

# Field Monitoring Protocol: Mini-Split Heat Pumps

D. Christensen, X. Fang, J. Tomerlin, and  
J. Winkler

*National Renewable Energy Laboratory*

E. Hancock

*Mountain Energy Partnership*

March 2011

## NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy  
and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
phone: 865.576.8401  
fax: 865.576.5728  
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
phone: 800.553.6847  
fax: 703.605.6900  
email: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
online ordering: <http://www.ntis.gov/ordering.htm>



Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

## **Acknowledgment**

The authors thank Ben Larson of Ecotope, Inc. for his comments and input, as well as for laying some groundwork on the methods developed for (and omitted from) this protocol.

## **Foreword**

The purpose of the Building America Mini-Split Heat Pump (MSHP) Field Monitoring Protocol is to provide a consistent methodology for performance measurement of MSHPs when installed in a building. This document provides instruction on instrumentation, short-term testing, and long-term monitoring of these systems. It further provides an abbreviated field test report of the authors' validation of the described methodologies.

This protocol is intended for application by the U.S. Department of Energy's Building America program, and optionally by outside entities, when studying MSHPs in buildings. The report describes the method for a single-head MSHP, but the sensors and methods can logically be duplicated for measuring a multi-head MSHP. It can be used in new construction and retrofit applications, and although the document targets residential installations, it could also be applied to performance measurement of small commercial building MSHP. This report focuses primarily on ductless MSHPs; ducted installations will be addressed in a future revision.

# Contents

<b>Acknowledgment</b> .....	iii
<b>Foreword</b> .....	iii
<b>Figures</b> .....	v
<b>Tables</b> .....	v
<b>Definitions</b> .....	vi
<b>Introduction</b> .....	1
<b>Relevance</b> .....	3
<b>Monitoring a Mini-Split Heat Pump</b> .....	4
Site Selection.....	4
<b>Monitoring Parameters</b> .....	6
Quality Assurance Protocol.....	7
<b>Short-Term Testing</b> .....	9
Steady-State System Curve Measurement.....	9
Short-Term Efficiency Test.....	10
<b>Long-Term Monitoring</b> .....	11
<b>Data Collection and Documentation</b> .....	12
Data Collection.....	12
Coefficient of Performance Calculations and Uncertainty.....	12
<b>Other Considerations</b> .....	13
<b>References</b> .....	14
<b>Appendix A. Field Test for Protocol Validation</b> .....	15
Objective.....	15
Short-Term Air Flow Test.....	18
Fan Revolutions per Minute Measurement.....	18
Supply Flow Measurement With Powered Flow Hood.....	19
About Fan Power, Unit Power, and Control Signals.....	22
Short-Term Test Results.....	22
Long-Term Monitoring.....	23
Monitoring Package.....	23
Results.....	23
Error Analysis.....	26
<b>Appendix B. Rigid Plenum Method (for reference)</b> .....	29

## Figures

Figure 1. Measured air flow versus tachometer frequency .....	9
Figure 2. Living room unit.....	15
Figure 3. Bedroom unit.....	16
Figure 4. Outdoor unit .....	16
Figure 5. Indoor unit nameplate information.....	17
Figure 6. Outdoor unit and nameplate information .....	17
Figure 7. Proximity sensor mounted.....	18
Figure 8. Fan balancing weight .....	19
Figure 9. Thermistors .....	19
Figure 10. Trash bag .....	20
Figure 11. Trash bag plenum with wire support .....	20
Figure 12. Inflatable plenum.....	21
Figure 13. Flow test setup.....	21
Figure 14. Air flow measured and submittal data.....	22
Figure 15. Living room unit air flow measured .....	24
Figure 16. MSHP outdoor condensing unit total power.....	24
Figure 17. MSHP outdoor condensing unit total power on August 20, 2010 .....	25
Figure 18. Living room unit air flow and temperatures trend on August 20, 2010.....	25
Figure 19. MSHP EER with living room unit operating only .....	26
Figure 20. Indoor living room unit air flow and outdoor unit power.....	26
Figure 21. Uncertainty propagation analysis .....	27
Figure 22. Uncertainty propagation table .....	28
Figure 23. Uncertainty propagation results.....	28
Figure 24. MSHP for indoor heat air flow test rigid plenum method .....	29
Figure 25. Researcher examining MSHP for indoor heat air flow test rigid plenum method.....	29
Figure 26. Researchers testing MSHP .....	30
Figure 27. Opening for unit room temperature thermistor sensing.....	30

## Tables

Table 1. Long-Term Monitoring Instrumentation Package .....	7
Table 2. Air Flow Measured and Submittal Data .....	22

## Definitions

AC	alternating current
AHRI	Air-Conditioning, Heating and Refrigeration Institute
ANSI	American National Standards Institute
CDD	cooling degree day
CFM	cubic feet per minute
COP	coefficient of performance
DC	direct current
DOE	U.S. Department of Energy
EER	energy efficiency ratio
HDD	heating degree day
HERS	Home Energy Rating System
HSPF	Heating Seasonal Performance Factor
HVAC	heating, ventilating, and air conditioning
MSHP	mini-split heat pump
NREL	National Renewable Energy Laboratory
RH	relative humidity
RPM	revolutions per minute
SEER	seasonal energy efficiency ratio

## Introduction

The mini-split heat pump (MSHP) is an emerging technology in the United States. Worldwide, however, MSHPs have an established and stable market in residential applications. Throughout Asia, this is the dominant technology for space conditioning. MSHPs are also common in Europe, largely because the ductless designs provide easily retrofitted point-source climate control. MSHP manufacturers are thus beginning to aggressively compete with more established unitary systems in the United States.

- MSHPs have large turndown ratios and can address wider variation in thermal loads than equipment manufactured by major U.S. heating, ventilation, and air-conditioning (HVAC) companies. Through innovative control methods, a variable-speed compressor, and variable-speed fans, the refrigerant system operation can be quickly adjusted through feedback control methods to provide cooling over a broad range rather than stepping between stages. In this way, part-load conditions are accommodated more efficiently with lower losses.
- An MSHP is often installed in a ductless configuration, and can serve one or more rooms individually. Originally these systems were designed with a single small outdoor fan/coil/compressor unit and a wall-mount “head” (fan/coil). Current products often have a remote-control interface, which may also contain the system thermostat.
- Multiple indoor coils can be installed for a single outdoor coil. This system configuration is termed a *multi*-split heat pump, and the methods described in this document are expected to apply to that configuration as well.

Manufacturers claim substantially higher coefficients of performance (COPs) for these systems than for the ducted unitary splits common in America, often claiming seasonal energy efficiency ratio (SEER) 22/heating seasonal performance factor (HSPF) 9 or higher. Some manufacturers do not provide engineering data to support these claims, so achieving rated performance in real homes is uncertain. Further, the novel features of MSHPs must be studied to understand whole-house impacts. For example:

- Variable-speed components enable “load-matching” rather than cycling on and off.
- Point-source space conditioning may leave some rooms or areas uncomfortable.
- Latent performance (humidity control) is less understood.
- COP variability as outdoor temperatures change is less certain. Some equipment claims to provide high performance at very low ambient temperatures in heating mode.
- Operating modes and control methods are not uniform between manufacturers. Different control and operation methods allow optimization to climate and to occupant loads. They also enable the occupant to use this equipment differently than other heating and cooling equipment.

MSHP merits significant evaluation because:

- It is all-electric and can provide heating at a COP well above 1.0, making it an attractive replacement system for electric resistance heating where natural gas is not available.
- Its high SEER rating promises substantial energy savings compared with more common unitary-split equipment.

