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Assessment Report of Existing In-Field Performance Measurement and Testing Protocols for Cold Climate Variable Refrigerant Flow Systems

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1. Background and Purpose

The primary objectives for this project are to generate and assess high quality, observed, in-field data on VRF actual energy performance and refrigerant leakage, and effectively communicate these results to key audiences that directly impact HVAC system selection in commercial institutional and multifamily buildings (e.g. design engineers, commercial building developers, state/local housing agencies, municipalities, and energy efficiency program administrators).

The project will target VRF cold climate applications (IECC climate zone 5 and above) with a focus on the most common building types in the Northeast – including multifamily, school/universities, office, and retail. The project will focus on common sizes and layouts within these sectors, and sites that match VRF systems with high efficiency dedicated outdoor air systems (DOAS). The project will capture a full year of performance data to assess variations in operation during heating and cooling months.

Due to a very limited body of existing in-field performance measurement of VRF, especially cold-climate applications, NEEP elected to release an RFI to manufacturers, engineering firms and VRF project partners to request best practices and recommended strategies. NEEP and VEIC reviewed and included a list of draft test parameters for respondents to comment on the importance and method for best measuring or documenting for in-field applications. These methods include onsite third-party metering, vendor VRF system building automation/management systems (BAS/BMS), building energy models and commissioning documentation and other building operation and characteristic surveys.

VEIC compiled and summarized the (7) RFI responses and developed a consensus list of VRF metering parameters and methods. This document provides a narrative compendium of that information, but the detailed summary in Excel workbook form (Appendix B) and the RFI released in October 2020 is available upon request.

2. VRF Systems Overview

Variable Refrigerant Flow (VRF) systems are refrigerant based heating and cooling systems. They consist of air-cooled outdoor, or water-cooled indoor refrigerant compressor units that supply refrigerant to a building at varying flow rates to meet the heating and cooling loads of the building. The refrigerant is piped to an assortment of indoor fan-coil terminal units that perform the required cooling and/or heating based on call from the local zone thermostat. Refrigerant can also be supplied to make-up air units to temper the ventilation air. The compressor units typically range in capacity from 6-tons (72,000 Btu/hr) to 40-tons (480,000 Btu/hr) with the larger units consisting of a series of modules. The number of compressor units can be varied if higher loads within the building must be met, or if the interior loads vary significantly due to interior loading or building orientation. Typically, systems are limited to roughly 62 indoor units per system and limited to maximum lengths for network piping. Additional systems would be employed if these limitations are exceeded for a given facility.

The indoor terminal units vary in capacity from as small as 5,800 btu/hr to as large as 96,000 btu/hr. VRF indoor system installations range from as few as two units up to as many as sixty-two units per system based on the capacity required to satisfy all building zone loads. Whereas the air-cooled units heat and cool by drawing heat from or rejecting heat to 100% outdoor air, water-cooled units typically draw heat from boiler water, reject heat to cooling towers, or interface with ground coupled systems. VRF systems tend to be very efficient because they employ inverter driven compressors and condenser fans on the compressor units, as well as ECM fan motors on the terminal units.

VRF systems are typically one of two different arrangements. The heat pump arrangement (2-pipe) is a change-over system where the indoor units are in heating mode, or cooling mode, but not both. The second arrangement is a heat recovery system that can simultaneously provide both heating and cooling to different building zones. The heat recovery system is either a three-pipe system utilizing branch selectors, or a two-pipe system utilizing branch circuit controllers. The branch circuit controllers and the branch selectors separate sub-cooled refrigerant liquid to send to zones requiring cooling, from superheated gas to send to zones requiring heating.

