BEST PRACTICES GUIDE

Variable Refrigerant Flow (VRF) Heat Pump Systems in Cold Climates

ESTCP Project EW-201515

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This field study was a side-by-side demonstration of two VRF heat pump technologies that offer significant potential for energy and cost savings, as well as improved comfort with zoned temperature control. The first VRF system was a natural gas engine-driven heat pump (GHP) - an emerging technology designed to reduce peak electric demand and generate savings in both annual energy costs and life-cycle costs compared to conventional equipment. The second VRF system was an electric cold climate heat pump (CCHP) - a relatively mature technology, designed for colder ambient conditions without supplemental heating.
This document provides a summary of best practices and lessons learned from the ESTCP demonstration that can improve performance, energy efficiency, and/or minimize costs. Some of these best practices could be applied to existing HVAC equipment as well as the installation of new equipment.

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ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
CCHP	electric cold climate heat pump; a type of ASHP designed for cold climate use
COP	Coefficient of Performance
DoD	United States Department of Defense
DoE	United States Department of Energy
DOAS	dedicated outdoor air system
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
GHP	Natural gas engine-driven heat pump
HVAC	Heating, Ventilation and Air Conditioning
kW	Kilowatt
M&V	Measurement and verification
NAVFAC	Naval Facilities Engineering Command
OA	Outside air
RCL	Refrigerant Concentration Limit
VAV	Variable air volume packaged HVAC unit; provides variable air flow, gas heating, and electric air conditioning with electric reheat.
VRF	Variable refrigerant flow aka VRV variable refrigerant volume (Daikin's proprietary VRF design)

1.0 INTRODUCTION

Variable refrigerant flow (VRF) heat pump systems are increasingly being used in small commercial buildings in the U.S. as a high efficiency heating and cooling option for multi-zone applications. However, the complexity of VRF configurations and the customized design make it difficult to monitor and predict energy savings relative to baseline HVAC systems. Due to limited field data available for VRF systems, especially in colder climates, energy savings are often based on energy modeling or data from controlled laboratory testing. This ESTCP demonstration provided a unique opportunity to directly compare detailed measured performance data for VRF heat pump technologies to a baseline variable-air-volume (VAV) system, installed in a small office building at Naval Station Great Lakes (NSGL).

This field study was a side-by-side demonstration of two VRF heat pump technologies that offer significant potential for energy and cost savings, as well as improved comfort with zoned temperature control. The first VRF system was a natural gas engine-driven heat pump (GHP) - an emerging technology designed to reduce peak electric demand and generate savings in both annual energy costs and life-cycle costs compared to conventional equipment. The second VRF system was an electric cold climate heat pump (CCHP) - a relatively mature technology, designed for colder ambient conditions without supplemental heating.

This document provides a summary of best practices and lessons learned from the ESTCP demonstration that can improve performance, energy efficiency, and/or minimize costs. Some of these best practices could be applied to existing HVAC equipment as well as the installation of new equipment.

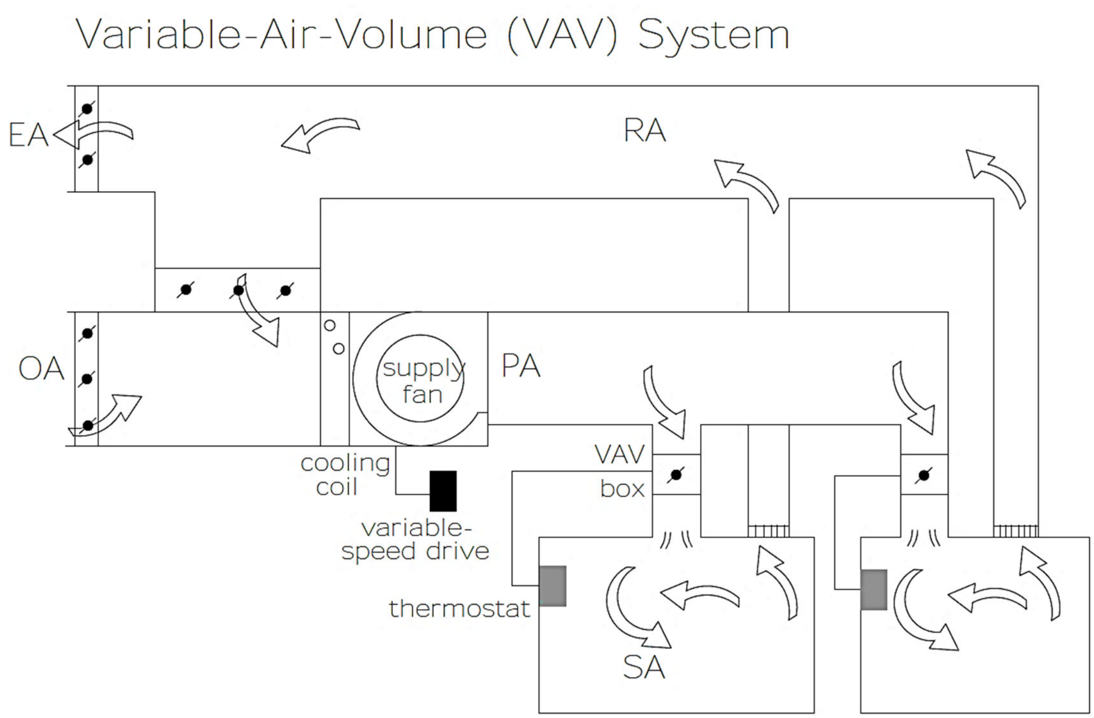
1.1 Multi-zone HVAC Systems for Commercial Buildings

1.1.1 Packaged VAV with Electric Reheat

Single-duct VAV systems are the most widely used HVAC systems for commercial buildings both in the U.S. and globally [2]. Conventional VAV systems use a central electric DX cooling coil and an optional gas-fired heating coil to deliver conditioned air to multiple zones in commercial applications such as an office building. A central supply fan combines required outdoor ventilation air with return air then delivers conditioned primary air (about 55°F) to each zone. Each zone has a terminal unit or VAV box with modulating dampers to control the amount of primary air delivered based on the thermostats installed in each zone. VAV boxes often include electric resistance heating elements to provide trim-heating as needed to satisfy the thermostat in each zone.