- It can supplement air-conditioning or heating, and can provide both.
- It is minimally invasive, which simplifies installation in homes without ductwork.
- It is small and quiet.
- It can meet the minimal heating and cooling needs of many extremely high-performance Building America new homes.

In a recently initiated pilot project in the Northwest, customer approval ratings are high and energy impacts appear compelling (Larson and Allan 2010). Further study in the laboratory and field will permit a true “lessons-learned” and “best practices” analysis. Topics of interest include:

- System design
- Distribution of cooling and heating throughout the home
- Real-world installed efficiency (for comparison to published and laboratory data), including multiple head systems
- Occupant usage characteristics
- Marketability, including installation issues and retrofit potential
- Climate and regional applicability
- System costs versus energy and carbon savings potential



## Relevance

More than 20% of the electricity supply in the United States is consumed by residential buildings (DOE 2009); roughly 40% of that goes to space conditioning. The U.S. Department of Energy (DOE) has increasingly raised minimum appliance efficiency standards, but inefficient legacy equipment abounds throughout the U.S. housing stock. Ideally, aging equipment is replaced by space conditioning systems that provide high efficiency at appropriate cooling, heating, and dehumidification loads.

Building America has recently been directed to expand retrofit opportunity analysis, and MSHP is a key retrofit technology in several applications. Emerging technologies entering the U.S. HVAC market must be evaluated early in their adoption period. MSHP technology promises to be a key component of the energy efficiency strategy of reducing HVAC loads by 30% compared with best-available technology (Anderson and Roberts 2008). Laboratory testing to enable simulation of these systems is underway. Installing equipment in homes and monitoring its performance with occupants will address the “real-world” complications.

An excellent Market Progress Evaluation Report was recently published (NEEA 2010).

## Monitoring a Mini-Split Heat Pump

A key field test objective is to measure the energy tradeoffs between a ductless MSHP and any other heating or cooling devices that are used in the home, such as backup resistance heaters. This evaluation may be performed as part of a whole-house monitoring effort, or may be a standalone study of the MSHP installation. In either case, basic characteristics of the home must be understood to enable simulation of the MSHP. For retrofit cases, a Home Energy Rating System rating (HERS Rating) is acceptable, but a less extensive home evaluation may be adequate. Of particular interest is the amount of heating energy use offset by the ductless heat pump, so historical utility bills are typically required.

When arriving at a new field test site, information about the home and equipment must be gathered. Second, monitoring equipment and a data logger must be installed. Then the field test technician must perform several short-term tests to correlate certain measurements to performance parameters, and to verify the system was installed and is functioning correctly. Finally, the site will be monitored in the “long-term” to capture seasonal performance of the MSHP. The measurement equipment will be retrieved following the long-term monitoring period.

### Site Selection

Installations of multiple manufacturers’ systems are sought in each climate region. Application to retrofits and new homes will be needed. New homes permit better prediction of heating and cooling loads (more controlled experimental conditions), but present fewer challenges for installation. Retrofits present many complications, but provide a much greater opportunity for energy and carbon savings. Selection of test sites should be based on the following considerations:

- Geographical location
- Home heating and cooling type (for retrofits)
- System configuration (single or multiple heads, distribution methods)
- Homeowner approval of monitoring for at least one year
- Homeowner approval for release of historical utility bills (for retrofits)
- Building energy audit or evaluation. For retrofits, the audit must be performed before the retrofit and aspects related to the retrofit must be repeated after work is complete.
- Reasonable expectation that MSHP can provide acceptable heating and cooling for occupants and climate, and can be measured.

The following information should be obtained during the initial phone screening, literature review, or exploratory site visit:

- **Building use** (number of occupants and typical occupancy schedule)
- **Location of indoor heat pump heads** (which rooms, square feet and use, ducted/ductless)
- Measured **refrigerant line length** from outdoor unit to each indoor head
- Heating and cooling **distribution method**, if any, and relevant details
- **Equipment specifications** (MSHP model numbers and backup heating equipment)

- Documentation of contractor's proposed **scope of work and design specifications**
- **HVAC contractor's information**, including the point(s) of termination between the separate scopes of work covered by each contractor. Determine installing contractor experience (number of previous jobs) and certifications.
- **System sizing calculations** (Manual J or other), name of party responsible for sizing, and cooling and design heating month run fraction (either heating degree day [HDD] or bin analysis)
- **Climate design conditions** (outdoor dry-bulb design temperature, HDD, cooling degree day [CDD])
- **System controls**, including: thermostat setpoints, deadband, available operating modes, zoning, and ventilation control settings
- **Home construction details** (or audit information), including blower door and duct blaster results if applicable, for later use in identifying the cause of any discrepancies between predicted and actual energy use
- **Installation cost and date**. Include any known installation issues and duration.
- **Recent operating costs**. Monthly utility bills and costs of alternative fuels such as wood burning, oil, and propane tanks
- **System commissioning** and quality installation verification by contractor (startup documentation, in-field testing after startup, and nature of any post-installation service calls)
- Installer-supplied and manufacturer-recommended **maintenance requirements**
- **Temperature limits or cutout** (heating mode only)
- Complete list and details of **other retrofits** occurring along with MSHP installation, and during the monitoring period.

## Monitoring Parameters

Only standard heat pumps are widely available in MSHP format. As other implementations become available, this report will be revised to address monitoring details particular to that type of system as those products gain market share.

To estimate system performance, two measurements are needed: power consumed and load delivered. To estimate MSHP as a retrofit measure, a good estimate of the cooling/heating offset by the MSHP must also be obtained. Power consumption is easily measured with a standard Watt node of appropriate size and accuracy. Delivered load is much more difficult to estimate, and must be calculated from several measurements: temperatures, relative humidity (RH), and air flows. This report focuses on methods to cost-effectively estimate these parameters, particularly indoor head air flow.

Data points required for all field monitoring sites:

- Whole-house power/energy
- MSHP system power/energy
- Backup heat power/energy
- Outdoor air temperature and humidity
- Indoor air temperature and humidity taken in each living zone supplied by system
- Location of outdoor unit.

Data points required for all sites where MSHP efficiency or performance is sought:

- Return air temperature, measured near each indoor head inlet, but shielded from indoor coil and other radiant heat sources
- Supply air temperature for each indoor head
- RH measurement at return and supply of each indoor head
- Air flow rate for each indoor head (obtained via system curve using tachometer correlation; see Short-Term Testing)
- Vapor line temperature, for device status
- System runtime during the measurement interval (%) – Power measurement can be used to calculate this quantity
- Any unit controls, sensors, or outputs that can be accessed and recorded.

In addition to installing the data logger and setting up the sensors, the site manager may need to perform a basic audit to collect occupant and thermostat information. The audit must include blower door (and duct blaster, for ducted installations) if this was not previously performed by a third party.

Optional measurements providing important information:

- Condensate flow for each indoor head – useful for rough validation of RH measurements
- Operation of dehumidification subcool/reheat mode, if system has this capability, at each indoor head
- Operation of defrost cycle.

Recommended monitoring points and make/model for common sensors are provided in Table 1. The table lists specific monitoring equipment used by Building America researchers in the past. Equivalent sensors that meet expected operating ranges and accuracies are acceptable. The indoor unit fan tachometer is used to measure the unit's fan speed. It must be installed in a convenient location to sense the fan without dramatically affecting flow. The recommended tachometer requires ferrous material for its magnetic measurements, so 0.005-in. shim material must be attached to the fan. Two pieces should be used to maintain fan balance, thus the reading will be twice the fan revolutions per minute (RPM). For fans made of ferrous material, an optical tachometer may be necessary. Some fan motors have a tachometer output, which can sometimes be read directly by the data system.