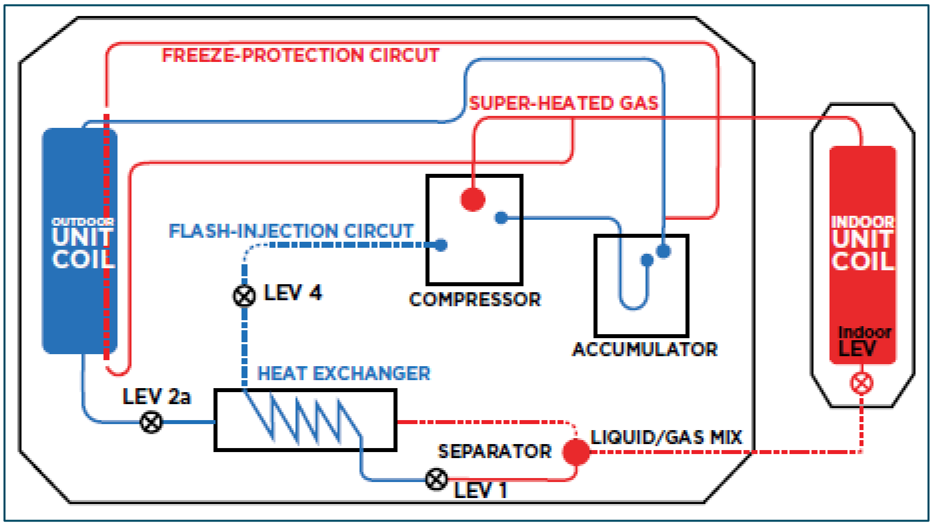

Figure 1 Mitsubishi VRF Flash-Injection Diagram: Heat Pump[1]

Two-pipe systems have liquid refrigerant piped from the compressor unit to the interior zones and refrigerant gas piped back. Three-pipe systems have a liquid refrigerant line, a gas refrigerant line, and a gas/liquid mixture line.

This assessment report of in-field performance measurement and testing protocols for cold climate VRF systems will focus on the more common air-cooled systems.

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[1] "Applying VRF Systems In Cold-Climate Applications" Mitsubishi Whitepaper, 2020

3. VRF Performance Metering

To determine efficiency or installed performance of VRF systems one must measure the energy consumption of the system relative to the heating and cooling loads that the system meets. For example, if we know the cooling load is 40 tons and the system draws 40 KW to meet the load the simple instantaneous system efficiency is 1.0 KW/ton of cooling. However, verifying performance of VRF systems can be significantly more difficult. First, determining the instantaneous load on the system can be a challenge, as it requires determining the air-flow of each terminal unit (cfm), the inlet and outlet enthalpy (temperature and relative humidity) of each terminal, and the electrical power consumption (kW) of the terminal fan. Second, the power demand of the outdoor variable speed compressors and fans needs to be measured as it matches the demand of the indoor load. Third, the load and consumption will vary throughout the year, requiring monitoring the above data over complete heating and cooling seasons relative to outdoor temperature and humidity. Complexity is increased with scale, as for the relatively small 40-ton system we referenced there may be as many as sixty-two indoor units to meter per system. To measure 100% of the load, and the effort of the compressor system to meet the load a metering system would need to log more than 400 control points. To design and install a 3rd party system of controls to monitor 400 points, the cost could be in the hundreds of thousands of dollars per metered system, rendering it impractical for most installations and requires alternative approaches to simplify the metering system.

One significant simplification is instead of measuring the heating/cooling load separately for all the terminal units, use overall refrigerant mass flow and refrigerant temperature and pressure from the compressor units instead. For example, a 40-ton VRF system using R-410A as a refrigerant would have a peak refrigerant mass flow in the range of 5,300 lbs/hr. If the flow on average is one-half of 5,300 lbs/hr, the building load would be approximately 20-tons. One simple way to measure liquid flow would be to use a clamp-on Ultra-sonic flow meter, but as the refrigerant flow from the compressor unit could be a multi-phase combination of liquid and gas and ultrasonic meters may not be accurate in these conditions. However, an alternative solution would be with the use of Coriolis flow meters for the refrigerant metering. Coriolis meters must be installed in-line in the refrigerant piping, and are expensive, but are accurate to 0.1% in this application. It is important to note that the HVAC systems during different times of day and year may be lightly loaded, requiring a meter be chosen that measures the lower flows accurately. A single Coriolis meter in the refrigerant liquid line would be adequate in two-pipe systems, while an additional meter would be required in the refrigerant gas line for a three-pipe application. Pressure sensors wells and sensors will need to be added to the refrigerant piping. Temperature measurements can be performed with strap-on sensors if adequately insulated.

Figure 2 Example of a Coriolis flow meter available from Omega – a Spectris Company.

