Hot Water Heaters - Material | $ 65,000.00 |
| Drains & Carriers - Material | $ 60,000.00 |
| Plumbing Pumps -Material | $ 133,000.00 |
| Cistern Plumbing - Materials | $ 28,000.00 |
| Cistern Plumbing - Labor | $ 22,000.00 |
| Cistern Equipment - Materials | $ 113,000.00 |
| HVAC Piping Mains - Materials | $ 125,000.00 |
| HVAC Piping Mains - Labor | $ 135,000.00 |
| HVAC Equipment Trim & Piping - Material | $ 28,000.00 |
| HVAC Equipment Trim & Piping - Labor | $ 20,000.00 |
| GSHP - Material | $ 550,000.00 |
| OAU's - Material | $ 450,000.00 |
| ERV's - Material | $ 28,500.00 |
| Fans - Material | $ 57,500.00 |
| HVAC Pumps & Accessories | $ 50,000.00 |
| VFD's - Material | $ 25,000.00 |
| Set P/HVAC Equipment- Pre-K | $ 5,000.00 |
| Set P/HVAC Equipment - Boiler Room | $ 10,000.00 |
| SCI P/11VAC Equipment - Stage Mech | $ 8,000.00 |
| Set P/HVAC Equipment - Pod #1 Roof | $ 5,000.00 |
| Set P/HVAC Equipment - Pod #2 Roof | $ 8,000.00 |
| Set P/HVAC Equipment - Pod #3 Roof | $ 8,000.00 |

| | |
|---|---|
| 1st Floor Duct Work - Furnish | $ 234,000.00 |
| 1st Floor Duct Work -Install | $ 124,000.00 |
| 2nd Floor Duct Work - Furnish | $ 265,000.00 |
| 2nd Floor Duct Work - Install | $ 143,000.00 |
| 3rd Floor Duct Work - Furnish | $ 127,500.00 |
| 3rd Floor Duct Work - Install | $ 69,000.00 |
| Roof Level Duct Work - Furnish | $ 138,000.00 |
| Roof Level Duct Work - Install | $ 75,000.00 |
| Fire Dampers - Furnish | $ 10,000.00 |
| Registers, Grills & Diffusers - Furnish | $ 72,000.00 |
| Registers, Grills & Diffusers -Install | $ 58,000.00 |
| Engineering/Submittals | $ 49,000.00 |
| Programming/Graphics | $ 10,000.00 |
| Panel Fabrication | $ 5,000.00 |
| Electrical Install | $ 291,000.00 |
| Automation Materials | $ 200,000.00 |
| Electrical Materials | $ 48,000.00 |
| Valves | $ 74,500.00 |
| Dampers | $ 29,500.00 |
| Checkout Labor | $ 88,000.00 |
| System Demonstration/framing | $ 32,000.00 |
| Testing & Balancing | $ 28,224.00 |
| Contract Allowances | $ 6,565,224.00 |
| Geothermal Fields and Wells | $ 2,221,219.00 |
| CO #1- VE Credit | $ 408,850.00 |
| CO #2 - Cistern Dewatering | $ 34,841.00 |
| CO #3 - Duct Changes | $ 104,118.00 |
| Grand Total | $ 8,516,552.00 |

This grand total[28] can be divided by the total building area to get a mechanical system cost of $69.24 per square foot. That number represents almost 26% of the total building cost; an extremely high relative mechanical system cost. Because of this high relative cost, opportunities for system refinement were readily detectable. These system optimizations can be reviewed in a later section of this report titled *System Optimization Investigation*.

## Additional Indirect Costs due to Mechanical Area Allocations

The mechanical system of the initial design has an associated indirect cost which comes from floor space and vertical shaft space requirements of the system itself. Because this space is in a school building and thus not considered leasable space, the indirect cost will be in terms of construction costs per square foot, and not leasable cost per average pay period.

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[28] On a typical high efficiency design, the design team or owner will work to decrease the total cost of the mechanical system by trying to obtain some type of government rebate or tax relief. It has been reported by Manassas Park City Schools Superintendent Thomas DeBolt that although many incentives were looked into, only one $50,000 grant was obtained.

The main ductwork system in Manassas Park Elementary School is only used to transport the minimum required outside air as specified by ASHRAE Standard 62.1. This represents the minimum sized ductwork that could be used for this building design, independent of the mechanical conditioning system selection in the building. Because of this, vertical shaft area can be neglected in this analysis as it consumes the least amount of space of any comparable system.

The heating and cooling load requirements of the building are met via a hydronic system, which takes advantage of the high thermal capacity of water to minimize wall and ceiling space consumption. This type of system is also able to provide a relatively high level of flexibility to the design team. Hydronic piping volume will be ignored in this analysis, as it can be considered negligible with respect to volume requirements of a comparable all-air design.

The aforementioned neglected system components left only the mechanical room and penthouse spaces to be considered for study. Penthouse space requirements are held responsible for approximately 7,350 square feet of the building's rooftop space. Because this is unconditioned space located on the building roof, it would be inaccurate to assume that this space costs the same as a comparable area of furnished and conditioned interior space. Instead, the structure of the building was analyzed to determine indirect costs of the mechanical penthouse. Currently, the areas of the roof that do not hold any of the mechanical equipment are made up of 1 ½ inch deck supported by W12 X 16 beams. The portion of the roof that supports the structural load of the mechanical penthouses is made up of 4 inch normal weight concrete on $^{9}/_{16}$" X 28 gage metal deck, supported by beams up to W24 X 55 in size.

Without needing to support the total penthouse area of 7,350 square feet, the roof would have used 18,375 less cubic feet of concrete, and would have been able to size down beams from W24X55 to W12X16. That would account for a savings of 39 pounds of steel per linear foot of beam used for the roofing system[29]. Additional savings came from reduced column sizes and reduced reinforcing bar requirements.

Mechanical rooms on the first floor, second floor, and under the stage could be held responsible for approximately 2,005 square feet of interior building space. At an average floor area cost of $268.29 per square foot, it was roughly estimated that the inclusion of this mechanical space cost the building owner $537,930. This number is not a major factor in the total building value, as it only represents approximately 1.63% of the total building cost.

## System Optimization Investigation:

### Outdoor Air Unit Optimization:

The OAUs were originally designed to reject heat to the ambient air. Because of the aforementioned benefits of using ground water for heat absorption and rejection, integrating the OAUs into the existing ground loop was thoroughly investigated. The primary hypothesis which led to this study was that the current ground loop (or a slightly modified ground loop) could potentially be used to meet the

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[29] The total weight of the penthouse associated structural steel was not calculated for the study.

ventilation cooling requirements as well as to meet the ventilation reheat requirements, replacing the current air-cooled condenser and natural gas direct fire method of reheat, respectively.

Another important OAU optimization opportunity existed in the energy wheel layouts of the original system. The OAUs were originally designed to utilize both an enthalpy wheel and a sensible wheel in series. However, the overall benefit of the second wheel (sensible) in the system was questionable. The secondary hypothesis regarding the OAU configuration and operation was that removing the sensible wheel would decrease the size requirements of the supply and exhaust fans without negatively affecting the energy use and capacity of the heating and cooling portions of the system.[30] This hypothesis was derived from lectures and consultation by Stanly Mumma, DOAS[31] expert and Professor Emeritus at The Pennsylvania State University.

### Ground Source Heat Pump Optimization:

One of the most interesting design decisions of the original mechanical system was the configuration of the GSHPs in relation to the OAUs. All of the pre-conditioned ventilation air that was provided to the space by the OAUs was forced to go through the zonal GSHPs. This configuration did not allow the GSHPs to be de-energized unless the natural ventilation system was in operation. The primary hypothesis regarding GSHP optimization was that if the relation between the OAUs and the GSHPs was converted from a series configuration to a parallel configuration[32], the GSHPs could be de-energized and thus completely bypassed when the ventilator supplied adequate space conditioning. This would synergize with the previously suggested system modification of removing the sensible wheel from the OAUs, as doing so would decrease the temperature of the air coming from the OAUs.

### Envelope and Operation Mode Optimization:

The initially designed “green light natural ventilation system” heavily relied on human/system interaction. This interaction created a significant chance of detrimental human error, with many possible scenarios of human ineptitude. For instance, if the ventilation system is in green light operation mode when a teacher leaves his or her classroom for the day, an alternative method of sealing the fenestrations must be adhered to once the system returns to normal operation. In the event that the fenestrations do not get properly sealed, there could potentially be significant associated energy losses, as well as an associated infiltration of water, mold spores, dust, dander, and etcetera from the outdoor environment. In another instance, if a substitute teacher is unaware of the variable mechanical system ventilation operation modes, then there is a good chance that he or she will not know to open the specified fenestrations when the system enters green light operation mode. This would deprive the teacher and the students of proper ventilation air, and could be potentially dangerous to the health of the building occupants. The same outcome could occur if a teacher simply was unaware that the ventilation system had entered green light operation mode, as the green lights are in the corridors, and are not readily visible from most areas of the classrooms.

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[30] This hypothesis will be the first one discussed in the Proposed System Alterations section, and will be followed with the primary OAU study for clarity.

[31] DOAS is an acronym for Dedicated Outside Air System.

[32] This would involve moving the OA/RA mixing point from the individual heat pumps intake side to their supply side.

The primary hypothesis regarding the current envelope was that if the human dependability requirements were eliminated, there would be a greatly reduced chance of any detrimental effects of the natural ventilation system. Investigated options include increasing the number of green lights, installing automatic window actuators, and switching out operable windows for a more tightly configured façade. This last suggestion would eliminate the option of natural ventilation altogether, and structural implications were assessed in the investigation.

### Building Electrical Optimization:

Manassas Park Elementary School's current design does a fine job of conserving energy. Its current mechanical and electrical systems are well integrated, and the associated energy use is minimal. What the building does not do, however, is generate any of its own capacity to offset its critical energy consumption from the grid. The primary hypothesis regarding the current energy consumption of the building is that energy efficiency is already well refined, and that a renewable generation system (specifically a PV system) would be a beneficial environmental improvement to the existing building. A PV array has the potential to minimize the overall grid dependence of the school, also minimizing demand and energy use charges from the local utility.

## Tools and Methods of Study:

Research was conducted on the aforementioned material using computer programs such as Engineering Equation Solver, Trane Trace, and Microsoft Excel. These programs were used to confirm or dismiss the primary hypotheses that were outlined in the previous section. Conclusions drawn during the testing period are detailed in the following section, and include references to related material.

Microsoft Excel was primarily used to solve systems of equations regarding the outside air unit modifications. This was the first study conducted as part of the required research, and the familiarity and ease of use of Microsoft Excel was beneficial in that the first phase of research was fairly quick and the results were reasonable. Study related calculations, tables, and figures that were produced with Microsoft Excel can be seen throughout the report.

Trane Trace was primarily used to emulate all of the zones served by OAU-1, and to verify conclusions drawn using Microsoft Excel. A single system including 1 OAU, 27 GSHPs, and 27 zones was created to emulate conditions that are expected within Pod 1 of Manassas Park Elementary School. Both the initial system and the conclusive system from the previous study were modeled in Trane Trace, and the independent simulations of these individual arrangements shows the results of the conditioning method specified.

Engineering Equation Solver (EES) was particularly useful in the photovoltaic portion of the required research. It allowed a substantially large series of equations to be entered as inputs, and it solved those equations simultaneously with outputs in parametric tables and associated graphs. The information retrieved from EES was eventually put into Microsoft Excel to produce tables that were stylistically acceptable for this report.