### Quality Assurance Protocol

At or before monitoring installation, test personnel will assemble test equipment to verify proper operation and measuring tolerances. Equivalent quality assurance measures, such as an ice bath calibration test for thermocouple probes, are acceptable. Test personnel should maintain a sufficient supply of spare parts and sensors for the installation site visit. It is also advised that the field technician verify that the equipment installation follows manufacturer guidelines, particularly refrigerant line length.

**Table 1. Long-Term Monitoring Instrumentation Package**

Monitored Parameter	Sensor Description	Sensor Manufacturer	Sensor Part Number	Sensor Accuracy
Whole house electrical	Watt node power meter	Continental Control Systems	WNB-3D-240-P 100HZ output	± 0.5%
	Split core current transformer	Continental Control Systems	CTS-0750-100	± 1%
<b>Outdoor Unit</b>				
MSHP system power	Watt node power meter	Continental Control Systems	WNB-3D-240-P 100HZ output	± 0.5%
	Split core current transformer	Continental Control Systems	CTS-0750-030	± 1%
Outdoor temperature and RH	Temperature and humidity sensor	Vaisala	HMP60A12A0A3B0	±0.6 °C, ± 3% RH
Outdoor unit radiation shield	Radiation shield from solar radiation	Campbell Scientific	41303-5A	NA
Data logger	Main logger	Campbell Scientific	CR1000	± 0.06%
<b>For Each Indoor Unit</b>				
Indoor fan RPM	Tachometer	Extech	461950 Panel Tachometer w/Proximity Sensor	± 2%
Supply air temperature and RH	Temperature and humidity sensor	Vaisala	HMP60A12A0A3B0	± 0.6°C, ± 3% RH
Supply air sectional temperature	Thermistor	Omega	44000	± 0.1°C
Return air temperature and RH	Temperature and humidity sensor	Vaisala	HMP60A12A0A3B0	± 0.6°C, ± 3% RH

Monitored Parameter	Sensor Description	Sensor Manufacturer	Sensor Part Number	Sensor Accuracy
Return air sectional temperature	Thermistor	Omega	44000	± 0.1°C
Space air temperature and RH	Temperature and humidity sensor	Vaisala	HMP60A12A0A3B0	± 0.6°C, ± 3% RH
Condensate flow rate	Tipping bucket	Campbell Scientific	TB4-25	
Data logger	Wireless data logger	Campbell Scientific	CR206X	± (0.25% of reading +1.2 mV offset)

Comments:

- A. Supply and return thermistors need to be properly located per velocity profile measurements. Refer to Short-Term Test in Appendix A.
- B. Only used for each additional indoor unit. Wireless logger only has up to 5 channels for analog signals, 2 loggers are required for each additional indoor unit.
- C. Temperature accuracy is over a temperature range of -40°-60°C. RH accuracy is over temperature range of 0° -40°C, and 0%-90% RH.

## Short-Term Testing

After monitoring instrumentation is installed, short-term testing is used to exercise the new system and establish baseline performance characteristics under set, known, and well-controlled conditions. The researcher may seek to compare the results with previous laboratory data, manufacturer's data, or a performance map to establish that the equipment was properly installed. A system curve for the indoor head must be established for use in later COP monitoring. Additional sensors and equipment are required for these tests.

### Steady-State System Curve Measurement

The supply air flow from the indoor unit is the most challenging measurement to make and monitor in-situ. Accurate measurement of supply air flow with corresponding fan speed is the key to success of a MSHP system performance measurement. A system curve must be created.

Follow the procedure shown in the *Duct Blaster Operation Manual* (The Energy Conservatory 2009) to connect a powered flow hood to the indoor head's supply vent. Fashion a plenum from a simple trash bag or heavy plastic sheet, using internal support (springy metal rings from an automotive windshield shade work well) to hold the trash bag open and to aid in visible monitoring of plenum pressure. Operate the powered flow hood with zero static pressure (gauge) at the MSHP supply outlet. Actuate the MSHP from the lowest to highest fan speeds during heating or cooling mode (preferably both), or adjust the thermostat set point to carefully induce the heat pump to operate in several modes. Record air flow and fan speed at several flow rates across the fan's operating range (one near low end, one at maximum flow, and up to three in between). If the system has discrete fan speeds rather than being fully variable, measure each unique speed.

Plot the data and fit with a line; use Tachometer frequency on x-axis and Measured Flow on y-axis. (See blue points and linear fit in Figure 1.) Take several additional air flow measurements and compare them to the line to ensure repeatability. If they fit well, remove the flow hood. Repeat the heating methods and calls for cooling as closely as possible, and ensure that at each point the RPM measurement matches the previous dataset.

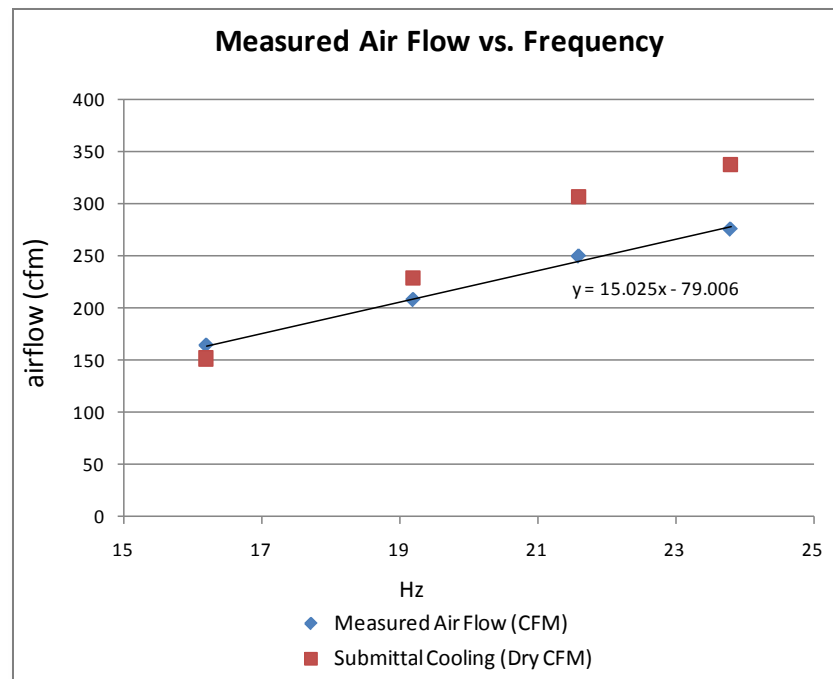


Figure 1. Measured air flow versus tachometer frequency

Finally, perform error analysis to determine the uncertainty associated with the system curve.

A few air flow test details require special attention by the field test technician:

- Ensure the pressure probe inserted into the supply plenum is clean and unclogged. If it is a pitot-type bent tube probe, ensure it is oriented properly.
- The steel wire rings support the inflatable plenum, preventing the bag from collapsing. You must still examine the area around the pressure probe and ensure the bag is not locally collapsed and generating more local turbulence.
- Slowly adjust the pressure in the supply plenum to 0.00-in. static pressure (gauge). Over- or underpressurizing the inflatable plenum will result in discrepant flow readings. Use the plastic bag as a visual cue to confirm the pressure reading.
- Use the correct flow ring for the supply air flow. For steady-state fan flow measurement, allow the fan speed enough time to stabilize. To ensure repeatability, make at least two test series with fan speed from low to high and from high to low. Use the mean air flow measurement at each fan setting if the numbers are close to each other.

According to Ecotope (2009), a typical inverter-driven ductless MSHP indoor unit does not have a brushless DC motor or electronically commutated motor. Thus clogged filters will reduce air flow and system performance. Inspect the cleanliness of the air filter before conducting the air flow test. On older MSHP installations, you should conduct air flow tests and compare the dirty filter to the cleaned filter. On new MSHP installations, several air flow tests during the monitoring period will be valuable. The air filter must be cleaned regularly; remind the homeowner about this maintenance task.