Below is an example of a design for an in-situ VRF metering system in which both an ultrasonic and a Coriolis mass flow meters were installed for assessing the accuracy of the non-invasive ultrasonic flow meter. In a comparison (see Figure 3), ultrasonic flow meters have been shown to report a 10% lower flow rate than coriolis meters.[2]

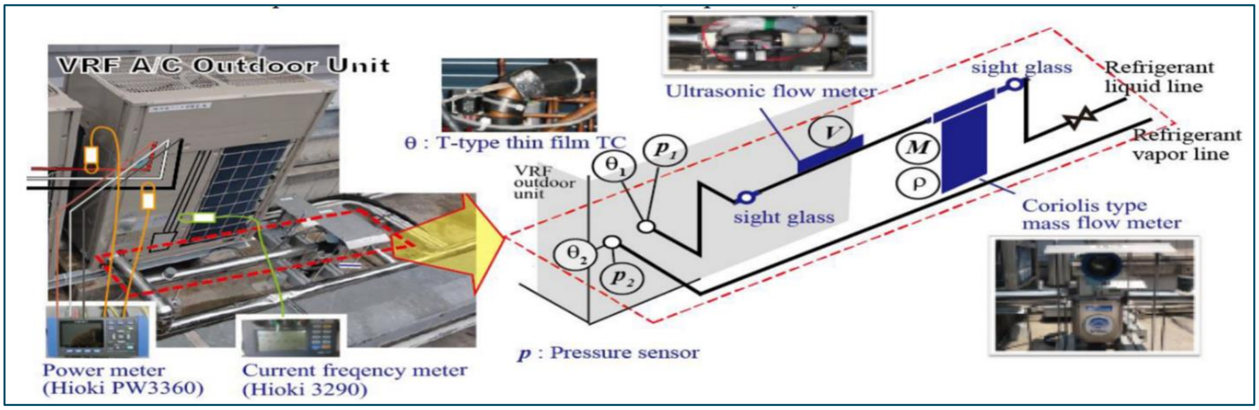

Figure 3 In-situ monitoring method for variable refrigerant flow (VRF) systems

Another significant consideration is that typical compressor units have a peak electrical demand of about 1 KW/ton of cooling. So, a 40-ton compressor unit draws roughly 40 KW. The indoor terminal units have low wattage ECM fan motors and draw approximately 70 watts/unit (0.07 KW) or about 2.8 KW collectively for a system. As a result, the compressor unit will draw 93% of the electrical energy, and the indoor terminal units draw 7% of the electrical energy. If a system test determines that this ratio remains constant through the range of compressor load, the electrical measurements can be simplified by just metering the power of the compressor unit and utilizing the predetermined proportional power of the indoor units.

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[2] Katsumi Hashimotoa, Hanazakib , Tanakac, Idac, Edahirod, Okad. "Study of In Situ Monitoring Method for (Cooling and Heating) Capacity of Variable Refrigerant Flow (VRF) Multi-Split Air Conditioners for Commercial Buildings". 12th IEA Heat Pump Conference, 2017.

As noted above, it will be impractical to meter all the indoor terminal units, so it will be important to choose a statistically significant sampling of the population. The more units metered, the higher the accuracy of the results, but with increased cost and metering system complexity. California's 2000 LNSPC Program Procedures Manual Appendix G has a statistical algorithm for the selection of sample size and this approach is also used by NYSERDA. The following table outlines results from the sample size calculation.

Table 1: Indoor Unit Metering Sample Size

# of Indoor Terminal Units	10% Precision Sample Size	20% Precision Sample Size
5	5	4
10	9	6
20	14	7
30	18	8
40	21	9
50	23	9
60	25	9
80	28	10

When selecting the indoor units to meter, once sample size is selected, it will also be important to select terminals from several representative zones. For example, select units serving south middle and corner zones, north middle and corner zones, interior zones, first floor and top floor zones.

Layering Metering Systems:

To accurately verify building load and HVAC system energy consumption it is necessary to independently meter significant equipment to establish a standardized approach and avoid introducing error into the process. To reduce the cost of the metering process it will be necessary to simplify and streamline data collection as much as possible without creating additional complexity or redundancy or errors. An example of this approach is utilizing data from the existing installation of a manufacturer's proprietary building automation system (BAS). The existing system conveniently reports compressor unit KW, but as these tend to be calculated values, and not measured values, it would be important to independently verify these values. It would be reasonable to use the BAS logging features to record equipment run status, and direct measurements of temperature, humidity, airflows, amperage, and demand based on 3rd party meter inputs to the building automation systems. Examples of data that can be reasonably collected from a manufacturer's based onsite BAS system such as the Daiken "Intelligent Manager III", and the Mitsubishi Electric "Diamond Controls Solution" include:

1. Space setpoint and actual space temperatures
2. Indoor unit calls for heating or cooling
3. Fan/compressor on-off
4. R/A & S/A temperature

5. Expansion valve position[3]
6. Outdoor air temp
7. Outdoor unit run status
8. Compressor inverter rpm
9. Outdoor unit fan step
10. Refrigerant system temperatures and pressures if accuracy can be independently verified by spot measurement.
11. Independently programmed I/O modules for measuring amperage and/or power directly.