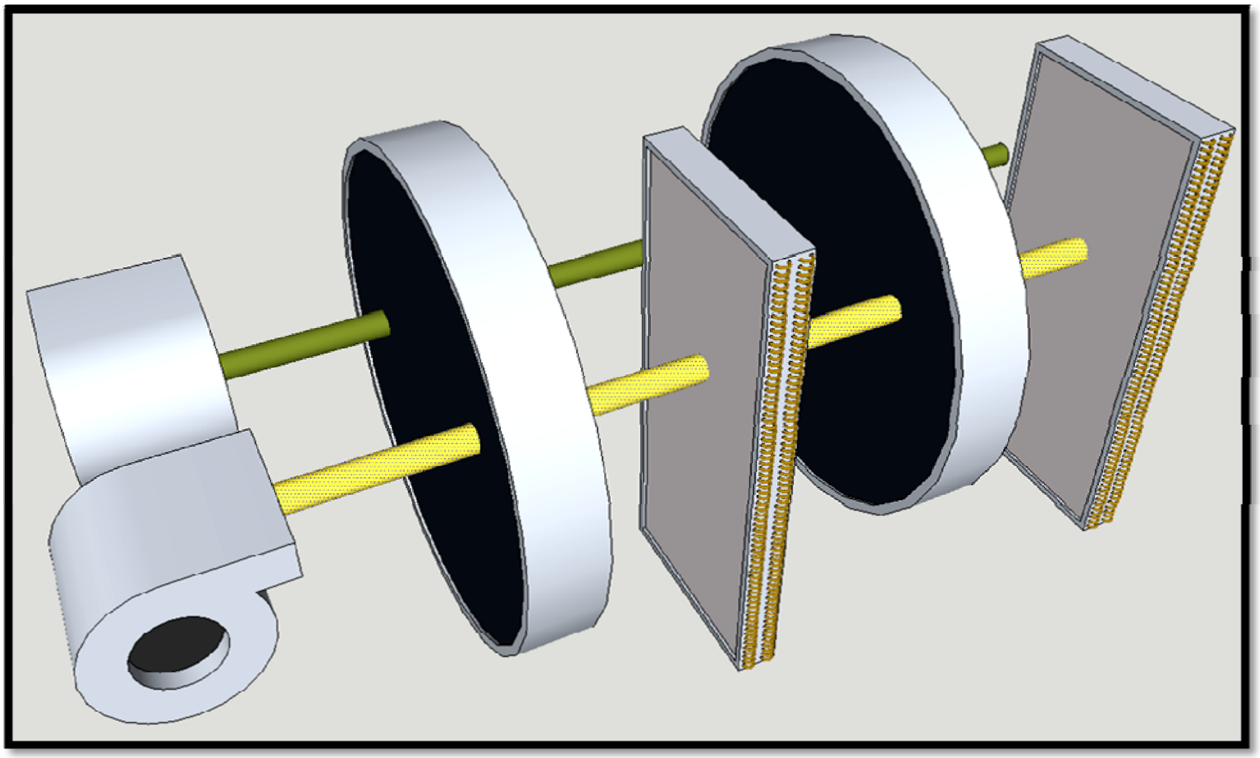
## Proposed System Alterations:

Although the current system has been one of praise, slight configuration modifications have proven to make a significant impact on the initial cost of the system, as well as the full and part load energy consumption of the system.

### Energy Wheel Alterations:

The first system alterations that were analyzed in this study were the internal components and layout of the individual OAUs. The OAUs were originally designed in a dual wheel configuration. Figure 4, below, shows the as-designed configuration.

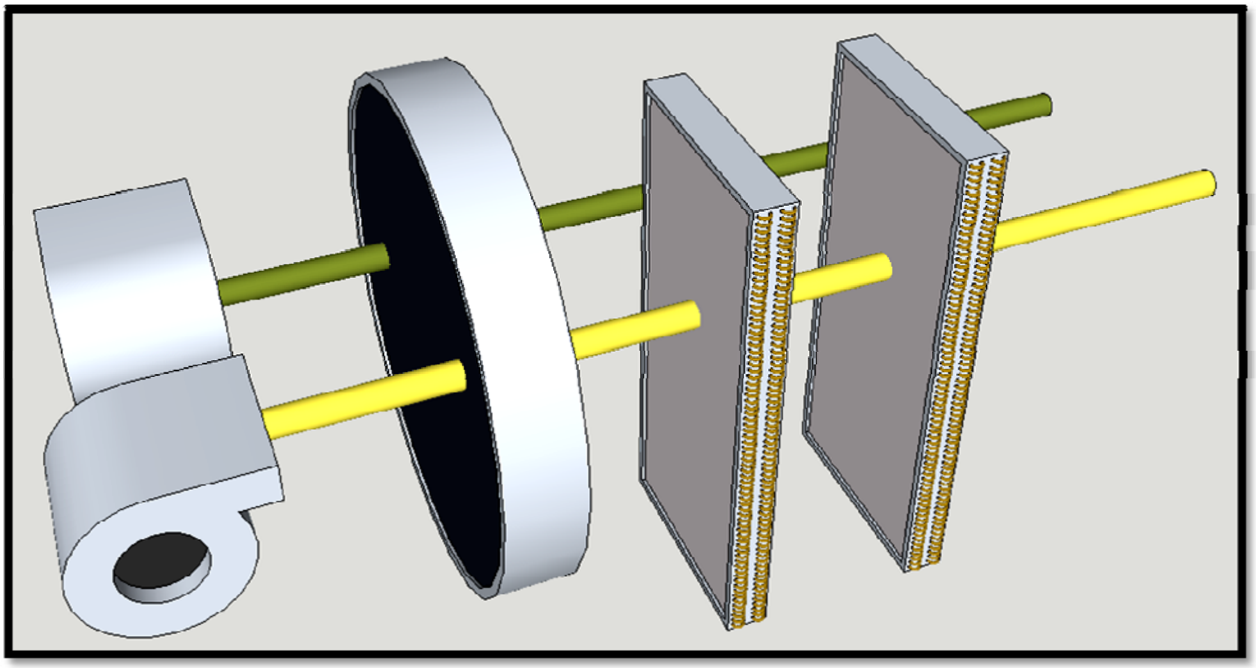
Figure 4: Current OAU Configuration



From left to right, the equipment in Figure 4 includes fans, an enthalpy wheel, cooling coils, a sensible wheel, and reheat coils. The yellow and green cylinders were added to show the paths of supply air and exhaust air, respectively. These two air streams are isolated from one another in the actual unit; however the separation wall was been removed from Figure 4 for graphical clarity.

The dual wheel configuration in Figure 4 has a relatively high pressure drop, as both air streams have to penetrate two separate energy wheels. Removal of the sensible wheel was investigated to decrease pressure drop, and this proposed system configuration can be seen in Figure 5, below.

Figure 5: Proposed OAU Configuration



While analyzing the results of sensible wheel removal, it was concluded that the benefit of decreased pressure drop did occur. This benefit was also accompanied by other effects. Seemingly detrimental effects of sensible wheel removal include the loss of free reheat[33] and an increase in the total unit capacity requirements.

The 'loss of free reheat' issue was initially troubling. The air after the cooling coils was cooled down to 55 degrees Fahrenheit, and one of the sensible wheels original jobs was to reheat that air to 72 degrees Fahrenheit. Upon further investigation, it was concluded that the supply air after the cooling coils (but before the sensible wheel) would not overcool when directly supplied to the occupied space[34]. In fact, supplying the ventilation air at 55 degrees Fahrenheit substantially decreases the terminal capacity requirements. This leads us to the second of the two seemingly detrimental effects of removing the sensible wheel. The difference between the initial OAU capacity requirements and the modified OAU capacity requirements is smaller than the difference between the initial GSHP capacity requirements and the modified GSHP capacity requirements, and thus the proposed system has a smaller total capacity requirement than the original system.

Sample calculations for the above information can be viewed in Appendix E.

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[33] This term is intuitive yet ultimately illogical. It was originally created by advocates of sensible wheel technology to help support and promote the product, however it has been concluded that the system operator is paying for reheat in the form of increased fan power and increased terminal cooling.

[34] If a space is not fully occupied, this setup may overcool, however this can be remedied by effective use of occupancy sensors.

Another energy saving method investigated was to utilize thermal people counters[35] in all of the zones supplied by the OAUs. These zones already have infrared occupancy sensors integrated into the building automation system (BAS) which were designed to control light levels. Choosing to install thermal people counters as opposed to the as-designed infrared systems will cost approximately $1,200 more per space[36], and can do all of the tasks of the originally designed sensors as well as the tasks of a system that uses $CO_2$ sensors to control ventilation. The cost of this setup is on par with the total cost of an infrared occupancy sensor/$CO_2$ sensing setup, which can be estimated at $75 per occupancy sensor and $800 per $CO_2$ sensor.

The software utilized in the building automation system could be adjusted such that the OAU systems supply minimum ventilation (as specified by ASHRAE Standard 62.1-2007) to specific zones based on the dynamic number of occupants in them. This would significantly decrease fan energy associated with the OAUs, further increasing the efficiency of the integrated building systems. It is difficult to pinpoint exact energy savings for this type of system in an elementary school because the schedule of the applicable classrooms changes 6 times each year (due to 4 standard marking periods and 2 summer marking periods).

### Heat Pump Alterations:

To reiterate a previously mentioned study result, the proposed OAU configuration (without a sensible wheel) greatly decreases the temperature and enthalpy of the air stream coming off of the OAUs. The ducting between the terminal heat pumps and the OAUs could be modified to take full advantage of this newly acquired 55 degree supply air, and this configuration modification would be another example of a small change that makes a considerable difference[37].

The proposed change to the configuration of the ductwork leading from the OAUs to the GSHPs includes removing the current series configuration in favor of a parallel configuration[38]. This would synergize with the aforementioned change of removing the sensible wheel from the OAU's, as it would allow the GSHP to be bypassed for OAU only cooling. In this arrangement, dampers would be added on the Outdoor Air (OA) side of the unit, and these dampers would be actuated by a people counter that is compatible with the current Building Automation System (BAS). This proposed people counter would both indirectly actuate the dampers and ramp down the associated OAU's variable frequency drive, saving a significant amount of energy associated with both ventilation fan consumption and terminal air conditioning[39]. These people counters would also replace the existing occupancy sensors that are integrated into the

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[35] Thermal people counters are a type of occupancy sensor that can calculate the actual number of occupants that are in a room at any given time based on the heat signatures of the occupants heads.

[36] Thermal-type people counting technologies with accuracy rates of 95% and all of the require accessories can be purchased for around $1,300 per space.

[37] This terminal unit configuration modification would only be logical when combined with the aforementioned OAU modifications. Rerouting the ductwork at the GHSPs without modifying the OAUs would be detrimental to system performance.

[38] This would involve moving the OA/RA mixing point from the individual heat pumps intake side to their supply side. The terms 'series' and 'parallel' are in reference to the relation between the specific OAU and GSHP of interest.

[39] Air conditioning refers to both heating and cooling.

existing lighting system, minimizing the first costs associated with outfitting specific rooms with people counters.

Figure 6 and Figure 7, below, show the proposed modifications to the air-side of the GSHP system.