### **Short-Term Efficiency Test**

Set the system to provide maximum cooling (or heating). Use your measurements and calculations from ANSI/AHRI 210/240-2008 to estimate the loads being removed from the space. Compare load, power consumption, and supply conditions to manufacturer submittals or engineering data sheets for the specific articles being measured. The measurements described in this protocol, when applied correctly, are expected to result in load calculations that are accurate within  $\pm 20\%$ , compared to manufacturer data. If any measured performance value is more than 20% off the expected value, double-check sensor performance.



## **Long-Term Monitoring**

Long-term monitoring should take place to ensure multi-seasonal operating performance of the MSHP is captured across the common operating conditions specific to that climate. A typical field test for a heat pump would occur over at least 6 months which overlap both heating and cooling seasons. In addition, the performance limits during extremely hot summer days, or very cold winter nights, should be inspected where possible. These explorations should be driven by research questions specific to the field test and technology.

## **Data Collection and Documentation**

The following data and documentation are required.

### **Data Collection**

A data logger shall be used to collect data from the installed sensors. The logger will be configured to take measurements at short intervals (such as every 10 or 15 seconds) and to store data as appropriate. For most measured parameters, recording a mean or sum at 1-minute and hourly periods is appropriate. At minimum, every parameter's average (or total) shall be recorded at 15-minute intervals. The logger must be configured for remote communication via a land-line modem, wireless modem, Internet, or equivalent method. Data will be transferred at an interval such that modem faults and sensor issues may be noticed and corrected before critical data are lost.

### **Coefficient of Performance Calculations and Uncertainty**

Performance metrics such as HSPF, EER, and SEER shall be calculated per the most recent relevant standards. That standard is currently ANSI/AHRI 210/240-2008. Efficiency calculations must consider the runtime fraction for the given period. Error analysis providing uncertainty estimates is strongly encouraged when data will be presented, particularly in public reports.

## Other Considerations

Optional: Discussion or results from measurements on air mixing in the space during high load situations. How well is heating/cooling distributed around the served space(s), as determined by temperature, relative humidity, or occupant comments. Which zones in the house are warm and cold, and when (time of year, weather) does the discomfort seem to occur? How is the thermal distribution from room to room? Have any thermal comfort issues been reported? Other times of interest are low-load periods such as shoulder seasons. Are other heating sources, such as wood-burning stoves or gas fireplaces, used in the home?

Occupants should be reminded of maintenance issues pertaining to their MSHP, including when to clean air filters. The Field Technician should demonstrate the filter cleaning process.

Refrigerant lines for MSHP systems can often travel long distances to remote indoor heads. If these lines are within the thermal enclosure of the home, they may be providing some unintended load to the space. This occurs because most MSHPs have expansion devices in the outdoor unit, so cold, two-phase refrigerant flows through one line to each indoor head (in cooling mode, hot in heating mode). If those lines are poorly- or un-insulated, they may provide a non-negligible cooling or heating load which, if neglected, will lead to calculated efficiencies that do not fairly represent the system's performance.

## References

Anderson, R.; Roberts, D. 2008. *Maximizing Residential Energy Savings: Net Zero Energy House (ZEH) Technology Pathways*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-550-44547. Available at [www.nrel.gov/docs/fy09osti/44547.pdf](http://www.nrel.gov/docs/fy09osti/44547.pdf).

“ANSI/AHRI 210/240-2008: 2008 Standard for Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment.” Air Conditioning, Heating and Refrigeration Institute. 2008. Available at [www.ahrinet.org/](http://www.ahrinet.org/).

DOE. 2009. Energy Data Book. Available at <http://buildingsdatabook.eren.doe.gov/>.

Ecotope. 2009. “Mini-Split Ductless Heat Pump Bench Test Results.” Available at [www.bpa.gov/energy/n/emerging\\_technology/BPA-Report\\_Ductless-Heat-Pump-June2009\\_FINAL.pdf](http://www.bpa.gov/energy/n/emerging_technology/BPA-Report_Ductless-Heat-Pump-June2009_FINAL.pdf)

Larson, B.; Allan, A. 2010. Private communications.

NEEA. 2009. *Report: Northwest Ductless Heat Pump Pilot Project, Market Progress Evaluation Report #1*. Portland, OR: Northwest Energy Efficiency Alliance. Report #E10-215. Available at <http://neea.org/research/reportdetail.aspx?ID=773>.

The Energy Conservatory. 2009. *Minneapolis Duct Blaster Operation Manual (Series B Systems)*. Available at [www.energyconservatory.com/download/dbmanual.pdf](http://www.energyconservatory.com/download/dbmanual.pdf).

## Appendix A. Field Test for Protocol Validation

### Objective

This test report documents a pilot test on validating the above MSHP field test monitoring protocol. Alternate test methods were proposed and tried, and final recommendations documented. The main focus was to determine:

- How to measure the installed indoor unit fan flow under different speeds with the system under different operating modes.
- Which test parameters—fan power, control signal, and fan speed—can be adopted as repeatable and valid monitoring parameters to correlate to the system air flow.
- The definition of the basic set of instrumentation package to monitor the installed system performance.

### Test Equipment Description

The pilot test was conducted in downtown Denver, Colorado, from late July to mid-August 2010. The test home is a two-bedroom condominium. The MSHP system has one outdoor condensing unit connected with two indoor wall-mounted units. The test home is located on the third floor of a renovated historic building, an ideal application for ductless mini-split systems. Indoor Unit A is mounted in the master bedroom and Unit B is mounted in the living room. The outdoor condensing unit is on the deck (see Figure 2 through Figure 4). The MSHP is the sole cooling source and a supplemental heating source. The main heating source is hydronic baseboard heaters fed by building hydronic loops with two condensing boilers in a mechanical room. Each condo has its own thermostat control for heating.



NREL/PIX 18324,  
Credit: Xia Fang

Figure 2. Living room unit



**Figure 3. Bedroom unit**

NREL/PIX 18325,  
Credit: Xia Fang



**Figure 4. Outdoor unit**

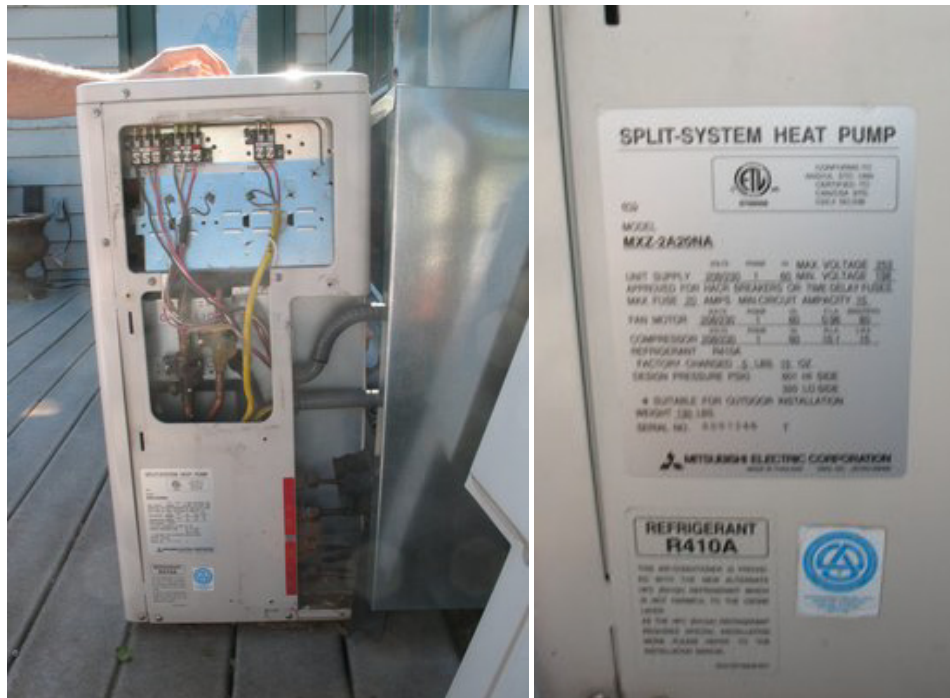
NREL/PIX 18326,  
Credit: Xia Fang

Figure 5 and Figure 6 provide nameplate information of the outdoor and indoor units. The outdoor unit model is Mitsubishi MXZ2A20NA. The indoor unit A and B model is Mitsubishi MSZA09NA.



