BONNEVILLE POWER ADMINISTRATION

Controlled Condition Performance Mapping of Advanced Variable Refrigerant Flow Heat Recovery Systems

Stage Gate 1 – Design of Test Stand and Design of Experiment

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Controlled Condition Performance Mapping of Advanced Variable Refrigerant Flow Heat Recovery (VRF-HR) Systems

Test Stand Design (Document and Schematic)

This document summarizes the test stand design for testing variable refrigerant flow heat recovery (VRF-HR) systems and summarizes the experimental design and approach to testing. This document will serve as a guide for constructing the test stand at EPRI's Thermal Environmental Lab in Knoxville, TN and serves as the deliverable required for Stage Gate 1.

Design of Experiment

Two VRF-HR units from different manufacturers will be tested in this project. One test unit will have a three pipe heat recovery setup (LG Electronics) while the other will have a two pipe heat recovery setup (Mitsubishi). Table 1 gives information on the units to be tested. The general approach will be to control relevant air-side parameters while collecting output performance data at discreet points of steady-state operation. The primary metrics include system power consumption and zonal heating and cooling capacity as delivered by the VRF system. Testing is designed to capture the steady-state performance of the equipment and will not take into account anticipated building load or rate of reaching set point. Secondary metrics include supply air temperature and relative humidity. Single parameters will be changed in discreet steps while holding others constant. This process will be repeated across multiple designated variables to construct a multi-dimensional performance map relating measured output to input parameters. Primary air side variables are: outdoor-air dry-bulb temperature, indoor-unit return-air dry-bulb temperature, indoor-unit return-air relative humidity (cooling only), and outdoor-air relative humidity (heating only). Two additional parameters that will be changed in discreet steps are the ratios of the number of indoor-units providing cooling divided by the total number of indoor-units, and the number of indoor-units providing heating divided by the total number of indoor-units. The performance map will allow the parametric curve construction using least squares or another appropriate regression analysis method. The equation set will be the basis for development of a VRF-HR module for use in building modeling software. EPRI's overall effort in performance characterization and modeling for VRF and VRF-HR systems is being funded by three parties, BPA, Southern California Edison (SCE) and the Florida Solar Energy Center (FSEC) in complementary projects. EPRI will provide to FSEC laboratory data on VRF systems as parametric performance curves (or equations) for incorporation into a coded module. An additional, complementary modeling effort will be undertaken by EPRI or a chosen subcontractor under the guidance of SCE using EPRI lab data provided by the SCE and BPA efforts. The goal is to have coded modules available for incorporation into several commonly used building simulation software packages.

The three projects began in the late part of 2010. The BPA effort in conjunction with SCE co-funding will lead the schedule in the near term to collect performance data. The primary laboratory data collection of two, and possibly three VRF systems will take place over the next ~8-10 months and this data will be shared with FSEC for their modeling effort as it becomes available. EPRI will also work with SCE during this period to identify other modeling agents or other modeling tasks that will complement the work being done by FSEC. The greater SCE project includes additional tasks considered outside the scope of performance characterization, including field monitoring of an installed system in Southern California.

Table 1: Manufacturer's data for the units to be tested

TEST UNITS		
MANUFACTURER	**LG ELECTRONICS**	**MITSUBISHI ELECTRIC**
OUTDOOR UNIT	**Multi V Sync II**	**CITY-MULTI R2 Series**
Model #	ARUB076BT2	PURY-P72THMU-A
Electrical	208-230V/60Hz/3 Ph	208-230V/60Hz/3 Ph
Capacity		
Cooling	76400 Btu/h	72000 Btu/h
Heating	86000 Btu/h	80000 Btu/h
Power Input		
Cooling	6.2 kW	5.9kW (estimated)
Heating	7.0 kW	6.5kW (estimated)
Refrigerant	R410a	R410a
Refrigerant Charge	17.6 lbs	n/a
Indoor Units	4	4
Air Flow Max	6700 cfm	6550 cfm

