The Ed Roberts Campus

Final Report

Anderson Clemenceau

Mechanical Option

Advisor: Dr. Donghyun Rim

April 8, 2015

Contents

Building Overview

Leddy, Maytum, Stacy Architects

The Ed Roberts Campus is a 2-story, 82,000 sq. ft. community center located in downtown Berkeley, California with a focus on accessability for people with disabilites. Completed in 2011, the ERC is home to exhibition spaces, meeting spaces, a child development center, a fitness center, vocational training facilities, and general offices. The building is designed far and above the requirements of the Americans with Disabilities Act through a design concept called "Universal Design", which aims to create environments that are useful for people of all ages and abilities. Extra-wide corridors, automatic doors, two-sided elevators, and a handicap-accessible connection to a Bay Area Rapid Transit station are examples of this design ideal. While the Ed Roberts Campus is not currently LEED certified, it nevertheless has many design features that allow for sustainability and efficient operation. As part of the Universal Design concept, the ERC employs the use of high quality air filters that help minimize contaminants. Additionally, as will be discussed in the mechanical overview, the building takes in 100% of its ventilation air from outside, ensuring indoor air quality stays far above most standard designs as well as LEED requirements.

ED ROBERTS CAMPUS

Anderson Clemenceau
Mechanical Option
Advisor: Donghyun Rim

PROJECT TEAM

OWNER: THE ED ROBERTS CAMPUS
ARCHITECT: LEDDY MAYTUM STACY
S-MEP: ARUP SAN FRANCISCO
CONSTRUCTION: CAHILL CONSTRUCTION

BERKELEY, CA
COMMUNITY/EDUCATION CENTER
TWO STORIES - 82,000 GROSS SQFT

ARCHITECTURE

Universal Design is the name of the concept utilized in every design choice within the ERC in order to make every feature useful to as many people as possible. Extra-wide corridors and elevators, automatic doors, low signage, and audio cues are examples. The building takes advantage of ample daylight with large skylights and windows to ease daytime lighting loads.

STRUCTURE

The structural system is a combination of concrete and steel frame construction. The basement foundation and first floor are concrete with some steel beam reinforcement. The second floor is 3-1/4" slab on metal decking supported by steel frame, with steel braced frame walls providing shear support.

MEP

5 Dedicated Outdoor Air AHUs supply ventilation air to the building while sensible cooling and heating needs are met by water source heat pumps as air is delivered to each zone. The tall, open lobby and court areas utilize an underfloor radiant heating and cooling system to efficiently condition the occupied zone.

Electricity entering as 480/277V, 3-Phase power is distributed to nine panel boards serving different sectors of the building, and is converted to both high and low voltage power to cover the diverse loads within the building.

The building's lighting system includes 42,000 Watts of lighting fixtures for the 66,000 sqft of occupied, illuminated space. These fixtures are all controlled by occupancy sensors and programmable time switches for maximum efficiency.

Executive Summary

This objective of this report is to analyze the previously described building, the Ed Roberts Campus, and implement potentially energy efficient changes to the mechanical system as part of a primary depth investigation. In addition, two secondary breadth investigations will be conducted into the structural and electrical systems of the building. These investigations are purely for academic interest and may result in positive or negative changes to building operation. They do not suggest that the current design is flawed in any way.

The depth investigation consisted of two sections: the conversion of a Water Source Heat Pump based system to a Variable Refrigerant Flow system, and the installation of a Solar Thermal Hot Water system for the building's domestic hot water and limited space heating requirements. The focus of the analysis will be recognize any potential to save energy and evaluate the economic feasibility of any change. Additionally, two investigations were performed into the effects the mechanical renovations may have on other building systems. First, a structural analysis of the roof was performed to determine what effect the solar thermal panel array might have. Second, an electrical analysis was performed to determine if any changes were necessary to the electrical system in the building.

The results of these investigations were as follows:

Mechanical Depth

- Variable Refrigerant Flow System
    - First Cost: $364,300
    - Annual Energy Savings: 14.3%, $23,610
    - Payback Period: 20 years
- Solar Thermal Hot Water System
    - Domestic Hot Water and Radiant Floor Space Heating
        - First Cost: $75,000
        - Annual Energy Savings: $3,020
        - Payback Period: >25 years
    - Domestic How Water Only
        - First Cost: $25,000
        - Annual Energy Savings: $2,016
        - Payback Period: 18 Years

The results of the mechanical investigation led to recommendations into the Variable Refrigerant Flow system and a Solar Thermal system for domestic hot water, which both showed potential to save energy with reasonable payback periods. A solar thermal system for space heating application proved too costly compared to the limited energy benefits provided. The structural and electrical breadth investigations both came to the conclusion that, while it would be possible to downsize some elements of those building systems, it would not be necessary to make any changes as part of a mechanical system renovation.

Acknowledgements

I would like to recognize those individuals that helped me in the process of creating this report over the course of the past academic year.

Thanks to the Penn State Architectural Engineering Department for giving me the strong educational foundation without which this entire report would have been impossible.

Thank you Dr. Donghyun Rim, as well as the rest of the A.E. Mechanical faculty, for you advice and guidance throughout the length of this project.

Thank you to Dmitri Belser, of the Center for Accessible Technology at the Ed Roberts Campus, for you enthusiastic support and help obtaining the crucial information to complete this report.

Thank you to my parents, George and Cielle Clemenceau, for giving me the opportunity for this wonderful education and for supporting me in all my endeavors.

Existing Mechanical System Evaluation

Mechanical Equipment

The mechanical system in the Ed Roberts Campus can be described as Water Source Heat Pump (WSHP) System with Dedicated Outside Air, and includes an additional Radiant Floor System.

Waterside Equipment

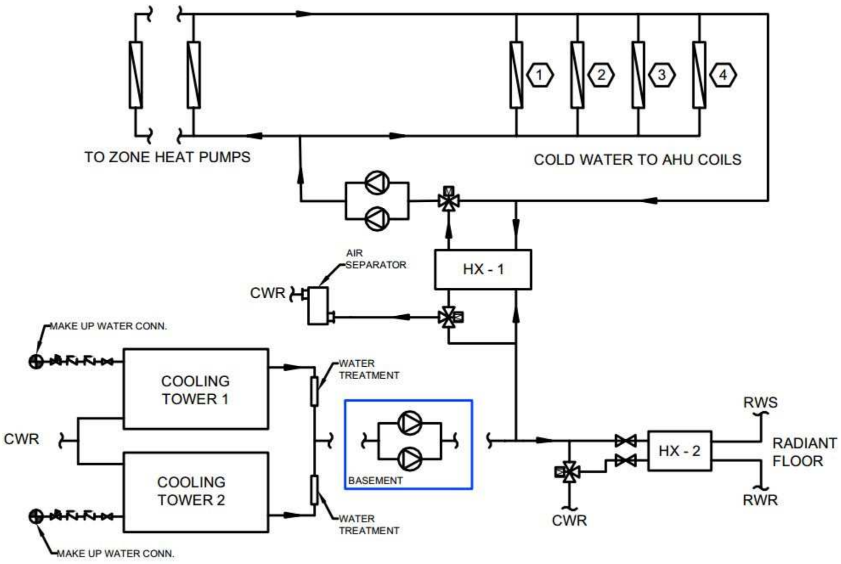


Figure 1: Chilled Water Schematic for WSHP System

Chilled water is supplied to the building by two open cooling towers, mounted on the rooftop, each with a capacity of 100 tons. Each tower has an approach of 7F and a design flowrate of 200 gpm. This condenser water is isolated from coils by a plate heat exchanger for botht the WSHP system radiant floor. This chilled water is used to supply the cooling coils in AHU 1-4, all of the water source heat pumps, and all three zones of the radiant floor system.

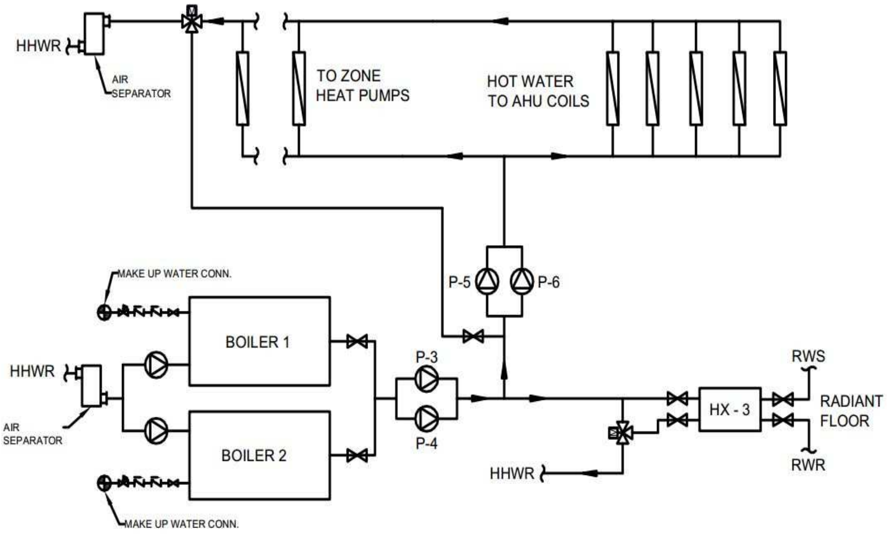


Figure 2: Hot Water Schematic for WSHP System

Hot water is supplied by two gas-fired boilers located in the mechanical room on the roof. Each boiler has a capacity of 900 MBH and operating efficiency of 98%. Water enters the boiler at 80 F and is heated to 120 F for supply to heating coils in all five AHUs, all water source heat pump coils, and radiant floor zones.

The Ed Roberts Campus uses a radiant floor heating/cooling system for conditioning needs in the large, multistory lobby and courtyard spaces of the building. This system works by circulating chilled or hot water through piping embedded into the concrete floor slab in order to heat or cool air in the occupied zone of the tall, open space above. Energy is transferred from the cooling tower and boiler water loops by two plate heat exchanger that serves only the radiant system. There are three separate zones (piping networks) in the floor that cover a total area of approximately 7,150 sf. Each radiant water loop runs for a maximum of 300 ft and there is a total of about 13,500 ft of 5/8" pipe in the floor slab.

Airside Equipment

The airside equipment for the building includes five Air Handling Units that supply air to 59 zone-level water source heat pumps. The Air Handling Units do not utilize any return air from the space and could be more accurately described as Dedicated Outdoor Air System (DOAS) units. They work to supply the building with the appropriate volume of ventilation air and meet the latent load in the building. AHU-1, AHU-3, and AHU-4 are constant volume units. AHU-2 and AHU-5 utilize fans with Variable Frequency Drives.

AHU	Area Served	% Outside Air	CFM
AHU-1	East Wing - South	100	7,800
AHU-2	BORP	100	5,500
AHU-3	West Wing - South	100	3,500
AHU-4	West Wing - North	100	6,000
AHU-5	Covered Court	100	5,000

Since the building utilizes 100% outdoor air, all return air is exhausted by nine fans that serve different areas of the building. Exhaust Fans 1, 3,4,5, and 7 serve the general office spaces throughout the building. EF-2 serves restroom exhaust requirements and the largest fan, EF-6, serves the entire basement level parking garage with 72,000 cfm of airflow. The remaining fans serve smaller electrical, elevator and garbage rooms.

Water Source Heat Pump units manufactured by McQuay meet most of the sensible load within each zone. Building zones are served by heat pumps of varying capacities, based on the load requirements of the space, and there were a total of 59 units at design. Each unit contains one coil for both heating and cooling requirements, as well as one double inlet forward curved centrifugal supply fan which maintains duct static pressure and moves air supplied by the air handling units through the unit and into the space.

Building Loads

Trane Trace 700 was the sofware program used to model loads and energy use of the Ed Roberts Campus for this report. To create the model, information was collected from drawings and specifications and entered into the program.

Climate Conditions

The Ed Roberts Campus is located in Berkeley, CA near the San Francisco Bay area. The closest choice in the Trace 700 weather database was San Francisco (CZ03). This refers to the ASHRAE 90.1 climate zones, investigated in Technical Report 1, and matches with the previously determined zone. The table below lists more detailed climate design data for the nearby Oakland International Airport.

Oakland Intl. Airport			Heating DB		Cooling DB/MCWB					
					0.4%		1%		2%	
Lat.	Long.	Elev.	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB
37.76N	122.22W	89	37.2	39.5	81.8	65	77.7	64.1	74.3	63.1

Occupancy and Internal Loads

As the Ed Roberts Campus was not fully leased at the time of design it was impractical to model each individual room in Trace 700. Instead, the spaces modeled in the program reflect the water source heat pump zoning plan in the mechanical plans, which grouped together spaces of similar load characteristics to be served by the heat pump units. This may have resulted in some lost accuracy in the model, but the assumptions made about the loads were more consistent across the building.

Templates were generated for offices, meeting rooms, break rooms, lobbies, etc… and applied to the different zones. Lighting loads were entered based on Table 9.5.1 Lighting Power Densities from ASHRAE 90.1 and the electrical building plans. The office and classroom spaces included an additional load for computers and other office equipment based on values from the ASHRAE Fundamentals Handbook. Trace 700 gives the option to implement a ventilation strategy based on ASHRAE Std. 62.1 2007 values for different room types. This might correctly calculate the amount of air required but would not accurately represent the operation of the DOAS units. Therefore, the option for 100% outdoor air to every space was selected.

Mechanical Equipment

As stated in the mechanical overview the ERC is served by five air handling units, primarily for ventilation air, and zone level water source heat pumps that meet space sensible loads. In Trace 700 this type of system can be modeled by selecting Water Source Heat Pumps as the primary system with added DOAS inputs. The Ed Roberts Campus also utilized a radiant floor heating and cooling system for the Lobby, Reception, Art Gallery, and Courtyard areas. Unfortunately, Trace 700 is unable to model this part of the system. The listed design capacities of the three radiant zones will have to be manually added to the results, and energy use can be estimated using differences between the modeled and actual energy costs.