NREL/PIX 18326,  
 Credit: Xia Fang

Figure 5. Indoor unit nameplate information



NREL/PIX 18328 and 18329,  
 Credit: Xia Fang

Figure 6. Outdoor unit and nameplate information

Electrical power is connected to the outdoor unit, and branches off to Unit A and Unit B. One remote controller controls both indoor units. The remote controller has the following modes:

- On / Off with Timer
- Fan: Auto – Low – Med – High
- Vane: Auto – 1 – 2 – 3 – 4 – Swing
- Mode: Auto – Cool – Dry – Heat
- Econo Cool (SWING vane mode, with 4°F high temperature set)
- Powerful Cool (POWERFUL fan speed, HORIZONTAL (1) vane position, no temperature setting, automatically cancelled in 15 minutes)

### **Short-Term Air Flow Test**

#### ***Fan Revolutions per Minute Measurement***

In preparation for the air flow measurement, fan RPM recording was first installed. The proximity sensor (see Figure 7 and Table 2) is mounted next to the flow fan (Figure 7, 8 and 9). The proximity sensor detects the steel shim as the fan blade rotates. By capturing the sensor detection rate, the fan RPM or rotation frequency is calculated. In the case of a non-magnetic fan, a section of thin steel shim can be bonded to the fan for detection by the proximity sensor. Note that application of additional shim pieces on opposing fan blades may be necessary to keep the fan balanced.



NREL/PIX 18330,  
Credit: Xia Fang

**Figure 7. Proximity sensor mounted**





NREL/PIX 18331,  
Credit: Xia Fang

**Figure 8. Fan balancing weight**



NREL/PIX 18332,  
Credit: Xia Fang

**Figure 9. Thermistors**

### ***Supply Flow Measurement With Powered Flow Hood***

Ecotope (2009), section 13.3 describes the test procedure followed in our test. This flow calibration method uses a DG-700 digital gauge, according to the manual guideline, to introduce  $\pm 3\%$  error. Flow ring 1 was used for the low-speed measurement; ring 2 for the medium and high speeds. The MSHP indoor unit has long, narrow slot supply opening. It requires a custom-built plenum to cover the opening, capture the air flow, and allow the air flow development. Our study tried both a field-built inflatable plenum and a rigid plenum method. Our final recommendation is the inflatable plenum method because of its ease of construction and equally reliable measurement repeatability. (Refer to Appendix B for the rigid plenum method.)

Figure 10 through Figure 13 show the construction of the inflatable plenum. It is built from a heavy-duty, construction-grade trash bag supported by two steel wire rings from a windshield sunshade that eliminated some sensitivity on the pressure probe location when the bag collapsed.



NREL/PIX 18333,  
Credit: Xia Fang

**Figure 10. Trash bag**



NREL/PIX 18334,  
Credit: Xia Fang

**Figure 11. Trash bag plenum with wire support**



NREL/PIX 18335,  
Credit: Xia Fang

**Figure 12. Inflatable plenum**



NREL/PIX 18336,  
Credit: Xia Fang

**Figure 13. Flow test setup**

### About Fan Power, Unit Power, and Control Signals

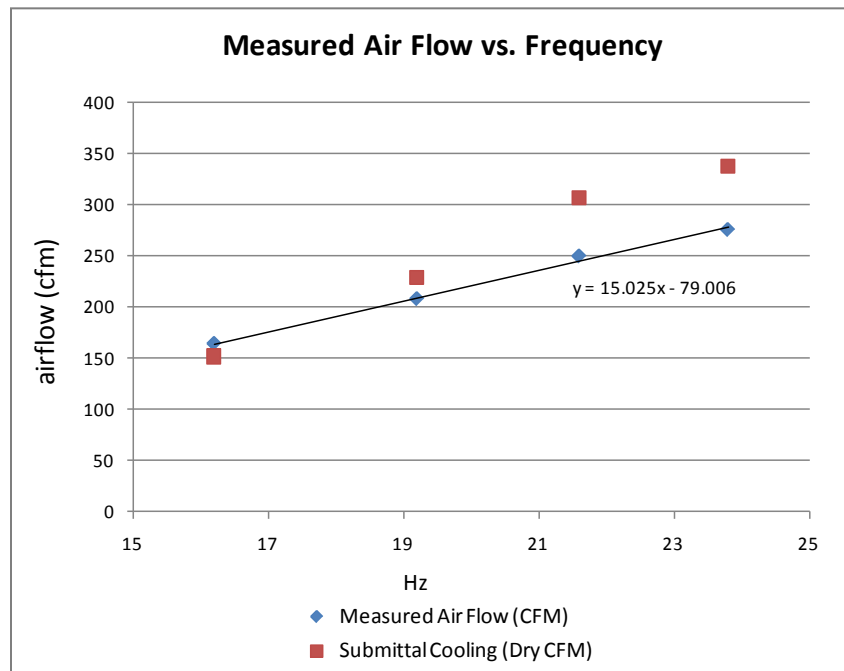
We did not measure indoor unit power or control signal methods. The indoor unit power (S1 / S2 – 208 / 230 V, 1Ph, S3 – 12-24 V DC) is fed to an electronic PC board. The PC board has DC power to indoor fan motor, vane motor, and other sensors such as operator indication lights and coil and room temperature thermistors. Indoor unit power or control signal measurements will not be good indicators.

### Short-Term Test Results

Table 2 and Figure 14 show the comparison of field test data and manufacturer’s equipment submittal data. The cooling coil observed was mostly dry during the short term test period, so dry coil cooling air flow was used for comparison with corresponding fan frequency. The air flow tests using inflatable plenum method were very repeatable with the rigid plenum method.

**Table 2. Air Flow Measured and Submittal Data**

Mode	Low	Medium	High	Powerful
Fan Frequency (Hz)	16.2	19.2	21.6	23.8
Measured Air flow (CFM)	164	208	250	276
Submittal Air flow (Dry CFM)	152	229	307	338
Difference (%)	-8%	9%	19%	18%



**Figure 14. Air flow measured and submittal data**

Linear fit for air flow correlation was as follows:

$$Q_{\text{airflow}} = 15.025 * \text{Frequency}_{\text{fan}} - 79.006 \quad (1)$$

where

$Q_{\text{airflow}}$  is Fan air flow, in CFM

$\text{Frequency}_{\text{fan}}$  is measured proximity sensor frequency, in Hz

As-installed or field operating conditions are normally not comparable to manufacturer's data. In this prepackaged integrated unit, a dirty filter and mounting the unit close to ceiling may have affected the air flow delivery. The data listed here are for reference only.

Testing the system air flow and developing air flow correlation with fan rotation speed enable long-term MSHP performance monitoring.

### **Long-Term Monitoring**

#### Monitoring Package

Table 1 details the long-term monitoring package used for this field test. Data were recorded on one-minute intervals.