**Figure 6: Current GSHP Schematic**

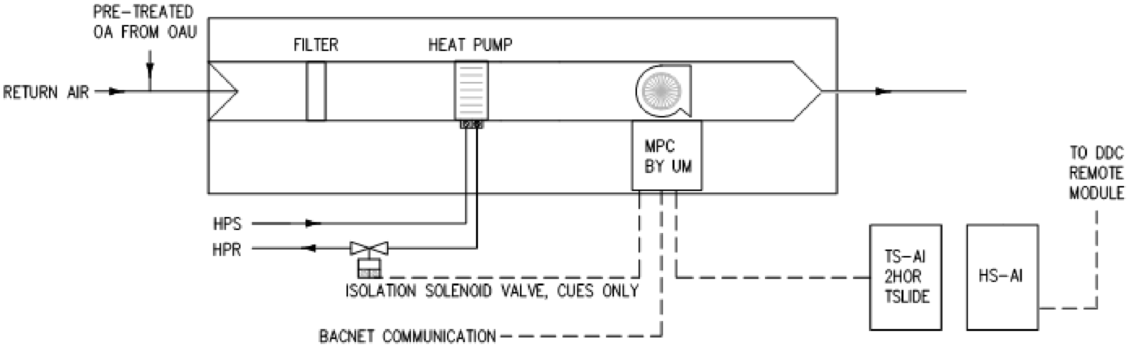
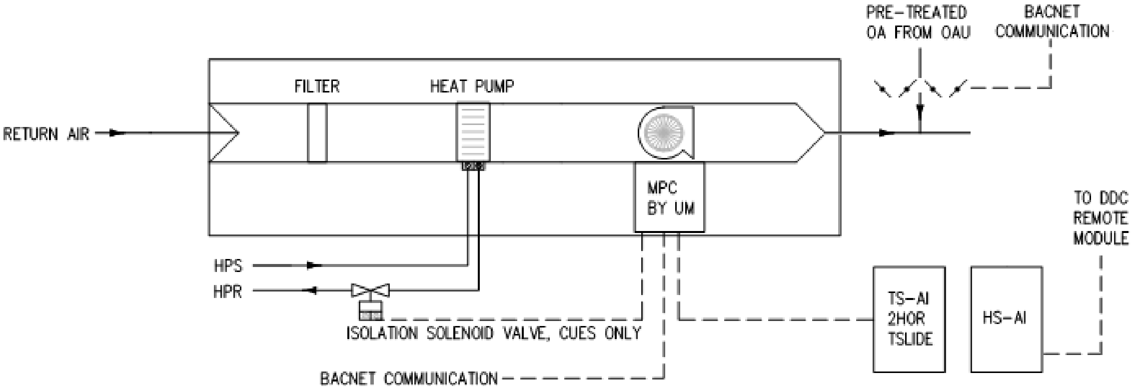


**Figure 7: Proposed GSHP Schematic**



**The results of the aforementioned capacity savings can be viewed in Table 9, below. Note that although the OAU capacity increases, the overall system capacity decreases over 4%. Fan power and size savings can be seen in**

Table 10.

**Table 9: Capacity Savings of Modified System**

| System: | OAU | | GSHP | | Total | |
|---|---|---|---|---|---|---|
| As Designed | 1,021.89 | MBH | 3,577.30 | MBH | 4599.19 | MBH |
| | 1021890 | Btu/hr | 3577300 | Btu/hr | 4599190 | Btu/hr |
| | 299.50 | kW | 1048.45 | kW | 1347.95 | kW |
| | 85.16 | Tons | 298.11 | Tons | 383.27 | Tons |
| As Proposed | 1,273.99 | MBH | 3136.98 | MBH | 4410.97 | MBH |
| | 1273987 | Btu/hr | 3136981 | Btu/hr | 4410968 | Btu/hr |
| | 373.38 | kW | 919.40 | kW | 1292.78 | kW |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 106.17 | Tons | 261.42 | Tons | 367.58 | Tons |
| Reduction | -252.10 | MBH | 440.32 | MBH | 188.22 | MBH |
| | -252097 | Btu/hr | 440319 | Btu/hr | 188222 | Btu/hr |
| | -73.89 | kW | 129.05 | kW | 55.16 | kW |
| | -21.01 | Tons | 36.69 | Tons | 15.69 | Tons |
| | -24.67 | % | 12.31 | % | 4.09 | % |

Table 10: Supply and Exhaust Fan Energy Savings

| Fan Type | OAU ID | Original Motor Size (HP) | Original Fan Power Usage (HP) | Reduced Fan Power Usage (HP) | Original Fan Power Usage (kW) | Reduced Fan Power Usage (kW) | Percent Reduction |
|---|---|---|---|---|---|---|---|
| Supply | 1 | 5 | 3.040 | 2.396 | 2.267 | 1.787 | 21.2% |
| | 2 | 5 | 3.040 | 2.396 | 2.267 | 1.787 | 21.2% |
| | 3 | 5 | 3.040 | 2.396 | 2.267 | 1.787 | 21.2% |
| | 4 | 15 | 9.850 | 8.028 | 7.345 | 5.987 | 18.5% |
| | 5 | 7.5 | 4.630 | 3.687 | 3.453 | 2.749 | 20.4% |
| | Sum | 37.5 | 23.600 | 18.905 | 17.599 | 14.097 | 19.9% |
| Exhaust | 1 | 3 | 2.370 | 1.927 | 1.767 | 1.437 | 18.7% |
| | 2 | 3 | 2.370 | 1.927 | 1.767 | 1.437 | 18.7% |
| | 3 | 3 | 2.370 | 1.927 | 1.767 | 1.437 | 18.7% |
| | 4 | 10 | 6.980 | 5.684 | 5.205 | 4.239 | 18.6% |
| | 5 | 5 | 3.430 | 2.773 | 2.558 | 2.068 | 19.1% |
| | Sum | 24 | 17.520 | 14.239 | 13.065 | 10.618 | 18.7% |

An average savings of around 19% is seen through all operating conditions of the fans, as the constant pressure drop of the sensible wheels has been removed. Although the actual energy use savings of the suggested motors is around 19% less than the as-designed energy use, the suggested motors are sized at only 70% of the capacity of the original motors. This is because the original motors were largely oversized for their applications to accommodate the manufacturer's nominal sizes. As the capacity requirements of the motors decreased, they descended multiple levels of nominal motor size increments, accounting for a larger total maximum capacity savings. Fan motor replacement suggestions can be seen below, in Table 11; the suggested fans will maximize operating efficiencies as well as minimize upfront costs.

Table 11: Fan Replacement Suggestions

| Fan Type | OAU ID | Original Motor Size (HP) | Peak Motor Usage (HP) | Suggested Motor Size (HP) |
|---|---|---|---|---|
| Supply | 1 | 5 | 2.396 | 2.5 |
| | 2 | 5 | 2.396 | 2.5 |
| | 3 | 5 | 2.396 | 2.5 |
| | 4 | 15 | 8.028 | 10.0 |
| | 5 | 7.5 | 3.687 | 5.0 |
| | Sum | 37.5 | 18.905 | 22.5 |
| Exhaust | 1 | 3 | 1.927 | 2.5 |
| | 2 | 3 | 1.927 | 2.5 |
| | 3 | 3 | 1.927 | 2.5 |
| | 4 | 10 | 5.684 | 7.5 |
| | 5 | 5 | 2.773 | 5.0 |
| | Sum | 24 | 14.239 | 20.0 |
| Total Sum | | 62 | 33 | 43 |

## Ground Loop Alterations:

The capacity of the as-designed ground loop is 4,000 MBH, or around 20 MBH per well. The maximum capacity of all 5 OAUs (after removal of the sensible wheels) is 1,274 MBH, and the capacity of the terminal units was decreased 440 MBH with the removal of the sensible wheels, leaving 3,137 MBH of capacity on the terminal units. The entire system capacity requirements (after the sensible wheels were removed from the OAUs) was reduced to 4,411 MBH, as is shown in Table 9. However, with a ground loop capacity of 4,000 MBH, there is still 420[40] MBH of capacity still unaccounted for; adding this extra capacity to the existing ground loop would require new wells to be drilled. Because of the sheer size of the existing system, it is a safe assumption that a relatively small addition of wells to the existing system would deliver a linear addition of total capacity. Adding 10.5% to the original 200 wells means that an additional 21 wells would need to be drilled. This was estimated to cost approximately $233,250.00, and the new system would save an average of $1,820 in energy costs each month. The equivalent associated simple payback of this system is 10.7 years, which is acceptable considering that an elementary school of this type will be in use for well over 30 years.

## Façade and Ventilation Alterations:

The current natural ventilation system is highly dependent on human interaction for proper operation. This human interaction requirement is the biggest setback of the current system, as the overall theory behind the system is sound. If the human dependability requirements were eliminated, there would be a greatly reduced chance of any detrimental effects occurring while in green light operation mode, and the overall efficiency of the system would be increased. Three specific alternatives were investigated for

---

[40] This value was increased from 411 MBH to 420 MBH to maintain a conservative financial estimate.

this study, including increasing the number of green lights, installing automatic window actuators, and switching out operable windows for a more tightly configured façade.

Putting a natural ventilation operation indicator light in each of the perimeter zones would require many additional green lights to be installed in the building. Along with associated wiring, this procedure would cost approximately $5,400. In retrospect, this would cause an insignificant financial impact considering that the entire budget for the building was around $33 million.

While adding green lights to each perimeter zone is able to decrease dependence on human interaction, it is not able to eliminate it. Eliminating dependence on human interaction can, however, be achieved by the two remaining methods of mitigating the problem.

Adding actuators to the buildings operable windows is the more expensive of the two options. Each of the perimeter zones would need an actuator for its respective windows, and thus adding actuators is a considerably larger investment than adding more green lights to the system. Being said, there exists a definite potential for the investment to be awarded. Proper installation of window actuators would let the natural ventilation system work as designed without the accompaniment of significant human error. This would include mechanical system energy use that is associated with errors in the original design as well as the additional yearly mechanical system energy use that would be required if there were no natural ventilation at all.

If the natural ventilation system was eliminated from the design completely, there would definitely be an increase in annual ventilation costs. The OAUs would need to be in operation whenever the building was occupied, even during times that could have potentially been covered by a natural ventilation system. However, the system would require 9 less green lights (and the associated wiring, installation, etcetera), 10 less dampers in the ductwork, and all of the operable windows in the façade could be replaced with non-operable windows, greatly reducing the initial investment. Also, the tightness of the façade would be increased, which would inversely affect infiltration and exfiltration effects on the heating and cooling loads of the exterior zones. Inefficiencies associated with human error would be completely eliminated, and the aforementioned changes to the OAUs and the GSHPs would more than make up for the energy increase of the proposed ventilation scheme. The structural requirements of the façade would remain the same, as the operable windows that were originally designed are only minimally heaver than the proposed static windows.

Along with the removal of human error, moving to a non-naturally ventilated design would virtually eliminate the possibility for outdoor allergens to infiltrate the educational space. This would decrease the possibility of associated negative health effects in students and teachers with sensitive immune systems, chronic respiratory diseases, ocular sensitivities, and etcetera. It is mainly for these reasons that the non-naturally ventilated design is suggested, as student attentiveness and productivity concerns[41] greatly outweigh energy efficiency concerns in an elementary school setting.