BAS can also provide outdoor unit amperage and power, but again, these may be calculated values, not measured, so it would be useful in the cross verification of energy consumption.

4. Leak Detection:

When the construction and installation of the piping systems is complete in a VRF system and before the equipment is placed into service, it is very important to perform comprehensive leak detection of the refrigerant system. If leaks do exist the high-pressure refrigerant will leak out which is problematic environmentally, expensive in the replacement of the leaked refrigerant, will allow the introduction of contaminants such as air and water into the system, will degrade system performance, and will possibly result in the failure of the system compressors. Ideally it would be good to know what the typical leak rates are for VRF systems. Unfortunately, it is hard to measure leakage rates while the system is operating, so it is recommended that a system of checks be implemented to first directly measure leakage, and to second provide representative monitoring of the system to determine if leakage is likely to be occurring. For direct measurement of leakage, it is first recommended that once initial leak detection is complete that the refrigeration mechanics record the number of pounds of refrigerant that are required to charge the system. After a period of time the system should be checked with system gages, and more refrigerant added as necessary. The mass of refrigerant added would be an indication of the leakage rate per unit of time.

During the metering process it would be important for the auditor to document the procedure originally used by the contractor to test the system for leaks and to charge the system. This will help identify if a particular leak identification process is better than others. The documentation would include: the procedure used to leak test, the length of time for the pressure test, the pressure used, and was any form of temperature compensation employed.

A non-invasive system for indicating whether the system may be losing refrigerant charge would be to monitor compressor unit energy consumption. If the refrigerant charge is low the

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[3] It is not clear if this is a calculated value or received as a signal from the expansion valve.

compressors will have to work harder to serve a given load. So, if the building heating and/or cooling load (UA) is established relative to outdoor temperature, the compressor energy can be monitored over time. If the compressor demand rises significantly relative to a reference temperature the system should be checked for refrigerant loss.

5. Site Selection:

Success in the metering of VRF system performance is contingent on the proper selection of test sites. To minimize error and control cost it is proposed that the selected sites have the following characteristics:

- Simple building configuration, square or rectangular would be best without excessive glazing area.
- Ideally the building will have been energy modeled.
- Building area between 10,000 and 40,000 square feet.
- Existing Building Automation System that communicates directly with the VRF system and has expansion capability to accept 3rd Party inputs and outputs.
- An owner that is open to sharing access or data from the BAS system for the furtherance of science.

6. Consensus Metering Parameters:

Several organizations contributed time and expertise in assessing the best and most practical means to meter these complex systems, and in evaluating the parameters that most affect and reflect the performance of these systems. These organizations included Daiken, Frontier, Mitsubishi Electric US (METUS), Ridge Analytics, Red Car and Pacific Gas & Electric.

The groups above have submitted lists of what they believe to be the most important parameters to meter the operational efficiency and performance of VRF systems. The following is a consensus list of these parameters and approach or system for metering.

Table 2: VRF Metering Parameters

Parameter	Units	Consensus Metering Strategy
Compressor amperage	A	3rd Party Power Meter
Compressor voltage	V	3rd Party Power Meter
Compressor power	kW	3rd Party Power Meter

Compressor frequency	Hz	Log from Manufacturer's BAS
Expansion valve position	%	Log from Manufacturer's BAS
Outdoor unit power	kW	3rd Party Power Meter
Indoor unit power	kW	3rd Party CT's measuring amperage
Supply airflow	CFM	Establish by airflow characterization and establish proxy using continuous amperage readings
Supply fan speed	Low/ med/ high	Use amperage at fan as proxy; with TAB airflow measurements to confirm airflows at various speeds.
Supply air temperature	deg F	3rd Party T/RH Probe or via BAS
Supply air humidity	%RH	3rd Party T/RH Probe or via BAS
Return air temperature	deg F	3rd Party T/RH Probe or via BAS
Return air humidity	%RH	3rd Party T/RH Probe or via BAS
Output power	BTUH	Calculated from airflow and delta enthalpy
Output energy	BTU	
Capacity	BTUH	
Space temperature set point	deg F	BAS trend (if available); spot observations of t-stats
Space temperature	deg F	3rd party wall mount T/RH/CO2 sensor
Space humidity	%RH	
CO2	ppm	
Outdoor temperature	deg F	3rd party Integrated T/RH probe or local weather station data
Outdoor humidity	%RH	
Particulate matter	ppm	Unnecessary - doesn't affect load or efficiency and difficult to meter
Refrigerant Mass Flow	Lbs/hr	Coriolis meter on refrigerant liquid line for 2-pipe systems, and on refrigerant liquid, and refrigerant suction for 3-pipe systems (calculate mix line flow).