MANUFACTURER **LG ELECTRONICS** **MITSUBISHI ELECTRIC**

INDOOR UNITS

	LG ELECTRONICS	MITSUBISHI ELECTRIC
Model #	ARNU243B2G2	PEFY-P24NMSU-E
Electrical	208-230V/60Hz/1 Ph	208-230V/60Hz/1 Ph
Capacity		
Cooling	24200 Btu/h	24000 Btu/h
Heating	27300 Btu/h	27000 Btu/h
Power Input		
Cooling	0.8 kW	n/a
Heating	0.8 kW	n/a
Air Flow Max	671 cfm	706 cfm

Measured Data Points

To calculate capacity, power consumed and COP, sensors and transducers will be installed in the test stand. Some points will be both input parameters and output measurements, while others are for general system diagnostics. The main parameters of interest are:

Indoor Unit (4 total):	**Outdoor Unit:**
Return Air Relative Humidity	Condenser Entering Air Temperature
Supply Air Relative Humidity	Condenser Leaving Air Temperature
Unit Power	Total Power
Suction Line Temperature	Suction Line Pressure
Refrigerant Flow Rate (only on one unit initially)	Condenser Entering Air Relative Humidity (or other moisture indicating measurement)
Return Air Temperature	Condenser Leaving Air Relative Humidity (or other moisture indicating measurement)
Supply Air Temperature	Suction Line Temperature
Air Flow Rate	Liquid Line Temperature
Liquid Line Temperature	
Suction Line Pressure	
Condensate Measurement	

More details about instrumentation are provided in a later section.

Range of Test Conditions

The range of conditions under which the VRF systems will be tested will be sufficient to characterize heating and cooling capacity, and power use profiles under expected operating conditions. The initial range of testing was determined by the model development requirements as defined by FSEC. Outdoor air temperatures will generally range from 60˚F to 105˚F for net cooling operation and 10˚F to 60˚F for net heating operation. Within this range of conditions, the typical rating conditions as defined by standards such as AHRI 1230 or AHRI 210/240 will be a tested subset. In heat recovery operation, the outdoor air temperature range is 55˚F to 85˚F. These ranges may be expanded or adjusted according to available time and needs as they develop over the course of testing.

General testing for performance mapping falls into 5 general categories:

1. Full load cooling tests
2. Full load heating tests
3. Partial load cooling only tests
4. Partial load heating only tests
5. Heat recovery mode

Data from these tests will be incorporated into the overall performance map.

As the name suggests, the full load tests (heating and cooling) will be conducted with all 4 units providing heating or cooling at the same time. Partial load is simulated by turning off units. The following three steps will be simulated for partial load - 75% load (1 indoor-unit off), 50% load (2 indoor-units off) and 25% load (3 indoor-units off). The indoor units remaining in the ON state will operate at full load conditions which will represent the required partial load of the outdoor unit. These tests will be conducted at the rated indoor-unit airflow, however, as time permits and as warranted by data collected, some tests may be performed with reduced indoor unit fan speed and air flow. The outdoor unit will be allowed to reach its natural steady-state fan speed as determined by the VRF control system. Since all conditions on the system remain constant in a given test, the VRF control system will regulate the fan speed to satisfy the load. As per ANSI/AHRI Standard 1230 ‘Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment’ the outdoor unit fan should be configured per the manufacturer’s specifications and should be unchanged for all tests.

In heat recovery mode, instead of turning units off as in case of partial load, the units will be forced to operate in the opposite mode by supplying conditions appropriate for that mode. For example, 2 units will be forced to operate in cooling mode and 2 units forced to operate in heating mode. In heat recovery mode heat is recovered from the units in cooling mode and transferred to the units in heating mode. Thermostatic setpoints will be maintained at unachievable levels to ensure the indoor units continue to operate at fully loaded levels.

Indoor-unit temperature sensors will be installed in the return-air ducts. The set point on the thermostat will be lower (in cooling mode) or higher (in heating mode) than the return air temperature. For example, if the return air temperature is 80°F in cooling mode, the thermostat will be set at ~70°F. In this case since we are always supplying 80°F air on the return side, the thermostat will never be satisfied and the unit will continue to operate at full load. If time permits, additional conditions may be tested with set points closer to the return air temperature to study the dynamic performance of the system.