During the test period in the local dry climate, the indoor unit delivered sensible cooling only. RH had very slight variations across the coil face. Table 2 specifies four thermistors and one temperature and RH sensor mounted on the supply and return air grilles separately (see Figure 9). For other climate studies, more temperature and RH sensors may be installed.

During the monitoring period, a variance of 1.6°C was observed across the supply-side thermistor measurements, along with a variance of 3.0°C across the return-side thermistor measurements.

During the entire monitoring period, the indoor units operated at “Fan Auto” and “Cooling” modes, except that the bedroom unit was turned off on August 18 for part of the day.

### **Results**

The purpose of this pilot study is to find field test methods to test and monitor the performance of MSHP system. The bedroom unit was not instrumented and monitored. This affected the results analysis on obtaining full MSHP system performance with indoor unit(s) on/off and outdoor unit matching compressor modulating. This analysis is for illustration only.

Figure 15 is the trend of indoor unit fan air flow with recorded fan rotation frequency and linear correlation developed during the monitoring period. Data recording frequency is 1 minute.

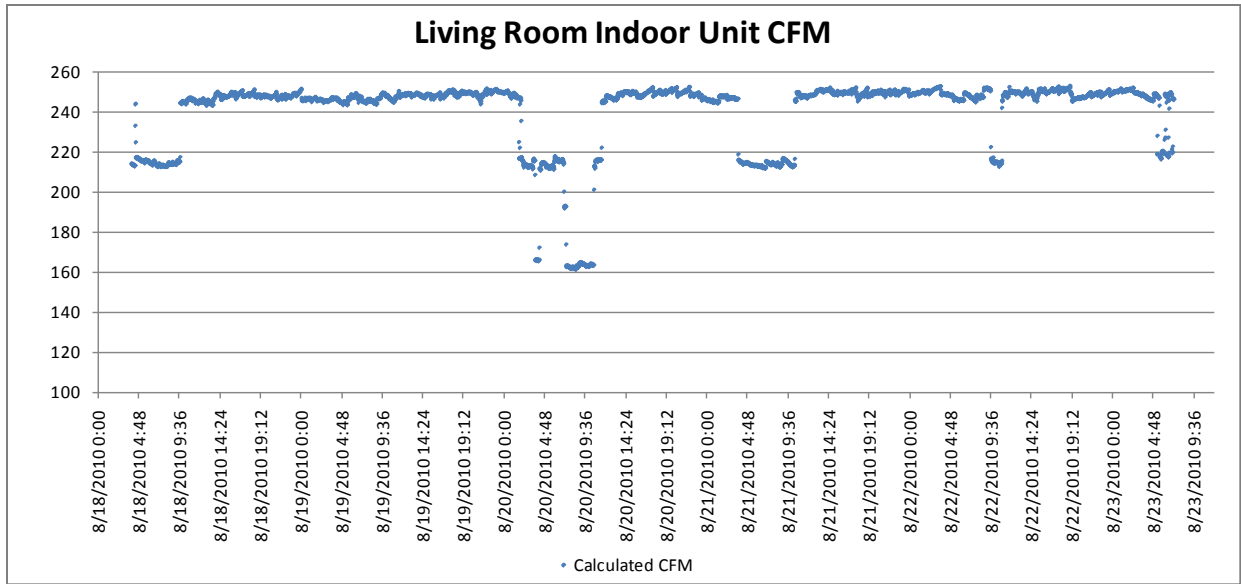


Figure 15. Living room unit air flow measured

Figure 16 shows the MSHP outdoor condensing unit total power draw as a function of outdoor dry bulb temperature and indoor unit (living room Unit A only) return air wet bulb temperature. Both indoor units were running during the monitoring period, except on August 18 between 6:30 a.m. and 2:30 p.m., when the bedroom unit was turned off.

With a relatively constant indoor unit return air wet bulb temperature, the outdoor unit power followed the rise and fall trend of outdoor dry bulb temperature. On August 20, 21, and 22, the unit power draws oscillated up and down, indicating unstable system operation.

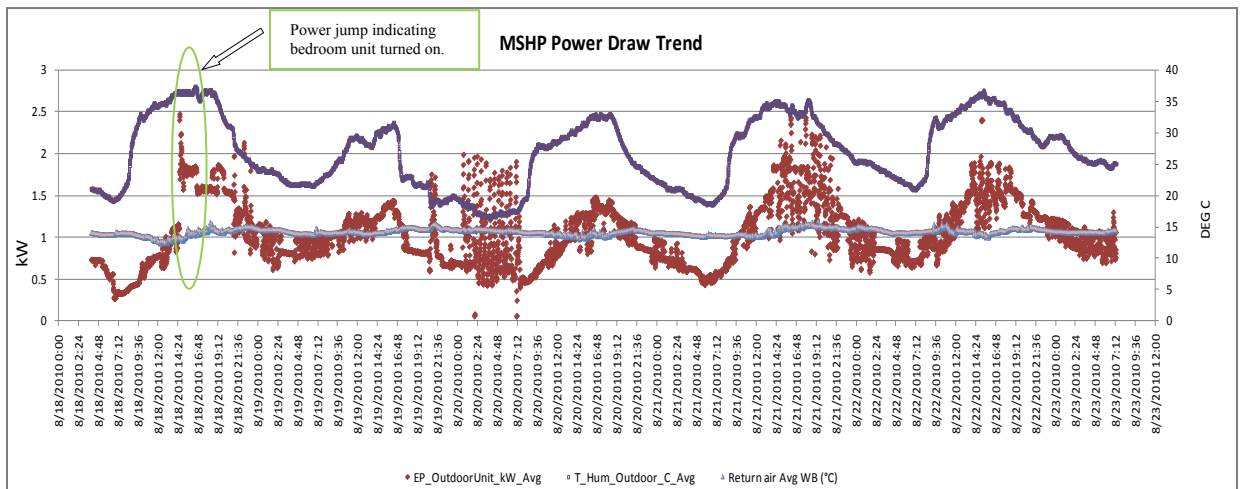
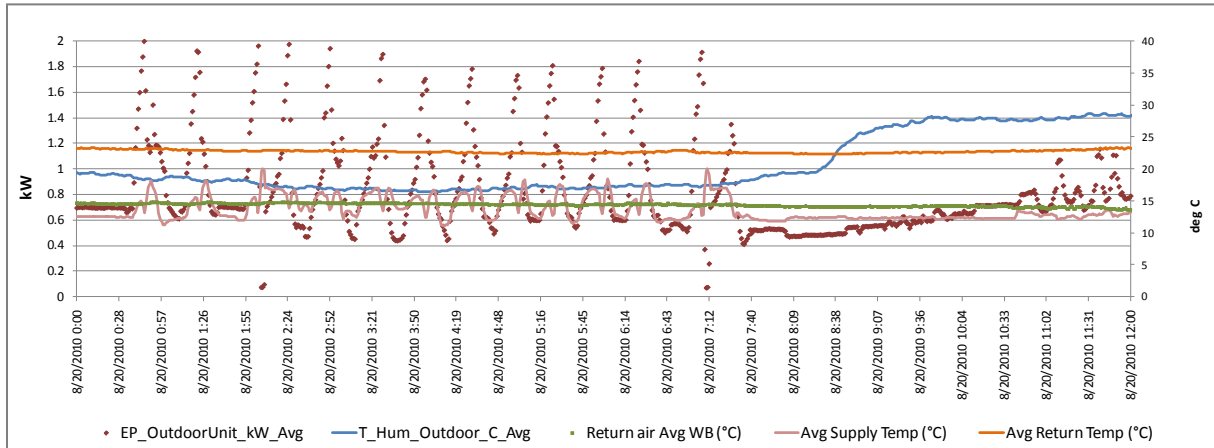