Model Results

The output from Trace 700 includes calculations for the load properties of the building as well as information on the energy use of the building systems. Since this model of the building will be used in the Depth investigation it is important to determine if the model accurately represents the load characteristics of the building.

As mentioned previously, some of the spaces in the ERC were not leased at the time of design and there is no way to compare the load results of these spaces with designed capacity for each space. However, some assumptions can be made about those missing spaces based on the total building load. The following table compares peak cooling and heating loads for the building model with the capacity of the existing complete system.

Sensible and Latent Cooling Load Peak		Equipment Capacity	Heating Load Peak		Equipment Capacity
1,935,766.0	btu/h		2,539,095.0	btu/h	
161.3	ton	200 ton	2,539.1	MBH	1800 MBH

The table clearly shows that the model created in Trane Trace 700 gave mixed results for the loads of the building. The total calculated peak cooling load of the ERC in the Trace 700 model was 161 tons, while the total capacity of the chilled water plant is 200 tons. This difference is significant, approximately 24%, but the model is still a reasonable estimation. However, the peak heating load from the model, 2,539 MBH, was nearly 41% larger than the hot water equipment capacity of 1800 MBH. This could result from Trace 700 overestimating the energy required to condition 100% outdoor air in the heating season. This is confirmed by the fact that gas usage was greater in the model than in the actual reported gas bill.

Trane Trace 700 also has the ability to calculate energy use from the modeled system. The primary utility provider in the Berkeley, CA area is Pacific Gas & Electric, from which the Ed Roberts Campus receives electricity and gas. Their most recent rate information was used in the model analysis.

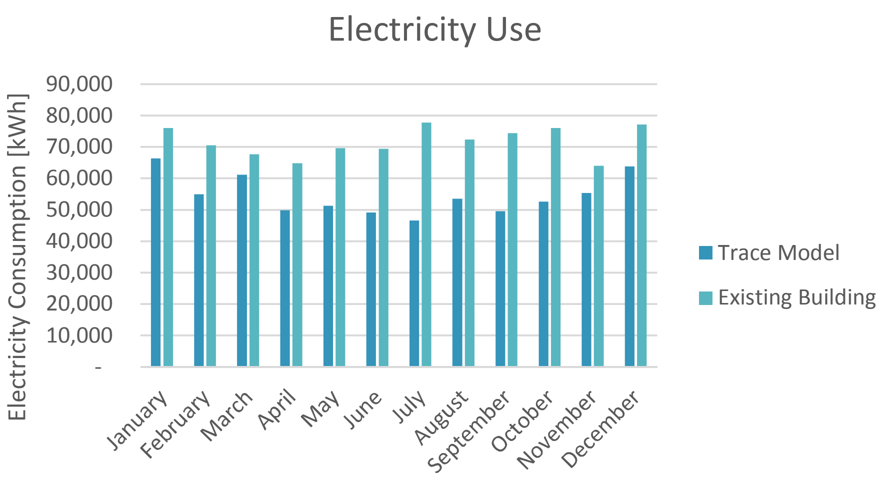


Figure 3: Comparison of Electricity Use Between Trace 700 Model and Actual Buidling Utility Bill Records

It is clear from this comparison of electricity use in the Trace model to an actual 2013 record from the building owner that the model underestimated the total energy use of the building. Based on this information, it is clear that the model is not a perfect representation of the building and its load characteristics. However, with some assumptions made, it will act as a base for completing the depth design portion of this thesis investigation.

Proposed Alternatives

The following is a list of options that were considered as possible areas of investigation for the Ed Roberts Campus. It is important to note that, while alternatives are being investigated, they are not suggesting that the current design is inadequate in any way. This is an academic exercise to explore energy use of different mechanical systems.

1. Implementation of on-site renewable energy sources
    a. Solar Panels (electricity or heating demand)
    b. Ground Source Heat Pump system
2. Use of a centralized air system with air-air heat recovery
3. Conversion to a Variable Refrigerant Flow System

Each of these alternatives would offer different challenges and comparisons with the current system, but need to be balanced to include an appropriate scope of work. Option 3, a Variable Refrigerant Flow system, will be selected as a primary investigation into the space condition of the building with a second investigation into a Solar Thermal system that could be used to address the radiant floor system.

Depth

Variable Refrigerant Flow

For the Mechanical Depth portion of the thesis project, I will look into the effects of converting the current mechanical system into a Variable Refrigerant Flow system. Initial research indicates that the current system is already set up well for conversion to such a system. The Water Source Heat Pumps installed around the building are similar to ceiling-mounted ducted units commonly available with VRF systems. New air-source condenser units will need to be installed on the roof to cool or heat refrigerant as the system demands, and new refrigerant lines to the fan coil units will need to replace old CHW/HW piping.

It will be useful to compare the energy use of this kind of system, which is immensely popular outside the United States, to the energy use of the current building. The new system will not require any equipment to cool/heat water so this equipment (cooling towers and boilers) could be removed from the rooftop mechanical room. The AHUs will no longer be supplied by cooling towers and boilers and could be replaced by single packaged units. These equipment changes, together with a good control and operations scheme, offer the possibility for great energy savings for the building. The tools required in this section of the thesis investigation will include energy modeling software, such as Trane Trace, to track the changes in mechanical system within the building.

Solar Thermal Hot Water

As a secondary consideration, I will look into the possibility of implementing a solar thermal heating system for hot water demand in the building. Solar Thermal is popular as a way to supply both domestic hot water and space heating water and the effects of a solar system on the energy use of the current hot water equipment will be investigated. It will be important to find the configuration and application of the system that allows for the most savings as well as a reasonable payback period. This part of the investiagation will utilize the solar thermal simulation program CombiSys.

Breadth

Structural Breadth

The removal of several types of chilled and hot water equipment from the rooftop mechanical room, as well as the addition of many VRF outdoor units, offer the possibility of redesigning the structure of the roof. The solar thermal system, depending on the weight of the panels and size of the panel array, could require a redesign of the roof structure. If the structure could be reduced in size there is the possibility of additional cost savings.

Electrical Breadth

Another possible effect of elimating equipment is an adjustment to the electrical system. The addition of a large amount of VRF equipment with different electric requirements could also require adjustments to the electrical system. This adjustment could mean redesigning a branch circuit, or the design of a completely new circuit, to suit the changing mechanical system. This change could result in a lower first cost for the electrical equipment, as well as a reduction in electricity use and monthly energy savings.

Mechanical Depth Analysis

Variable Refrigerant Flow System

Variable Refrigerant Flow (VRF) systems are common in many parts of the world, such as Japan and throughout Europe, but are relatively uncommon in the United States despite the potential for energy savings that they can provide. VRF systems are based on a reverse Rankine vapor compression cycle and utilize similar components to a direct expansion heat pump system. The system moves heat with a refrigerant flowing between a single outdoor unit and multiple indoor units installed throughout the building. There are two categories of VRF systems: heat pump systems and heat recovery systems. A heat pump system may provide heating or cooling by reversing the flow direction around the loop, but all connected units must be operating in the same mode. A heat recovery system can allow different indoor units to operate in heating and cooling modes simultaneously, as well as transfer heat between indoor units with the use of a heat recovery control unit, and is the system type that will be used in the depth investigation.

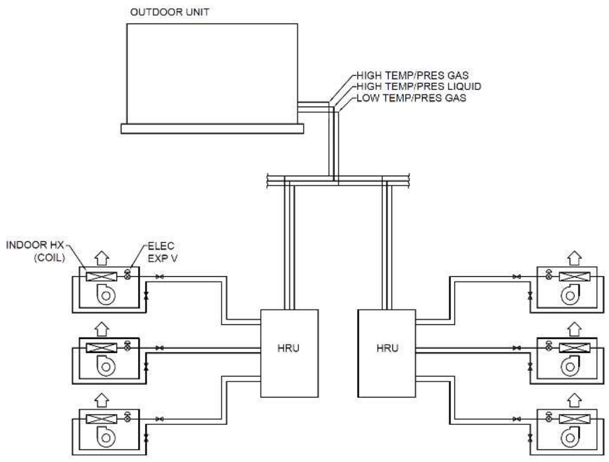


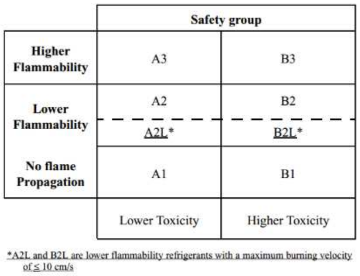
Figure 4: Variable Refrigerant Flow System Schematic

This diagram shows the basic schematic layout of the three-pipe heat recovery VRF system. A single outdoor unit contains a compressor, heat exchanger, fans and control equipment. The compressor can be controlled with a variable-speed drive that modulates the capacity of the unit as demand changes. This unit is connected to a heat recovery unit by three pipes that transport the refrigerant in different states depending on the current mode of operation (heating or cooling). The heat recovery unit controls the distribution of refrigerant to each indoor unit coil, as well as the re-distribution of heat to indoor units that may be operating in a different mode simultaneously.

For example, while the system is operating in heating mode the refrigerant in a high temperature high pressure gas state enters the indoor unit coil and is condensed to a high temperature high pressure liquid that is sent back to the outdoor unit. Some of this liquid could be re-routed to another indoor unit by the heat recovery unit and replicate the regular operation of the unit in cooling mode. It is most likely that all the indoor units will be operating in the same mode during most of the year, but this system allows the occupants to have greater control of the space conditioning without significant extra load on the outdoor equipment.

Johnson Controls is a well known manufacturer of HVAC equipment. Their York VRF product catalog will be used to obtain equipment data for both the outdoor and indoor units, but there are many other reputable manufacturers that offer equipment with similar performance characteristics. Available York VRF outdoor units come in a variety of configurations with capacities ranging from 6 to 30 ton and can be operated at either 208/230V or 460V (3-phase). The necessary changes to the electrical branch circuits for the roof equipment will be discussed as part of the electrical breadth investigation. The indoor units from Johnson Controls come in a range of capacities from 0.5 to 4.0 tons of nominal cooling capacity. There are ducted and un-ducted units available, but the ducted units will be selected in this investigation to maintain operation of the dedicated outdoor air system that currently works with the water source heat pump units.

The York VRF system utilizes refrigerant R-410A, which is a 50/50 zeotropic mixture of R-32 and R-125. ASHRAE Standard 34, which designates the safety classifications of common refrigerant types, rates R-410A in Safety Group A1. The figure to the right, from ASHRAE Standard 34-2007, shows that R-410A is classified by Lower Toxicity and No Flame Propogation. Thus, the risk of refrigerant leaking in large enough quantities to be toxic to the occupants of the building is very low and a leak would be not be likely to cause a fire. Based on manufacturer specifications, a total of almost 230 lb of refrigerant charge will be required to supply all of the VRF systems.



	Safety group	
Higher Flammability	A3	B3
Lower Flammability	A2 A2L*	B2 B2L*
No flame Propagation	A1	B1
	Lower Toxicity	Higher Toxicity

*A2L and B2L are lower flammability refrigerants with a maximum burning velocity of ≤ 10 cm/s

Figure 5: ASHRAE Std. 34 Refrigerant Safety Classifications

Sizing Procedure

The following steps outline the procedure to size an indoor VRF unit. Zone 120-2 is an open office zone in the East wing of the building. According to the Trace model, this space has a sensible cooling load of 14,026 Btu/h and latent load of 2,894 Btu/h. The heating load was calculated as 8,227 Btu/h, so the larger cooling load will be used for design. First, the minimum airflow to meet this latent load will be calculated using the difference in humidity ratio between the outside and space conditions:

$$[cfm] = \frac{2{,}984\ [Btu/h]}{4840 * (.008338 - 0.002272\ lb_w/lb_a)} = 98.57\ cfm$$

This is slightly less than the minimum ventilation air required by ASHRAE 62.1, so the ventilation air will act as the supply airflow. DOAS units, which will be discussed further in the report, work parallel with the VRF system to partially condition the ventilation air before the VRF indoor units meet the remaining sensible load. This usually means that the DOAS units condition the outdoor air to the desired dew point of the space which is about 53°F for a set point of 72°F and 50% Relative Humidity. This pre-conditioning of the air also meets a portion of the sensible load of the space.

$$q_s = 1.08[103.5\ cfm] * (72^{\circ}F - 55^{\circ}F) = 1{,}230\ Btu/h$$

The remaining load, 12,796 Btu/h, must be met by the cooling capacity of the indoor unit and the airflow through the coil. Using the equipment data obtained from the manufacturer catalog, a 15,000 Btu/h (1.2 ton) unit can supply a maximum of 512 cfm. This is more than enough to meet both requirements. This process can be repeated for each space to obtain the number of indoor units required, to which outdoor units they will be connected, and how much refrigerant piping will be needed. In some cases, the indoor unit selection may be based on the required heating load in the space. Based on these calculations, 53 indoor VRF units will be required to meet the sensible cooling loads of the building spaces and the full range of available ducted indoor units from York is available in the appendices.

Outdoor units must be sized based on the connected indoor unit capacity and the diversity of loads these indoor units are designed to meet. According to manufacturer specifications, the outdoor units can be serve a connected load of up to 130% the rated capacity. However, it is a conservative practice to add a small percentage to the capacity of the outdoor unit to accommodate future changes in the building. With some rezoning around the building to account for the capacity of outdoor units and limited piping lengths, a total of four VRF units will be placed on the rooftop with rated capacities of 18, 22, 26, and 28 tons.

	Nominal Size of Outdoor Unit [tons]	IEER (Cooling Mode)	COP (Heating Mode)	Dimensions (HxWxD) [in]	Gross Weight [lbs]
VRF Zone 1	26 (10+10+6)	18.8	3.56	68-1/8" x 134-7/8" x 31-7/32"	2165
VRF Zone 2	22 (10+6+6)	18.8	3.61	68-1/8" x 124-21/32" x 31-7/32"	1962
VRF Zone 3	18 (6+6+6)	19.2	3.49	68-1/8" x 173-5/32" x 31-7/32"	1760
VRF Zone 4	28 (8+8+6+6)	21.2	3.87	68-1/8" x 113-5/8" x 31-7/32"	2747

100% Outdoor Air System

As mentioned previously, it is common to pair VRF systems with Dedicated Outdoor Air System (DOAS) units and, in this case, Johnson Controls offers a product line of DOAS units that can easily be integrated into this system. These units, which operate on DX cooling and use natural gas or propane for heating, will supply the necessary amount of outdoor to the spaces within the building and will need to be sized to meet the ventilation airflow as well as have the capacity to condition the outside air. Units from Johnson Controls that met this criteria were selected as per the table below.

