Field Test Best Practices

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1 National Renewable Energy Laboratory
2 Mountain Energy Partnership
3 Slipstream (formerly Energy Center of Wisconsin)

** Formerly*

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Foreword

This document began as a cross-linked web resource on the Building America website[1] more than a decade ago. Multiple contributors shared their knowledge and expertise on a wide range of building field work issues. Over the intervening years, the maintenance and updating of the website has proved to be challenging, hence this report version of the document.

This report incorporates most of the original information and provides updates and additions in several areas. This Field Test Best Practices document will be of very high value to the relatively small but quickly expanding pool of researchers who engage directly in hands-on field research in homes—those working as part of Building America teams as well as researchers working on field research more broadly. Many contributors to the document have decades of building field research experience and have shared a wealth of basic knowledge, tips, and tricks on making relevant, accurate measurements in occupied and unoccupied homes.

Note that because most of the recommendations presented in this document resulted from Building America projects, the examples focus primarily on residential field work. However, much of the information applies more broadly to buildings in general—both residential and commercial. We hope you find this information helpful in your adventures in field work and we invite your comments and contributions for future versions of the document.

As life-long field researcher and mentor Ed Hancock is fond of saying, expect the "normal level of chaos" when working in real homes with real occupants. Have fun, stay safe, and we look forward to the results of your research.

Acknowledgments/Disclaimer

This work was supported by the U.S. Department of Energy through the Building America Program.

Please note that figures throughout the report show images of real equipment. The authors do not endorse any particular brand of equipment, and these figures are for illustrative purposes only. Safety is not comprehensively covered in this report. Field test practitioners should be well trained in safety and apply best practice when in the field.

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[1] For more information on Building America, see https://www.energy.gov/eere/buildings/building-america.

List of Acronyms

AC	alternating current
ACH	air changes per hour
ACH50	air changes per hour at 50 pascal pressure
CATS	capillary adsorption tube sampler
CFM	cubic feet per minute
CFM50	cubic feet per minute at 50 pascal pressure
CT	current transformer
DAS	data acquisition system
DC	direct current
gpm	gallons per minute
NREL	National Renewable Energy Laboratory
Pa	pascal, a measure of pressure
PV	photovoltaic
RH	relative humidity
RTD	resistance temperature detector
SF_6	sulfur hexafluoride
T&RH	temperature and relative humidity

Executive Summary

This report can be used as a resource for advice on every stage of field research in residential buildings. It can be used as a reference document to find descriptions of specific types of common measurements and tricks of the trade, or as a primer on home field research providing a basic education on the subject.

The report begins with descriptions of field experiment design and discusses advantages and disadvantages of different types of data acquisition systems. The bulk of the paper describes the common measurements needed in residential field work, the hardware options for making the measurements, and field notes on with tips, tricks, and cautions.

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1 Experiment Design and Execution

Field research projects typically progress through the following steps:

1. Formulate research questions that will be answered by the field work.
2. Determine modeling and analysis requirements to answer the research questions.
3. Determine measurements needed to complete the analysis and/or provide confidence in the model.
4. Visit the site to meet with local contacts, determine measurement locations and communications needs, and agree on the project approach.
5. Determine the appropriate type of sensors and data acquisition system (DAS) for the project.
6. Specify and order equipment.
7. Assemble, label, and test equipment to the greatest extent possible in the lab prior to shipping the equipment to the test site.
8. Pack the equipment in a manner that reduces the chance of damage, and ship to the site.
9. Work with local contacts to install and test the sensors, DAS, and communications, and troubleshoot issues as needed.
10. Begin data collection and data quality monitoring.
11. Analyze data, complete modeling, and write up the results.
12. Return to the site and remove the sensors and DAS.

Formulation of strong research questions that will guide the field research is the essential first step of quality field research. It is not uncommon, but it is generally ill advised to simply take as much data as you can and see what you can learn from it. This approach often leads to regrets like, “I wish we had measured X.” Starting with well-constructed research questions and determining the measurements needed to answer those questions will lead to stronger results.

Thoroughly testing the DAS prior to field deployment is an essential step that is often overlooked. Ordering the equipment and having it shipped directly to the installation site is a huge loss of opportunity. Once at the site, time is usually limited by flight plans and the occupant’s availability. Troubleshooting is more difficult on equipment that is already installed, and you may not have all the troubleshooting tools you would have in the lab. Assembling and testing the DAS and sensors in the lab and testing each sensor in advance is the best way to have a smooth installation on-site and minimize the probability of problems.

Sensors often must be shipped disconnected from the logger. Once on-site, best practice is to power the data logger first and open a screen that provides real-time output of the sensor data. Install one sensor at a time, checking that it shows up on the display in the correct location or with the correct label, and that the reading it provides is reasonable. There are some mistakes, such as applying too high a voltage on a sensor terminal, that can cause all of the readings in the logger to be in error. If you install all the sensors before looking at the readings, you will not know which sensor caused the problem and you will have to remove sensors until you find the problem.

Once the DAS is installed, don't wait until the end of the monitoring period to look at the data. Create tables or charts of the data and check periodically for any anomalies. Catch data problems before it is time to write up the results.

1.1 Research Questions

Begin each research project by carefully crafting the questions you wish to answer with the research. The data needed to answer these questions determine the measurements to be made, which in turn determine the sensor selection and sensor locations needed. Appropriate loggers and communications equipment are then chosen to meet the need of data collection, storage, and transfer from the sensors.

Formulating good research questions is the critical first step in planning an effective field test program. When drafting research questions, begin with the big picture. What are you trying to accomplish in the project at hand? The research question should flow from a clear project objective. Next, clearly define the areas that need to be addressed and determine why they need to be addressed. This process should include both research questions and hypothesized outcomes.