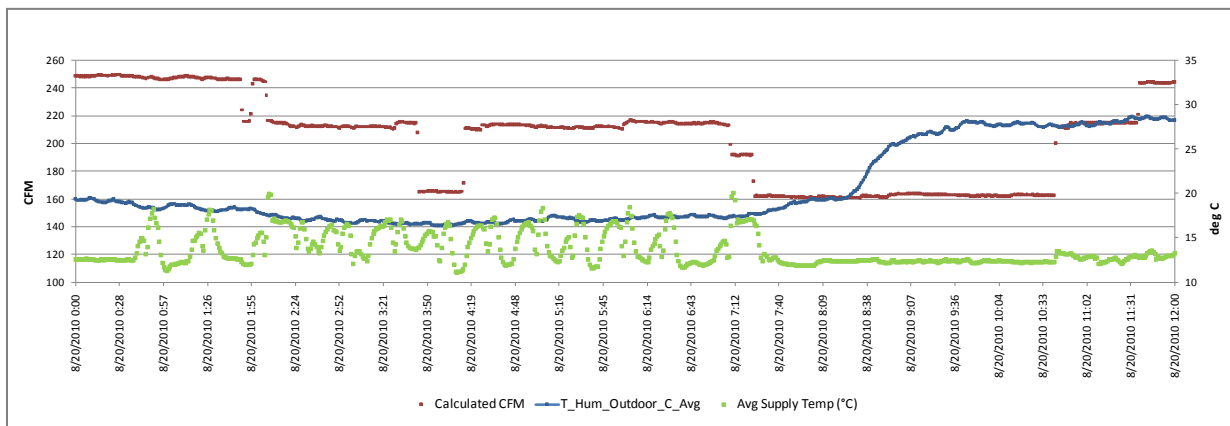
Figure 16. MSHP outdoor condensing unit total power

Figure 17 and Figure 18 are zoom-in views on the system power draw and air flow rate on August 20. From midnight (0:00) to early morning (7:00) on August 20, the outdoor temperature stayed at 17°–18°C (~ 62°–64°F) and the indoor temperature stayed at 21°–22°C (70°–72°F). Both the total system power draw and living room unit (the tested unit) air flow oscillated up and

down, indicating the system was operating into the unstable region. The temperature and pressure driving potential between the condenser and evaporator sides probably dropped below the compressor modulating range.



**Figure 17. MSHP outdoor condensing unit total power on August 20, 2010**



**Figure 18. Living room unit air flow and temperatures trend on August 20, 2010**

Figure 20 is a plot of cooling system EER on August 18, when only the instrumented living room unit operated. The system EER plotted is much lower than the rated efficiency of SEER 17. When the outside air dry bulb temperature increases, system EER drops and system unit power consumption increases (Figure 20).

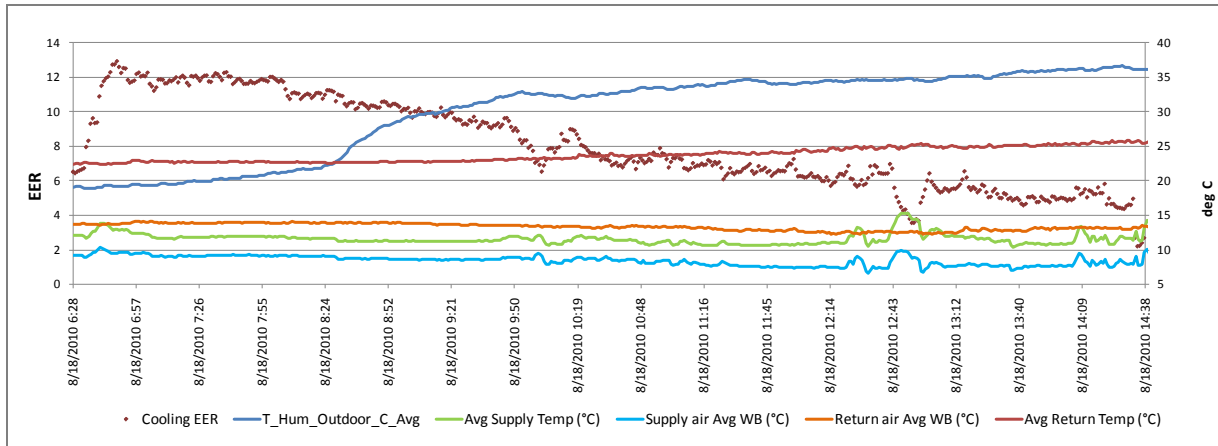


Figure 19. MSHP EER with living room unit operating only

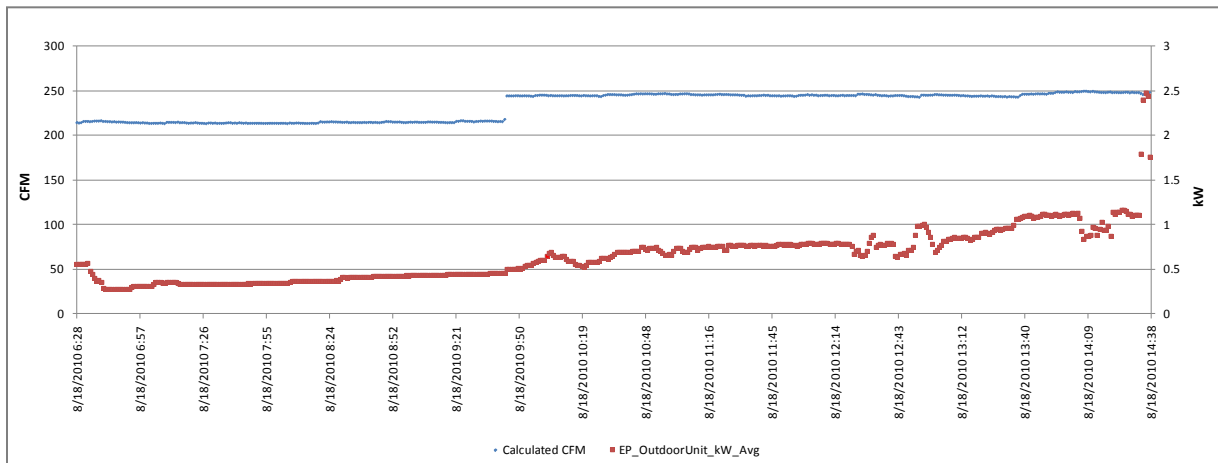


Figure 20. Indoor living room unit air flow and outdoor unit power

### Error Analysis

Figure 21 through Figure 23 show an uncertainty propagation analysis example with the listed instrumentation accuracy range for a general test condition, assuming

- $\pm 15\%$  experimental error introduced by the air flow measurement method
- Additional  $\pm 3\%$  error on supply air RH introduced by using only one temperature and RH sensor on the supply grille, (not a concern for this dry climate study).