1.1.2 Natural Gas Engine-driven Heat Pump (GHP)

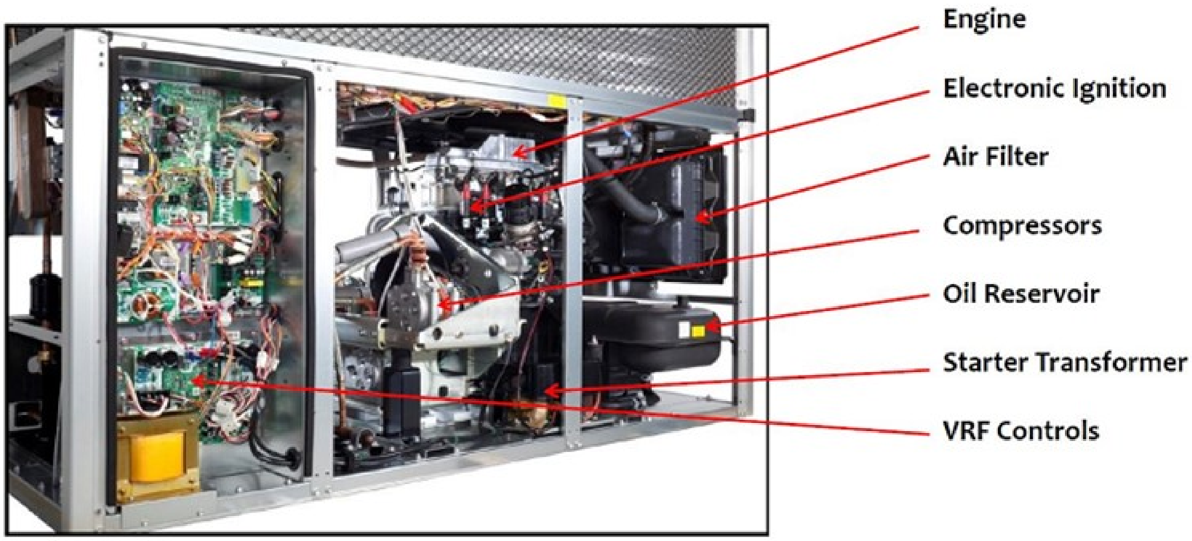
The overall GHP design is similar to an electric heat pump but with an advanced natural gas engine in place of an electric motor (Figure 3). The NextAire™ GHP uses high efficiency scroll compressors and a variable speed engine with a demonstrated long life (30,000 hours). GHPs combine high efficiency heating and cooling, with specified coefficient of performance [COP] of 0.95 to 1.4 at rating conditions. During cooling, GHPs consume natural gas in place of electricity, significantly reducing peak electric demand in comparison to electric chillers or electric heat pumps. During heating, GHPs are rated 50% more efficient than standard gas furnaces or boilers commonly used at DoD facilities. Heat recovered from the engine cooling jacket and exhaust can supplement the GHP output during heating mode to increase the overall system efficiency. Heat recovery also allows GHPs to deliver a higher supply temperature at cold ambient conditions and eliminates the need for inefficient defrost cycles. In contrast, electric heat pumps often require inefficient resistance heating to supplement their heating capacity at low outdoor temperatures.



Source: Trane Product Catalog VAV-PRC003-EN

Figure 1 Diagram of VAV System

Figure 2 Example of a ground-mounted VAV system

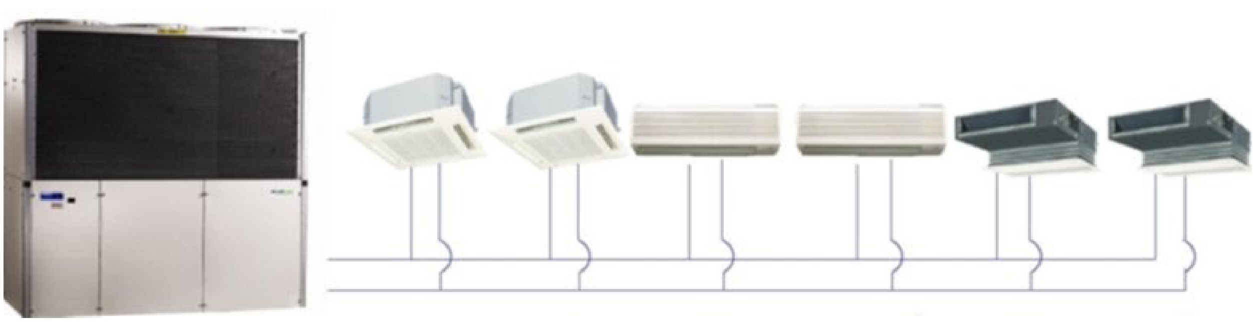


Source: IntelliChoice Energy

Figure 3 The GHP utilizes two scroll compressors and an advanced natural gas engine

1.1.3 Electric Cold Climate Heat Pump (CCHP)

Electric VRF heat pumps, such as the CCHP unit demonstrated in this project, are a mature technology with several U.S. manufacturers and a modest but growing market. VRF systems are increasingly used for multi-zone commercial buildings, driven by the potential for energy savings, economic benefits, and improved comfort with zoned temperature control. Electric VRF systems typically use variable-speed electric motors to drive variable-speed or multi-stage compressors and a single refrigerant circuit with individually controlled fan coils to provide zoned heating and cooling. Both the gas and electric heat pumps featured in this demonstration used the same type of indoor VRF fan coil units and controllers provided by the same manufacturer (Figure 4).