Table 2 provides proposed tests conditions. The test conditions are selected to align with the modeling needs of this project – for example, one parameter sweep might be done to find out if input power is a strong function of indoor dry bulb temperature or indoor wet bulb temperature. Sufficient data resolution is important for building the analytical models. Each VRF system performance map will consist of 200+ discreet test points along with some possible additional data during dynamic operation. The table shows specific dry bulb and wet bulb temperature increments that correspond to a fixed change in relative humidity. For example, every 3°F change in wet bulb temperature at 70°F corresponds to a 10% change in relative humidity. The proposed test conditions are also aligned with ANSI/AHRI Standard 1230 and the operating conditions recommended by the manufacturer.

The exact conditions are subject to modification during testing as guided by the results. For example if distinctly linear behavior is seen during certain parameter sweeps, the number of test points may be reduced. Conversely, if a parameter sweep shows distinctly non-linear behavior, additional points may be added. Some specific test conditions may be beyond the limits of the thermal chambers, particularly at low outdoor ambient and at high outdoor humidity in combination with high outdoor ambient temperature. Chamber capacity is nominally 10 tons, but capacity decreases at lower simulated outdoor temperatures. The exact operating envelope depends on the load provided by the unit under test and will be determined during testing. Some supplemental chamber conditioning systems may be used to augment the chamber testing range.

Frosting will likely occur on the outdoor coil in heating mode with the outdoor temperatures are below 40˚F. In such cases an attempt will be made to first collect non-frosted pseudo-steady state data starting with a dry-coil condition prior to substantial frost buildup. Additionally, data will be collected in non-steady-state frosting conditions capturing performance during the entire frosting and de-frosting cycle. EPRI will work with the manufacturer of each system to understand the anticipated behavior of the system during defrosting.

Table 2: Range of Test Conditions

TEST CONDITIONS

FULL COOLING LOAD - ALL 4 UNITS COOLING

	MIN	MAX	COMMENTS
OAT	65	105	Temperature steps - 5°F (65, 70,…105)
IAT (DB/WB)	70/58	85/70	Wet bulb steps - 3°F (58, 61,64,67,70)

FULL HEATING LOAD - ALL 4 UNITS HEATING

	MIN	MAX	COMMENTS
OAT (DB/WB)	10	63/51	Some conditions might not be reachable
IAT	55	80	Temperature steps - 5°F (60,65,…80)

COOLING PART LOAD - 75%, 50%, 25% LOAD (1,2 OR 3 UNITS TURNED OFF)

	MIN	MAX	COMMENTS
OAT	75	95	Temperature steps - 5°F (75,80,..95)
IAT (DB/WB)	70/58	85/70	Wet bulb steps - 3°F (58, 61,64,67,70)

HEATING PART LOAD - 75%, 50%, 25% LOAD (1,2 OR 3 UNITS TURNED OFF)

	MIN	MAX	COMMENTS
OAT (DB/WB)	34/33	63/51	Some conditions might not be reachable
IAT	65	80	Temperature steps - 5°F (65,70,…80)

HEAT RECOVERY MODE (1,2 OR 3 UNITS IN COOLING MODE, REMAINING IN HEATING & 1,2 OR 3 UNITS IN HEATING MODE, REMAINING IN COOLING)

	MIN	MAX	COMMENTS
OAT	55	85	
IAT (DB/WB)	70/61	80/67	Conditions are for cooling coils, heating coils at 70/60

OAT : Outdoor Air Temperature
IAT: Indoor –Unit Return-Air Temperature
DB: Dry Bulb
WB: Wet Bulb
All Temperatures in °F

Test Stand Design Criteria:

1. Test stand shall include an environmental chamber which has external means to control temperature (approximately between 10°F to 105°F) and relative humidity (approximately between 10% and 70%) inside the chamber. The outdoor unit of the VRF-HR system will be placed in this environmental chamber.
2. Test stand shall include four separately controlled ducted air stands with external means to control air temperature, relative humidity, air flow rate and static pressure. The air flowing through these duct runs will simulate the return air from the conditioned space. The air temperature and relative humidity will be individually controlled for each of the four duct runs to ensure each indoor unit operates in the required mode.
3. Test stand shall include instrumentation to measure air flow, system pressures and temperatures, power, refrigerant mass flow and relative humidity at different locations in the test system, and have flexibility for the addition of other measurement points as needed during testing.