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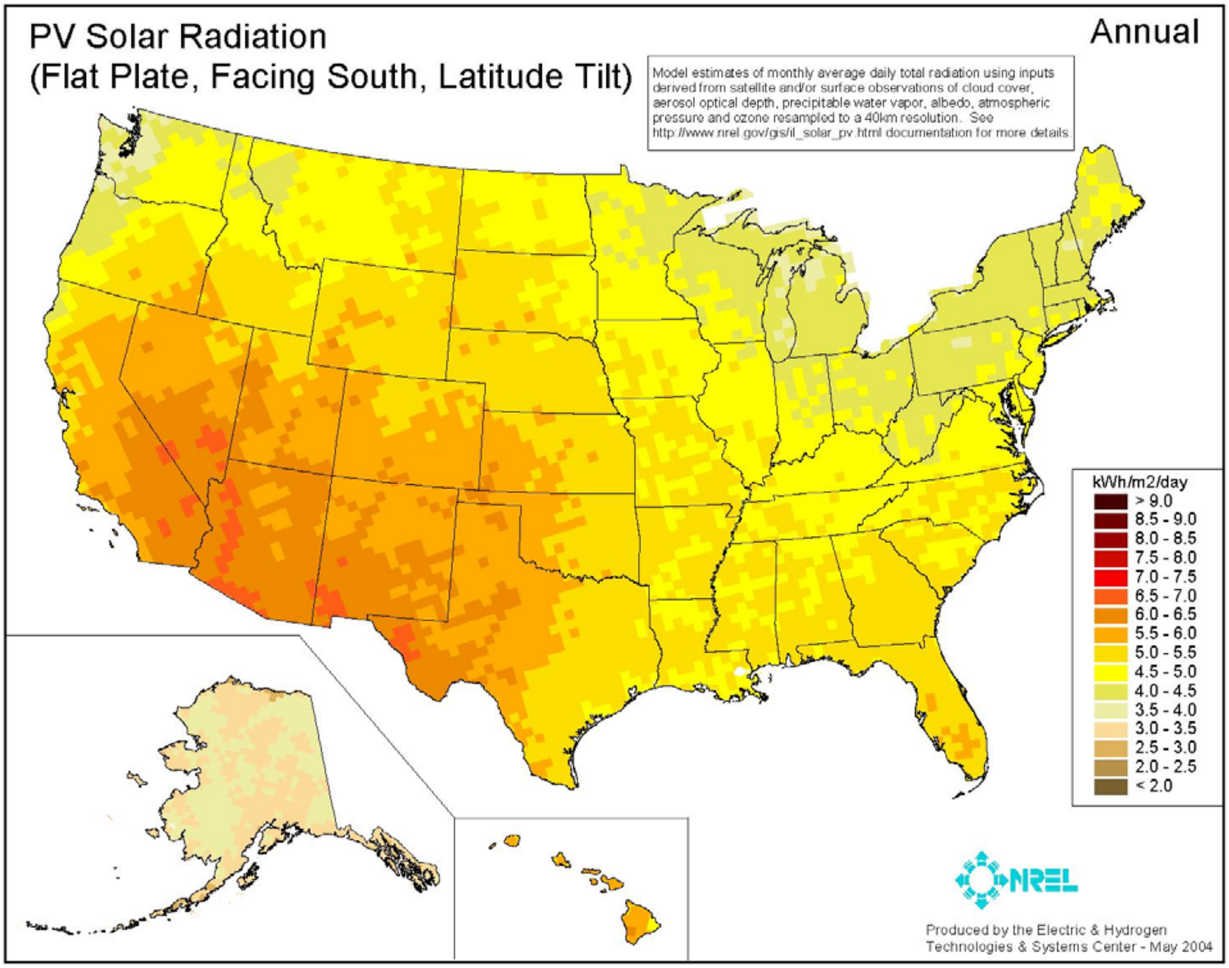
[41] It is assumed here that student attentiveness and productivity are decreased with the introduction of outdoor allergens into the interior zone.

## Electrical System Alterations:

Photovoltaic panels were investigated as a potential on site power generation technique to help decrease Manassas Park Elementary Schools dependence on the existing utility grid. PV panels work by converting solar electro-magnetic radiation into direct current electricity by means of a process called the photovoltaic effect. Along with the photovoltaic panels themselves, an inverter is required as part of a PV system. The inverter is used to convert the direct current electricity output of the photovoltaic panels into an alternating current that can be connected to an existing grid, stored[42], or used directly in building loads. Figure 8, below, is an annual PV solar radiation map of North America created by the National Renewable Energy Laboratory.

Figure 8: NREL Annual PV Solar Radiation Map of North America



Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_solar_pv.html documentation for more details.

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

According to Figure 8, photovoltaic arrays located in Manassas Park, VA with a tilt equal to the latitude will see an insolation of around 1,750 kWh/m2 in an average year[43].

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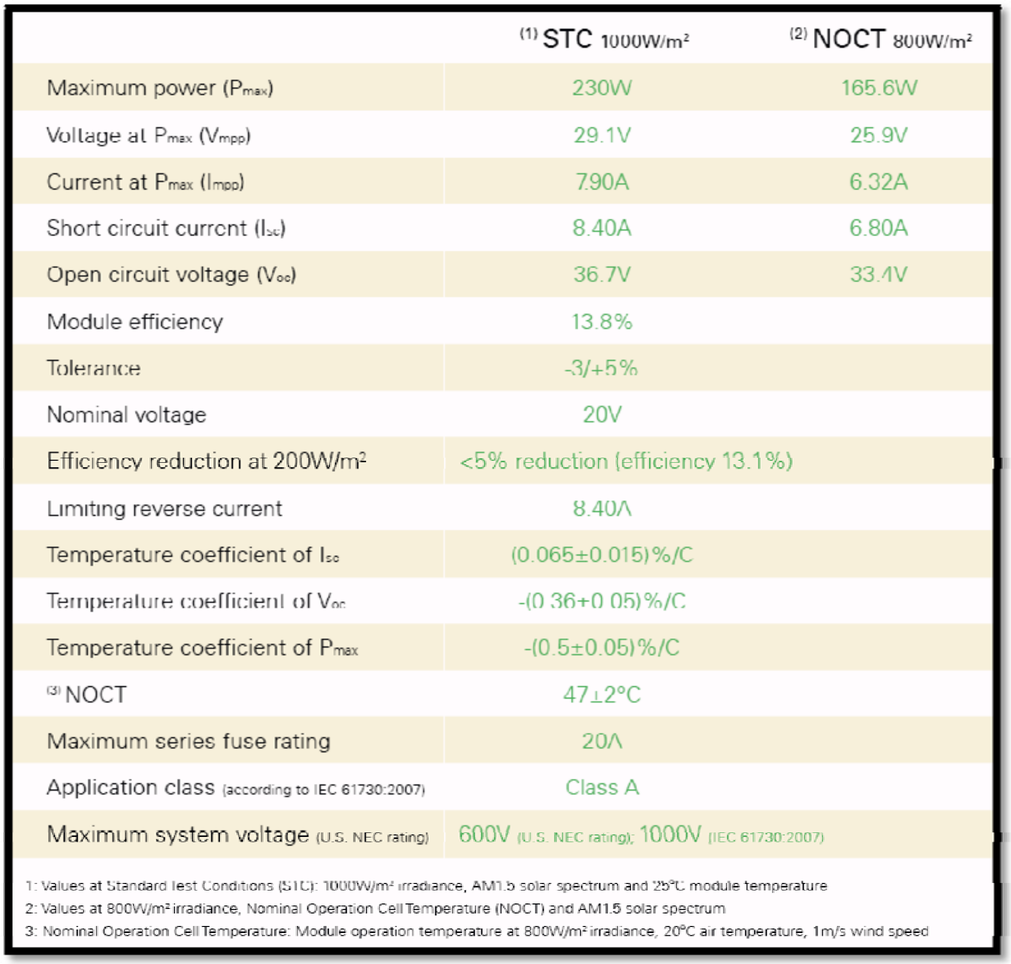
[42] There are many methods of PV energy storage in use today. The most common of which is battery bank storage.

[43] On average.

The specific photovoltaic module researched for utilization in the Manassas Park Elementary School was the BP 3230T by BP Solar. This module was very attractive due to its longevity and resistance to degradation, its high relative efficiency of 13.8%, its high part load efficiency[44], its high maximum power output, and of course the concrete reputation of the manufacturer, BP Solar. Electrical characteristics of the module can be seen in Figure 9, below.

Figure 9: Electrical Characteristics of the BP 3230T



| | (1) STC 1000W/m$^2$ | (2) NOCT 800W/m$^2$ |
|---|---|---|
| Maximum power ($P_{max}$) | 230W | 165.6W |
| Voltage at $P_{max}$ ($V_{mpp}$) | 29.1V | 25.9V |
| Current at $P_{max}$ ($I_{mpp}$) | 7.90A | 6.32A |
| Short circuit current ($I_{sc}$) | 8.40A | 6.80A |
| Open circuit voltage ($V_{oc}$) | 36.7V | 33.4V |
| Module efficiency | 13.8% | |
| Tolerance | -3/+5% | |
| Nominal voltage | 20V | |
| Efficiency reduction at 200W/m$^2$ | <5% reduction (efficiency 13.1%) | |
| Limiting reverse current | 8.40A | |
| Temperature coefficient of $I_{sc}$ | (0.065±0.015)%/C | |
| Temperature coefficient of $V_{oc}$ | -(0.36±0.05)%/C | |
| Temperature coefficient of $P_{max}$ | -(0.5±0.05)%/C | |
| (3) NOCT | 47±2°C | |
| Maximum series fuse rating | 20A | |
| Application class (according to IEC 61730:2007) | Class A | |
| Maximum system voltage (U.S. NEC rating) | 600V (U.S. NEC rating); 1000V (IEC 61730:2007) | |

1: Values at Standard Test Conditions (STC): 1000W/m$^2$ irradiance, AM1.5 solar spectrum and 25°C module temperature
2: Values at 800W/m$^2$ irradiance, Nominal Operation Cell Temperature (NOCT) and AM1.5 solar spectrum
3: Nominal Operation Cell Temperature: Module operation temperature at 800W/m$^2$ irradiance, 20°C air temperature, 1m/s wind speed

The BP 3230T PV module's main drawback is the actual weight of the unit. At almost 45 pounds per module, a large array can pose a significant structural problem for rooftop utilization. Manassas Park Elementary School has a large amount of available field space adjacent to the building which could be partially utilized to house a moderate array of panels. This ground-based array would not have any structural implications on the building, as it would be a completely separate entity.

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[44] The term part load efficiency is not usually used in association with photovoltaic panels. In this case, it is being used to represent the ability of the BP 3230T module to maintain a high efficiency with minimal available radiation. Specifically, the module is 13.1% efficient when exposed to only 200 W/m$^2$. This efficiency is 95% of the 1000 W/m$^2$ efficiency specified in the report.

According to resources provided by BP Solar, the estimated system cost of a 40 kW array is around $320,000. Available federal and state tax credits could equal around $96,000, leaving a net system cost of $224,000. After the 25 year lifetime of the array, the cumulative savings would equal approximately $251,000. This value takes into account the expected system degradation as well as a 4% per year electricity bill escalation, and gives a return on invest of 22 to 23 years. This is not a reasonable return on investment, and the primary hypothesis regarding electrical building optimization is ultimately incorrect. More detailed information regarding the financial aspect of the PV study can be reviewed in Appendix F.