Source: IntelliChoice Energy

Figure 4 GHP system utilize the same indoor VRF air handlers as the electric VRF system

1.1.4 Energy Savings and Economic Benefits

Due to the custom nature of VRF installations, direct comparisons of energy use and economics can be difficult to quantify. In addition, the performance of all air source heat pumps (both electric and gas engine-driven) vary significantly with ambient temperatures, so performance and energy savings for one climate will not be the same as another. VRFs are primarily installed in moderate or hot climates that can benefit from their high cooling efficiency. In colder climates, VRFs are often installed in heated mechanical rooms or with backup electric resistance heaters, thus increasing installed costs and reducing energy savings. Recently some manufacturers introduced cold climate versions of electric VRF systems without supplemental heating; but limited field data is available to validate their performance. This demonstration provides measured field data needed to validate modeled energy savings for VRF systems, especially in colder climates.

For this demonstration, VRF systems were paired with a conventional dedicated outdoor air system (DOAS) with standard-efficiency gas-fired heating and electric DX cooling to condition the ventilation air for the facility. For cold climates, gas heating is often needed to achieve the large temperature rise for conditioning 100% outdoor air (OA). The DOAS delivered conditioned air year-round at 64°F.

Figure 5 A DOAS conditioned ventilation air (100%OA) for the demonstration site

2.0 BEST PRACTICES AND LESSONS LEARNED

During the baseline and demonstration monitoring, a number of best practices were identified that could improve performance, energy efficiency and/or reduce costs. Some of the following practices could be applied to existing HVAC equipment as well as the installation of new equipment.

2.1 Optimize Existing VAV Systems

The baseline equipment at the ESTCP demonstration site was a conventional VAV system with modulating gas-fired heating and electric DX cooling. Terminal units or VAV-boxes were installed in each zone to adjust air flow and provide electric resistance heat for trim-heating and to satisfy thermostats in each zone.

During heating operation, baseline electric consumption was much higher than expected. Baseline data in Figure 6 shows VAV-boxes operating at peak heating capacity (yellow) to achieve setpoints while the outdoor unit's modulating gas burner (orange) operated at low fire.

The VAV equipment manufacturer confirmed that a building automation system (BAS) is required to integrate the controls for the gas burner and VAV-boxes. Without a BAS, the central VAV gas heating and distributed VAV-boxes operated independently resulting in excessive electric resistance heating by the VAV boxes. In addition to high electricity use and energy costs, electric resistance heating generated the highest hourly peak electric demand (65kW) exceeding the peak electric demand (43 kW) during cooling operation. Although this VAV system did not operate as designed, this may be typical for smaller buildings or sites without a central BAS.