	Required Airflow [cfm]	Model	DOAS Unit Airflow [cfm]	Cooling Capacity [tons]	Heating Capacity at 90% Eff. [MBH]
VRF Zone 1	4,426.47	JDMA-210	2275-5250	17.5	207
VRF Zone 2	5,480.2	JDMA-300	3400-7500	25	276
VRF Zone 3	3,808.54	JDMA-180	2000-4400	15	138
VRF Zone 4	5,867.72	JDMA-300	3400-7500	25	276
Lobby/Reception	2,503.64	JDMA-120	1300-3000	10	138

Energy Use Results

In Trace 700, accurately modeling the exact layout and operation of a variable refrigerant flow system is fairly challenging. In reality, the plant consists of one unit that can supply coils with cooling and heating by changing the flow direction. However, due to limitations in the way Trace 700 must assign coils to systems it is necessary to model the cooling plant with an air-cooled unitary system and the heating plant with electric resistance backup. This does not exactly match how the system operates but, like the previous system model, can paint a reasonable picture of how the system will operate and use energy. The expected outcome of this investigation was that the VRF system would acheive energy savings over the existing system. The outdoor VRF units that replace the existing cooling/heating plants are smaller and have the ability to vary capacity and operate efficiently at part load.

For an initial comparison, the two graphs below display the monthly energy use, by equipment category, for both the WSHP system and the VRF system. It should be noted, as explained in the caption, that the boiler energy in the graph for the Water Source Heat Pump system represents the gas usage in therms and has been converted to units of kWh, leading to the disproportionate representation below.

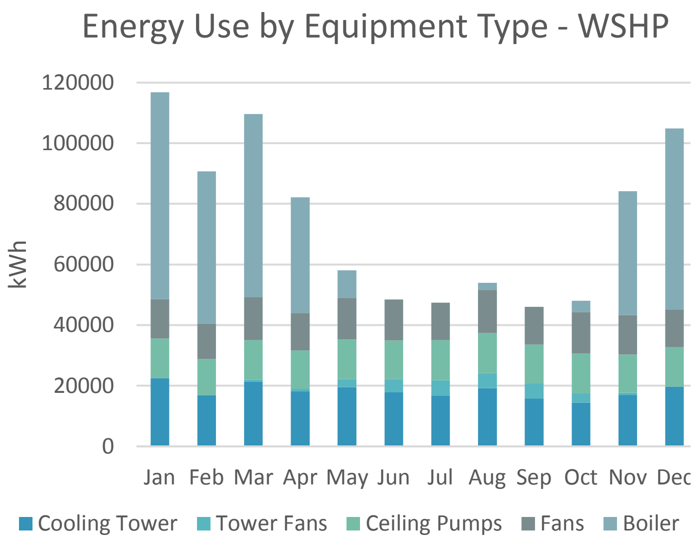


Figure 7: Existing WSHP System Monthly Energy Use, by Equipment Type

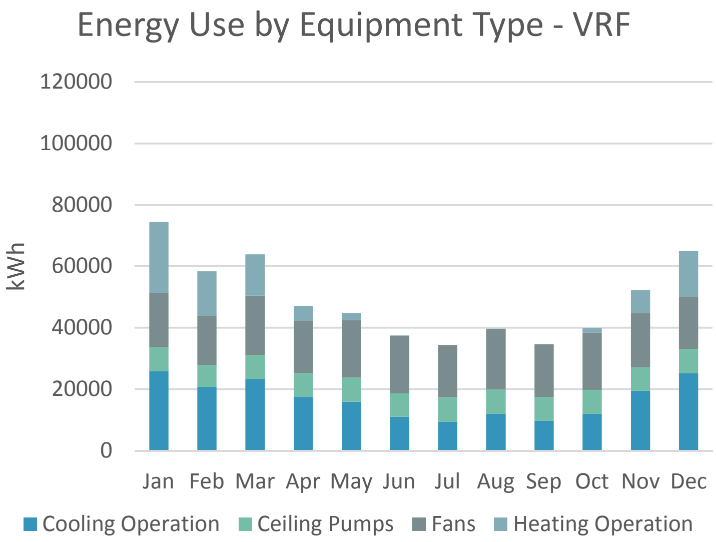


Figure 6: VRF System Montnly Energy Use, by Equipment Type

However, the other equipment energy comparisons yield useful results. The total energy used for fans and ceiling pumps is about equal between the two systems, though the VRF system appears to use less pump energy and slightly more fan energy. The VRF system appears to use less energy on cooling in the summer months than the WSHP system, althought it is unclear why the cooling operation energy increases in the winter months. This could be due to the operation of the heat recovery system and simultaneous cooling and heating within the building. Next, the effects on utility cost between these two systems will be evaluated.

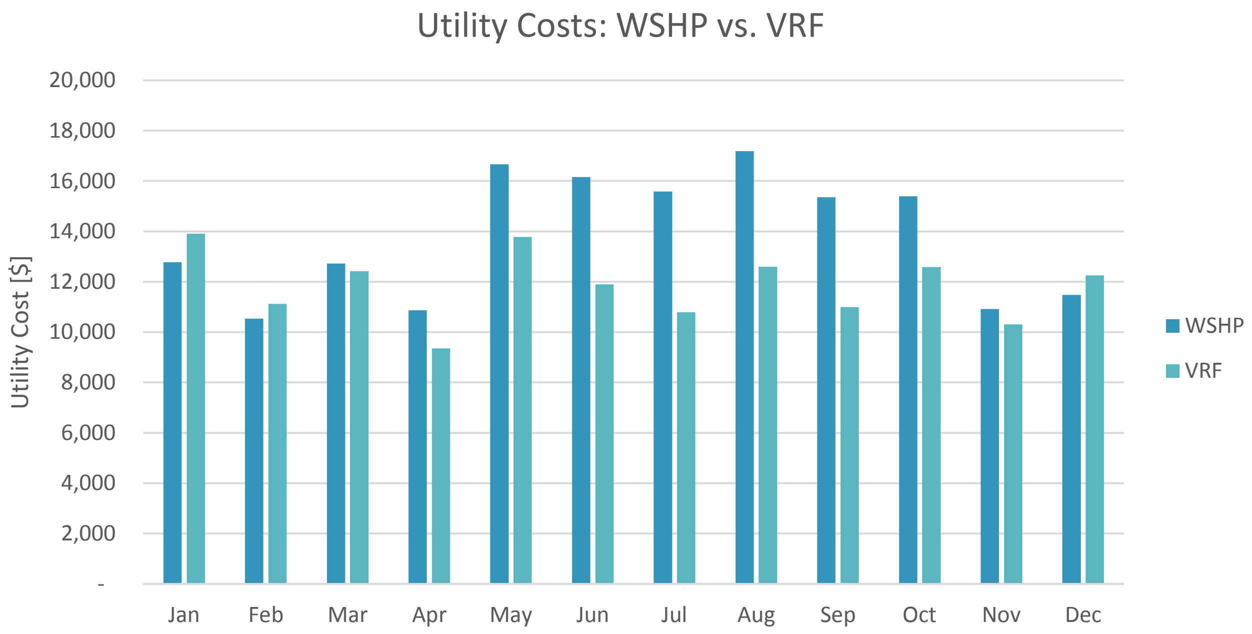


Figure 8: Comparison of Montly Utility Costs, WSHP System vs. VRF System, Modeled in Trace 700

As the graph above shows (Fig. 8), the largest difference in energy cost between the WSHP and VRF systems occurs during the Summer months in cooling operation, with a maximum of 30.78% savings occuring in the month of July. This suggests that the VRF outdoor units use energy more efficiently in cooling operation than the current cooling towers, which is likely due to the variable capacity of the VRF system. However, during the Winter months of December, January, and February, the VRF system slightly increases the cost of energy over the existing system and peaks in January with an 8.86% increase in cost. This suggests that the VRF outdoor units do not operate as efficiently in heating mode as the current gas-fired boilers, which are rated at 98% efficiency. Upon completion of a cost analysis the feasibility of this system can be evaluated.

% Change in Utility Cost - WSHP vs. VRF											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8.86%	5.55%	-2.40%	-13.90%	-17.26%	-26.34%	-30.78%	-26.67%	-28.40%	-18.22%	-5.59%	6.78%

Life-Cycle Cost

Over the course of the entire year the energy savings achieved by the Variable Refrigerant Flow system are $23,610 for a change of 14.3% over the Water Source Heat Pump system. A table with the life-cyle cost calculations is available on the following page.

Year		Escalation Rate	WSHP Energy Costs	VRF Energy Costs	Net Savings	Discounted Payback	Investment
0							**$364,300.00**
1	2014	1.00	$165,624.00	$142,035.00	$23,589.00	$22,904.92	
2	2015	1.01	$167,280.24	$143,455.35	$23,824.89	$45,374.64	
3	2016	1.02	$168,936.48	$144,875.70	$24,060.78	$67,421.80	
4	2017	1.02	$168,936.48	$144,875.70	$24,060.78	$88,829.58	
5	2018	1.04	$172,248.96	$147,716.40	$24,532.56	$110,074.64	
6	2019	1.05	$173,905.20	$149,136.75	$24,768.45	$130,932.64	
7	2020	1.04	$172,248.96	$147,716.40	$24,532.56	$150,956.71	
8	2021	1.04	$172,248.96	$147,716.40	$24,532.56	$170,400.08	
9	2022	1.03	$170,592.72	$146,296.05	$24,296.67	$189,050.55	
10	2023	1.02	$168,936.48	$144,875.70	$24,060.78	$206,931.10	
11	2024	1.03	$170,592.72	$146,296.05	$24,296.67	$224,522.16	
12	2025	1.03	$170,592.72	$146,296.05	$24,296.67	$241,603.09	
13	2026	1.03	$170,592.72	$146,296.05	$24,296.67	$258,188.66	
14	2027	1.04	$172,248.96	$147,716.40	$24,532.56	$274,522.31	
15	2028	1.04	$172,248.96	$147,716.40	$24,532.56	$290,382.28	
16	2029	1.05	$173,905.20	$149,136.75	$24,768.45	$306,011.35	
17	2030	1.05	$173,905.20	$149,136.75	$24,768.45	$321,187.19	
18	2031	1.06	$175,561.44	$150,557.10	$25,004.34	$336,151.98	
19	2032	1.07	$177,217.68	$151,977.45	$25,240.23	$350,911.83	
20	2033	1.07	$177,217.68	$151,977.45	$25,240.23	**$365,243.65**	
21	2034	1.07	$177,217.68	$151,977.45	$25,240.23	$379,159.85	
22	2035	1.08	$178,873.92	$153,397.80	$25,476.12	$392,901.53	
23	2036	1.09	$180,530.16	$154,818.15	$25,712.01	$406,473.74	
24	2037	1.10	$182,186.40	$156,238.50	$25,947.90	$419,881.42	
25	2038	1.10	$182,186.40	$156,238.50	$25,947.90	$432,900.27	
			NPV	NPV	Net Savings		
Discount Rate	**3%**		$4,336,036.32	$3,718,476.30	$617,560.02		

NIST Manual 135 is a resource for understanding and effectively implementing a life-cycle cost analysis and contains information for adjusting energy costs and discount rates. Using RS-Means 2015 and manufacturer resources, the estimated cost of the equipment required for the new VRF system is approximately $364,300, and the yearly energy costs from Trace 700 total $142,035. Using discount rates and energy price escalation rates from a 2014 NIST addendum, the calculated Net Present Value (NPV) of the VRF system initial investment and energy costs for the next 25 years is $3,718,476. The net savings, which is the cumulative difference in utility costs, over this 25 year period add up to $617,560. Finally, using the DOE discount rate of 3%, the discounted payback period for the new VRF system is 20 years.

Solar Thermal Hot Water

This section of the depth investigation will discuss the design and implementation of a solar thermal hot water system in the Ed Roberts Campus. Solar thermal systems are a popular way to save energy on water heating for both domestic and HVAC applications and are often more cost effective than photovoltaic panels. Solar energy can be used to heat air directly, but this investigation will focus on the application of a liquid heating system in which the heated fluid flows directly through the collector apparatus.

One of the initial concerns with a liquid heating system is freeze protection within the collectors and there are several ways to a address the issue. An indirect non-freezing sytem isolates the collector fluid loop from the main water supply by using a heat exchanger and adding an anti-freeze solution. While freezing is not a huge concern in this climate, the water will be used for a combination of space heating and domestic water applications and an indirect system is beneficial for maintaining water quality and preventing fouling in the collectors. This solar thermal liquid heating system will be used to meet the building's current domestic hot water needs, as well as supply the radiant floor system with hot water. This combined use will allow the system to provide some space heating during the winter season and take advantage of higher temperatures for domestic water heating during the summer.

The radiant floor system in the ERC currently depends on gas-fired boilers to supply hot water in the winter months. The domestic hot water demand for the building, which only supplies restroom lavatories and janitor sinks, is currently met by electric instantaneous water heaters installed beneath the fixtures themselves.