Test Stand Design:

Outdoor Section: The outdoor section of EPRI’s dual-room climate chamber shown in Figure 1 will be used to house the outdoor unit of the VRF-HR units. The nominal capacity of the outdoor climate chamber is 10 tons. The VRF-HR units to be tested will have a nominal capacity of 6 tons. This chamber will have a steam generator and a dehumidifier to control the temperature and humidity conditions for the outdoor unit. Precise air temperature (± 0.5° F) and relative humidity (± 1%) will be controlled by integrated Honeywell programmable controllers. The climate chamber will be maintained nominally in the range from 10°F to 60°F for heating mode testing. In cooling mode, the chamber will simulate conditions up to approximately 110°F.

Figure 1: Dual Room Climate Chamber at EPRI's Thermal Lab (The right side chamber will house the VRF outdoor units under test.)

1. **Indoor Section:** The design of the indoor testing facility is a unique challenge. Since the systems to be tested have 4 indoor units, there needs to be 4 separately controlled air streams to simulate different conditions for different zones. For example, 2 indoor units will be forced to provide cooling while the remaining 2 will be forced to provide heating, which could not be accomplished with one environmental chamber.

To overcome the difficulties associated with testing 4 indoor units simultaneously, a duct based test setup is proposed. Instead of creating and conditioning four separate climate chambers, a four-zone ducted test stand was designed where the air supplied to each ducted zone is independently controllable. Each ducted zone will supply specific amounts of conditioned air to the return-air intake of the indoor unit. To condition the return air, a common supply duct with a variable speed fan and a cooling coil will pre-cool and dehumidify the air supplied to each ducted zone, which will have heaters, air / water atomizing humidifiers for humidity control and a damper system for flow regulation. This entire setup will provide independent control over conditions at the inlet of each indoor unit. Figure 2 shows the plan view of the test setup.

The principle of operation is as follows: Ambient air is drawn into a common intake and through a pre-cooling coil which cools the air stream and reduces the absolute humidity. Beyond the cooling coil, the air stream splits into four separate 12” x 12” ducts with individual dampers to control volume flow through each circuit. Each of the four ducts has a resistance duct heater and a spray mist humidifier to bring the conditioned air up to prescribed conditions. The heaters and humidifiers in each duct are independently controlled to maintain temperature and relative humidity at the prescribed set point. The variable speed fan will provide the required air pressure to overcome the resistance of the test stand ducts, resistance heater, blenders and instrumentation equipment. The fan speed will not be varied during an individual test. The fan is variable speed to ensure the prescribed air flow rate is supplied to the indoor units.

2. **Instrumentation:** The data acquisition and control of the test stand will be accomplished through a dedicated National Instruments PXI system. Programming will be done using LabVIEW software from National Instruments.

   Table 3 lists the sensors and transducers that will be used to gather VRF system test data. The Setra pressure transducers have an accuracy of ±0.13% of full scale which translates to ±0.65psi. The type T thermocouple accuracy is better than 0.5°C. The Vaisala is rated at ±1% RH and ±0.2°C. Power measurement is done via Shark 100T meter which is a revenue grade meter with accuracy better than ±0.2% of reading. The precision of the performance measurements is expected to be ± 3 percent.