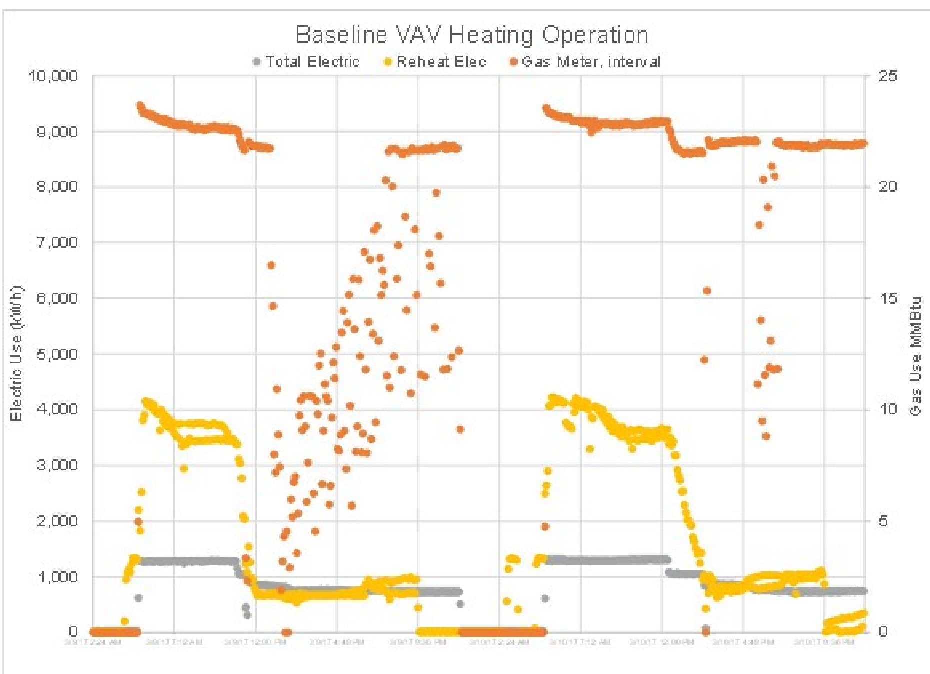


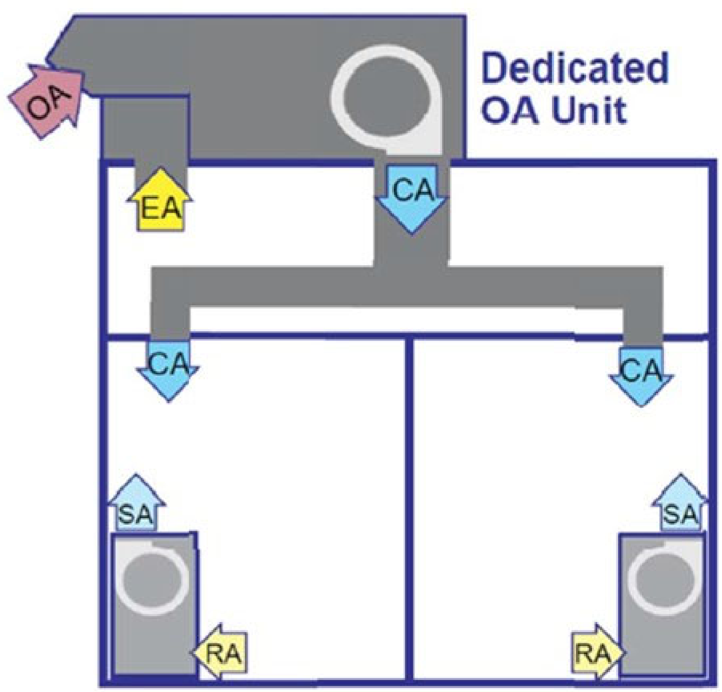
Figure 6 Lack of integrated controls for the VAV natural gas burner and the electric resistance heaters in the VAV-boxes resulted in higher than expected energy use

Despite the high energy use for the baseline system, the field site had frequent comfort complaints from tenants, and some occupants relied on electric resistance space heaters for supplemental heating. Since VAV systems are widely used for multi-zone applications, such as office buildings, retro-commissioning and/or retrofitting integrated controls may improve efficiency and reduce energy costs for existing equipment.

2.2 Reducing VRF Installation costs

VRF systems provide zoned space conditioning providing a high level of comfort; however, VRF configurations require a more customized design for specific buildings, resulting in higher installation costs than conventional HVAC. For the ESTCP demonstration, the project team considered a number of design approaches to minimize the installed costs of the VRF equipment. The project team considered using the existing VAV system to condition and supply the required ventilation, but due to its higher capacity, the system performance and control might be compromised when the VAV system is operated below 10% design capacity. If ventilation supply temperatures are not adequately controlled, it may also impact comfort levels.

The engineering design firm had used energy recovery ventilation (ERV) with success in other projects, but this option was not selected due to significantly higher installed costs. ERVs recover heat from exhaust air streams to pre-condition outside air for ventilation. For this climate, the ERV would require two additional 480V electric duct heaters. One would be installed upstream from the ERV to prevent freezing at the heat exchanger, and a second duct heater would be installed downstream from the ERV to provide trim-heating to achieve the required supply air temperatures.



Source: ASHRAE Design Guide for Dedicated Outdoor Air Systems (DOAS)

Figure 7 Schematic of DOAS supplying conditioned air (CA) directly to zones. Zones contain local HVAC units addressing sensible loads using recirculated air, such as radiators, VRF, or chilled beam, etc.

Based on contractor estimates, the installation of additional ductwork from the toilet exhaust fans to the ERV, and from the ERV to each fan coil, added significant cost to the installation as well as more disruption to the building occupants. In addition, eliminating the ERV electric pre- and post-heaters significantly reduced costs by eliminating the need to upgrade the existing transformer and removing one of the new electric panels. Instead, a conventional standard efficiency DOAS, with gas-fired heating and electric cooling, was selected to condition ventilation air.

For this demonstration site, the existing VAV ductwork was used for the DOAS supply air reducing installation costs. Although the minimum design ventilation was much lower than the baseline supply air, the DOAS supply was balanced using the dampers in the existing VAV-boxes and all electric reheat coils were powered off. For new construction, the reduced DOAS supply air flow can often be used with smaller diameter ductwork resulting in lower material and installation costs. To further reduce installed costs, some VRF fan coil units were combined, resulting in a total of 20 fan coil units instead of the 25 fan coil units in the original VRF design.

2.3 Importance of trained service providers

Performance monitoring identified some operational issues and limitations of the CCHP and GHP systems. Some outages occurred with conventional equipment, while others were due to unique installation issues and operating limitations of the VRF systems. While some were unique issues related to M&V for the demonstration, others occurred under typical operating conditions. This highlights the importance of well-trained service providers, which is a common concern for many emerging technologies.

The DoD Unified Facilities Criteria design considerations for VRF also raises concerns that only factory-authorized technicians are required to install and service VRF systems, which may reduce the ability to obtain competitive quotes leading to higher life-cycle costs. To address this concern, DoD facility staff can be trained to provide first-level service of VRF equipment and build this expertise in-house for faster response and lower life-cycle operating costs.

As part of the project Technology Transfer task, NAVFAC facility staff received two days training by the GHP manufacturer on servicing the VRF systems and performing routine engine maintenance. Feedback after the training session showed NAVFAC facility staff felt confident they could transfer their current expertise from conventional air conditioning and vehicle engine maintenance to providing technical support for the VRF systems. As another training alternative, the Daikin factory authorization for VRF equipment consists of one to two-day training for system installation and commissioning with an additional two-day training for advance service.

In addition, the growing market for VRF is expanding regional service networks for qualified VRF technicians and contractors. Daikin Service has hundreds of service technicians throughout the U.S., Mexico, and Canada. In addition, several VRF systems including the two GHP manufacturers (Yanmar and Blue Mountain Energy, formerly IntelliChoice Energy) use Daikin controllers and fan coils which can build on existing expertise. As a growing number of contractors become more familiar with the technology, both service and installation costs are expected to decrease as well.