## Conclusion:

Manassas Park Elementary School was originally designed to change the way things are done in elementary school construction in Northern Virginia. It used a fine selection of systems along with progressive green architecture to achieve a relatively low-energy, high-efficiency LEED® Gold building. With all of the positives that go along with a well-designed building, this study was fairly difficult to compile. However, sustained investigation of the existing systems brought to light some of the design choices that may have kept the design team from reaching the full potential of Manassas Park Elementary School. These choices made by the design team were most likely the result of time pressures brought about by the project schedule and/or differences in opinion between different sectors within the design team. As has been shown time and time again, a truly integrated design team is an extremely hard feat to achieve. However, the design team of Manassas Park Elementary School proved that if a design team truly can come together, they can create truly fantastic buildings.

# Resources:

*2005 ASHRAE Handbook—Fundamentals*, Chapter 8, Physiological Principles and Thermal Comfort

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| | |
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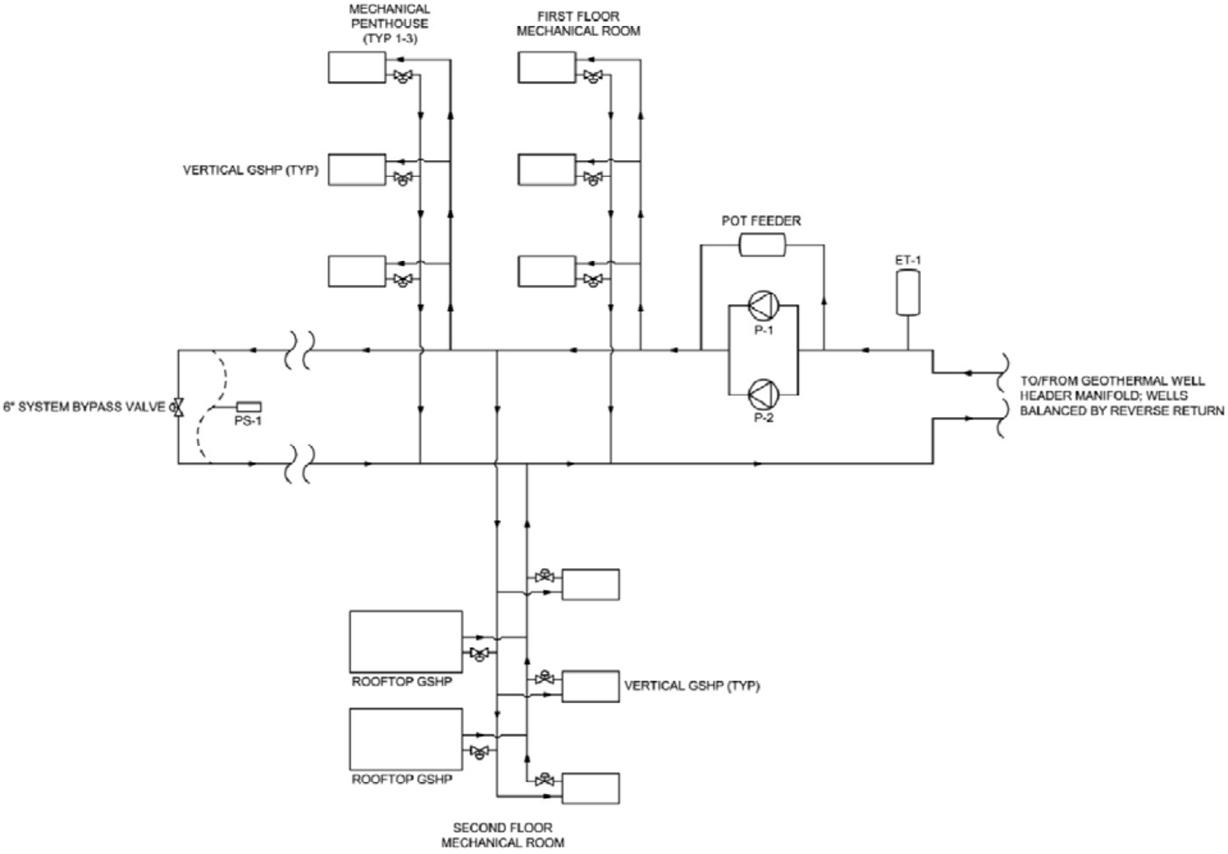
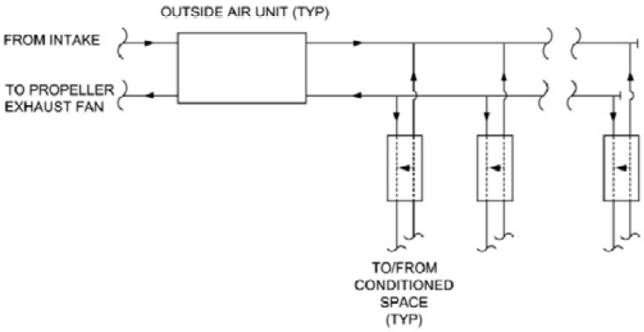
# Appendix A: System Schematics