Research questions should be clear, specific, and structured in such a way that the outcome of the research can be more broadly valuable than simply addressing the particular range of conditions covered in the test. Questions that can be answered with "yes" or "no" and questions very narrow in scope (e.g., What is the temperature in the wall?) are weak research questions and should be avoided. Biased questions such as "How much energy was saved?" or "How much did the comfort improve?" should also be avoided. These questions assume there will be savings and comfort improvement. A more neutral question would be "How do the observed results compare to design intent and expectations?"

Research Question Examples

Following are some examples of possible research questions.

Poor Question: What is the annual energy use of the heat pump?

Better Question: What is the installed efficiency of the heat pump in an occupied home, and how does the performance vary under a range of operating conditions?

Poor Question: What is the duct leakage?

Better Question: What is the net increase in air change rate when the air handler is operated in cooling mode?

Even Better Question: What are the major sources of duct leakage, and the system performance impacts of each?

1.2 The Role of Building Simulation in Field Test Design

In most cases, field research projects should include modeling. A field test without modeling may only provide an understanding of how a particular technology performed in a specific building and climate. If the measured performance is used to gain confidence in a model, the model can then be applied to different buildings and climates to assess the applicability of the technology more widely. Design the experiment so that the preliminary model can be verified and/or fine-tuned for improved accuracy over a wide range of environmental conditions. Clearly define the control volume that is being used to calculate air, moisture, and energy balances. Often, a cleverly designed experiment can take a relatively short time (no more than a week) to conduct, yet still yield the desired verification of the model. Some phenomena are, by their nature, very slow-moving (e.g., deep-ground temperatures), and experiments that involve these types of measurements may last many months or even years. Experiments focusing on the seasonal effects may need to run for a full year or more to measure the seasonal variation.

Use a building energy simulation program to refine initial estimates of project benefits. The researcher should make their best effort to accurately simulate the behavior of the energy conservation measure or phenomenon being investigated. This may involve reviewing the source code to understand how the physics is currently modeled and what the relevant underlying assumptions are. A literature search should help guide the development of a reasonable mathematical model based on available information. This preliminary simulation process is vital because it reveals what measurements are required in the experiment to verify and/or fine-tune the model. Modeling inputs with high uncertainty should be included in the measurement plan. If there is no reasonable model to use as a starting point, the researcher must determine what critical information is lacking that is needed before a simulation can be run.

1.2.1 Comparison of Model to Measurement

The formal process of comparing model to measurement is a vast field of study that is mostly beyond the scope of this document. A brief overview is presented below.

The experimental design should describe how the model will be compared to measurements. A good approach is to control sources of error external to the software (inputs) by driving the simulation with measured data (e.g., solar radiation, outdoor temperature) and then to compare the simulated response of the system with the measured response. This may require modifications to the source code and the creation of weather files that contain measured data. The simulation program must be capable of modeling the actual details of the system without making gross assumptions. It is difficult to determine exactly what shortcomings the model may have and how to fix them if the details cannot be examined carefully.

Having verified the accuracy of the model using the measured data, a simulation study can now be conducted near the range of validation conditions. The modeler should be cautious about extrapolating the model to predict performances under conditions that are significantly outside the range of the validation study; further testing may be needed to verify the accuracy of the model under different conditions. A useful simulation study results in general recommendations regarding the feature or measure that has been studied, including under what circumstances the measure may or may not be desirable.

1.3 Short-Term Tests and Long-Term Monitoring

Short-term experiments provide valuable information that often can be obtained only when the home is unoccupied and hence the internal conditions can be controlled. They are appropriate for brief, high-value tests such as measuring building UA and tracer-gas measurements of airtightness and distribution. One limitation of short-term experiments is that data sets cannot be obtained for a wide range of weather conditions and occupants.

In contrast, long-term monitoring involves installing sensors and collecting time series data from the sensors over a long period of time. Data are often collected for a full year to capture the system performance in all seasons and a wide variety of weather conditions.

If seasonal variations and occupant effects are key concerns, long-term monitoring is more appropriate than short-term testing. Typically, these homes are occupied (except in special circumstances such as lab houses, where occupancy effects are eliminated or simulated) and therefore allow investigations of house performance under realistic operating conditions, which include human interactions, a range of weather conditions, and equipment degradation over time. An inherent complication with occupied long-term monitoring is that occupant behavior can have a strong influence on the results; however, it must be noted that the performance of the building with real occupants is ultimately the relevant metric.

1.4 Assessment of the Current State of Knowledge

Research the existing literature to find what is already understood about the issue and identify the type of data sets required to further that understanding. Are the relevant questions best addressed through field testing? Are there faster, easier, or less expensive ways to answer the questions? Is there a highly validated modeling tool that can address the research questions? Based on the current knowledge, what are the remaining gaps? What are the estimated benefits of resolving these gaps? What are the options for addressing the gaps? Which approaches have the highest chance of success?

1.5 Research Involving Human Subjects

A field test *may* involve procedures that are legally classified as human subjects research. Common examples in residential field testing include usability testing of home energy management devices, focus groups and surveys to collect data on consumer opinions and preferences, and studies of human behavior based on detailed monitoring data. The laws governing human subjects research are outlined in Title 24 of the Code of Federal Regulations, Part 46 (45 CFR 46), “The Protection of Human Subjects.” Your local Institutional Review Board can help you determine if your project falls under this regulation.

2 Data Acquisition

To decide what type or class of DAS to use, consider the following:

- What physical parameters do you need to measure to answer the research questions?
- How many separate locations need to be observed?
- How frequently do measurements need to be made?
- Do you want to process individual measurements onboard the DAS (e.g., process 1-second temperature observations to create and record 5-minute averages)?
- How much onboard memory will the logger need?
- What is the duration of the measurements?
- If logger is battery powered, how long will the battery last?
- If the logger is powered from an outlet, should it also be equipped with a battery backup?
- Is it important to have data transmitted back to the researcher's office?