Figure 2: Plan View for Test Setup

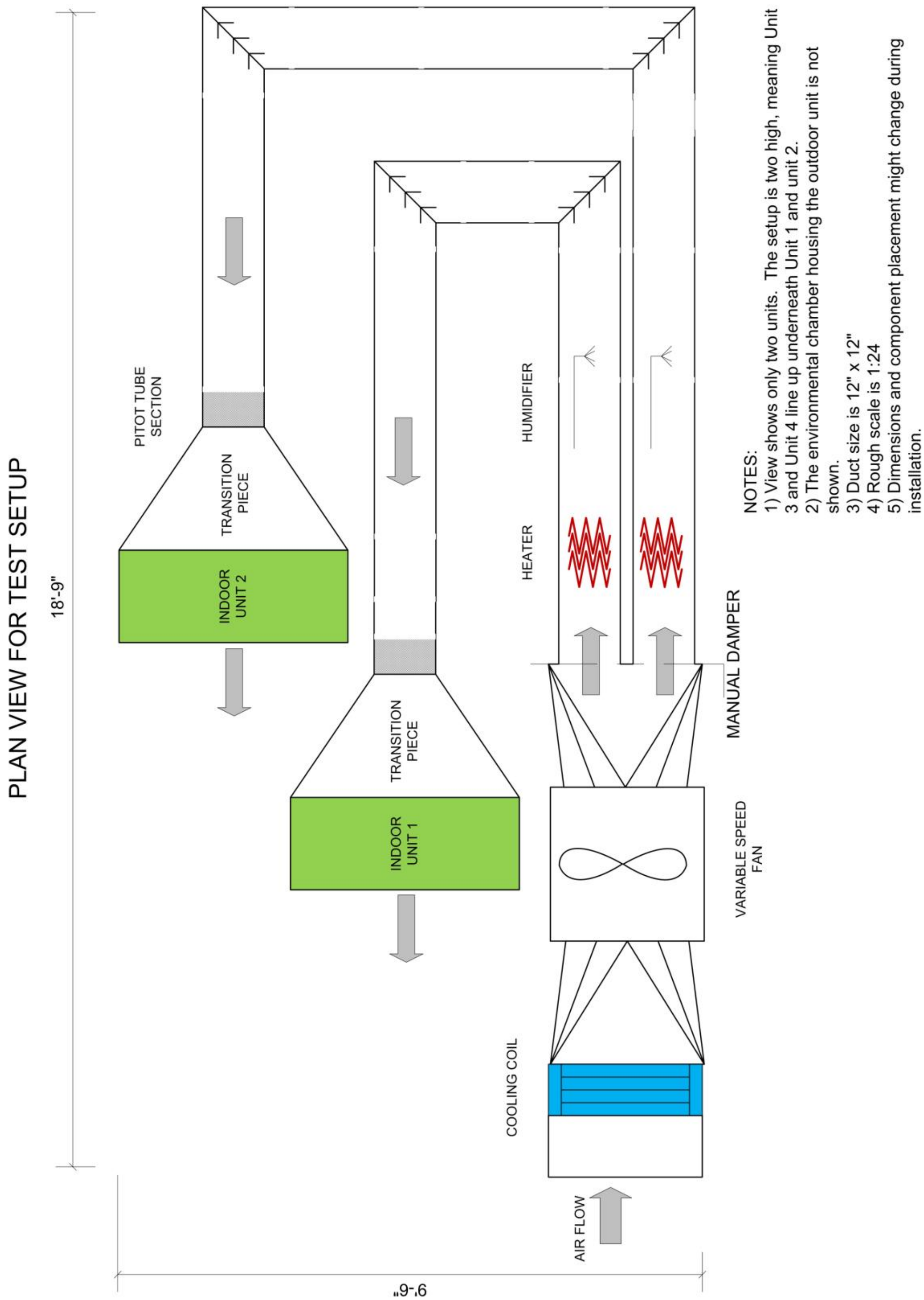

Table 3: List of sensors and transducers for data acquisition

DATA ACQUISITION EQUIPMENT	H/W	P/N	QTY	COMMENTS
PRESSURE				
Differential Pressure		DPT2500		Air flow measurement
Pitot Tube	Veltron	Plus	4	Flow thru indoor unit
Absolute Pressure				Refrigerant Pressure
Indoor Unit (IN)	Setra	205-2	4	
Indoor Unit (OUT)	Setra	205-2	4	
Liquid Line	Setra	205-2	1	
Suction Line	Setra	205-2	1	
Hot Gas Line	Setra	205-2	1	
TEMP + REL. HUMIDITY				Air side measurement
Indoor Unit (RETURN)	Vaisala	HMD60Y	4	
Indoor Unit (SUPPLY)	Vaisala	HMT333	4	
Return Air for test setup	Vaisala	HMD60Y	1	
Outdoor Chamber	Vaisala	HMD60Y	1	
TEMPERATURE				Refrigerant Temperature
Liquid Line	Omega	Type T	1	
Suction Line	Omega	Type T	1	
Hot Gas Line	Omega	Type T	1	
Indoor Unit (OUT)	Omega	Type T	4	
Indoor Unit (IN)	Omega	Type T	4	
POWER				
Indoor Unit	Shark	Shark 100T	4	For each indoor unit
Outdoor Unit	Shark	Shark 200T	1	For outdoor unit

To reach and maintain a particular set point, numerous components need to be controlled. The hardware that is adjusted to maintain steady state conditions is listed in Table 4.