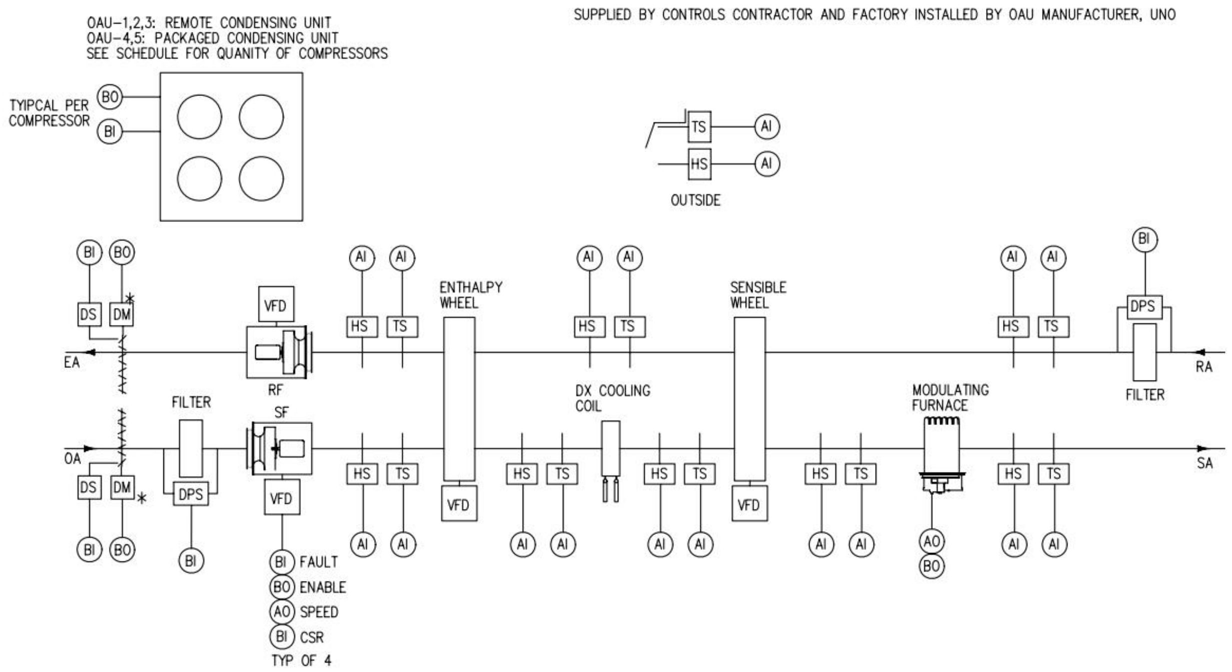
## Water Side System Schematic



## Air Side System Schematic



# Appendix B: Outside Air Unit Schematic



OAU–1,2,3: REMOTE CONDENSING UNIT
OAU–4,5: PACKAGED CONDENSING UNIT
SEE SCHEDULE FOR QUANITY OF COMPRESSORS

SUPPLIED BY CONTROLS CONTRACTOR AND FACTORY INSTALLED BY OAU MANUFACTURER, UNO

# Appendix C: Building Envelope Requirements for Climate Zone 4A

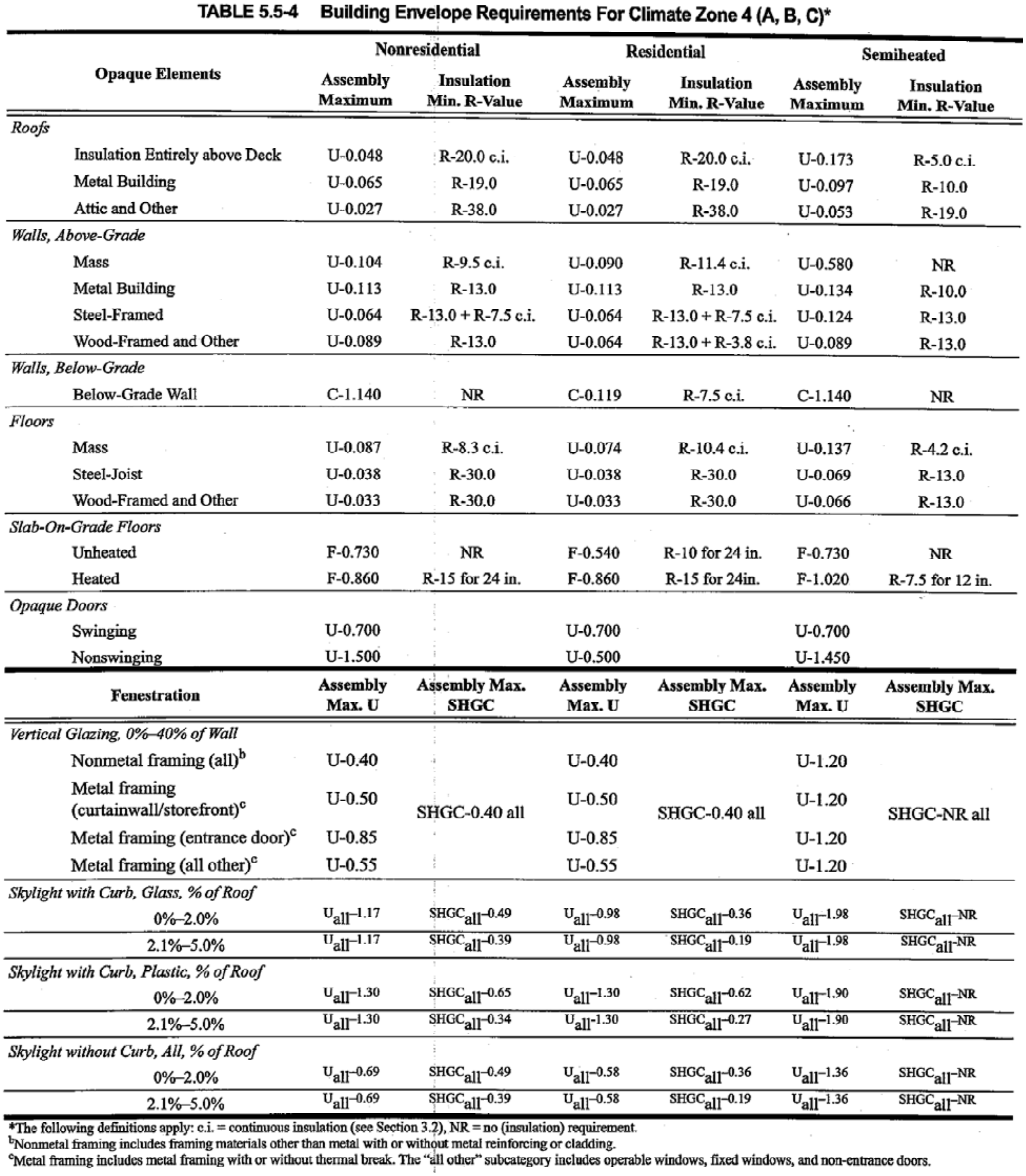


**TABLE 5.5-4 Building Envelope Requirements For Climate Zone 4 (A, B, C)***

| Opaque Elements | Nonresidential |  | Residential |  | Semiheated |  |
|---|---|---|---|---|---|---|
|  | **Assembly Maximum** | **Insulation Min. R-Value** | **Assembly Maximum** | **Insulation Min. R-Value** | **Assembly Maximum** | **Insulation Min. R-Value** |
| *Roofs* |  |  |  |  |  |  |
| Insulation Entirely above Deck | U-0.048 | R-20.0 c.i. | U-0.048 | R-20.0 c.i. | U-0.173 | R-5.0 c.i. |
| Metal Building | U-0.065 | R-19.0 | U-0.065 | R-19.0 | U-0.097 | R-10.0 |
| Attic and Other | U-0.027 | R-38.0 | U-0.027 | R-38.0 | U-0.053 | R-19.0 |
| *Walls, Above-Grade* |  |  |  |  |  |  |
| Mass | U-0.104 | R-9.5 c.i. | U-0.090 | R-11.4 c.i. | U-0.580 | NR |
| Metal Building | U-0.113 | R-13.0 | U-0.113 | R-13.0 | U-0.134 | R-10.0 |
| Steel-Framed | U-0.064 | R-13.0 + R-7.5 c.i. | U-0.064 | R-13.0 + R-7.5 c.i. | U-0.124 | R-13.0 |
| Wood-Framed and Other | U-0.089 | R-13.0 | U-0.064 | R-13.0 + R-3.8 c.i. | U-0.089 | R-13.0 |
| *Walls, Below-Grade* |  |  |  |  |  |  |
| Below-Grade Wall | C-1.140 | NR | C-0.119 | R-7.5 c.i. | C-1.140 | NR |
| *Floors* |  |  |  |  |  |  |
| Mass | U-0.087 | R-8.3 c.i. | U-0.074 | R-10.4 c.i. | U-0.137 | R-4.2 c.i. |
| Steel-Joist | U-0.038 | R-30.0 | U-0.038 | R-30.0 | U-0.069 | R-13.0 |
| Wood-Framed and Other | U-0.033 | R-30.0 | U-0.033 | R-30.0 | U-0.066 | R-13.0 |
| *Slab-On-Grade Floors* |  |  |  |  |  |  |
| Unheated | F-0.730 | NR | F-0.540 | R-10 for 24 in. | F-0.730 | NR |
| Heated | F-0.860 | R-15 for 24 in. | F-0.860 | R-15 for 24in. | F-1.020 | R-7.5 for 12 in. |
| *Opaque Doors* |  |  |  |  |  |  |
| Swinging | U-0.700 |  | U-0.700 |  | U-0.700 |  |
| Nonswinging | U-1.500 |  | U-0.500 |  | U-1.450 |  |
| **Fenestration** | **Assembly Max. U** | **Assembly Max. SHGC** | **Assembly Max. U** | **Assembly Max. SHGC** | **Assembly Max. U** | **Assembly Max. SHGC** |
| *Vertical Glazing, 0%–40% of Wall* |  |  |  |  |  |  |
| Nonmetal framing (all)[b] | U-0.40 | SHGC-0.40 all | U-0.40 | SHGC-0.40 all | U-1.20 | SHGC-NR all |
| Metal framing (curtainwall/storefront)[c] | U-0.50 |  | U-0.50 |  | U-1.20 |  |
| Metal framing (entrance door)[c] | U-0.85 |  | U-0.85 |  | U-1.20 |  |
| Metal framing (all other)[c] | U-0.55 |  | U-0.55 |  | U-1.20 |  |
| *Skylight with Curb, Glass, % of Roof* |  |  |  |  |  |  |
| 0%–2.0% | $U_{all}$-1.17 | $SHGC_{all}$-0.49 | $U_{all}$-0.98 | $SHGC_{all}$-0.36 | $U_{all}$-1.98 | $SHGC_{all}$-NR |
| 2.1%–5.0% | $U_{all}$-1.17 | $SHGC_{all}$-0.39 | $U_{all}$-0.98 | $SHGC_{all}$-0.19 | $U_{all}$-1.98 | $SHGC_{all}$-NR |
| *Skylight with Curb, Plastic, % of Roof* |  |  |  |  |  |  |
| 0%–2.0% | $U_{all}$-1.30 | $SHGC_{all}$-0.65 | $U_{all}$-1.30 | $SHGC_{all}$-0.62 | $U_{all}$-1.90 | $SHGC_{all}$-NR |
| 2.1%–5.0% | $U_{all}$-1.30 | $SHGC_{all}$-0.34 | $U_{all}$-1.30 | $SHGC_{all}$-0.27 | $U_{all}$-1.90 | $SHGC_{all}$-NR |
| *Skylight without Curb, All, % of Roof* |  |  |  |  |  |  |
| 0%–2.0% | $U_{all}$-0.69 | $SHGC_{all}$-0.49 | $U_{all}$-0.58 | $SHGC_{all}$-0.36 | $U_{all}$-1.36 | $SHGC_{all}$-NR |
| 2.1%–5.0% | $U_{all}$-0.69 | $SHGC_{all}$-0.39 | $U_{all}$-0.58 | $SHGC_{all}$-0.19 | $U_{all}$-1.36 | $SHGC_{all}$-NR |

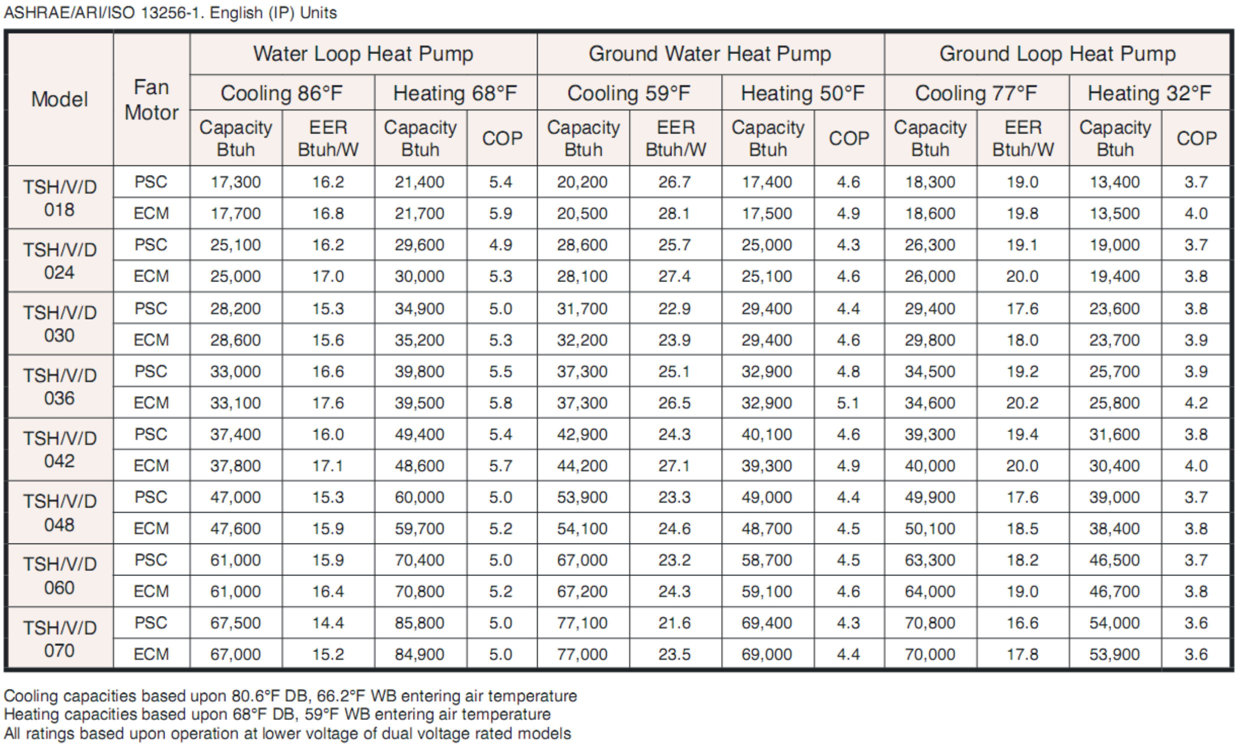
*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.

[b] Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.