What type of data acquisition makes sense for this project?

- Highly flexible with the ability to make many different types of measurements.
- Focused on particular type of measurement such as temperature or electric consumption.
- Small, stand-alone battery-powered loggers that store data that must be downloaded manually.
- Include internet-connected gateways with manual download or an application. programming interface
- Capable of communicating using cellular modems.

2.1 Compact and Stand-Alone Data Loggers

Compact data recorders usually measure and record one to four parameter values at fixed time intervals (e.g., every second, every 15 minutes) and are battery powered. They often have built-in sensors for temperature, relative humidity, or light.

They may also connect to plug-in sensors. One type of compact recorder is the "state logger," which records the time at which a switch (triggered by the operating current of a load) opens or closes. Compact recorders are relatively low in cost and are convenient when a single parameter is to be measured, when running cables is undesirable, and when transmission of data back to the researcher's office isn't required. They're widely used in characterizing building conditions and operation of individual loads.

These compact loggers have the advantage of being simple to use, small, and relatively inexpensive. Their main disadvantage is the lack of remote communication. The data are generally downloaded by direct wired connection to the logger. Therefore, during the data logging period, there is no feedback on the quality of the data. If the logger is not launched correctly, you will not know about the error until you attempt to download the data from the logger. Attention must be paid to the expected battery life and the logger memory capacity when launching the logger. Another disadvantage is the time required to integrate the data from multiple compact loggers into a single database or spreadsheet for visualization and analysis.

2.2 Internet-Connected Sensors and Loggers

In recent years there has been a proliferation of relatively inexpensive internet-connected sensors and loggers. Some of these systems provide research-grade measurements, but many others are targeted at the consumer market and may not have the accuracy required for research. Most of the systems piggy-back onto the homeowners' existing internet service and Wi-Fi router. Internet reliability can be an issue when using these systems. Some systems use a gateway, connected directly to the internet router, to communicate wirelessly to the sensors. The gateway may include memory, so data are not lost during an internet service outage. Some smart thermostats act as a gateway and offer a variety of wireless sensors with data download through an internet connection to the thermostat.

Some issues to consider when evaluating internet-connected sensors and loggers include:

- Rated accuracy of the sensors.
- Battery life of wireless sensors.
- Memory—do the sensors or gateway have memory or are data lost during an internet or power outage?
- Ease and flexibility of downloading data.
- Is there an application programming interface available that could be used to setup automatic data downloads?

2.3 Programmable Multichannel Loggers

Programmable multichannel systems include sophisticated devices that offer up to 30 or more input channels including both analog and digital measurements, programming capability that allows measurements at a wide range of time intervals, onboard data processing, and outputs that can control external devices. These systems are often used for whole-building monitoring, especially projects focused on mechanical system performance and electric loads when most sensors can be placed in a mechanical room and cabled to the DAS. These systems will often support communication from remote sites via telephone modem, cellular modem, or internet. Wireless sensors can be used with these systems by connecting a transceiver to the logger. The transceiver can then communicate with distributed wireless sensors and the data can be integrated with other wired sensor data in the logger memory.

2.4 Computer-Connected Data Acquisition Systems

These systems typically include analog and digital measurement capability but use a live connection to deliver data for processing and storage on a personal computer. USB connections are common, but plug-in cards (e.g., Peripheral Component Interconnect) are also used. Computer-connected systems offer the same range of measurement and programming sophistication as do programmable multichannel systems. The need to be connected to a computer makes them more attractive in a permanent office or lab setting, and they are used less frequently in field research. The use of a PC can be less reliable than dedicated stand-alone logger systems when used in field research. Rebooting a PC remotely can be challenging.

2.5 Software

In most cases, the manufacturers of packaged data acquisition equipment provide software for setting operating parameters and for full-featured programming of more sophisticated systems. Manufacturers' software may also provide utilities for saving data files in standard formats, for simple analysis (e.g., finding maximum and minimum values), and for graphing. The software may also allow tracking of connection statistics of remote loggers. Some internet-connected sensors and loggers provide a web page to view and download data. Some also provide an application programming interface that can be used to write a script for automatic data downloads.

2.6 Other Aspects of System and Sensor Selection

There is a broad spectrum of DAS and sensor types. The variety is growing rapidly. This section covers some additional aspects to consider when selecting the right system and sensors for your project.

2.6.1 Multiplexing

Multiplexing refers to using switches so several different sensors can be connected in turn to a single input on a DAS, increasing the capacity of the system to monitor multiple sensors. Multiplexers make use of either electromechanical relays or solid-state switches, and are often available through the manufacturers of DAS.

2.6.2 Communications

Communication between a remote research site and the researcher's office is generally desirable, and sometimes critical, in allowing evaluation of the performance of both the system under study and the data acquisition equipment without travel to the site. Data communications from remote sites can use several methods:

- Conventional ("landline") telephone service using modems (although this is increasingly less common).
- Cellular modem service with data plans and communications.
- Internet-based communications (TCP/IP).

When using internet-based communication in occupied homes it is common to use the occupant's internet service. Data transfers typically takes very little bandwidth and do not cause any appreciable impact on the occupant's internet experience. Both internet and cellular service may be inconsistent in some areas. It is good practice to take equipment to test the communications on the site visit. The availability of a cellular signal or the location of ethernet ports may contribute to the design of the DAS.