Maintenance for the GHP system is similar to VAV or other VRF systems except for additional maintenance tasks related to the natural gas engine. As shown in Figure 8, these tasks, such as oil change, belts, etc., are similar to the required maintenance for automobiles or engine-based standby generators. One GHP manufacturer includes an optional service agreement in the equipment purchase to address customers' concern about unexpected service costs. This service agreement provides engine maintenance at intervals of 1,000, 2,000, and 3,000 runtime hours. This option was selected for the demonstration and was also used for the cost assessment.

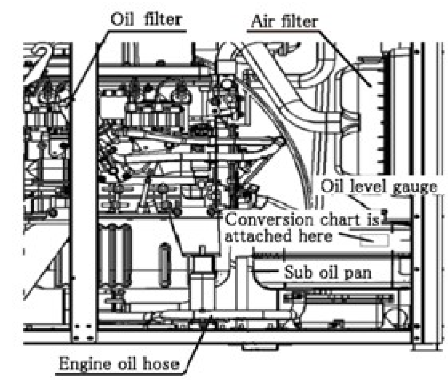
1) Engine Oil Refilling

1. Check the oil level with the oil level gauge on the sub oil pan.
2. Supply fresh oil until the level reaches "F" level. (Refer to the table below or the conversion chart shown in the illustration below for the refilling amount.)

Refilling amount per scale of the oil level gauge	Approx. 0.4 gal (2 L)

Refilling intervals	Every 3 years (6,000 hours)

Specified amount	Sub oil pan	Level "F" : 0 ~ 0.8 inch (0 ~ 20 mm)



Source: IntelliChoice Energy Service Manual

Figure 8 Example of additional maintenance required for GHP engine.

2.4 Sizing of Cold Climate Heat Pump and Supplemental Heating

This CCHP model demonstrated was specifically designed for cold climate applications without supplemental heating. For this field site, the CCHP outdoor unit was oversized to meet the heating load at the coldest design conditions due to its reduced heating capacity at lower ambient temperatures. Specifications for the heat pumps and DOAS are listed in Table 1.

To accurately size the heat pumps to the building load, a design engineering firm developed load calculations based on code-required minimums taking into account a range of DOAS setpoints, e.g. 60°F supply air, to address outdoor latent loads during the cooling season and a neutral 70°F during the heating season. A 10% safety factor was added to both heating and cooling capacities.

Table 1 Demonstration Equipment Specifications

Component	Cooling	Heating
NextAire Multi-Zone Gas Heat Pump Model: AXGP096D1NHS, R410A 208/230V 1Ph, 6 MCA, 20 MOCP Dimensions: 52"L x38"W x 82"H 1365 lbs	96 MBH / 8RT (28 kW) Efficiency: 1.3 COPg Gas use: 73 MBH Power consumption: 1.12kW	103 MBH (30 kW) Efficiency: 1.3 COPg Gas use: 79.5 MBH Power consumption: 0.9kW
Daikin Electric Heat Pump Model: RXYQ144TYDN, R410A 460V-3-60, 25.9 MCA, 35 MOCP Dimensions: 49"L x 30"W x 67"H, 12" stand added for snow clearance 710 lbs	138 MBH / 12RT (40 kW) Efficiency: 12.3 EER; 24.1 IEER *2018 Federal Min: 12.2 IEER*	154 MBH (45 kW) Rated at -4°F Efficiency: 4.1 COP @ 47°F 2.3 COP @ 17°F
Ventilation: Daikin DOAS Model: DPS006A, 800 cfm 460V-3-60, 10.8 MCA, 15A MOCP Modulating natural gas heat; electric R410A air conditioner	73.5 MBH / 6RT Efficiency: 11.3 EER	96 MBH Gas use: 120 MBH Efficiency: 80%Et

Indoor VRF fan coils are sized to meet the calculated heating or cooling loads for each zone. The outdoor unit can be paired with a total indoor fan coil capacity up to 130% the outdoor rated capacity, as it is unlikely all indoor fan coils will operate at peak loads at the same time. In addition, sizing of the outdoor unit relative to the building load will also depend on the available sizes in the product line. For example, the GHP product line includes only two sizes, an 8-ton and a 15-ton unit, although multiple units can be combined for larger systems. When specifying the outdoor unit, heating or cooling capacity must be rounded up to the next available size.

For this demonstration in ASHRAE Climate Zone 5, the electric CCHP was unable to meet the heating load for several days despite oversizing to match the estimated peak heating load. During the monitoring period, ambient temperatures dropped below winter design conditions on several occasions. During extreme cold, the CCHP continued to function but was unable to maintain zone temperatures and operated at very low efficiencies. Both the GHP and DOAS were not operational during this period due to unrelated component issues, and so were not evaluated at those extreme cold conditions.

As weather conditions become less predictable with more extreme temperatures, the CCHP will require a means of supplemental heating for reliable cold climate operation. The use of supplemental heat will impact both energy use and life-cycle costs. GTI is investigating control strategies for gas-fired DOAS to provide supplemental heat at low ambient temperatures to reduce first costs, maintain efficiency, and improve comfort and reliability for the occupants.

2.5 Part-load Operation of VRF Heat Pumps

Most conventional HVAC equipment are over-sized to ensure adequate capacity, and often part-load operation can have an adverse effect on efficiency. Likewise, heat pump efficiency is also impacted by part-load operation. VRF systems often operate at lower part-loads depending on the sizing of the indoor VRF fan coils units and the outdoor heat pump. By design, VRF heat pumps modulate to meet the heating and cooling loads of each zone and closely maintain temperature setpoints.