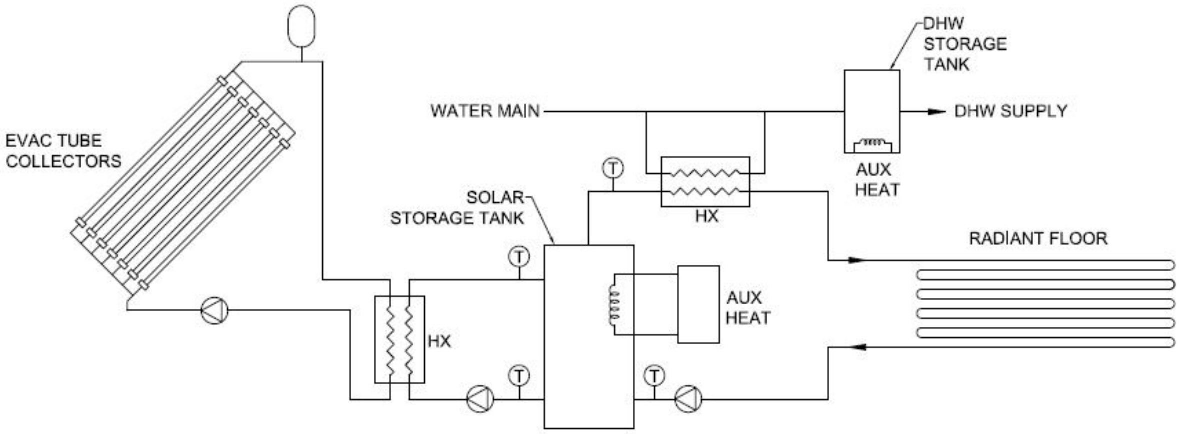


Figure 9: Solar Thermal Hot Water Schematic

In order to meet the load of the radiant floor, the solar thermal system needs to provide water at an acceptable temperature and flowrate to allow for adequate heat transfer to the concrete slab floor. The current radiant floor system lists that the total heating capacity for the three floor zones, totaling 6,720 ft^2, is 68,000 Btu/h. The room ambient temperature and heat loss characteristics, and subsequent radiation and convection heat transfer rates, indicate that the floor temperature would need to be approximately 80-90°F to supply the space with the required heat. With some assumptions made about the heat transfer characteristics of the concrete slab it can be estimated that the required supply water temperature should be approximately 100°F, which is well within the range of water temperatures that can be supplied by a solar thermal system.

CombiSys Inputs

If this solar thermal system will be meeting the domestic hot water loads and supplying the radiant floor system it would be inefficient and economically infeasible to install a solar thermal system large enough to meet 100% of this load. However, there is still potential for vast energy savings if the solar is able to remove a portion of the load from the boilers and instantaneous water heaters.

Using the software program CombiSys, a solar energy analysis program, it is possible to estimate the useful energy provided by a solar thermal panel arrangement. Using this program with inputs for location, domestic hot water load, building loads, and solar panel specifications it is possible to model an entire year of operation and paint a clearer picture of how effective the specified solar thermal system will be in operation. However, there are some drawbacks to the software primarily because it was designed to model a house and not a medium-sized commercial building. As such, some of the inputs (occupancy for domestic hot water and building heat loss) in the program do not allow values large enough to model the real building. However, the program can still provide useful output on the amount of energy that can be harnessed by a solar thermal panel installation.

The following collector performance characteristics and information on space and domestic hot water loads were entered into the CombiSys software input menu. Collector information was obtained from the technical specifications of a commercial grade evacuated tube collector from a major solar thermal manufacturer. While a collector area of 90 m^2 was used in this simulation, an economic study is better suited to finding an optimum collector area and will be performed based on the results of this value.

Collector Area: 90 m^2 (970 ft^2)

Collector Performance Characteristics: $\eta_0=0.687$, $a_1=1.505$ [W/m^2-K], $a_2=0.011$ [W/m^2-K]

Dom. Hot Water Load: 11.3 l/d (3 gal/d) per occupant, 50 occupants

Space Loss Coefficient and Set Point: 500 W/K (~1700 Btu/h/°F), 20°C (68°F)

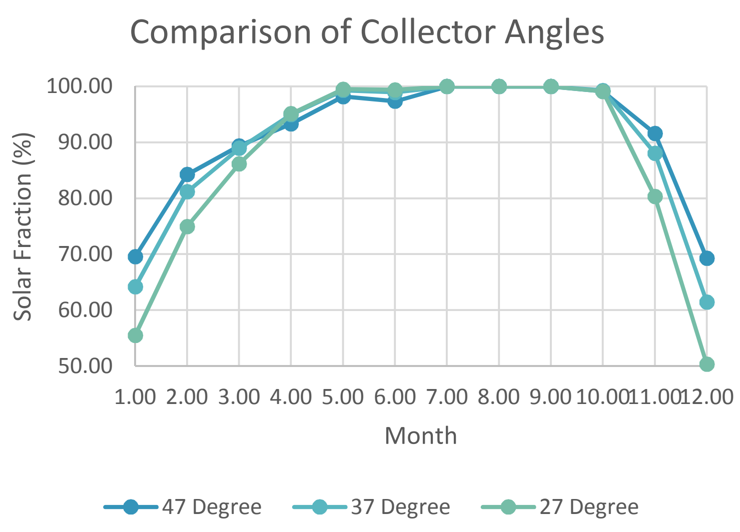


Figure 10: Comparison of Solar Fraction for Collector Array at 27, 37, and 47 Degree Tilt

The optimum collector tilt angle is usually assumed to be equal to the latitude of the site of the solar thermal installation which, in this case, was 37.78° N for San Francisco. However, a check of tilt angles ranging from 27° to 47° was performed to find the optimal setup for the loads of the building. The following plot of solar fraction for each collector shows the results of this check.

Solar Fraction indicates the percentage of the total load that can be met by the solar thermal collectors. The comparison shows that a collector tilt angle of 47° allows for more solar gains in the winter season when the loads on the randiant floor system will be high and was selected as the preferred angle for this installation. The average Solar Fraction over the entire year was 90%. However, it is likely that this factor could decrease with the actual loads of the building.

A collector area of 90 m^2 (970 ft^2) would certainly be able to cover the domestic hot water load, as well as a portion of the load from the radiant floor. It is also important to consider the roof area that will be occupied by the collectors when they are spaced to avoid shading. Based on the collector slope of 47° and an estimated minimum solar incident angle of ~28° the panels will be spaced 12.5 ft apart to minimize shading of other panels (Fig. 11). The figure on the right (Fig. 12) illustrates an example layout of panels in a parallel reverse-return array. Parallel rows such as this allow for a lower, but more steady, water temperature compared to a long series row. With the correct spacing of each collector row this setup would occupy approximately 2,500 ft of roof space. The effects of this panel installation on the building will be discussed in the structural breadth section.

Simulation Results

The graph below (Fig. 13) shows the results of the simulation in CombiSys integrated over an entire year. The shaded areas represent the sum of building loads that must be met by the solar and auxiliary heat system, while the single lines represent the total energy collected from the panels and the total auxiliary heat required. The panel array has the capacity to collect enough energy to meet the loads for most of the year.

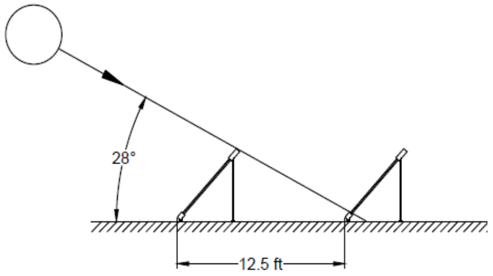


Figure 11: Collector Spacing Diagram

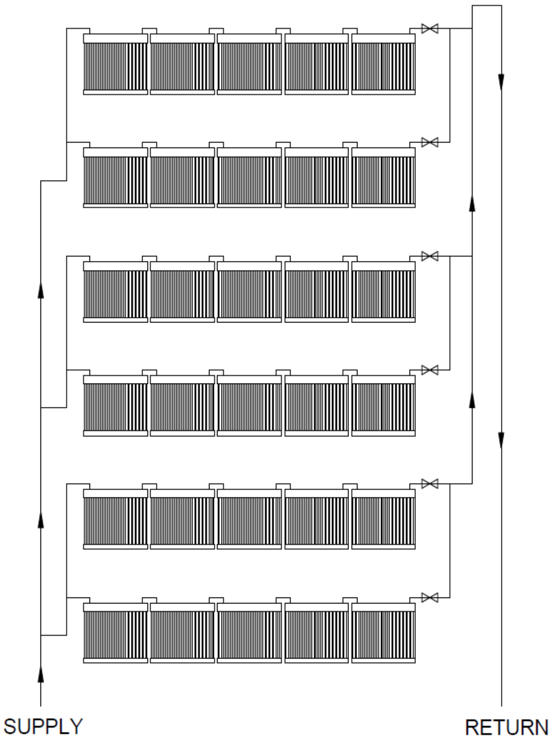
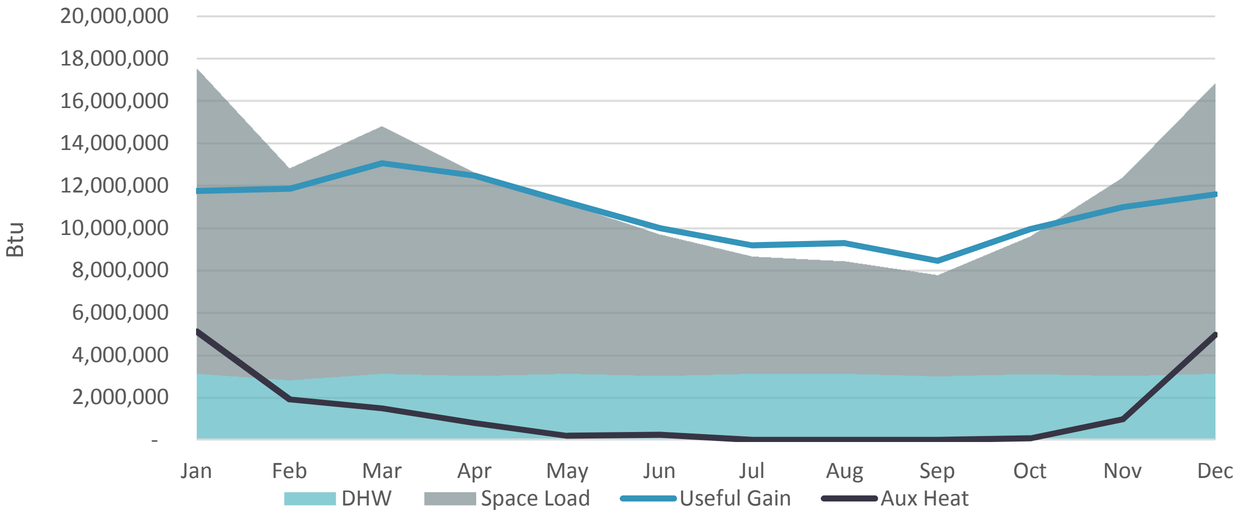


Figure 13: Parallel Collector Array Schematic

Figure 12: Building Loads vs. Solar Gains and Auxiliary Heat, Integrated Monthly



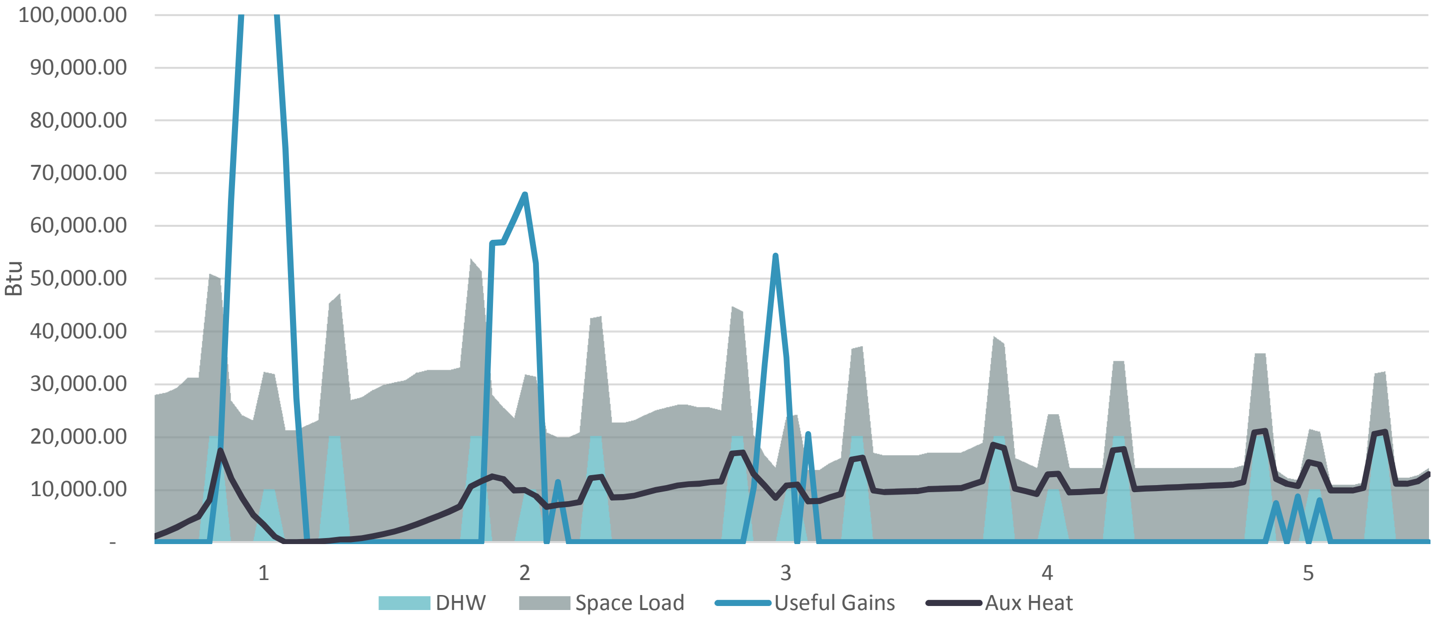


Figure 14: Buidling Loads vs. Solar Gains and Auxiliary Heat, Instantaneos Values, Five Day Period

While this figure (Fig. 14) does not exactly represent the day to day operation of the system, it acts as a guide to the overall effectiveness of the collector array during different times of the year. The most auxiliary energy will be needed in the winter months, whereas the collectors have an excess of available energy in some of the summer months.