Refrigerant concentration	ppm	Impractical for small, decentralized systems
Refrigerant receiver level	%	Impractical for small systems many of which lack receivers
Refrigerant Temperature	deg F	3rd party strap-on insulated temperature sensors
Refrigerant pressure	PSI	3rd party pressure sensors via test ports
Refrigerant charge	lbs.	Comparison between start-up report and subsequent maintenance reports detailing quantity of refrigerant added.

7. Appendix A – Coriolis Flow Meters

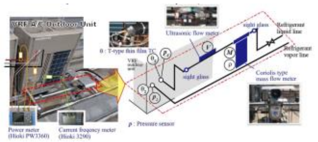
Technical Notes on Coriolis Flow Meters:

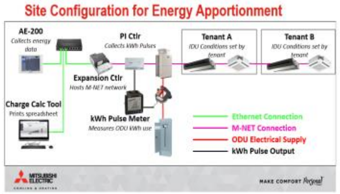
- Coriolis flow meters work well to measure multi-phase refrigerant mass flow and can achieve accuracies of 0.1%
- R-410A is a typical refrigerant used in VRF systems.
- The heat of vaporization of R-410A is 91.7 Btu/lb at 45 degrees F.
- A ton of cooling is 12,000 Btu/hr
- Most VRF systems fall in the range of 6 to 40 tons cooling capacity.
- Mass flow of refrigeration systems is then:
    - 10 tons – 1,309 lbs/hr or 595 Kg/hr
    - 20 tons – 2,618 lbs/hr or 1,190 Kg/hr
    - 40 tons – 5,236 lbs/hr or 2,380 Kg/hr
- Tactical Flow meter sells a Coriolis flow meter, ½" connections, 300 to 3,000 Kg/hr flow for: $5,300., and a 1" meter, 600 – 8,000 kg/hr for $6,300.
- Omega sells a Coriolis flow meter, ½" connections, 100 to 3,000 Kg/hr flow for: $4,655.
- Omega also sells a clamp-on Ultrasonic flow meter for $2,157 which is estimated to be +/- 1% accurate with liquids.
- Since the VRF systems are variable flow and are likely to experience light flow for much of the year it would probably be better to find units that are accurate at lower flow conditions.
- The ½" connection size for the flow meters in the correct flow range is smaller than would be encountered in the system liquid line, so it will be necessary to create a length of pipe on the inlet and discharge from the meter with pipe reductions at each end to transition to the system piping. It will need to be verified the minimum straight pipe length for accurate flow measurement.
- Coriolis flow meters are accurate, but expensive to purchase, and invasive to install. It may be a good idea to install a clamp-on Ultrasonic flow meter in series with a Coriolis meter to determine if the Ultrasonic meters are accurate enough for simplifying future metering projects.

Coriolis flow meter available from Omega – a Spectris Company.

8. Appendix B – Summary of NEEP RFI Responses

Summary of Field Validation of VRF System Performance in Cold Climates RFI Responses