2.6.3 Wireless Sensors

Wireless technology is a fast-growing area that will play an increasingly important role in data acquisition. By eliminating the need for cabling from sensors to a central gateway or data logger, wireless devices reduce the disruption and cost of sensor placement in occupied building spaces. Wireless sensors raise new issues in system design, however. For example, analog-to-digital conversion will generally take place onboard individual sensors, which may imply a reduction in accuracy as compared to measurements made on a high-performance programmable system. A low-cost gateway or router that works exclusively with digital data may be adequate as the central controller, replacing conventional programmable data acquisition equipment, or it could be integrated into the conventional system such that some sensors are wired directly to the logger and others are wireless, with the gateway wired to the logger using Modbus or another communication protocol.

2.6.4 Measurement Range

Can the sensor provide output across the expected range of experimental conditions to be studied? Can it tolerate exposure to the maximum possible conditions?

2.6.5 Power Requirements

Some sensors require external power for operation. Some may allow for a wide range of supply voltage (e.g., 8 to 30 VDC) while others require a well-regulated power supply (e.g., 12 +/- 0.1 VDC). The current draw of sensors should be checked against the output capacity of the power supply.

2.6.6 Analog Output

Sensor output should be compatible with the DAS. Analog-output sensors typically provide output voltages of 0 to 1V, or up to 0 to 12V. Output voltages that exceed the measurement capability of the DAS can readily be dropped to a lower level by adding a voltage divider. In some cases, sensor output is proportional to power supply voltage. Check the capability of the DAS before selecting sensors with low-range output, such as resistive bridge devices and thermocouples.

2.6.7 Digital Output

The digital inputs on a DAS interpret the input as representing either a low value (low, zero, and off are all used to describe this state), or a high value (usually called high, one, or on). Digital output (i.e., an on/off signal) may be implemented using several types of hardware:

- A voltage that switches between 0 and a positive value, such as +5 V.
- A switch with a voltage applied to one side, so the output becomes either an on or off ("high" or "low") value.
- An open collector. This refers to the use of a transistor as a solid-state switch.

DAS digital inputs may also have the ability to count digital pulses. The system manufacturer should specify a maximum input voltage that will always be interpreted as low, a range where the interpretation is ambiguous, and a minimum voltage, above which will always be interpreted as high. Make sure the sensors produce output that will always be interpreted correctly.

Open collector and switch outputs are usually connected to a voltage source through a "pullup resistor" that provides a stable positive signal when the transistor is inactive (or switch is open). When the transistor is energized (or switch closed), the voltage is drawn to near zero. With proper selection of the voltage source and pullup resistor, the input of the DAS sees these two conditions as OFF and ON.

2.6.8 Accuracy and Resolution

The accuracy, or maximum expected error, of sensors is usually reported in manufacturer specifications. The importance of sensor accuracy depends on the way the sensor is being used. Measurement of a water temperature difference of 5ºF across a heat exchanger may call for higher accuracy than measuring outdoor temperature for use in studying heating loads. Resolution, the smallest step or change that can be observed, is a function of both the sensor and the device that converts the output to a digital value, called an A to D converter (usually the DAS). An A to D converter is usually identified by the number of bits of resolution. For example a 12 bit A to D divides its input range into 4096 parts. Better resolution becomes more important as smaller changes or differences are to be observed.

2.6.9 Grounding for Measurement Accuracy and Safety

Proper grounding is an essential step in assembling a DAS. Improper grounding can result in inaccurate measurements and damage to the logger or the sensor.

Typically, the terms “ground” or “earth” or “earth ground” refer to the voltage potential of, literally, the earth. Most buildings have a “grounding rod,” which is pounded into the earth and all electrical devices that are “grounded” within the building are ultimately electrically connected to this grounding rod.

The Distinction Between "Earth Ground" and "Data Logger Ground"

In DAS, all measurements are ultimately based on measurements of the voltage potential between various points in the circuitry and a common reference voltage often referred to as the “data acquisition system (or the data logger) ground.” The internal circuitry of the DAS is all referenced to the data logger ground. It is important to understand that the *data logger* ground is not the same as the *earth* ground unless the former is explicitly tied to the latter. Even in a handheld voltmeter (which is an example of a simple DAS), there is a common reference voltage within the circuitry that is the data logger ground. In the case of a handheld voltmeter, this reference voltage is not connected electrically to any other reference, and indeed may be at a very large potential above or below the earth ground.

This difference between the data logger ground and the earth ground is illustrated in Figure 1. Here, a handheld voltmeter is used to measure the voltage across battery #2. In this case the negative lead of the voltmeter, which is internally connected to the circuitry’s reference voltage (the data logger ground), is 12 volts higher than the earth ground. The voltmeter reads the correct value of 13 volts across battery #2 even though the reference voltage of the meter is 12 volts above *earth ground*.