The plot above (Fig. 15) illustrates the performance of the solar collector over a 5-day work week in January. Day 1 in this plot shows extremely high solar gains that are able to meet 100% of the building loads. However, in the same week, Day 4 and 5 see almost no energy collected by the panels. As a result the auxiliary energy required increases to meet the full load. Even on days with high solar gains, some auxiliary energy is required in the mornings to meet load before peak solar gains around the early afternoon. Uncertainty of solar gain is the primary drawback for a solar thermal system. However, the energy collected during the peak daytime hours should provide enough of an economic advantage to make this system worthwhile.

As stated previously in this section, the loads modeled in CombiSys and shown here in this graph do not represent the full building load and are only the maximum value that can be modeled by the program. Therefore, any collected energy above the simulated load is not wasted and and can be used to meet increasing amounts of hot water demand. The best way to determine how much of the boiler energy the solar thermal collectors are able to offset would be to convert the total collected energy into therms of natural gas saved. Based on the integrated solar gain values obtained from the CombiSys simulation of an entire year, it is estimated that the collector array is capable of harnessing between 9 and 12 million Btu per month, depending on the season. The table below shows the energy offset by the modeled solar thermal system and the difference in gas utility bill.

	Solar Heat Transferred to Water [Btu/h]	DHW Energy [kWh]	Offset Boiler Energy [therms]	Cost Savings
January	11,749,785	747.94	91.98	$243.43
February	11,866,605	754.55	92.92	$252.39
March	13,072,864	854.52	101.57	$287.36
April	12,475,325	847.37	95.84	$262.57
May	11,225,011	903.27	81.43	$265.11
June	10,006,641	871.56	70.33	$245.49
July	9,187,184	917.29	60.57	$249.71
August	9,290,513	916.43	61.64	$248.04
September	8,456,102	884.23	54.39	$240.29
October	9,953,259	910.78	68.46	$260.37
November	10,996,376	840.71	81.28	$254.19
December	11,605,428	748.35	90.52	$249.68
	129,885,093	10,197.00	950.91	**$3,058.63**

The savings in electricity and gas use are approximately ~1-2% and 10% of the respective monthly bills. The cumulative savings over a one year period add up to $3,058. The estimated cost of installation for the panel array, required storage tanks, and distribution systems is approximately $75,000. In terms of simple payback, this system should take about 25 years to pay back. With identical methods for life-cycle cost as in the previous depth section the exact discounted payback cannot be calculated without further energy escalation rate data, but the calculation up to 25 years indicated that the discounted payback period would be over 25 years.

Follow-Up Investigation

While the previous simulation investigated using this solar thermal system for space heating applications in addition to domestic hot water, a secondary investigation into an exclusive domestic hot water heating system will be performed. As this load is predictable and constant throughout the year, the system can be sized to fit the daily loads. Using the CombiSys software and the same evacuated tube collectors, a simulation was run modeling only the domestic hot water load with roughly ¼ the panel area.

Figure 15 shows the resulting solar gains and solar fraction for a domestic hot water application. The average year solar fraction was 96%, with an average collector efficiency of 23%.

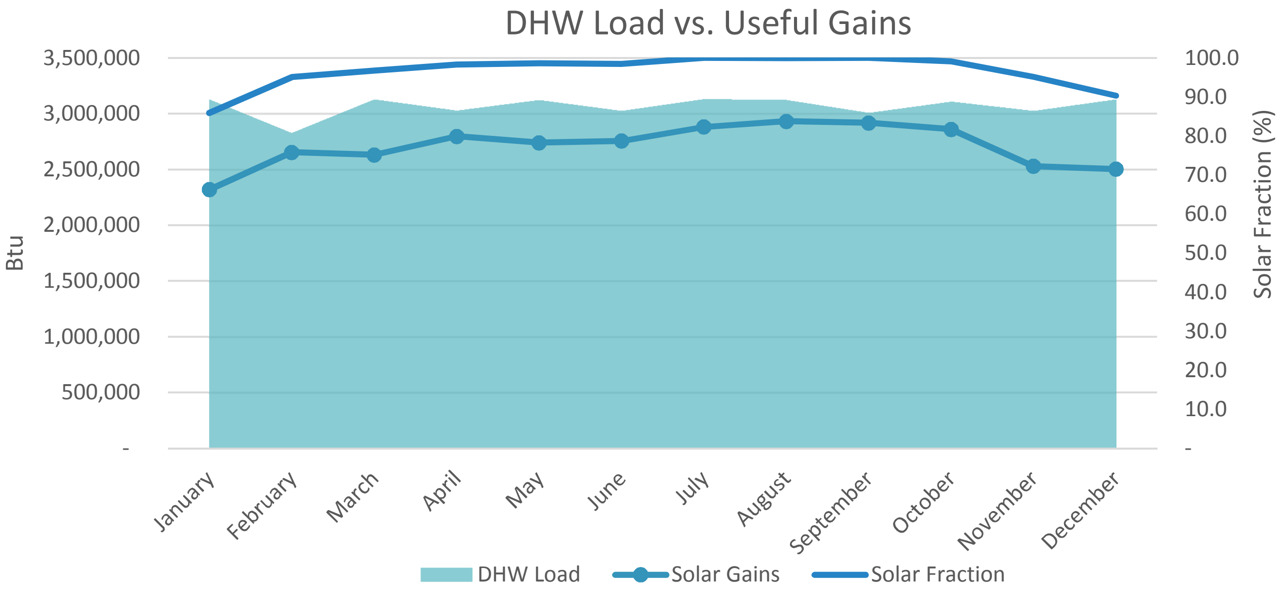


Figure 15: Load vs. Solar Gains for Domestic Hot Water Application

The resulting energy collected over the year added up to 32,529,971 Btu, offsetting the equivalent of almost 10,000 kWh that would have otherwise been required to heat the water. The resulting savings on electric costs over they year amount to $2,016. Performing a life-cycle cost analysis using the same methodology previously presented in the report resulted in a discounted payback period of 18 years. Over the 25-year analysis, the net savings totaled over $50,000.

Structural Breadth

The Mechanical Depth section discusses two options for new mechanical equipment to be installed in the Ed Roberts Campus. Both the Variable Refrigerant Flow and Solar Thermal systems will require that equipment of substantial weight be installed on the roof. However, it was determined that the maximum piping lengths associated with the VRF Outdoor Units were long enough to permit the units' installation on areas of the roof already strengthened for mechanical equipment. Therefore, roof structure elements that will support the solar thermal panel array will be reexamined and, if necessary, redesigned to accommodate this extra loading.

The current structural system of the Ed Roberts Campus is a combination concrete and steel construction. The basement parking garage and first floor are supported by poured concrete slab, columns, and beams. A steel framing system is used above the first floor slab, with Buckling Resistant Braced Frame lateral supports throughout the building for additional strength.

The manufacturer for the evacuated-tube solar collectors used in the mechanical investigation reports that each panel weighs approximately 225 lb, and with 30 panels being installed, this is an additional 6,750 lb on the roof structure. This load is spread over roughly 1,100 ft^2 of roof space and will only result in an increase of 6-6.5 psf of dead load. It is possible that this small increase over the design loads would not impact the structure significantly. However, one of the largest considerations for solar panel installation is restraining the panels in case of extreme winds. The manufacturer installation guide indicates that extreme wind conditions of 130 mph could result in a vertical pull equivalent to nearly 610 lb per panel, so each panel must have adequate connection strength to resist being ripped off the roof by strong wind. Concrete "ballast" blocks are a common way to achieve this. When this wind loading, the necessary restraining equipment, and an additional 20% safety factor is taken into account the additional dead load on the roof area could be as much as 27 psf, which nearly doubles the current load.

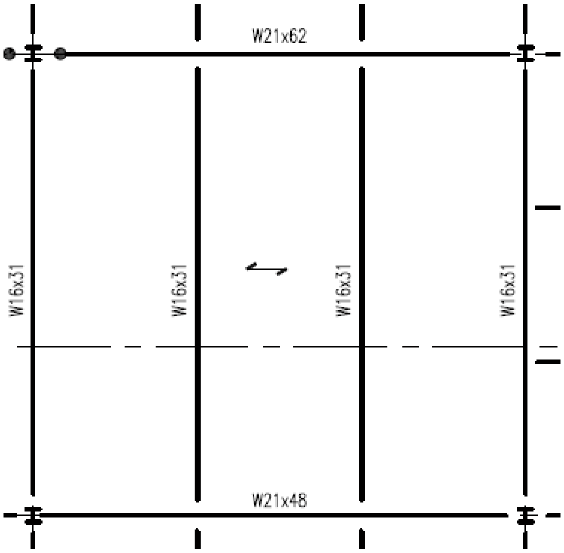


Figure 16: Structural Roof Plan, Southeast Wing

A 3-span area of roof deck in the South-East wing of the building, pictured left, will be tested with these new loads to determine if the current deck is adequate.

The current deck is specified as Verco W3 18-Gauge deck with a minimum of 3-1/2" Lightweight Concrete topping. Referencing the online specifications from this manufacturer, the minimum available LW concrete topping available is 5". For the 32' @ 10'-7" 3-span condition of the selected framing panel, the maximum unshored clear span of the current deck is 15'-7" and the allowable superimposed load is 207 psf. This is greater than the combined superimposed live load and deck self-weight.

If a new deck were to be chosen, it is possible that the size could be reduced. #3 VLI is a composite type metal deck with lightweight concrete topping listed in the Vulcraft Deck Manual that is similar to the Vervo deck in the existing building. The smallest gauge deck that can span the conditions above using unshored construction is 22-Gauge deck with 2” concrete topping. However, the largest superimposed live load allowed at the span of 10’-7” is 60 psf, which is inadequate considering the deck weight of 35 psf. The smallest possible deck size to meet the live load of 57 psf and deck weight appears to be 3VLI19 with an allowable superimposed live load of 105 psf.

With this analysis it is clear that the current roof deck and supporting structure will be more than adequate to handle the additional loads of the solar panel array. It would not be economical to renovate the structure, even if the deck could be smaller, and as a result no adjustments to the structural system will be required.

Electrical Breadth

The changes discussed in the Mechanical Depth section of the report will all have an impact on the electrical systems of the Ed Roberts Campus. However, the most comprehensive changes would come from the installation of a VRF system which could require that the existing feeders and panels for the mechanical system be replaced.

The main distribution throughout the building comes from a 2000A, 480Y/277V bus. In the basement electrical room this power supply is distributed to different zones of the building. Each branch uses a transformer in order to supply power at both 480/277V and 208/120V to receptacles, lighting, appliances, and the water-source heat pumps on 1st and 2nd floors. There are two 400 A panelboards that supply power (480/277 3-Phase) to the air handling units, cooling towers, boilers, and several water circulation pumps.

The rooftop mechanical equipment being installed as a part of the Variable Refrigerant Flow sytem operates with voltage supplied at 208/230V 3-Phase. This is different than the 480/277V 3-Phase power that is currently supplied to the rooftop panelboards. It will most likely be necessary to install a transformer to convert the power supplied to the lower voltage required by the new equipment. Additionally, the VRF indoor units operate at 230V 1-Phase power. This is different than the current WSHP units that operate at either 208V 1-Phase or 460V 3-Phase, depending on the size of the heat pump.

Equipment		Count	Power [V - Phase]	kW	Amps	Load [kVA]	Total Load [kVA]
Three Phase Equipment							
VRF Zone 1	26 (10+10+6)	1	208/230V 3ϕ	30.83	95.1	59.3424	59.3424
VRF Zone 2	22 (10+6+6)	1	208/230V 3ϕ	24.47	75.5	47.112	47.112
VRF Zone 3	18 (6+6+6)	1	208/230V 3ϕ	19.5	59.9	37.3776	37.3776
VRF Zone 4	28 (8+8+6+6)	1	208/230V 3ϕ	28.83	88.9	55.4736	55.4736
							199.31

DOAS 1	JDMA 210	1	208/230V 3ϕ		36	22.464	22.464
DOAS 2	JDMA 300	1	208/230V 3ϕ		36	22.464	22.464
DOAS 3	JDMA 180	1	208/230V 3ϕ		36	22.464	22.464
DOAS 4	JDMA 300	1	208/230V 3ϕ		36	22.464	22.464
DOAS 5	JDMA 120	1	208/230V 3ϕ		36	22.464	22.464
							112.32

Equipment		Count	Power [V - Phase]	kW	Amps	Load [kVA]	Total Load [kVA]
Single Phase Equipment							
VRF Indoor Units	.5 Ton VRF	8	208/230V 1ϕ	0.56	2.5	0.575	4.6
	.7 Ton VRF	3	208/230V 1ϕ	0.56	2.5	0.575	1.725
	1.0 Ton VRF	8	208/230V 1ϕ	0.66	3	0.69	5.52
	1.3 Ton VRF	2	208/230V 1ϕ	0.67	3	0.69	1.38
	1.5 Ton VRF	7	208/230V 1ϕ	0.77	4	0.92	6.44
	2.0 Ton VRF	8	208/230V 1ϕ	1.31	4	0.92	7.36
	2.5 Ton VRF	11	208/230V 1ϕ	1.31	5	1.15	12.65
	3.0 Ton VRF	3	208/230V 1ϕ	2.43	5	1.15	3.45
	4.0 Ton VRF	3	208/230V 1ϕ	2.43	6	1.38	4.14
							47.27

Converting these loads from kVA to the full load amps required to size the circuit breakers can be done with the following equations for single phase and three phase power:

$$I\ [A] = \frac{1000\times kVA}{V_{1\varphi}} \qquad I\ [A] = \frac{1000\times kVA}{(3\times V_{3\varphi})}$$

The resulting calculations indicate the load from the VRF Outdoor Units are equivalent to a current of 319.4 A. These new units could be combined onto a single circuit breaker rated for 350 amps. DOAS units would require a circuit breaker rated for 200 to cover the load current of 179.9 A. Both of these breaker panels would require that a transformer convert the voltage from 480/277V to the 208V that they require, and this transformer would be sized at 350 kVA based on the combined load of 311.63 kVA. The total load from all VRF Indoor units is equivalent to current of 227.25 A. As these units would be distributed throughout the buiding it is impractical to supply them from the same breaker. There are suitable panels throughout the ERC with 208V single phase power, that supply the current WSHP units, that could be used for the VRF indoor units. No further adjustments to the electrical system would be required.