RFI Response	Resource	Year	Primary Objectives	Field Measurement Approach	Key Metrics	Important Appraoch, Equip, Site Notes - Problems/Solutions	Monitoring/ Measurement Details	Refrigerant leakage
Daikin	In Situ Monitoring Method for (Cooling and Heating) Capacity of Variable Refrigerant Flow (VRF) Multi-Split Air Conditioners for Commercial Buildings	2017	Calculate capacity (for cooling and heating), power consumption and coefficient of performance (COP) using measurement values	Refrigerant flow measurement utilizing an ultrasonic flow meter (UFM), a Coriolis flow meter (CFM), 12 thermocouples and an absolute pressure sensor.	-T-type thermocouple - Surface temperature of liquid piping of outdoor unit [oC] - Surface temperature of vapor piping of outdoor unit [oC] Pressure sensor - [High pressure] Outdoor unit liquid line pressure [MPa] - [Low pressure] Outdoor unit vapour line pressure [MPa] Coriolis-type flow meter - Mass flow rate [kg/min] and density [kg/L] of liquid refrigerant Ultrasonic-type flow meter -Volumetric flow rate of refrigerant liquid [L/min] Power meter - Electric power consumption [kW]			
Energy350	Reference to a neea study of "Combination Ductless Heat Pump & Heat Pump Water Heater Lab and Field Tests" This report summarizes the lab and field test findings for Mitsubishi's prototype Ductless Heat Pump (DHP) Plus H2O product.	2015	Use refrigerant based measurements to measure work done on VRF/ductless systems.	Three Approaches given: 1- Refrigerant based measurements using a Coriolis flow meter, airside measurements of indoor unit, factory submetering. 2 - Airside measurement using air flow and delta T. 3 - Factory submetering, typically used for tenant billing.	Refrigerant parameters used to calculate enthalpy: - flow - temperature - pressure Airside - airflow, cfm - delta t Factory submetering - kWh by IDU - kWh of ODU Refrigerant Leakage -using air quality	Cost – These meters are ~$15,000 each and need to be very specifically sized for each application, making them difficult to reuse. Potential refrigerant leakage – This meter is installed in line with the refrigerant and requires fittings to transition between the flow meter and refrigerant line. This introduces meaningful risk of causing additional refrigerant leakage, potentially resulting in the classic "observer effect", which is the problem of measurement affecting the outcome. Heat Recovery – Given the cost of these flow meters and potential refrigerant leakage, it would be impractical to measure work done at the zone or maybe even branch box level. Measuring it at the Outdoor Unit (ODU) level would provide a good measure of net total work done, but would exclude the benefits of heat recovery at the branch boxes.	None given.	We have not found an easy factory option or automated way to measure refrigerant leakage. Options include: 1- For the post case measurement, we propose pumping down the system and weighing the recovered refrigerant. 2 - recommend that the official record of starting refrigerant charge not be the factory charge + added refrigerant. Instead we recommend releasing the factory charge plus the required added refrigerant, then conducting an initial pump down and weighing of the refrigerant before adding it all back into the system. This will create an apples to apples measurement approach between baseline and post case measurements
Frontier Energy, Inc.	Response is based on real field experience of VRF systems with various configurations and applications—primarily in the Northeast, where we have performed field research studies for NYSERDA and national lab clients. Monitoring and verification test standard for residential ccASHPs for Brookhaven National Lab. Frontier is directly involved in monitoring twenty of these test sites around New York State.	current	Collect three types of data to properly ascertain performance of any VRF system: 1. Performance metrics 2. Characteristic data 3. Measured performance data	See table on 'Frontier parameter table' tab of this spreadsheet	In some cases, a surrogate method to obtain an estimated or implied value may be possible at reduced cost or intrusion. We have had success determining the following metrics on VRF systems, among others: - VRF electrical energy and peak demand consumption - Air side capacity - Short time-step efficiency at steady state (COPheating / COPcooling) - Seasonal efficiency (COPheating / COPcooling) - Condenser refrigerant temperatures (entering, mid-coil, leaving) vs ambient temperature - Evaporator refrigerant temperatures (mid-coil) vs ambient temperature - Evaporator refrigerant temperatures (mid-coil) vs return (room) temperature	We find that the distributed nature of VRF systems (one outdoor unit, many indoor sections) often means that running wires to all these locations is impractical. Therefore, we often use distributed data loggers that are connected via WiFi or radio connections. While wireless sensors are theoretically possible, we find that the cost, accuracy, and reliability/response time of these sensors makes then less practical. It is also important to make sure the readings all sensors are carefully time-synchronized. Therefore, we recommend that any field protocols ensure that wireless approaches from proposers must demonstrate the accuracy and reliability/response criteria are met. We find that response times of five (5) seconds are often minimum possible for distributed wireless systems.	While laboratory standards such as ASHRAE Standard 37 allow for capacity measurements based on refrigerant side measurements, we believe these are impractical in the field and even less practical for VRF systems. VRF systems are more likely be sensitive to liquid line pressure drops imposed by refrigerant flow meters. Furthermore, these systems are more likely to operate with a mixed-phase liquid line at part load conditions—making this measurement approach unworkable. Air-side capacity measurements of a conventional system with good instrumentation generally come up with measurement uncertainties of ±5 to 15%. As more measurements are included, the uncertainty increases. As the number indoor heads exceeds 4 or 5, the measurement uncertainty may become a problem. Therefore, other techniques such as doing an air-side heat balance on the outdoor unit may start to become a more cost effective means to measure performance.	We have found that long term measurements of refrigerant pressure are problematic on VRF systems. Any permanently installed pressure sensor on a service port has a significant probability of causing refrigerant loss over several months. Therefore, we are proponents of only using temperature sensors that are properly installed on the outside of refrigerant piping.