The ratio of VRF indoor fan coil capacity to the outdoor unit capacity is referred to as the diversity factor. Per manufacturer specifications, VRF systems can combine indoor fan coil capacities up to 130% the capacity of the outdoor unit, since not all fan coils are expected to operate at peak heating and cooling at the same time. For this demonstration, the 8-ton outdoor GHP unit was paired with 7.2 tons of indoor VRF fan coil capacity or 90% diversity factor. Throughout the demonstration, the GHP operated between 20% and 35% full heating or cooling capacity. The 12-ton outdoor CCHP unit paired with indoor VRF fan coil capacity about 60% its total capacity, resulting in even lower part-load operation for the outdoor unit. The CCHP operated at part-loads ranging from 5% and 30% for both heating and cooling. VRF designs with higher diversity factors may operate at higher part-loads; however, this is limited by the building design loads and available product sizes.

Part-load operation adversely impacted the performance of both heat pumps; however, ambient temperatures had a larger impact on CCHP heating efficiency than part-load operation. On the other hand, the GHP model used in this demonstration had lower than expected performance due to reduced efficiency at part-load operation below 60% rated output. This issue may be due to product-specific controls and engine sizing and is not inherent in this class of technology. This finding warrants further investigation into optimizing GHP part-load performance.

This demonstration highlights how VRF heat pumps regularly operate at very low part-loads even when sized appropriately. While VRF systems typically operate at lower part-loads by modulating to meet the multi-zone heating and cooling loads, this is amplified when paired with a DOAS which can reduce the facility heating or cooling loads. Currently, GHP manufacturer specifications are based on full-load operation at select rating conditions; however, depending on the climate, the heat pump might never operate at those specific conditions. Current efforts to update GHP performance metrics to more closely reflect actual installed conditions, including part-load operation, will support the development of more optimized designs.

2.6 UFC HVAC Requirements for DOAS

For this demonstration, the NSGL Asset Management Group reviewed the demonstration plan and issued a Site Approval Review Checklist (SA17-0004). The following HVAC requirements per UFC 4-010-01 *DoD Minimum Antiterrorism Standards for Buildings* were identified as applicable for this demonstration:

- ***DoD Standard 16 (1) Air intakes requirements to heating, ventilating, and air conditioning (HVAC) systems***.

  (a) HVAC Replacements and Upgrades. Where air handling equipment in heating, ventilating, and air conditioning systems is being replaced or when they are being upgraded,

need to ensure that air intakes are either 10 feet / (3 meters) above the ground or extend the intakes to that height.

Status: DOAS air intake was extended to 10 feet above ground (Figure 9, left photo).

- ***DoD Standard 18 (1) Emergency Air Distribution Shutoff for HVAC systems.***

  (a) HVAC systems being installed for new and existing buildings are required to have Emergency Air Distribution Shutoff for HVAC systems IOT immediately shut down the air distribution and exhaust systems throughout the building and that'll close all dampers leading to the outside except where interior pressure and airflow control would more efficiently prevent the spread of airborne contaminants and/or ensure the safety of egress pathways.

  (b) HVAC shutoff switches must be located to be easily accessible by building occupants so that the travel distance to the nearest shutoff switch will not be in excess of 200 feet (61 meters). They must also be well labeled, and of a different color than fire alarm pull stations.

  Status: Emergency shutoff switches were installed to shutoff air intake at the DOAS (Figure 9, right photo).