Conclusion

An overall evaluation of the two mechanical depth topics yields two very different conclusions. As discussed in the depth section, the conversion to a Variable Refrigerant Flow system has potential to save a significant amount on energy costs. With a 14.3% reduction in yearly utility bills the building would save about $23,600 every year. However, due to the high cost of VRF equipment, it would take 20 years to pay off the initial investment. This payback period may be considered too long and may not be economically feasible for some building owners. However, with the cumulative savings adding up to well over $500,000 in the 25 year life-cycle cost analysis, I think it is clear that a VRF system should be a serious consideration when designing for new construction where the difference in first cost between two comparable systems would allow for much shorter payback periods.

The results of the Solar Thermal Hot Water system analysis were not as promising as the VRF analysis. After the CombiSys simulation was run for 980 ft^2 of panel, the amount of energy that could be successfully transferred to process water was only enough to offset approximately 10% of the natural gas requirement of the heating plant and 1-2% of the electric consumption. The resulting savings of $3,058 per year would result in a payback period of over 25 years, which is most likely too long to be feasible. For a building this large, the required panel area to offset a more significant portion of the space heating load would be too large an investment for many owners. I would conclude that a solar thermal system for space heating is not a good choice for implementation in the Ed Roberts Campus. However, a secondary analysis showed that a smaller system designed only to meet the domestic hot water needs of the building would be more economical. The domestic hot water heating system reduced the first cost of the equipment significantly, and allowed for yearly savings of $2,000 and a payback period of 18 years. This is a more reasonable payback period and exemplifies one of the best applications for a solar thermal system, and is my recommendation for the Ed Roberts Campus.

These conclusions to do not suggest that the current design of the mechanical systems in the Ed Roberts Campus are flawed in any way. This has been a purely academic exercise in the energy use implications for different types of mechanical systems and the results have been obtained through a variety of estimation methods. Greater analysis is required before any options are seriously considered.

References

"Solar Energy Equipment." *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Systems and Equipment*. Atlanta: ASHRAE, 2012.

"Variable Refrigerant Flow." *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Systems and Equipment*. Atlanta: ASHRAE, 2012.

"Nonresidential Cooling and Heating Load Calculations." *ASHRAE Handbook: Fundamentals.* Atlanta: ASHRAE, 2013.

"Solar Energy Use." *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications.* Atlanta: ASHRAE, 2011.

"Radiant Heating and Cooling." *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications.* Atlanta: ASHRAE, 2011.

Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. 4th ed. Hoboken: John Wiley & Sons, 2013. Print.

Thornton, Brian, and Anne Wagner. "Variable Refrigerant Flow Systems." Pacific Northwest National Laboratory, 1 Dec. 2012. Web. 1 Feb. 2015.

"Apricus AP solar Collector Installation and Operation Manual – USA Edition." Apricus Solar Hot Water, May 2012. Web. March 2015.

"York Variable Refrigerant Flow System Product Catalog, Commercial VRF HVAC Systems for New Construction and Renovation Projects." Johnson Controls. Web. February 2015.

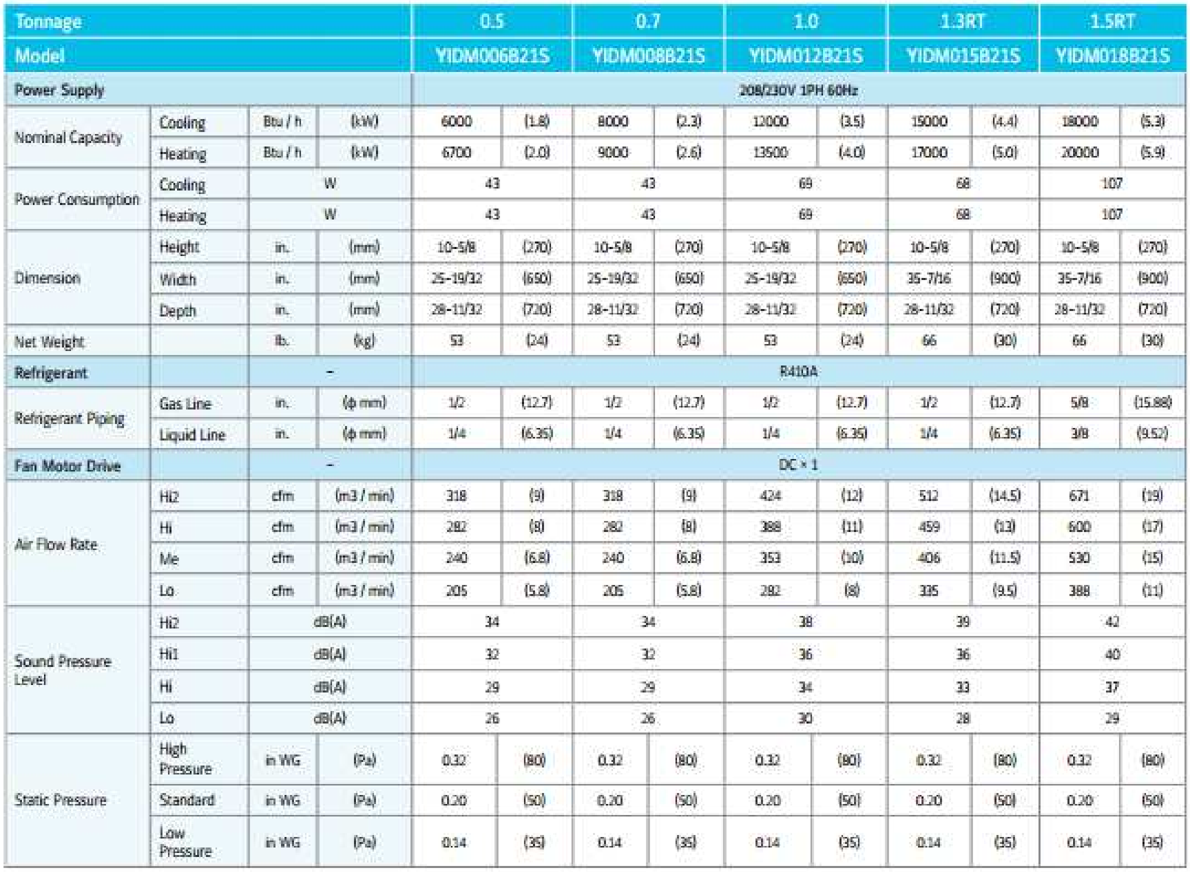
Appendices

Ducted Medium Static Indoor Unit

Features

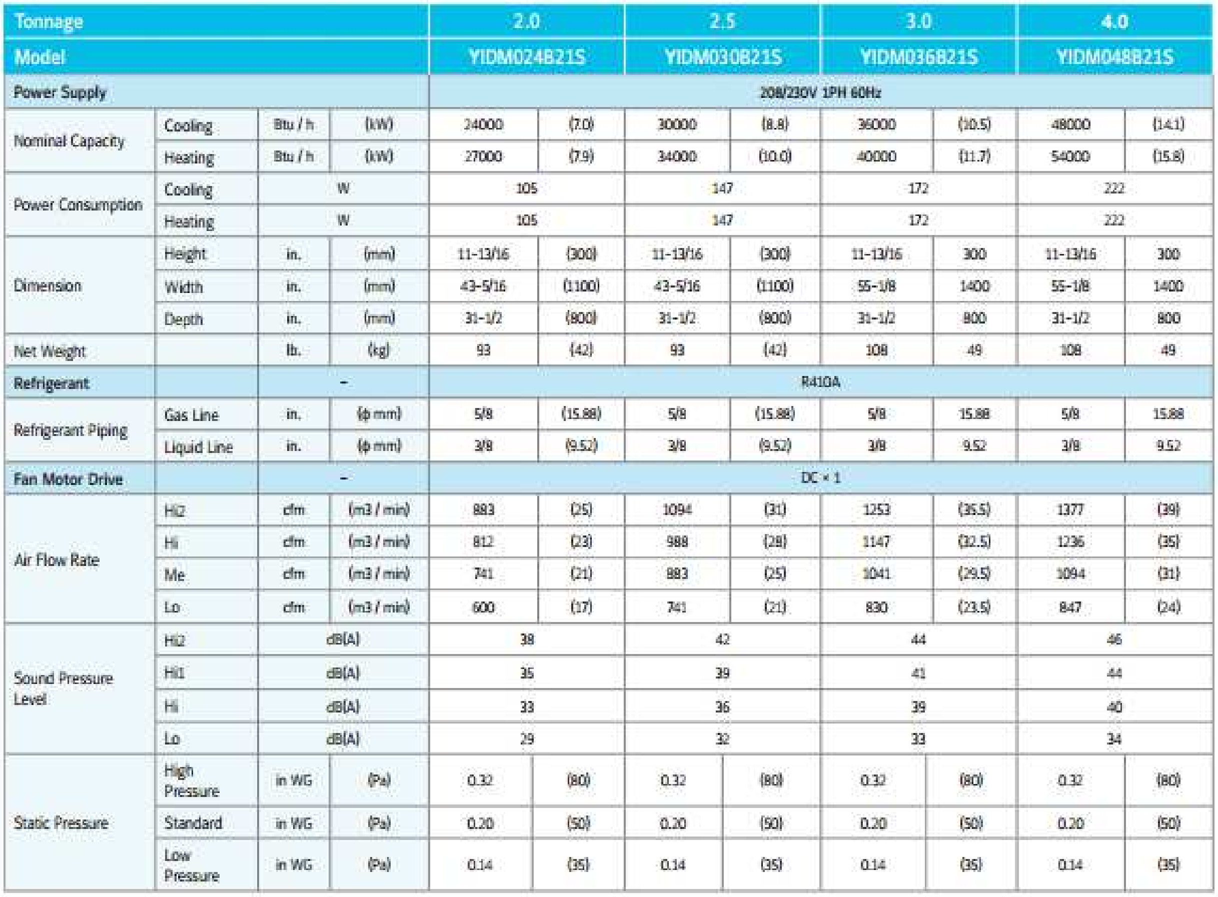
- High-efficiency DC fan motor
- Multiple fan speed settings
- Up to .32 WG static pressure
- Bottom access for easy service and troubleshooting
- Built-in condensate pump