[c] Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

# Appendix D: Heat Pump Energy Compliance

## TS:

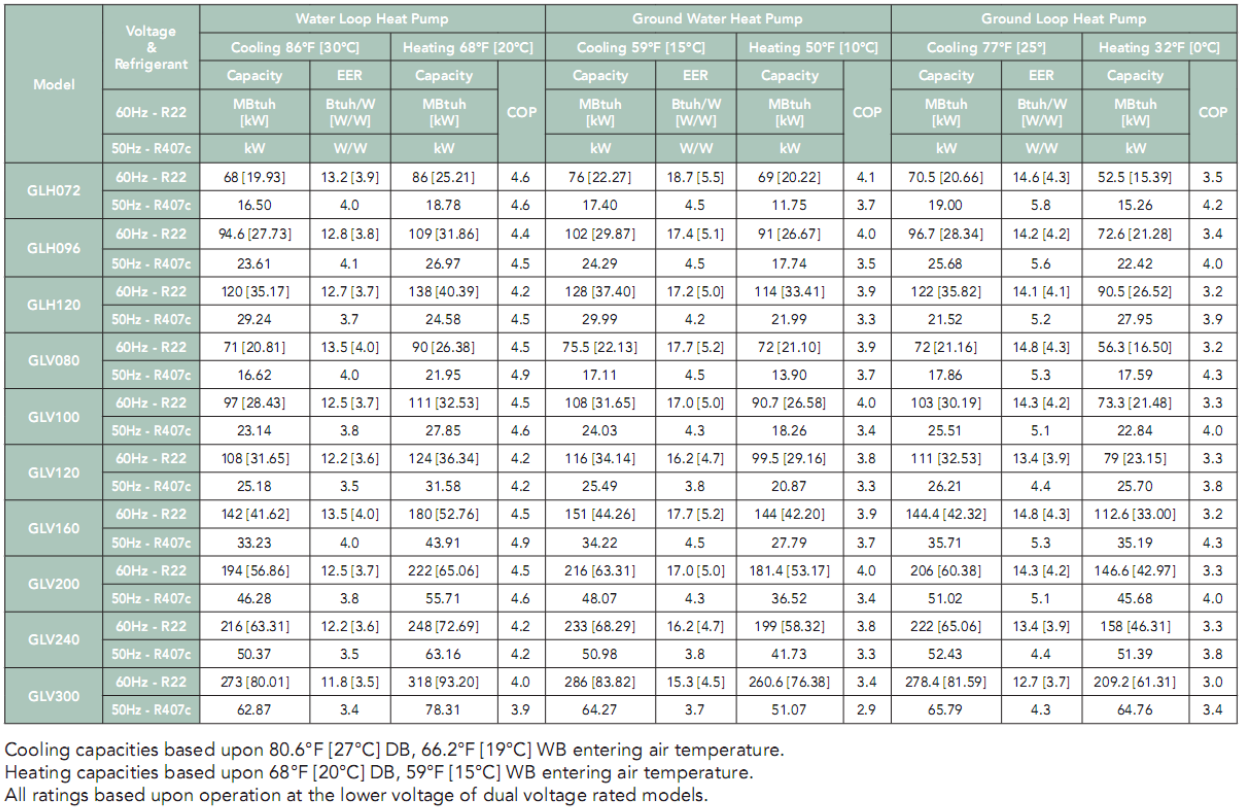


ASHRAE/ARI/ISO 13256-1. English (IP) Units

| Model | Fan Motor | Water Loop Heat Pump | | | | Ground Water Heat Pump | | | | Ground Loop Heat Pump | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cooling 86°F | | Heating 68°F | | Cooling 59°F | | Heating 50°F | | Cooling 77°F | | Heating 32°F | |
| | | Capacity Btuh | EER Btuh/W | Capacity Btuh | COP | Capacity Btuh | EER Btuh/W | Capacity Btuh | COP | Capacity Btuh | EER Btuh/W | Capacity Btuh | COP |
| TSH/V/D 018 | PSC | 17,300 | 16.2 | 21,400 | 5.4 | 20,200 | 26.7 | 17,400 | 4.6 | 18,300 | 19.0 | 13,400 | 3.7 |
| | ECM | 17,700 | 16.8 | 21,700 | 5.9 | 20,500 | 28.1 | 17,500 | 4.9 | 18,600 | 19.8 | 13,500 | 4.0 |
| TSH/V/D 024 | PSC | 25,100 | 16.2 | 29,600 | 4.9 | 28,600 | 25.7 | 25,000 | 4.3 | 26,300 | 19.1 | 19,000 | 3.7 |
| | ECM | 25,000 | 17.0 | 30,000 | 5.3 | 28,100 | 27.4 | 25,100 | 4.6 | 26,000 | 20.0 | 19,400 | 3.8 |
| TSH/V/D 030 | PSC | 28,200 | 15.3 | 34,900 | 5.0 | 31,700 | 22.9 | 29,400 | 4.4 | 29,400 | 17.6 | 23,600 | 3.8 |
| | ECM | 28,600 | 15.6 | 35,200 | 5.3 | 32,200 | 23.9 | 29,400 | 4.6 | 29,800 | 18.0 | 23,700 | 3.9 |
| TSH/V/D 036 | PSC | 33,000 | 16.6 | 39,800 | 5.5 | 37,300 | 25.1 | 32,900 | 4.8 | 34,500 | 19.2 | 25,700 | 3.9 |
| | ECM | 33,100 | 17.6 | 39,500 | 5.8 | 37,300 | 26.5 | 32,900 | 5.1 | 34,600 | 20.2 | 25,800 | 4.2 |
| TSH/V/D 042 | PSC | 37,400 | 16.0 | 49,400 | 5.4 | 42,900 | 24.3 | 40,100 | 4.6 | 39,300 | 19.4 | 31,600 | 3.8 |
| | ECM | 37,800 | 17.1 | 48,600 | 5.7 | 44,200 | 27.1 | 39,300 | 4.9 | 40,000 | 20.0 | 30,400 | 4.0 |
| TSH/V/D 048 | PSC | 47,000 | 15.3 | 60,000 | 5.0 | 53,900 | 23.3 | 49,000 | 4.4 | 49,900 | 17.6 | 39,000 | 3.7 |
| | ECM | 47,600 | 15.9 | 59,700 | 5.2 | 54,100 | 24.6 | 48,700 | 4.5 | 50,100 | 18.5 | 38,400 | 3.8 |
| TSH/V/D 060 | PSC | 61,000 | 15.9 | 70,400 | 5.0 | 67,000 | 23.2 | 58,700 | 4.5 | 63,300 | 18.2 | 46,500 | 3.7 |
| | ECM | 61,000 | 16.4 | 70,800 | 5.2 | 67,200 | 24.3 | 59,100 | 4.6 | 64,000 | 19.0 | 46,700 | 3.8 |
| TSH/V/D 070 | PSC | 67,500 | 14.4 | 85,800 | 5.0 | 77,100 | 21.6 | 69,400 | 4.3 | 70,800 | 16.6 | 54,000 | 3.6 |
| | ECM | 67,000 | 15.2 | 84,900 | 5.0 | 77,000 | 23.5 | 69,000 | 4.4 | 70,000 | 17.8 | 53,900 | 3.6 |

Cooling capacities based upon 80.6°F DB, 66.2°F WB entering air temperature
Heating capacities based upon 68°F DB, 59°F WB entering air temperature
All ratings based upon operation at lower voltage of dual voltage rated models

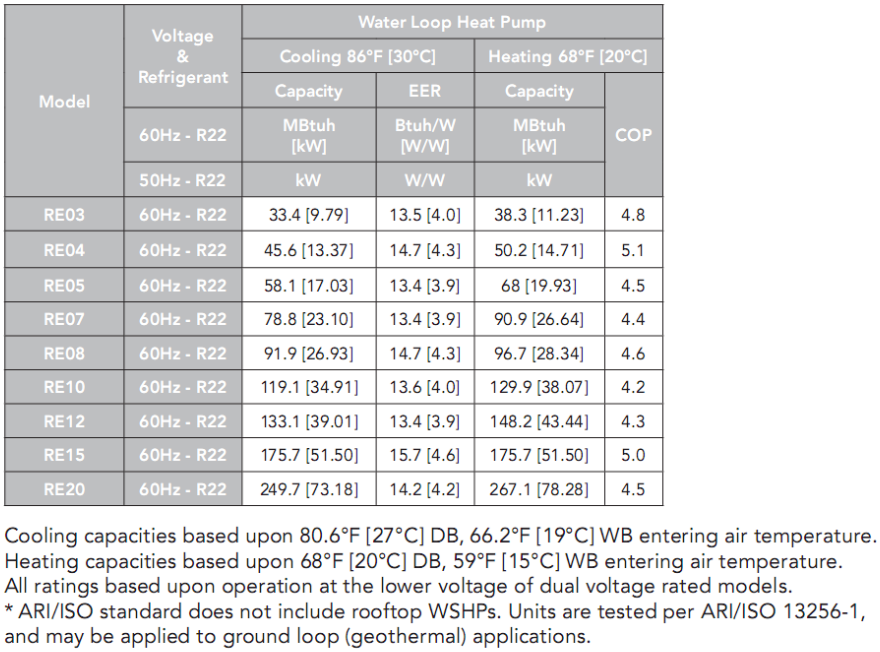
## GL:



| Model | Voltage & Refrigerant | Water Loop Heat Pump | | | | Ground Water Heat Pump | | | | Ground Loop Heat Pump | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cooling 86°F [30°C] | | Heating 68°F [20°C] | | Cooling 59°F [15°C] | | Heating 50°F [10°C] | | Cooling 77°F [25°] | | Heating 32°F [0°C] | |
| | | Capacity | EER | Capacity | COP | Capacity | EER | Capacity | COP | Capacity | EER | Capacity | COP |
| | 60Hz - R22 | MBtuh [kW] | Btuh/W [W/W] | MBtuh [kW] | | MBtuh [kW] | Btuh/W [W/W] | MBtuh [kW] | | MBtuh [kW] | Btuh/W [W/W] | MBtuh [kW] | |
| | 50Hz - R407c | kW | W/W | kW | | kW | W/W | kW | | kW | W/W | kW | |
| GLH072 | 60Hz - R22 | 68 [19.93] | 13.2 [3.9] | 86 [25.21] | 4.6 | 76 [22.27] | 18.7 [5.5] | 69 [20.22] | 4.1 | 70.5 [20.66] | 14.6 [4.3] | 52.5 [15.39] | 3.5 |
| | 50Hz - R407c | 16.50 | 4.0 | 18.78 | 4.6 | 17.40 | 4.5 | 11.75 | 3.7 | 19.00 | 5.8 | 15.26 | 4.2 |
| GLH096 | 60Hz - R22 | 94.6 [27.73] | 12.8 [3.8] | 109 [31.86] | 4.4 | 102 [29.87] | 17.4 [5.1] | 91 [26.67] | 4.0 | 96.7 [28.34] | 14.2 [4.2] | 72.6 [21.28] | 3.4 |
| | 50Hz - R407c | 23.61 | 4.1 | 26.97 | 4.5 | 24.29 | 4.5 | 17.74 | 3.5 | 25.68 | 5.6 | 22.42 | 4.0 |
| GLH120 | 60Hz - R22 | 120 [35.17] | 12.7 [3.7] | 138 [40.39] | 4.2 | 128 [37.40] | 17.2 [5.0] | 114 [33.41] | 3.9 | 122 [35.82] | 14.1 [4.1] | 90.5 [26.52] | 3.2 |
| | 50Hz - R407c | 29.24 | 3.7 | 24.58 | 4.5 | 29.99 | 4.2 | 21.99 | 3.3 | 21.52 | 5.2 | 27.95 | 3.9 |
| GLV080 | 60Hz - R22 | 71 [20.81] | 13.5 [4.0] | 90 [26.38] | 4.5 | 75.5 [22.13] | 17.7 [5.2] | 72 [21.10] | 3.9 | 72 [21.16] | 14.8 [4.3] | 56.3 [16.50] | 3.2 |
| | 50Hz - R407c | 16.62 | 4.0 | 21.95 | 4.9 | 17.11 | 4.5 | 13.90 | 3.7 | 17.86 | 5.3 | 17.59 | 4.3 |
| GLV100 | 60Hz - R22 | 97 [28.43] | 12.5 [3.7] | 111 [32.53] | 4.5 | 108 [31.65] | 17.0 [5.0] | 90.7 [26.58] | 4.0 | 103 [30.19] | 14.3 [4.2] | 73.3 [21.48] | 3.3 |
| | 50Hz - R407c | 23.14 | 3.8 | 27.85 | 4.6 | 24.03 | 4.3 | 18.26 | 3.4 | 25.51 | 5.1 | 22.84 | 4.0 |
| GLV120 | 60Hz - R22 | 108 [31.65] | 12.2 [3.6] | 124 [36.34] | 4.2 | 116 [34.14] | 16.2 [4.7] | 99.5 [29.16] | 3.8 | 111 [32.53] | 13.4 [3.9] | 79 [23.15] | 3.3 |
| | 50Hz - R407c | 25.18 | 3.5 | 31.58 | 4.2 | 25.49 | 3.8 | 20.87 | 3.3 | 26.21 | 4.4 | 25.70 | 3.8 |
| GLV160 | 60Hz - R22 | 142 [41.62] | 13.5 [4.0] | 180 [52.76] | 4.5 | 151 [44.26] | 17.7 [5.2] | 144 [42.20] | 3.9 | 144.4 [42.32] | 14.8 [4.3] | 112.6 [33.00] | 3.2 |
| | 50Hz - R407c | 33.23 | 4.0 | 43.91 | 4.9 | 34.22 | 4.5 | 27.79 | 3.7 | 35.71 | 5.3 | 35.19 | 4.3 |
| GLV200 | 60Hz - R22 | 194 [56.86] | 12.5 [3.7] | 222 [65.06] | 4.5 | 216 [63.31] | 17.0 [5.0] | 181.4 [53.17] | 4.0 | 206 [60.38] | 14.3 [4.2] | 146.6 [42.97] | 3.3 |
| | 50Hz - R407c | 46.28 | 3.8 | 55.71 | 4.6 | 48.07 | 4.3 | 36.52 | 3.4 | 51.02 | 5.1 | 45.68 | 4.0 |
| GLV240 | 60Hz - R22 | 216 [63.31] | 12.2 [3.6] | 248 [72.69] | 4.2 | 233 [68.29] | 16.2 [4.7] | 199 [58.32] | 3.8 | 222 [65.06] | 13.4 [3.9] | 158 [46.31] | 3.3 |
| | 50Hz - R407c | 50.37 | 3.5 | 63.16 | 4.2 | 50.98 | 3.8 | 41.73 | 3.3 | 52.43 | 4.4 | 51.39 | 3.8 |
| GLV300 | 60Hz - R22 | 273 [80.01] | 11.8 [3.5] | 318 [93.20] | 4.0 | 286 [83.82] | 15.3 [4.5] | 260.6 [76.38] | 3.4 | 278.4 [81.59] | 12.7 [3.7] | 209.2 [61.31] | 3.0 |
| | 50Hz - R407c | 62.87 | 3.4 | 78.31 | 3.9 | 64.27 | 3.7 | 51.07 | 2.9 | 65.79 | 4.3 | 64.76 | 3.4 |

Cooling capacities based upon 80.6°F [27°C] DB, 66.2°F [19°C] WB entering air temperature.
Heating capacities based upon 68°F [20°C] DB, 59°F [15°C] WB entering air temperature.
All ratings based upon operation at the lower voltage of dual voltage rated models.