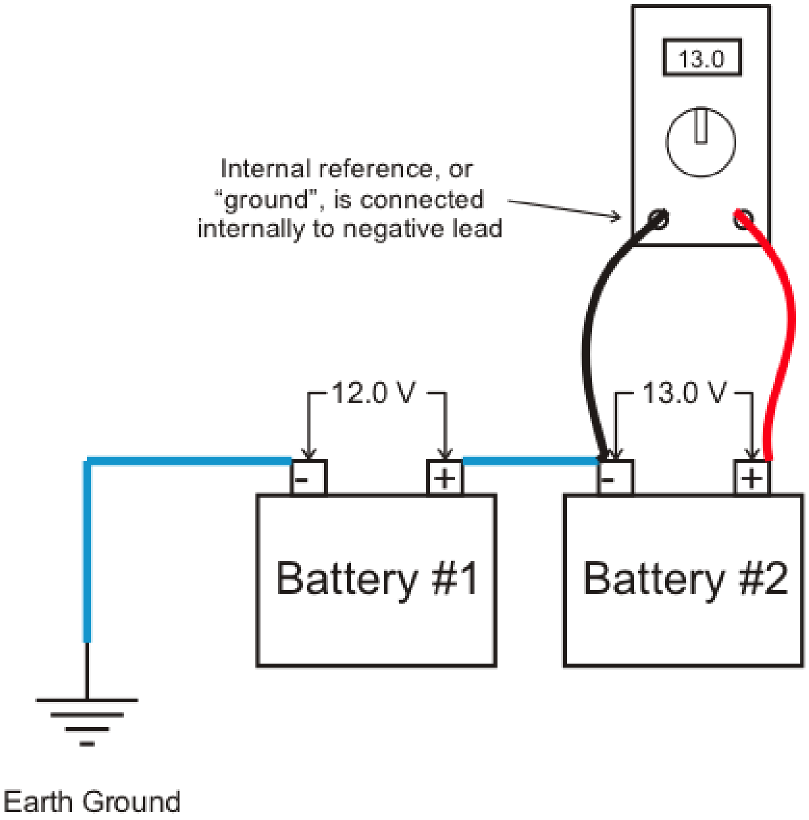


Figure 1. Measuring battery #2's voltage using a voltmeter. The voltmeter ground is 12 V higher than the earth ground.

A multichannel data logger can be thought of as several volt meters combined into one package, with all voltage measurements internally referenced to the data logger ground.

Grounding to Avoid Exceeding the Input Limit and Common Mode Range of Your Data Logger

The data logger has two voltage limits that must be observed:

- The *input limit,* which is the maximum voltage between the two measurement terminals.
- The *common mode range,* which is the maximum voltage between any measurement terminal and the data logger ground.

The *input limit* may be software-configurable or may be fixed, whereas the *common mode range* typically varies as a function of the voltage across the two measurement terminals. The input limit is always greater than or equal to the common mode range.

If either the input limit or the common mode range is exceeded by a small amount, the measurement is likely compromised. In fact, it is possible that all measurements on the data logger are compromised, although the data logger may not be damaged.

To avoid exceeding the common mode range, each sensor connected to the data logger must be connected to the data logger ground.

Data loggers may be capable of making single-ended measurements, differential measurements, or both. In a *single-ended measurement*, one of the two terminals across which the voltage is to be measured is internally connected to the data logger ground, so that the measured voltage is referenced to the data logger ground. In this case the input limit will be exceeded before the common mode range because the input limit is always greater than or equal to the common mode range.

In a *differential measurement* neither terminal is internally electrically connected to the data logger ground. The data logger measures the voltage difference between the two terminals even if neither terminal is at the same potential as the data logger ground. In a differential measurement it is possible to exceed the common mode range without exceeding the input limit, and it is important to avoid this situation by explicitly grounding one of the terminals to the data logger ground. Many self-powered sensors and devices such as thermocouples, pyranometers, and batteries, are not, by default, connected to the data logger ground when the voltage generated by the sensor is measured as a differential measurement.

Consider Figure 2, in which a data logger is used to measure the current generated by a thermopile-type pyranometer. The data logger has an input limit of 250 mV (which means the maximum voltage difference it can measure between the two terminals is 250 mV), and the pyranometer generates a maximum of 200 mV under full-sun conditions, so the input limit will not be exceeded. Let’s look at the common mode range, which is 2.5 V for this data logger. In Figure 2, the pyranometer is not connected to the data logger ground. Even though the voltage generated by the pyranometer will never exceed the input range of 250 mV, the common mode range can be exceeded because the potential between the pyranometer and the data logger ground can “float”: atmospheric conditions and electromagnetic fields can cause the voltage between the sensor and the data logger to be several volts. To make this problem particularly tricky, this often does not happen immediately after connecting a sensor, but the sensor’s voltage gradually floats farther and farther from the data logger ground until the common mode range is exceeded days or weeks after installation. The result is that the measurements look fine for many days, then suddenly are clearly wrong. Sometimes after a while the sensor’s voltage will float back down on its own and the measurements make sense again. In Figure 2 the sensor has floated to 4.1 V above the data logger ground potential, which exceeds the common mode range of 2.5 V.

To keep the sensor’s potential from “floating away,” a jumper must be added (Figure 3) to connect one side of the sensor to the data logger ground. The jumper can be a small length of wire or a resistor of relatively low resistance (less than 1000 Ohm). The sensor is thus now grounded (at the data logger ground) so that neither measurement terminal will ever be more than 200 mV above the data logger ground and the common mode range will never be exceeded.

Grounding the Data Logger to Earth Ground for Safety

In Figure 4 the data logger ground is connected to earth ground. This is generally done for safety reasons, to keep the data logger and all its connected sensors from floating far from earth ground. Because people and buildings are generally connected to earth ground, if a data logger has floated 100 V above earth ground (this can happen under some circumstances!) then when someone touches the data logger, he/she will receive a dangerous electrical shock.