Capacities: 6,000 to 48,000 Btu/hr

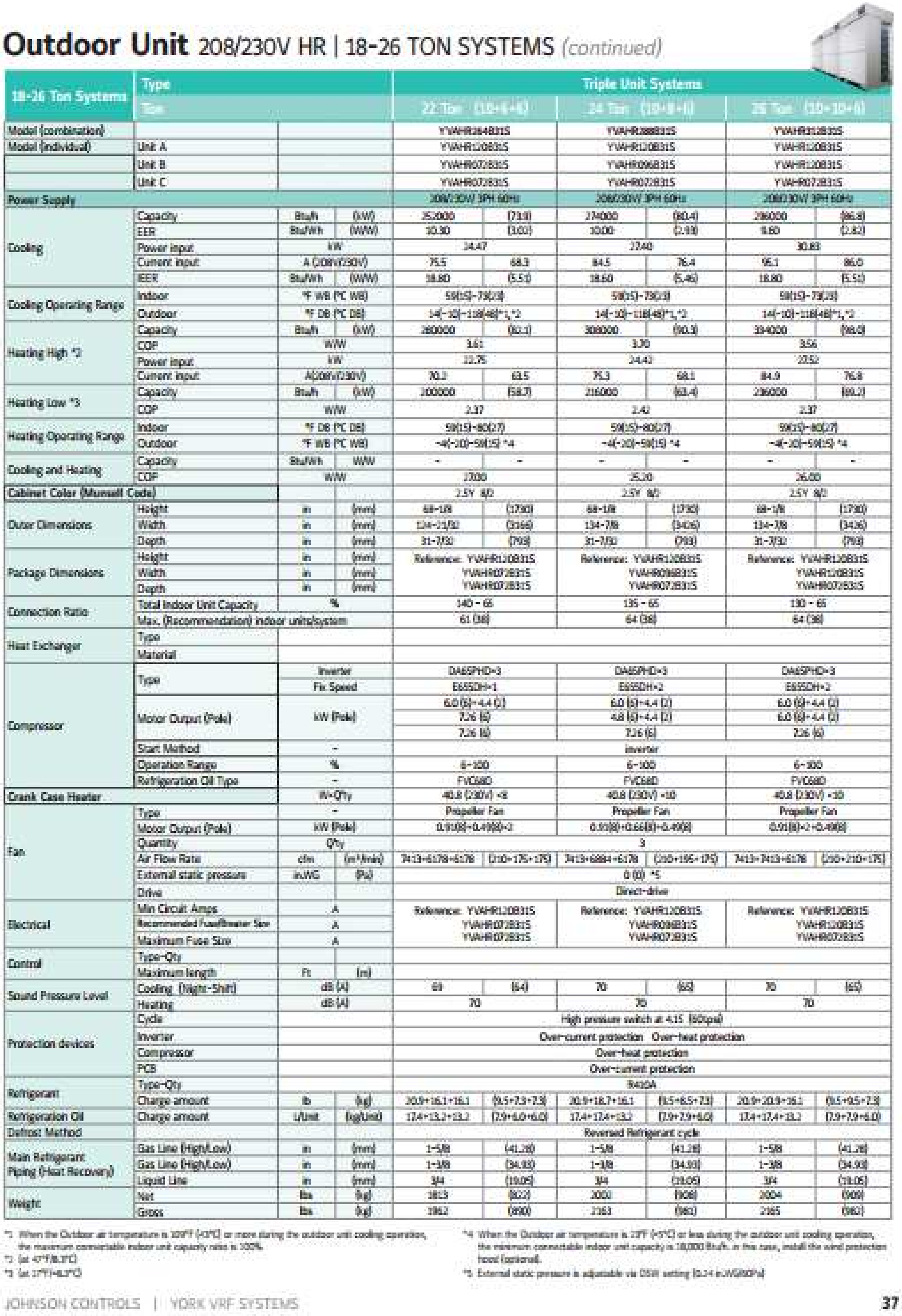


Tonnage				0.5		0.7		1.0		1.3RT		1.5RT	
Model				YIDM006B21S		YIDM008B21S		YIDM012B21S		YIDM015B21S		YIDM018B21S	
Power Supply				208/230V 1PH 60Hz									
Nominal Capacity	Cooling	Btu / h	(kW)	6000	(1.8)	8000	(2.3)	12000	(3.5)	15000	(4.4)	18000	(5.3)
	Heating	Btu / h	(kW)	6700	(2.0)	9000	(2.6)	13500	(4.0)	17000	(5.0)	20000	(5.9)
Power Consumption	Cooling	W		43		43		69		68		107	
	Heating	W		43		43		69		68		107	
Dimension	Height	in.	(mm)	10-5/8	(270)	10-5/8	(270)	10-5/8	(270)	10-5/8	(270)	10-5/8	(270)
	Width	in.	(mm)	25-19/32	(650)	25-19/32	(650)	25-19/32	(650)	35-7/16	(900)	35-7/16	(900)
	Depth	in.	(mm)	28-11/32	(720)	28-11/32	(720)	28-11/32	(720)	28-11/32	(720)	28-11/32	(720)
Net Weight		lb.	(kg)	53	(24)	53	(24)	53	(24)	66	(30)	66	(30)
Refrigerant		-		R410A									
Refrigerant Piping	Gas Line	in.	(ϕ mm)	1/2	(12.7)	1/2	(12.7)	1/2	(12.7)	1/2	(12.7)	5/8	(15.88)
	Liquid Line	in.	(ϕ mm)	1/4	(6.35)	1/4	(6.35)	1/4	(6.35)	1/4	(6.35)	3/8	(9.52)
Fan Motor Drive		-		DC × 1									
Air Flow Rate	Hi2	cfm	(m3 / min)	318	(9)	318	(9)	424	(12)	512	(14.5)	671	(19)
	Hi	cfm	(m3 / min)	282	(8)	282	(8)	388	(11)	459	(13)	600	(17)
	Me	cfm	(m3 / min)	240	(6.8)	240	(6.8)	353	(10)	406	(11.5)	530	(15)
	Lo	cfm	(m3 / min)	205	(5.8)	205	(5.8)	282	(8)	335	(9.5)	388	(11)
Sound Pressure Level	Hi2	dB(A)		34		34		38		39		42	
	Hi1	dB(A)		32		32		36		36		40	
	Hi	dB(A)		29		29		34		33		37	
	Lo	dB(A)		26		26		30		28		29	
Static Pressure	High Pressure	in WG	(Pa)	0.32	(80)	0.32	(80)	0.32	(80)	0.32	(80)	0.32	(80)
	Standard	in WG	(Pa)	0.20	(50)	0.20	(50)	0.20	(50)	0.20	(50)	0.20	(50)
	Low Pressure	in WG	(Pa)	0.14	(35)	0.14	(35)	0.14	(35)	0.14	(35)	0.14	(35)

Ducted Medium Static Indoor Unit *(continued)*



Tonnage				2.0		2.5		3.0		4.0	
Model				YIDM024B21S		YIDM030B21S		YIDM036B21S		YIDM048B21S	
Power Supply				208/230V 1PH 60Hz							
Nominal Capacity	Cooling	Btu / h	(kW)	24000	(7.0)	30000	(8.8)	36000	(10.5)	48000	(14.1)
	Heating	Btu / h	(kW)	27000	(7.9)	34000	(10.0)	40000	(11.7)	54000	(15.8)
Power Consumption	Cooling	W		105		147		172		222	
	Heating	W		105		147		172		222	
Dimension	Height	in.	(mm)	11-13/16	(300)	11-13/16	(300)	11-13/16	300	11-13/16	300
	Width	in.	(mm)	43-5/16	(1100)	43-5/16	(1100)	55-1/8	1400	55-1/8	1400
	Depth	in.	(mm)	31-1/2	(800)	31-1/2	(800)	31-1/2	800	31-1/2	800
Net Weight		lb.	(kg)	93	(42)	93	(42)	108	49	108	49
Refrigerant		-		R410A							
Refrigerant Piping	Gas Line	in.	(ϕ mm)	5/8	(15.88)	5/8	(15.88)	5/8	15.88	5/8	15.88
	Liquid Line	in.	(ϕ mm)	3/8	(9.52)	3/8	(9.52)	3/8	9.52	3/8	9.52
Fan Motor Drive		-		DC × 1							
Air Flow Rate	Hi2	cfm	(m3 / min)	883	(25)	1094	(31)	1253	(35.5)	1377	(39)
	Hi	cfm	(m3 / min)	812	(23)	988	(28)	1147	(32.5)	1236	(35)
	Me	cfm	(m3 / min)	741	(21)	883	(25)	1041	(29.5)	1094	(31)
	Lo	cfm	(m3 / min)	600	(17)	741	(21)	830	(23.5)	847	(24)
Sound Pressure Level	Hi2	dB(A)		38		42		44		46	
	Hi1	dB(A)		35		39		41		44	
	Hi	dB(A)		33		36		39		40	
	Lo	dB(A)		29		32		33		34	
Static Pressure	High Pressure	in WG	(Pa)	0.32	(80)	0.32	(80)	0.32	(80)	0.32	(80)
	Standard	in WG	(Pa)	0.20	(50)	0.20	(50)	0.20	(50)	0.20	(50)
	Low Pressure	in WG	(Pa)	0.14	(35)	0.14	(35)	0.14	(35)	0.14	(35)



Outdoor Unit 208/230V HR | 18-26 TON SYSTEMS *(continued)*

18-26 Ton Systems	Type			Triple Unit Systems					
	Ton			22 Ton (10+6+6)		24 Ton (10+8+6)		26 Ton (10+10+6)	
Model (combination)				YVAHR264B31S		YVAHR288B31S		YVAHR312B31S	
Model (individual)	Unit A			YVAHR120B31S		YVAHR120B31S		YVAHR120B31S	
	Unit B			YVAHR072B31S		YVAHR096B31S		YVAHR120B31S	
	Unit C			YVAHR072B31S		YVAHR072B31S		YVAHR072B31S	
Power Supply				208/230V 3PH 60Hz		208/230V 3PH 60Hz		208/230V 3PH 60Hz	
Cooling	Capacity	Btu/h	(kW)	252000	(73.8)	274000	(80.4)	296000	(86.8)
	EER	Btu/Wh	(W/W)	10.30	(3.02)	10.00	(2.93)	9.60	(2.82)
	Power input	kW		24.47		27.40		30.83	
	Current input	A (208V/230V)		75.5	68.3	84.5	76.4	95.1	86.0
	IEER	Btu/Wh	(W/W)	18.80	(5.51)	18.60	(5.46)	18.80	(5.51)
Cooling Operating Range	Indoor	°F WB (°C WB)		59(15)~73(23)		59(15)~73(23)		59(15)~73(23)	
	Outdoor	°F DB (°C DB)		14(-10)~118(48)*1,*2		14(-10)~118(48)*1,*2		14(-10)~118(48)*1,*2	
Heating High *2	Capacity	Btu/h	(kW)	280000	(82.1)	308000	(90.3)	334000	(98.0)
	COP	W/W		3.61		3.70		3.56	
	Power input	kW		22.75		24.42		27.52	
	Current input	A(208V/230V)		70.2	63.5	75.3	68.1	84.9	76.8
Heating Low *3	Capacity	Btu/h	(kW)	200000	(58.7)	216000	(63.4)	236000	(69.2)
	COP	W/W		2.37		2.42		2.37	
Heating Operating Range	Indoor	°F DB (°C DB)		59(15)~80(27)		59(15)~80(27)		59(15)~80(27)	
	Outdoor	°F WB (°C WB)		-4(-20)~59(15) *4		-4(-20)~59(15) *4		-4(-20)~59(15) *4	
Cooling and Heating	Capacity	Btu/Wh	W/W	-	-	-	-	-	-
	COP	W/W		27.00		25.20		26.00	
Cabinet Color (Munsell Code)				2.5Y 8/2		2.5Y 8/2		2.5Y 8/2	
Outer Dimensions	Height	in	(mm)	68-1/8	(1730)	68-1/8	(1730)	68-1/8	(1730)
	Width	in	(mm)	124-21/32	(3166)	134-7/8	(3426)	134-7/8	(3426)
	Depth	in	(mm)	31-7/32	(793)	31-7/32	(793)	31-7/32	(793)
Package Dimensions	Height	in	(mm)	Reference: YVAHR120B31S YVAHR072B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR096B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR120B31S YVAHR072B31S	
	Width	in	(mm)						
	Depth	in	(mm)						
Connection Ratio	Total Indoor Unit Capacity	%		140 - 65		135 - 65		130 - 65	
	Max. (Recommendation) indoor units/system			61 (38)		64 (38)		64 (38)	
Heat Exchanger	Type								
	Material								
Compressor	Type	Inverter		DA65PHD×3		DA65PHD×3		DA65PHD×3	
		Fix Speed		E655DH×1		E655DH×2		E655DH×2	
	Motor Output (Pole)	kW (Pole)		6.0 (6)+4.4 (2)		6.0 (6)+4.4 (2)		6.0 (6)+4.4 (2)	
				7.26 (6)		4.8 (6)+4.4 (2)		6.0 (6)+4.4 (2)	
				7.26 (6)		7.26 (6)		7.26 (6)	
	Start Method	-		Inverter					
	Operation Range	%		6~100		6~100		6~100	
	Refrigeration Oil Type	-		FVC68D		FVC68D		FVC68D	
Crank Case Heater		W×Q'ty		40.8 (230V) ×8		40.8 (230V) ×10		40.8 (230V) ×10	
Fan	Type	-		Propeller Fan		Propeller Fan		Propeller Fan	
	Motor Output (Pole)	kW (Pole)		0.91(8)+0.49(8)×2		0.91(8)+0.66(8)+0.49(8)		0.91(8)×2+0.49(8)	
	Quantity	Q'ty		3					
	Air Flow Rate	cfm	(m³/min)	7413+6178+6178	(210+175+175)	7413+6884+6178	(210+195+175)	7413+7413+6178	(210+210+175)
	External static pressure	in.WG	(Pa)	0 (0) *5					
	Drive			Direct-drive					
Electrical	Min Circuit Amps	A		Reference: YVAHR120B31S YVAHR072B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR096B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR120B31S YVAHR072B31S	
	Recommended Fuse/Breaker Size	A							
	Maximum Fuse Size	A							
Control	Type-Qty								
	Maximum length	Ft	(m)						
Sound Pressure Level	Cooling (Night-Shift)	dB (A)		69	(64)	70	(65)	70	(65)
	Heating	dB (A)		70		70		70	
Protection devices	Cycle			High pressure switch at 4.15 (60psi)					
	Inverter			Over-current protection Over-heat protection					
	Compressor			Over-heat protection					
	PCB			Over-current protection					
Refrigerant	Type-Qty			R410A					
	Charge amount	lb	(kg)	20.9+16.1+16.1	(9.5+7.3+7.3)	20.9+18.7+16.1	(9.5+8.5+7.3)	20.9+20.9+16.1	(9.5+9.5+7.3)
Refrigeration Oil	Charge amount	L/Unit	(kg/Unit)	17.4+13.2+13.2	(7.9+6.0+6.0)	17.4+17.4+13.2	(7.9+7.9+6.0)	17.4+17.4+13.2	(7.9+7.9+6.0)
Defrost Method				Reversed Refrigerant cycle					
Main Refrigerant Piping (Heat Recovery)	Gas Line (High/Low)	in	(mm)	1-5/8	(41.28)	1-5/8	(41.28)	1-5/8	(41.28)
	Gas Line (High/Low)	in	(mm)	1-3/8	(34.93)	1-3/8	(34.93)	1-3/8	(34.93)
	Liquid Line	in	(mm)	3/4	(19.05)	3/4	(19.05)	3/4	(19.05)
Weight	Net	lbs	(kg)	1813	(822)	2002	(908)	2004	(909)
	Gross	lbs	(kg)	1962	(890)	2163	(981)	2165	(982)

*1 When the Outdoor air temperature is 109°F (43°C) or more during the outdoor unit cooling operation, the maximum connectable indoor unit capacity ratio is 100%.

*2 (at 47°F/8.3°C)

*3 (at 17°F/-8.3°C)

*4 When the Outdoor air temperature is 23°F (-5°C) or less during the outdoor unit cooling operation, the minimum connectable indoor unit capacity is 18,000 Btu/h. in this case, install the wind protection hood (optional).