## RE:



| Model | Voltage & Refrigerant | Water Loop Heat Pump | | | |
|---|---|---|---|---|---|
| | | Cooling 86°F [30°C] | | Heating 68°F [20°C] | |
| | | Capacity | EER | Capacity | COP |
| | 60Hz - R22 | MBtuh [kW] | Btuh/W [W/W] | MBtuh [kW] | |
| | 50Hz - R22 | kW | W/W | kW | |
| RE03 | 60Hz - R22 | 33.4 [9.79] | 13.5 [4.0] | 38.3 [11.23] | 4.8 |
| RE04 | 60Hz - R22 | 45.6 [13.37] | 14.7 [4.3] | 50.2 [14.71] | 5.1 |
| RE05 | 60Hz - R22 | 58.1 [17.03] | 13.4 [3.9] | 68 [19.93] | 4.5 |
| RE07 | 60Hz - R22 | 78.8 [23.10] | 13.4 [3.9] | 90.9 [26.64] | 4.4 |
| RE08 | 60Hz - R22 | 91.9 [26.93] | 14.7 [4.3] | 96.7 [28.34] | 4.6 |
| RE10 | 60Hz - R22 | 119.1 [34.91] | 13.6 [4.0] | 129.9 [38.07] | 4.2 |
| RE12 | 60Hz - R22 | 133.1 [39.01] | 13.4 [3.9] | 148.2 [43.44] | 4.3 |
| RE15 | 60Hz - R22 | 175.7 [51.50] | 15.7 [4.6] | 175.7 [51.50] | 5.0 |
| RE20 | 60Hz - R22 | 249.7 [73.18] | 14.2 [4.2] | 267.1 [78.28] | 4.5 |

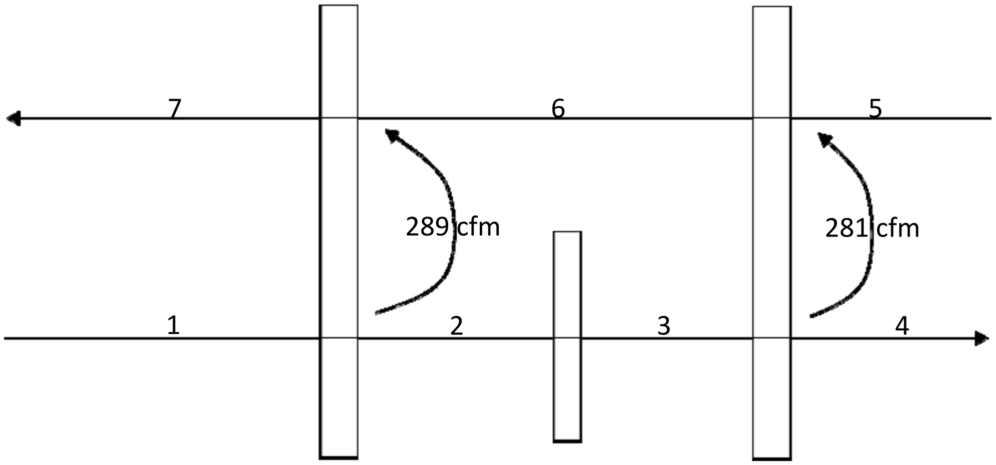
Cooling capacities based upon 80.6°F [27°C] DB, 66.2°F [19°C] WB entering air temperature.
Heating capacities based upon 68°F [20°C] DB, 59°F [15°C] WB entering air temperature.
All ratings based upon operation at the lower voltage of dual voltage rated models.
* ARI/ISO standard does not include rooftop WSHPs. Units are tested per ARI/ISO 13256-1, and may be applied to ground loop (geothermal) applications.

# Appendix E: Sample OAU Calculations

## OAU-1 through OAU-3

| State Pt # | Dry Bulb Temp | Grains | h |
|---|---|---|---|
| 1 | 91 | 118.3 | 40.4 |
| 2 | 69.3 | 93.6 | 31.2 |
| 3 | 55 | 60.5 | 22.5 |
| 4 | 72.1 | 60.5 | 26.7 |
| 5 | 79 | 75.2 | 30.7 |
| 6 | 60.4 | 75.1 | 26.1 |

Room Supply DB Temp [F]: 55



| Cooling Coil Load | [Tons] | |
|---|---|---|
| As is (@ AHU) | 11.879 | W/ SW: (Calculated using Q = 4.5 * CFM_2 * (h_2-h_3)) |
| Lost cool w SW | 5.2920 | W/ SW: (Calculated using Q = 4.5 * CFM_4 * (h_4-h_3)) |
| As is (w/ terminal) | 17.0498 | W/ SW: (Calculated using Q = As Is tons + [1.08 * CFM_4 * (T_supply-T_4))] |
| | | |
| No heat Rec | 22.6 | W/ SW: (Calculated using Q = 4.5 * CFM_4 * (h_1-h_3)) |
| No SW | 14.7 | W/o SW: (Calculated using Q = 4.5 * CFM_2_3_4 * (h_2-h_4)) |

| | | 1 OA EW | 2/3 OA SW | 4 | 5 RA SW | 6 RA EW | 7 |
|---|---|---|---|---|---|---|---|
| w/ SW | flow (CFM) | 3930.0 | 3641.0 | 3360.0 | 3025 | 3306 | 3595.0 |
| w/o SW | | 3649.0 | 3360.0 | 3360.0 | 3314 | 3314 | 3603.0 |
| | | | | | | | |
| | Fan Power | | | | | | |
| w/ SW | [HP, efficien below] | 0.721365639 | 0.59193937 | 0.546145 | 0.4442 | 2.30365 | |
| w/o SW | 60% | 0.669787078 | 0 | 0.547467 | 0 | 1.217254 | |
| Excess kW usage: | | 0.03846 | 0.44141 | -0.00099 | 0.33124 | 0.81013 | |
| Excess HP: | | 0.05158 | 0.59194 | -0.00132 | 0.44420 | 1.08640 | |
| | | | | | | | |
| | | supply | exhaust | | | | |

| | OA EW | OA SW | RA EW | RA SW |
|---|---|---|---|---|
| Pressure Drop Through | 0.7 | 0.62 | 0.63 | 0.56 |
| Wheels (in w.g.) | 0.7 | | 0.63 | |

*The reason that I can take this 17.05 and subtract 11.88 to get the reduced terminal load is because that is the amount of work the terminal equipment would have to do to get air to the same conditions that it is out of the 14.7 ton configuration that is in cell C65. Note that the capacity of the OAU goes up 14.7 minus 11.88 tons, but the terminal capacity decreases by more than that for an overall beneficial effect.


OAU 1-3
W, gr
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
90
95
DBT, F
1
2
3
4
5
6
7

# Appendix F: PV Study Details

PV Array Information:

| | |
|---|---|
| City, State: | Manassas Park, VA |
| Utility: | Northern Virginia Electric Cooperative (NOVEC) |
| Billing Rate Structure: | Net Metered Small Commercial Service (Billing Rate 2B) |
| Average Monthly Electricity Bill: | $13,000 |
| Annual Bill Excalation: | 4.00% |
| System Size (DC): | 40 kW |
| Module Cost: | $8.00 per Watt DC |
| Module Tilt: | 40 Degrees |
| Orientation: | Due South |
| Obstructions: | None |

Environmental Benefits:

| | |
|---|---|
| First Year $CO_2$ Impact (lbs): | 69,578 |
| Equivalent Trees (acres): | 5.38 |
| Equivalent Driving (miles): | 83,493 |

Annual Net Cash Flow:

| Year | Annual Electric Bill Savings | Electric Bill Tax Savings | Loan Payment | Loan Tax Savings | Depreciation Tax Savings | Total Net Cash Flow |
|---|---|---|---|---|---|---|
| 2010 | $6,022 | ($2,286) | ($20,746) | $6,762 | $19,235 | $8,987 |
| 2011 | $6,263 | ($2,377) | ($20,746) | $6,670 | $30,333 | $20,142 |
| 2012 | $6,513 | ($2,472) | ($20,746) | $6,570 | $18,495 | $8,360 |
| 2013 | $6,774 | ($2,571) | ($20,746) | $6,461 | $11,393 | $1,310 |
| 2014 | $7,045 | ($2,674) | ($20,746) | $6,344 | $11,393 | $1,361 |
| 2015 | $7,327 | ($2,781) | ($20,746) | $6,217 | $6,066 | ($3,918) |
| 2016 | $7,620 | ($2,892) | ($20,746) | $6,079 | $739 | ($9,201) |
| 2017 | $7,925 | ($3,008) | ($20,746) | $5,930 | $739 | ($9,161) |
| 2018 | $8,242 | ($3,128) | ($20,746) | $5,769 | $739 | ($9,125) |
| 2019 | $8,571 | ($3,254) | ($20,746) | $5,594 | $739 | ($9,096) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2020 | $8,914 | ($3,384) | ($20,746) | $5,405 | $739 | ($9,072) |
| 2021 | $9,271 | ($3,519) | ($20,746) | $5,200 | $739 | ($9,056) |
| 2022 | $9,641 | ($3,660) | ($20,746) | $4,977 | | ($9,787) |
| 2023 | $10,027 | ($3,806) | ($20,746) | $4,737 | | ($9,789) |
| 2024 | $10,428 | ($3,959) | ($20,746) | $4,476 | | ($9,800) |
| 2025 | $10,845 | ($4,117) | ($20,746) | $4,194 | | ($9,824) |
| 2026 | $11,279 | ($4,282) | ($20,746) | $3,889 | | ($9,860) |
| 2027 | $11,730 | ($4,453) | ($20,746) | $3,558 | | ($9,911) |
| 2028 | $12,200 | ($4,631) | ($20,746) | $3,200 | | ($9,978) |
| 2029 | $12,687 | ($4,816) | ($20,746) | $2,811 | | ($10,064) |
| 2030 | $13,195 | ($5,009) | ($20,746) | $2,391 | | ($10,169) |
| 2031 | $13,723 | ($5,209) | ($20,746) | $1,936 | | ($10,297) |
| 2032 | $14,272 | ($5,418) | ($20,746) | $1,443 | | ($10,449) |
| 2033 | $14,843 | ($5,634) | ($20,746) | $909 | | ($10,629) |
| 2034 | $15,436 | ($5,860) | ($20,746) | $331 | | ($10,839) |