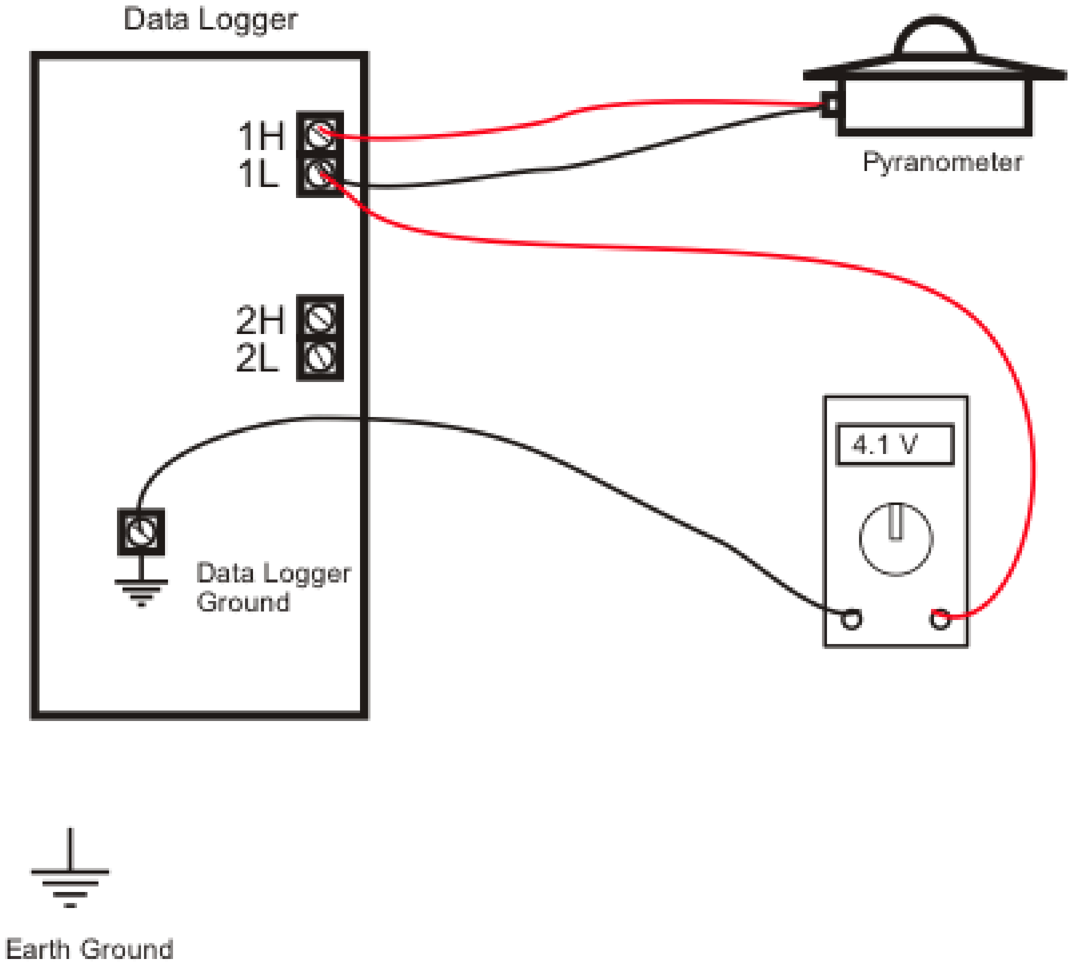


Figure 2. Sensor is not grounded, risking common-mode voltage over-ranging

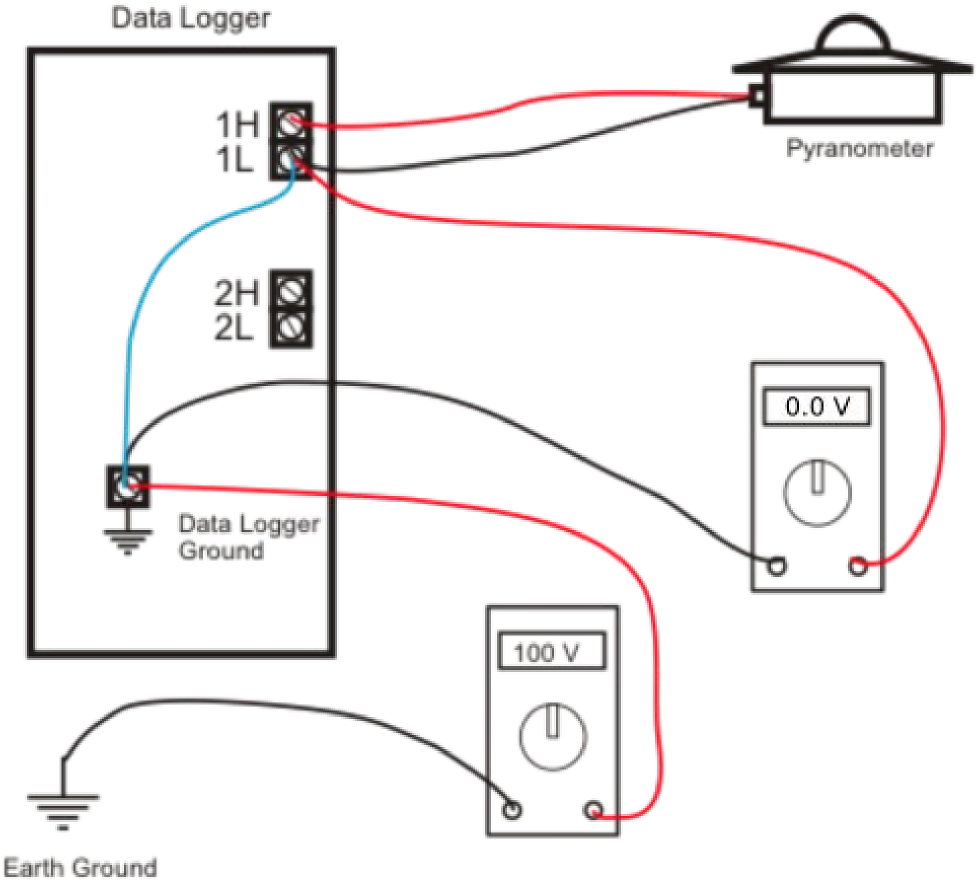


Figure 3. Sensor is grounded, preventing common-mode over-ranging, but data logger ground is floating