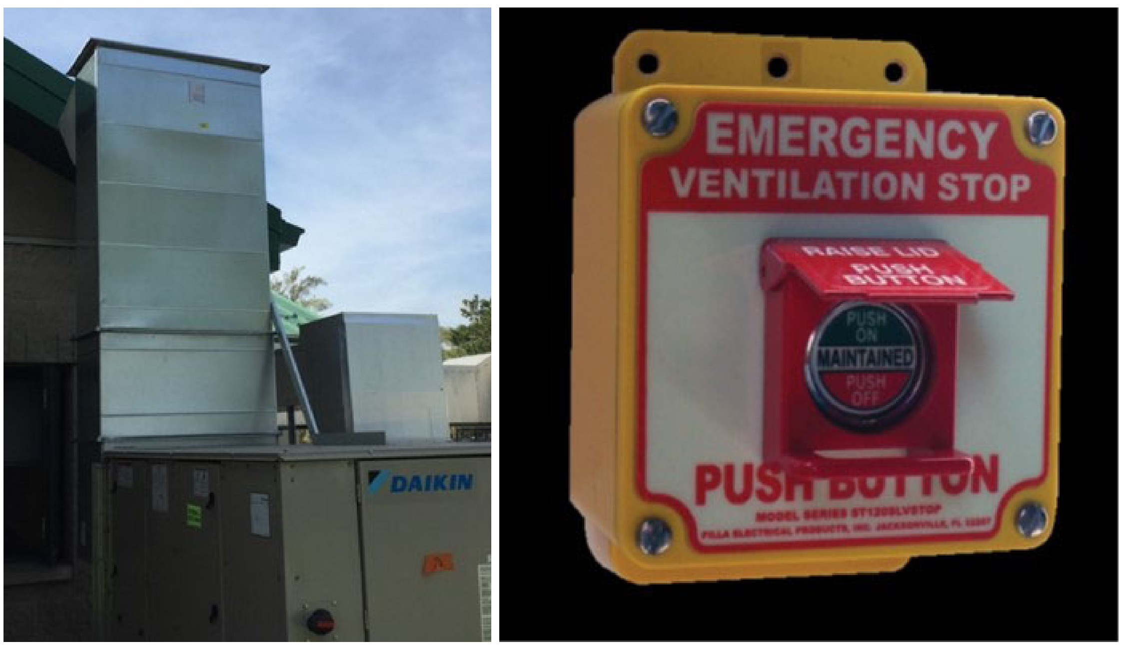


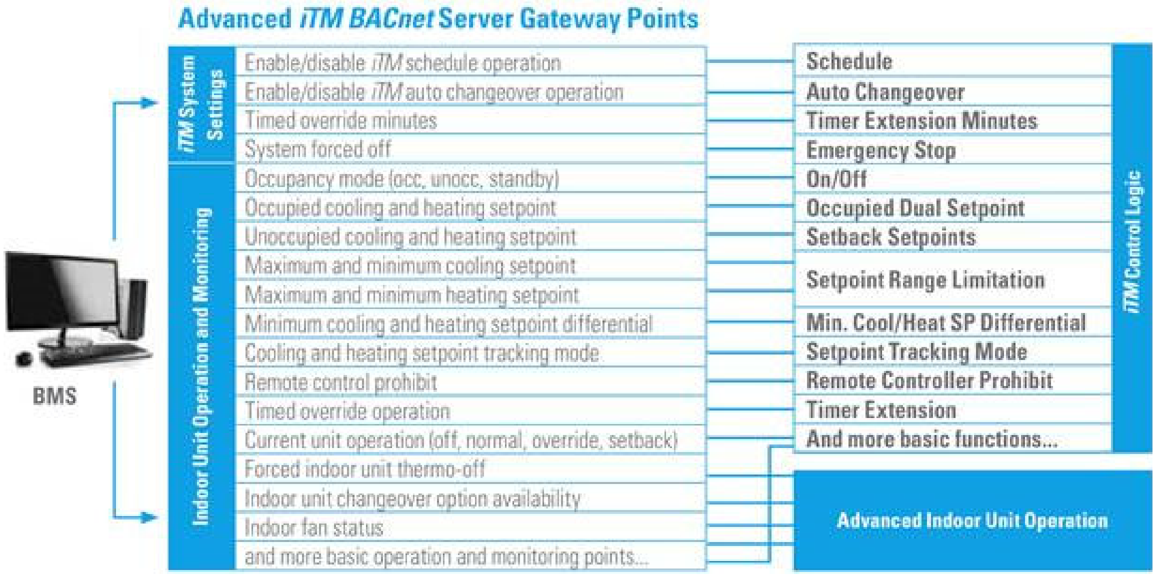
Figure 9 DOAS Installation Complied with DoD Standards 16 and 18

2.7 UFC Regulations for the Use of VRF in DoD Facilities

Several regulations specified in the *Unified Facilities Criteria UFC 3-410-01 Heating, Ventilating, and Air Conditioning Systems* apply to the use of VRF systems for DoD facilities. Previous versions (UFC 3-410-01 Change 3, January 25, 2017) limited or discouraged the use of VRF in various DoD facilities. The most recent version (Change 4, November 01, 2017) presents several requirements for VRF systems. Each regulation is discussed in detail in the final report for ESTCP EW-201515. The following sections address some best practices and design considerations regarding the use of VRF in DoD facilities:

1. *Unified Facility Guide Specifications require the installation of non-proprietary control networks down to the level of each individual device in the system.*

   i. Daikin currently offers a BACnet/Lon interface option which can communicate with non-proprietary building automation systems (BAS). The cost of the BACnet/Lon interface depends on the number of points and system size but is estimated at $3,000 and $6,000. The BAS interface is hard-wired access only, so security would be handled on the BAS side. At the local level the system can be password protected.



Source: Daikin intelligent Touch Manager™ (iTM) BACnet® Server Gateway Design Guide

2. *VRF systems piping/tubing must have all brazed connections…list of fittings and joints that are prohibited include but are not limited to the following: push-on fittings, extruded fittings, flare fittings, press-connect fittings, mechanical joints and groove joints.*

   i. Brazed fittings are commonly used for refrigeration piping as well as VRF systems. Brazed fittings create very reliable leak-free joints to withstands high and low temperatures and pressures and tend to be lower in cost. For this demonstration, threaded fittings were required to install M&V flow meters in the refrigerant lines. While threaded fitting were used successfully in refrigerant lines for M&V at other field sites, this site experienced multiple refrigerant leaks due in part to the contractor's lack of familiarity with the use of threaded fittings instead of brazed. This experience reinforces the UFC requirement for all brazed fittings in VRF systems.

3. *VRF refrigerant is heavier than air, and "puddles" on the floor of a room, displacing breathable air.*

   i. As with any HVAC equipment, VRF system must be designed to comply with all safety and code requirements. Safety issues regarding refrigerant are successfully addressed by ASHRAE Standards 15 and 34 offering guidelines for the design, construction, testing, installation, operation, and inspection of mechanical refrigeration systems. Since these are application-based standards, not equipment design guides, engineering judgment is required when applying the standards.

ii. ANSI/ASHRAE Standard 34 *Designation and Classification of Refrigerants* provides the most current information related to refrigerant and refrigerant blends designations, safety classifications, and refrigerant concentration limits (RCLs).

iii. Many national, state, and local building codes require compliance with ASHRAE Standard 15 and/or ISO Standard 5149, *Safety Standard for Refrigeration Systems*. It is necessary to follow any national, state, and local building codes and work with the local authority having jurisdiction (AHJ) to ensure best practice.

iv. While each VRF manufacturer recommends different refrigerant piping sizes and maximum to minimum vertical and horizontal lengths, ASHRAE Standard 15 establishes safeguards for persons and property. Complying with ASHRAE Standard 15 requires carefully considering the building's zones, determining connected spaces, and optimally placing the piping and indoor units to reduce any risks due to refrigerant leaks. The standard also provides guidelines on piping location and protection.

v. The following are examples of some ASHRAE Standard 15 guidelines for VRF systems [7]:

- ***Inspection:*** *keep site-installed pipe joints exposed to view until all pressure and vacuum tests are completed and passed.*
- ***Ventilated spaces***
  - *Know the refrigerant concentration limit and how it applies to each occupied space.*
  - *Know how much refrigerant is in the system in case a leak were to occur.*
  - *Evaluate connected spaces beyond the zone and connected ductwork.*
- ***Location of piping and refrigerant bearing components:*** *know where refrigerant may come from if a leak were to occur.*
- ***Protect refrigerant piping***
  - *Exposed piping*
    - *Ensure exposed piping is at least 7.25 ft above the floor or is against the ceiling.*
    - *Ensure exposed piping is not installed in an enclosed public stairway, stair landing, or means of egress; consider enclosing piping with gastight and fire-resistive material to isolate from such areas.*
  - ***Shafts and penetrations***
    - *Ensure piping is not located inside any elevator, dumbwaiter, or other shaft containing moving objects.*
    - *Ensure piping shaft is not open to living quarters or means of egress.*
    - *Use riser shafts with proper support between floors*
    - *Use protective sleeves to protect piping from abrasions where it passes through walls, obstructions, or other materials.*

4. *VRF system is designed around the thermodynamic properties of a specific refrigerant type, this means that when a refrigerant type is phased out in favor of a more environmentally friendly formulation, as is happening today, the price of the refrigerant increases rapidly, and the VRF system itself will likely need extensive modification or even replacement in order to function properly.*
    i. OEMs are investigating refrigerants with lower global-warming-potential (GWP) with a focus on maintaining safety and performance along with minimal changes in equipment; however, this may impact equipment design. R-410a is used in air conditioning as well as VRF systems, so all cooling equipment will be impacted by refrigerant changes. R-410a is a blend of multiple refrigerants, and some are considering components of the blend, such as R-32 which has a lower GWP (approx. 700) compared to R-410a GWP of 1980. Most manufacturers have placed plans on hold regarding the switch to a new refrigerant or blend due to the change in regulations by the current administration.
5. *Life-cycle Cost analysis comparing VRF with traditional systems can be difficult given the relative newness of VRF systems.*
    i. The complexity and customized design of VRF systems for specific buildings make it difficult to predict energy savings relative to baseline HVAC systems. Due to limited field data available for VRF systems, energy savings are often based on energy modeling or laboratory data obtained under controlled conditions. This demonstration provides a unique opportunity to directly compare measured performance data for a VRF system to conventional equipment. Combined with existing EnergyPlus models, adapted for cold climate performance, this data and cost assessment provides life-cycle cost assessment for VRF systems which validate previous modeled estimates.

2.8 Summary of Best Practices

In summary, both VRF heat pumps demonstrated improved comfort along with significant potential for energy savings and economic benefits compared to conventional HVAC. While this demonstration compared an emerging technology (GHP) with a more mature technology (CCHP) that has multiple manufacturers and decades of design optimization, both VRF heat pumps had operational limitations in this cold climate application. Results further suggest the need for additional research and development to optimize GHP part-load performance and to reduce installed costs in order to improve regional economics and support broader market adoption.

The following is summary of recommended best practices based on results from this ESTCP demonstration:

- Optimize existing VAV Systems using integrated controls for the gas burner and VAV-boxes to minimize electric resistance heating and peak electric demand. This may require a building automation system (BAS).
- Minimize VRF installation costs for retrofit applications by utilizing existing ductwork for DOAS. Incorporating other technologies such as ERV/HRV offer potential energy savings for DOAS systems, but the additional exhaust ductwork and electric service upgrade, if needed, may add significant costs to the installation. This applies to both VRF systems and other HVAC equipment.

- Well-trained service providers and installation contractors are critical for new emerging technologies, such as VRF, as well as any complex HVAC system. The growing VRF market is expanding regional service networks for qualified technicians and contractors. Alternatively, DoD facility staff can be trained to provide first-level service for VRF heat pumps building on existing skill sets with conventional air conditioning and vehicle engine maintenance.
- VRF systems for commercial buildings are typically sized based on the cooling load; however, for cold climates, electric VRF systems should be sized to meet the heating load based on coldest design conditions and its reduced heating capacity at lower ambient temperatures. As weather conditions become less predictable with more extreme temperatures, electric cold climate heat pumps may require supplemental heating for reliable cold climate operation. Correct sizing of VRF systems has a larger impact on efficiency and cost than conventional HVAC.
- Even when sized appropriately, VRF heat pumps regularly operate at very low part-loads which adversely impacts their efficiency. VRF equipment should optimized to maintain performance operating at part-loads down to 20%.
- Supplemental heating may be used to downsize the required capacity for either electric CCHP or GHP VRF systems in cold climates and enable higher utilization of the VRF capacity.
- DOAS installations for DoD facilities must meet UFC 4-010-01 requirements regarding the height of air intakes and emergency shutoff switches.
- Several regulations specified in *UFC 3-410-01* apply specifically to the use of VRF systems for DoD facilities. Results from ESTCP project EW-201515 address some of these best practices and design considerations.
    - UFGS/UFC require the installation of non-proprietary control networks down to the level of each individual device in the system. Daikin now offers a BACnet/Lon interface option for the VRF system which can communicate with non-proprietary building automation systems.
    - Concerns regarding VRF refrigerant leaks displacing air are addressed by ASHRAE Standard 15 and 34 in the design of the interior VRF configuration.
    - While there is limited availability of life-cycle costs analysis for VRF systems, Project EW-201515 provides a direct comparison of measured performance data for a VRF system to conventional equipment. These results validate previous modeled estimates of energy savings and were used to expand and refine EnergyPlus models for heat pump VRF systems.

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