*5 External static pressure is adjustable via DSW setting (0.24 in.WG/60Pa)

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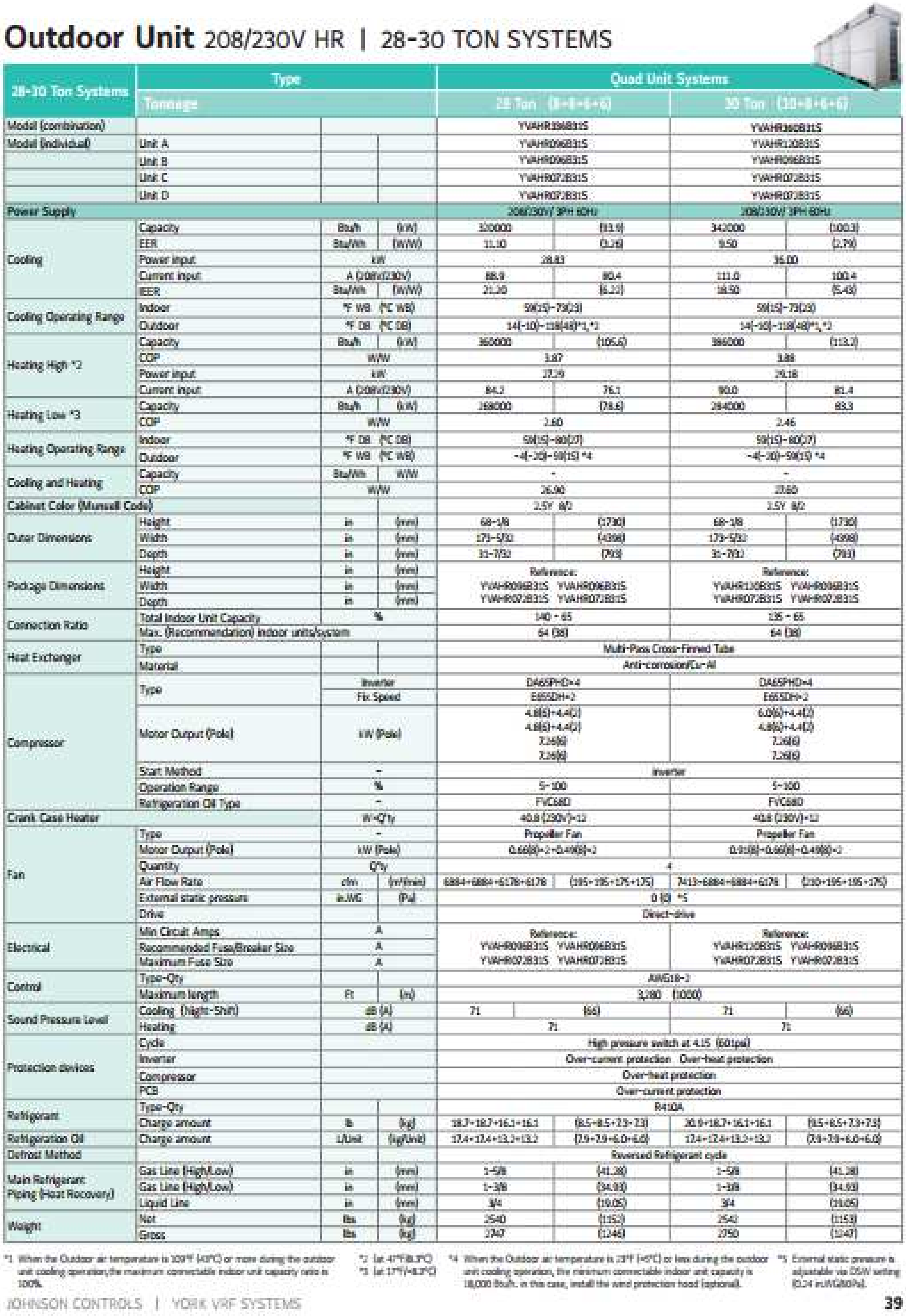

Outdoor Unit 208/230V HR | 28-30 TON SYSTEMS

28-30 Ton Systems	Type			Quad Unit Systems			
	Tonnage			28 Ton (8+8+6+6)		30 Ton (10+8+6+6)	
Model (combination)				YVAHR336B31S		YVAHR360B31S	
Model (individual)	Unit A			YVAHR096B31S		YVAHR120B31S	
	Unit B			YVAHR096B31S		YVAHR096B31S	
	Unit C			YVAHR072B31S		YVAHR072B31S	
	Unit D			YVAHR072B31S		YVAHR072B31S	
Power Supply				208/230V/ 3PH 60Hz		208/230V/ 3PH 60Hz	
Cooling	Capacity	Btu/h	(kW)	320000	(93.9)	342000	(100.3)
	EER	Btu/Wh	(W/W)	11.10	(3.26)	9.50	(2.79)
	Power input	kW		28.83		36.00	
	Current input	A (208V/230V)		88.9	80.4	111.0	100.4
	IEER	Btu/Wh	(W/W)	21.20	(6.22)	18.50	(5.43)
Cooling Operating Range	Indoor	°F WB	(°C WB)	59(15)~73(23)		59(15)~73(23)	
	Outdoor	°F DB	(°C DB)	14(-10)~118(48)*1,*2		14(-10)~118(48)*1,*2	
Heating High *2	Capacity	Btu/h	(kW)	360000	(105.6)	386000	(113.2)
	COP	W/W		3.87		3.88	
	Power input	kW		27.29		29.18	
	Current input	A (208V/230V)		84.2	76.1	90.0	81.4
Heating Low *3	Capacity	Btu/h	(kW)	268000	(78.6)	284000	83.3
	COP	W/W		2.60		2.46	
Heating Operating Range	Indoor	°F DB	(°C DB)	59(15)~80(27)		59(15)~80(27)	
	Outdoor	°F WB	(°C WB)	-4(-20)~59(15) *4		-4(-20)~59(15) *4	
Cooling and Heating	Capacity	Btu/Wh	W/W	-		-	
	COP	W/W		26.90		27.60	
Cabinet Color (Munsell Code)				2.5Y 8/2		2.5Y 8/2	
Outer Dimensions	Height	in	(mm)	68-1/8	(1730)	68-1/8	(1730)
	Width	in	(mm)	173-5/32	(4398)	173-5/32	(4398)
	Depth	in	(mm)	31-7/32	(793)	31-7/32	(793)
Package Dimensions	Height	in	(mm)	Reference: YVAHR096B31S YVAHR096B31S YVAHR072B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR096B31S YVAHR072B31S YVAHR072B31S	
	Width	in	(mm)				
	Depth	in	(mm)				
Connection Ratio	Total Indoor Unit Capacity	%		140 ~ 65		135 ~ 65	
	Max. (Recommendation) indoor units/system			64 (38)		64 (38)	
Heat Exchanger	Type			Multi-Pass Cross-Finned Tube			
	Material			Anti-corrosion/Cu-Al			
Compressor	Type	Inverter		DA65PHD×4		DA65PHD×4	
		Fix Speed		E655DH×2		E655DH×2	
	Motor Output (Pole)	kW (Pole)		4.8(6)+4.4(2) 4.8(6)+4.4(2) 7.26(6) 7.26(6)		6.0(6)+4.4(2) 4.8(6)+4.4(2) 7.26(6) 7.26(6)	
	Start Method	-		Inverter			
	Operation Range	%		5~100		5~100	
	Refrigeration Oil Type	-		FVC68D		FVC68D	
Crank Case Heater		W×Q'ty		40.8 (230V)×12		40.8 (230V)×12	
Fan	Type	-		Propeller Fan		Propeller Fan	
	Motor Output (Pole)	kW (Pole)		0.66(8)×2+0.49(8)×2		0.91(8)+0.66(8)+0.49(8)×2	
	Quantity	Q'ty		4			
	Air Flow Rate	cfm	(m³/min)	6884+6884+6178+6178	(195+195+175+175)	7413+6884+6884+6178	(210+195+195+175)
	External static pressure	in.WG	(Pa)	0 (0) *5			
	Drive			Direct-drive			
Electrical	Min Circuit Amps	A		Reference: YVAHR096B31S YVAHR096B31S YVAHR072B31S YVAHR072B31S		Reference: YVAHR120B31S YVAHR096B31S YVAHR072B31S YVAHR072B31S	
	Recommended Fuse/Breaker Size	A					
	Maximum Fuse Size	A					
Control	Type-Qty			AWG18-2			
	Maximum length	Ft	(m)	3,280 (1000)			
Sound Pressure Level	Cooling (Night-Shift)	dB (A)		71	(66)	71	(66)
	Heating	dB (A)		71		71	
Protection devices	Cycle			High pressure switch at 4.15 (601psi)			
	Inverter			Over-current protection Over-heat protection			
	Compressor			Over-heat protection			
	PCB			Over-current protection			
Refrigerant	Type-Qty			R410A			
	Charge amount	lb	(kg)	18.7+18.7+16.1+16.1	(8.5+8.5+7.3+7.3)	20.9+18.7+16.1+16.1	(9.5+8.5+7.3+7.3)
Refrigeration Oil	Charge amount	L/Unit	(kg/Unit)	17.4+17.4+13.2+13.2	(7.9+7.9+6.0+6.0)	17.4+17.4+13.2+13.2	(7.9+7.9+6.0+6.0)
Defrost Method				Reversed Refrigerant cycle			
Main Refrigerant Piping (Heat Recovery)	Gas Line (High/Low)	in	(mm)	1-5/8	(41.28)	1-5/8	(41.28)
	Gas Line (High/Low)	in	(mm)	1-3/8	(34.93)	1-3/8	(34.93)
	Liquid Line	in	(mm)	3/4	(19.05)	3/4	(19.05)
Weight	Net	lbs	(kg)	2540	(1152)	2542	(1153)
	Gross	lbs	(kg)	2747	(1246)	2750	(1247)

*1 When the Outdoor air temperature is 109°F (43°C) or more during the outdoor unit cooling operation,the maximum connectable indoor unit capacity ratio is 100%.

*2 (at 47°F/8.3°C)

*3 (at 17°F/-8.3°C)

*4 When the Outdoor air temperature is 23°F (-5°C) or less during the outdoor unit cooling operation, the minimum connectable indoor unit capacity is 18,000 Btu/h. in this case, install the wind protection hood (optional).

*5 External static pressure is adjustable via DSW setting (0.24 in.WG/60Pa).

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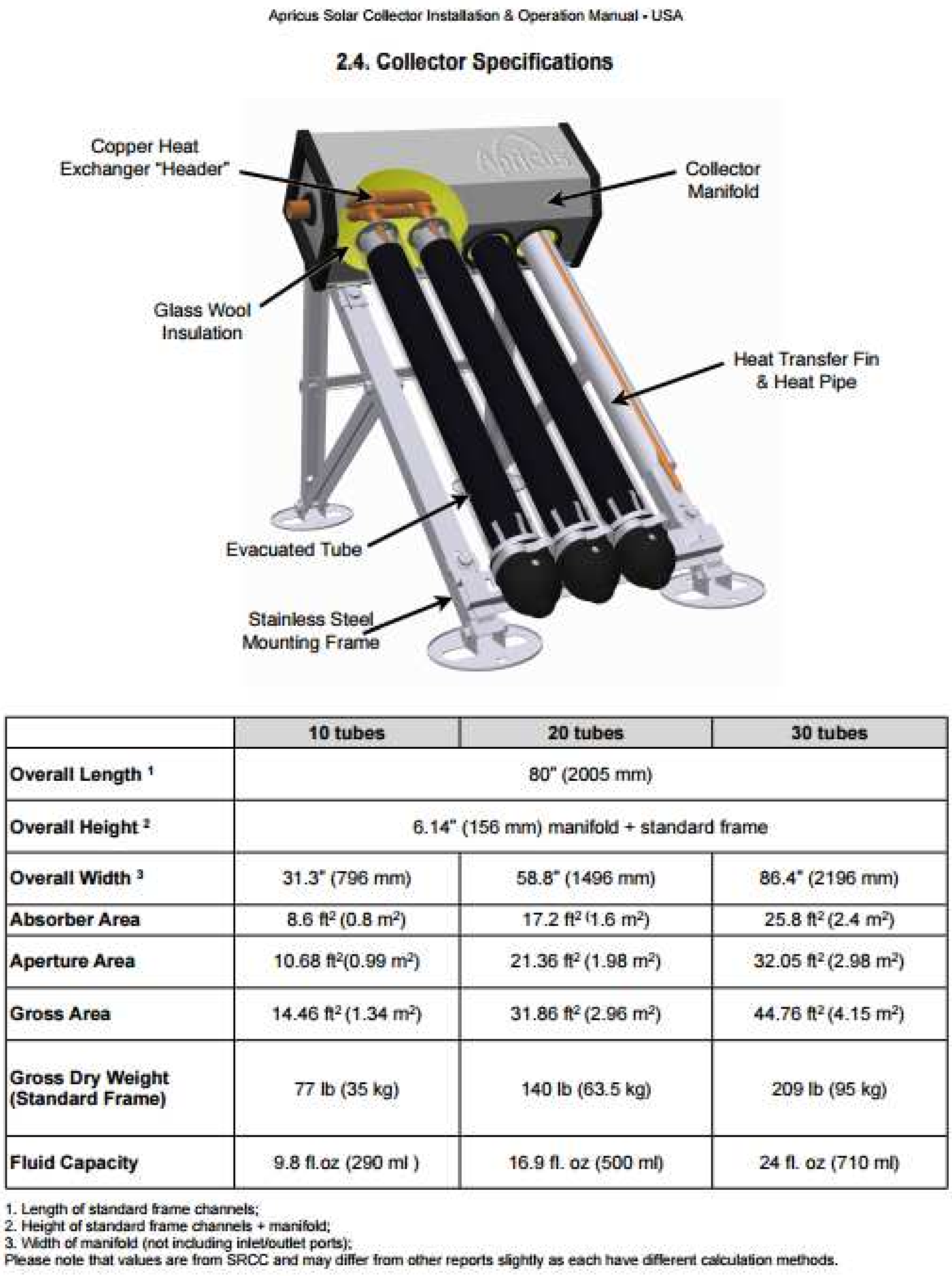

Apricus Solar Collector Installation & Operation Manual - USA

2.4. Collector Specifications

	10 tubes	20 tubes	30 tubes
Overall Length [1]	80" (2005 mm)		
Overall Height [2]	6.14" (156 mm) manifold + standard frame		
Overall Width [3]	31.3" (796 mm)	58.8" (1496 mm)	86.4" (2196 mm)
Absorber Area	8.6 ft^2 (0.8 m^2)	17.2 ft^2 (1.6 m^2)	25.8 ft^2 (2.4 m^2)
Aperture Area	10.68 ft^2(0.99 m^2)	21.36 ft^2 (1.98 m^2)	32.05 ft^2 (2.98 m^2)
Gross Area	14.46 ft^2 (1.34 m^2)	31.86 ft^2 (2.96 m^2)	44.76 ft^2 (4.15 m^2)
Gross Dry Weight (Standard Frame)	77 lb (35 kg)	140 lb (63.5 kg)	209 lb (95 kg)
Fluid Capacity	9.8 fl.oz (290 ml)	16.9 fl. oz (500 ml)	24 fl. oz (710 ml)

1. Length of standard frame channels;
2. Height of standard frame channels + manifold;
3. Width of manifold (not including inlet/outlet ports);

Please note that values are from SRCC and may differ from other reports slightly as each have different calculation methods.