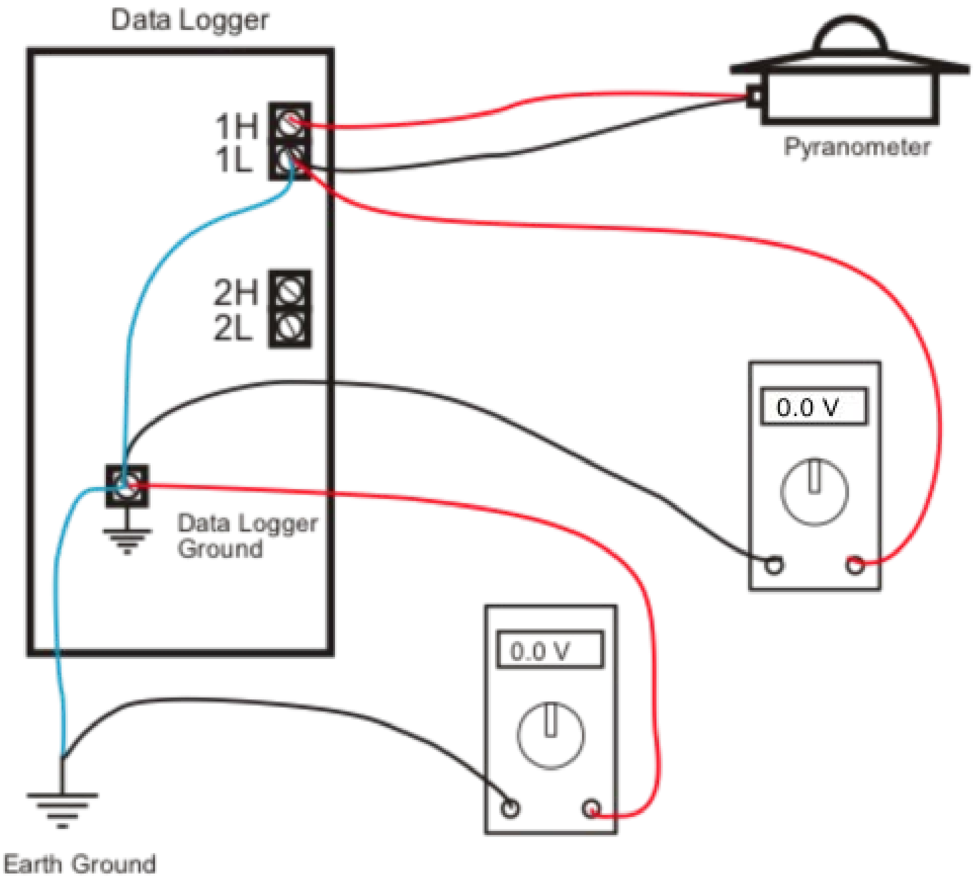


Figure 4. Recommended wiring. Common-mode voltage over-ranging is prevented, and data logger is grounded for safety.

Avoiding Ground Loops

Often in electrical circuit diagrams the electrical potential of the “ground” is depicted as being at exactly the same voltage in all places in the diagram. In fact, because all conducting materials have some electrical resistance, if there is any current flowing from one point to another along a conductor connected to ground, there will be a small voltage difference between one point and the next. This flow of current from one point of the ground to another is what is known as a *ground loop*.

When making measurements using a data logger it is important to understand that everything electrically connected to the data logger is part of the overall electrical circuit. In Figure 5, for example, a data logger is used to measure temperatures of water in a pipe using immersed temperature sensors. The data logger is grounded to earth ground by connecting to an electrical conduit, which is ultimately connected to the earth ground via the building’s grounding rod. Two thermocouples are used to measure the temperature of the fluid at two points in a pipe. The negative leads of the thermocouple wires are connected to the data logger ground to prevent the sensors from exceeding the common mode range. The thermocouples are sheathed in stainless steel tubes immersed in the fluid in the pipe. The pipe, if it is made of metal, is also connected to the earth because it is electrically connected to the metal cold water mains pipe entering the building. Even if the pipe is made of a non-conductive material like PEX, the water in the pipe is still electrically connected to earth ground, with some resistance, because non-distilled water is somewhat electrically conductive and the water is touching the inside of the metal cold water mains pipe. A person looking at Figure 5 might conclude then that the voltage potential at the data logger ground is the same as the potential at each pipe since all are shown connected to earth ground. This is not necessarily true, however, because the electrical resistance between each pipe and the data logger ground is non-negligible, the path being a circuitous route through the earth, grounding rod, electrical wires, and conduit. If two points are not connected with near-zero resistance, there is always the possibility that the voltage between the two points is not zero.

In Figure 5 the voltage between the data logger ground and the pipe is shown to be 1.0 mV when no conductor is connected between the pipe and the data logger ground (upper sensor). This magnitude of potential between one grounding point in a building and another is not uncommon. If the data logger terminals are at 20°C and the water temperature is 40°C, the voltage generated by a Type T thermocouple will be about 0.790 mV. This voltage is measured by the data logger and used to calculate the temperature of the thermocouple in the pipe. If the thermocouple wire is not electrically connected to the pipe or water the voltage between terminals H and L will be 0.790 mV and the correct temperature will be calculated (upper thermocouple in Figure 5). If, however, the thermocouple junction inside the metal sheath is connected to the sheath (this is called a “grounded sensor”), a *ground loop* will be present as current will flow from the junction, which is now at a higher voltage than the data logger ground, to the data logger ground. Because the electrical conductivity of the thermocouple wire is fairly high, the voltage between the pipe and the data logger ground may be reduced from the initial 1.0 mV, but it will not be brought to zero because the wire has a non-zero resistance. In this example the voltage between the lower pipe and the data logger ground is reduced to 0.5 mV because the negative lead of the thermocouple is conducting some current from the pipe to the data logger ground. Because of this ground loop, the voltage between terminals H and L will be raised from 0.790 mV to (0.790 + 0.5) = 1.290 mV. From this measured voltage the data logger will calculate a temperature of 52.3°C instead of the correct temperature value of 40°C.