Table 4: List of components controlled during a test

CONTROLLED HARDWARE			
HARDWARE	**CONTROLLER**	**TYPE**	**COMMENTS**
HEATERS			
Duct	LabVIEW	PWM	Mult. safety interlocks, manual override
Chamber	Honeywell	PWM	
HUMIDIFIERS			
Duct	OEM	Modulated	Air/water atomizing humidifier control
Chamber	Honeywell	PWM	Steam generator
DEHUMIDIFIER			
Duct	Cooling coil	ON/OFF	Cooling coil used for dehumidifying
Chamber	OEM	ON/OFF	Munters unit attached to the chamber
AIR FLOW			
Duct	Damper	Manual	
Overall	Fan drive	Manual	Adjust fan speed to required flow rate
COOLING			
Duct	Solenoid Valve	ON/OFF	Manually turn On/Off as per requirement
Chamber	Solenoid Valve	ON/OFF	Manually turn On/Off as per requirement
TEST SYSTEM			
Indoor Units	OEM Remote		Set conditions on remote control
Outdoor Unit			Minimal control, reacts to set conditions

The data collected from the indoor units will provide the necessary input for capacity calculation. All 4 indoor units will be instrumented for air side measurements. Air temperature and relative humidity will be measured in the “return-air” duct entering the indoor unit and at the exit of the indoor unit. Air pressure will be measured in the ambient air and differential pressure will be measured on each duct run, allowing for air density and air mass flow calculations for each test circuit. From these measurements, air-side capacity will be calculated.

On the refrigerant-side, refrigerant pressure and temperature will be measured at the inlet and exit of each test unit coil to allow for calculation of refrigerant enthalpy.

Standard laboratory practices will be followed and applicable testing standards such as ASHRAE standards for temperature, humidity, air flow, etc. will guide the effort. Additionally, AHRI standard 1230--*2010 Standard for Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment* will also act as a guide to testing. Any required deviations from these standards will be noted in the final report. The number of anticipated test conditions to build a performance map of VRF systems will greatly exceed those required by the 1230 rating standard, but the 1230 requirements will be a subset of overall testing. The tested performance at 1230 rating conditions will be compared to published manufacturer 1230 performance in the final report.

One of the indoor units will be instrumented with a mass flow meter on the refrigerant side to serve as a validity check on air side measurements. Since flow measurement on the refrigerant side is an invasive procedure that can affect performance of the unit, an initial test will be run to evaluate this procedure. If no discernable performance degradation is observed, then additional circuits may have refrigerant mass flow sensors added.

Power will be separately measured using a Shark 100T power meters for the outdoor unit, each indoor unit and any branch selector control box for a particular tested unit. Temperature and relative humidity of air entering and leaving the outdoor unit will be recorded. Additional temperature and pressure sensors may be placed at other points in the refrigerant circuit for diagnostic purposes, such as on the compressor inlet and exit manifolds. All raw data will be recorded electronically. The data recorded on the test report sheet will be included in the final report. The final report will also include graphical and/or tabular representations of data along with appropriate analysis and explanation. Figure 3 shows an example test report sheet.

Figure 3: Test Report Sheet

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Testing and Modeling of Advanced VRF Systems

DATE		SYSTEM		OPERATOR		TEST ID	

SET CONDITIONS

INDOOR	UNIT 1	UNIT 2	UNIT 3	UNIT 4
MODE				
CONDITION				
SET POINT				

OUTDOOR UNIT	DRY BULB	WET BULB

INDOOR UNITS DATA

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	
INLET AIR T					° F
INLET AIR RH					%
OUTLET AIR T					° F
OUTLET AIR RH					%
AIR FLOW RATE					
CAPACITY					BTU/hr
POWER					kW

OUTDOOR UNIT DATA

INLET AIR T		° F
INLET AIR RH		%
OUTLET AIR T		° F
OUTLET AIR RH		%
POWER		kW
COP		