The final system cooling capacity and associated system cooling EER have error of  $\pm 16.6\%$ .



```

EES Professional: C:\Projects\MSHP monitoring\Calculation\CapacitySensitivity.
File Edit Search Options Calculate Tables Plots Windows Help Examples

elevation = 0
P_atm = 14.696 * (1 - 0.0000225577 * elevation * 0.3048) ^ 5.2559

CFM = 248
Power_draw = 821 {W}

"Return conditions 75.2°F DB, 58.4°F WB at 5280 ft"
T_ret = 75.2
{WB_ret = 58.4
RH_ret = RelHum(AirH2O, T=T_ret, B=WB_ret, P=P_atm)}
RH_ret = 0.39
w_ret = HumRat(AirH2O, T=T_ret, r=RH_ret, P=P_atm)
rho_ret = Density(AirH2O, T=T_ret, r=RH_ret, P=P_atm)
h_ret = Enthalpy(AirH2O, T=T_ret, r=RH_ret, P=P_atm)
DP_ret = DewPoint(AirH2O, T=T_ret, r=RH_ret, P=P_atm)

h_fg = Enthalpy(Water, T=DP_ret, x=1.0) - Enthalpy(Water, T=DP_ret, x=0.0)
Cp = Cp(AirH2O, T=T_ret, r=RH_ret, P=P_atm)
m_dot = CFM * rho_ret * 60

{Q_dot_ref = 9000
SHR_ref = 0.76

Q_dot_ref_sens = SHR_ref * Q_dot_ref
T_sup_ref = T_ret - Q_dot_ref_sens / (Cp * m_dot)

Q_dot_ref_lat = (1 - SHR_ref) * Q_dot_ref
w_sup_ref = w_ret - Q_dot_ref_lat / (h_fg * m_dot)
RH_sup_ref = RelHum(AirH2O, T=T_sup_ref, w=w_sup_ref, P=P_atm)

h_sup_ref_1 = h_ret - Q_dot_ref / m_dot
h_sup_ref_2 = Enthalpy(AirH2O, T=T_sup_ref, w=w_sup_ref, P=P_atm)

T_sup = 52.4
RH_sup = 0.731

w_sup = HumRat(AirH2O, T=T_sup, r=RH_sup, P=P_atm)
h_sup = Enthalpy(AirH2O, T=T_sup, r=RH_sup, P=P_atm)

Q_tot = m_dot * (h_ret - h_sup)
Q_lat = m_dot * h_fg * (w_ret - w_sup)
SHR = (Q_tot - Q_lat) / Q_tot
EER = Q_tot / Power_draw

{U = UncertaintyOf(Q_tot)}

```

Figure 21. Uncertainty propagation analysis<sup>a</sup>

<sup>a</sup>(F-Chart Software. 2011. EES: Engineering Equation Solver. <http://www.fchart.com/ees/>)

Enter a numerical value or variable name

Variable	Value	Units	Absolute Uncertainty	Relative Uncertainty
CFM	248			0.15
Power_draw	821	W		0.01
RH_ret	0.39			0.03
RH_sup	0.731			0.06
T_ret	75.2		0.18	
T_sup	52.4		0.18	

Figure 22. Uncertainty propagation table

EES Professional: C:\Projects\WSPH monitoring\Calculation\CapacitySensitiv

File Edit Search Options Calculate Tables Plots Windows Help Examples

Uncertainty Results | Solution

**Unit Settings: Eng F psia mass deg**

Variable±Uncertainty	Partial derivative	% of uncertainty
<b>EER = 9.036±1.501 [Btu/hr-W]</b>		
CFM = 248±37.2	$\partial EER / \partial CFM = 0.03643$	81.48 %
Power <sub>draw</sub> = 821±8.21 [W]	$\partial EER / \partial Power_{draw} = -0.01101$	0.36 %
RH <sub>ret</sub> = 0.39±0.0117	$\partial EER / \partial RH_{ret} = 27$	4.43 %
RH <sub>sup</sub> = 0.731±0.04386	$\partial EER / \partial RH_{sup} = -12.1$	12.50 %
T <sub>ret</sub> = 75.2±0.18	$\partial EER / \partial T_{ret} = 0.6583$	0.62 %
T <sub>sup</sub> = 52.4±0.18	$\partial EER / \partial T_{sup} = -0.6488$	0.61 %
<b>Q<sub>tot</sub> = 7418±1230 [Btu/hr]</b>		
CFM = 248±37.2	$\partial Q_{tot} / \partial CFM = 29.91$	81.78 %
Power <sub>draw</sub> = 821±8.21 [W]	$\partial Q_{tot} / \partial Power_{draw} = 0$	0.00 %
RH <sub>ret</sub> = 0.39±0.0117	$\partial Q_{tot} / \partial RH_{ret} = 22167$	4.44 %
RH <sub>sup</sub> = 0.731±0.04386	$\partial Q_{tot} / \partial RH_{sup} = -9936$	12.54 %
T <sub>ret</sub> = 75.2±0.18	$\partial Q_{tot} / \partial T_{ret} = 540.4$	0.63 %
T <sub>sup</sub> = 52.4±0.18	$\partial Q_{tot} / \partial T_{sup} = -532.7$	0.61 %
<b>SHR = 0.82±0.05516</b>		
CFM = 248±37.2	$\partial SHR / \partial CFM = 0$	0.00 %
Power <sub>draw</sub> = 821±8.21 [W]	$\partial SHR / \partial Power_{draw} = 0$	0.00 %
RH <sub>ret</sub> = 0.39±0.0117	$\partial SHR / \partial RH_{ret} = -2.389$	25.68 %
RH <sub>sup</sub> = 0.731±0.04386	$\partial SHR / \partial RH_{sup} = 1.075$	73.13 %
T <sub>ret</sub> = 75.2±0.18	$\partial SHR / \partial T_{ret} = -0.02465$	0.65 %
T <sub>sup</sub> = 52.4±0.18	$\partial SHR / \partial T_{sup} = 0.02252$	0.54 %

1 potential unit problem was detected.

Calculation time = .1 sec.

Figure 23. Uncertainty propagation results

## Appendix B. Rigid Plenum Method (for reference)



NREL/PIX 18320,  
Credit: Xia Fang

Figure 24. MSHP for indoor heat air flow test rigid plenum method



NREL/PIX 18321  
Credit: Xia Fang

Figure 25. Researcher examining MSHP for indoor heat air flow test rigid plenum method



NREL/PIX 18322,  
Credit: Xia Fang

**Figure 26. Researchers testing MSHP**



NREL/PIX 18323,  
Credit: Xia Fang

**Figure 27. Opening for unit room temperature thermistor sensing**

# REPORT DOCUMENTATION PAGE

*Form Approved*  
*OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> March 2011		<b>2. REPORT TYPE</b> Technical Report		<b>3. DATES COVERED (From - To)</b>		
<b>4. TITLE AND SUBTITLE</b> Field Monitoring Protocol: Mini-Split Heat Pumps			<b>5a. CONTRACT NUMBER</b> DE-AC36-08GO28308			
			<b>5b. GRANT NUMBER</b>			
			<b>5c. PROGRAM ELEMENT NUMBER</b>			
<b>6. AUTHOR(S)</b> D. Christensen, X. Fang, J. Tomerlin, J. Winkler, and E. Hancock			<b>5d. PROJECT NUMBER</b> NREL/TP-5500-49881			
			<b>5e. TASK NUMBER</b> ARRB.2204			
			<b>5f. WORK UNIT NUMBER</b>			
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> DOE/GO-102011-3227 NREL/TP-5500-49881			
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>			<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> NREL			
			<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>			
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT (Maximum 200 Words)</b> The report provides a detailed method for accurately measuring and monitoring performance of a residential Mini-Split Heat Pump. It will be used in high-performance retrofit applications, and as part of DOE's Building America residential research program.						
<b>15. SUBJECT TERMS</b> Mini Split Heat Pump; MSHP; Air Conditioning; HVAC; Field Test; Monitoring; Protocol; Building America; Residential; Homes						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UL	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>	
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b>	

**Standard Form 298** (Rev. 8/98)  
Prescribed by ANSI Std. Z39.18

**EERE Information Center**

1-877-EERE-INF (1-877-337-3463)

*[www.eere.energy.gov/informationcenter](http://www.eere.energy.gov/informationcenter)*

U.S. DEPARTMENT OF  
**ENERGY**

Energy Efficiency &  
Renewable Energy

DOE/GO-102011-3227 • March 2011

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post-consumer waste.