RFI Response	Resource	Year	Primary Objectives	Field Measurement Approach	Key Metrics	Important Appraoch, Equip, Site Notes - Problems/Solutions	Monitoring/ Measurement Details	Refrigerant leakage
METUS	Mitsubishi Electric has an Enhanced Control offering for determining the percentage amount of outdoor unit energy used by each indoor unit. This offering is called Energy Apportionment and is comprised of Watt Meters, Pulse Input Controllers, a dedicated Central Controller, Software & Licenses to Calculate Energy Apportionment in 30 minute increments.	n/a	Proposed multiple measuring strategies for obtaining VRF performance	3 types of Collection Methods: 1) Available from manufacturer via Manufacturer Standard BACnet 2) Available from manufacturer via Manufacturer Enhanced Controls 3) Available by using additional 3rd party sensors/components	See table on 'METUS parameter Table' tab of this spreadsheet	Mitsubishi Electric has an Enhanced Control offering for determining the percentage amount of outdoor unit energy used by each indoor unit. This offering is called Energy Apportionment and is comprised of Watt Meters, Pulse Input Controllers, a dedicated Central Controller, Software & Licenses to Calculate Energy Apportionment in 30 minute increments. Shown below are an example schematic diagram & panel image. This Enhanced Control Offering could be used as a basis for collecting energy data at the site and would take advantage of data normally collected by the manufacturer through standard and enhanced methods, while requiring minimal 3rd party sensors and components that would add to the cost of the project significantly.		no information provided.
Slipstream	Investigating Cold Climate VRF as a measure for the Michigan utilities. Involved in Minnesota Power study involving savings and occupant comfort from installing air source VRF systems	2020		Not stated in response	N/A	Output Energy/Capacity - can be complex and costly, heat recovery introduces additional challenge. Refrigerant flow, Pressure, or Temerature Monitoring - evacuating refrigeration is expensive and potentially hazardous to the environment. Individual Component Power - outdoor unit is factory sealed. Refrigerant Leakage - Small sample size may not yield enough confidence in the true impact. VRF systems are often paired with a separate ventilation system. Supplimental heat is often specified with VRF systems	N/A	Refrigerant Leakage - Small sample size may not yield enough confidence in the true impact
Ridge Analytics	Study on maximizing the performance of minisplits, Evaluation on the impacts of ductless mini-split heat pumps, See 'Ridge Analytics Previous Studies' tab for full list of studies	Multiple See 'Ridge Analytics Previous Studies' tab		Have as many measurements as practical on cellular-enabled data loggers	See table on 'Ridge Analytics parameter table' tab of this spreadsheet	See table on 'Ridge Analytics parameter table' tab of this spreadsheet for comments on metering table		Refrigerant concentration note from parameter table - For all but the largest leaks I am not sure that this measurement would do much good. Are you thinking about spot measurements for leak detection? If so there are many meters available.
Red Card / PG&E	Completed monitoring (5) VRF systems in various size office/classroom builidngs in different climate zones in California. Starting monitoring of (3) additional office/classroom buildings in Q3/Q4 2020	2017-2020	Research Objectives 1) Measured outdoor unit power and indoor fan coil (some airside thermal load monitoring. 2) Informed comments to DOE on VRF test procedure and standards 3) Field testing was	Used ClimaCheck (home.climacheck.com) field monitoring system to measure performance of outdoor unit See table on 'Red Car Parameter Table' tab of this spreadsheet	See table on 'Red Car Parameter Table' tab of this spreadsheet	For site with Phase 2 detailed VRF monitoring, we also monitored individual compressor power (fairly difficult) and refrigerant temperatures inside outdoor units (6 points) and at select fan coils	Leveraged BMS data where available, used ClimaCheck and metering for evaluating performance metrics	Not monitored