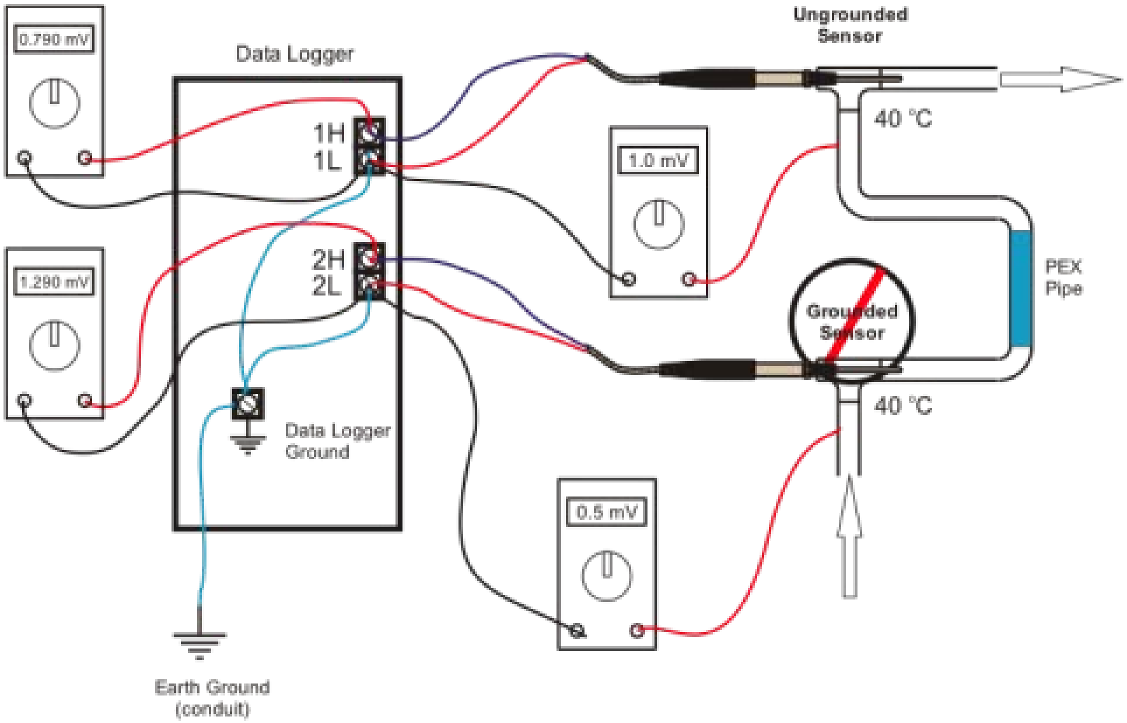


Figure 5**. Upper (ungrounded) sensor reads correct value. Lower (grounded) sensor reads incorrect value due to ground loop between lower pipe and data logger ground.**

Grounding: Conclusions/Rules of Thumb

If the following rules of thumb are followed, problems with common mode over-ranging and ground loops can be avoided:

1. The data logger should have its ground connected to *earth ground*.
2. Each sensor should be reliably connected to a ground to avoid *common mode* over-ranging.
3. Each sensor should be grounded at ONE POINT ONLY to avoid ground loops.

In order to achieve a single, reliable grounding point for the sensor, it is best to ground the sensor at the data logger and be sure that the sensor is electrically insulated from all electrically conductive media. Keep in mind that even a partial connection to earth ground, such as through water or by direct burial of an uninsulated sensor, can cause a ground loop if the sensor is grounded at the data logger.

3 Specific Measurements

This section describes specific types of measurements and includes tips and considerations for each measurement.

3.1 Airflow and Leakage

There are several approaches to airflow measurements depending on the specific question being addressed. These include blower door, powered ducted fan, tracer gas, passive and powered flow hoods, orifice plate, and pitot tubes.

3.1.1 Blower Door—Building Enclosure Leakage

A blower door is a device used to pressurize or depressurize a house to determine the leakage characteristics of the building enclosure. A variable-speed fan is temporarily mounted in a doorway or other opening to pressurize (or depressurize) the house by specified amounts. The flow rate through a calibrated orifice is measured at the different house pressures. The relationship between flow rate and pressure difference is an indication of shell airtightness. For an example of full details on blower door operating procedures for a blower door, see reference [1].

Figure 6. A blower door installed in the front door of a test house, from the outside

Photos by Ed Hancock, NREL

The results of the blower door tests can be expressed as one of several figures of merit. One simple expression of the envelope tightness is the blower door flow rate at a single pressure difference—usually 50 pascals (Pa) or "CFM50." This test is the simplest and easiest to perform because it requires the blower door operator to achieve only one pressure (50 Pa) and measure a single flow rate. The 50-Pa pressure is the highest used in a typical blower door test and is the least sensitive to the influence of wind variation during the test. It, therefore, tends to be more repeatable than other tests that require measurements at a range of lower pressures. However, a single point test does not provide adequate information to use in algorithms for calculating actual air-exchange rates. Another quantity that can be calculated by pressuring the house to 50 Pa is the air changes per hour (ACH50) at 50 Pa (equal to the CFM50 multiplied by 60 minutes per hour and divided by the house volume). ACH50 can be a useful metric for comparing houses of different sizes.

The equivalent leakage area (ELA) is defined as the area of a calibrated orifice that would have the same airflow rate the house does at a pressure of 4 Pa. The equivalent leakage area, therefore, is an estimate of the aggregate size of all the leaks in the building. An equivalent leakage area can be calculated from the results of a *multipoint* blower door test. This is generally done using a laptop computer with software provided by the blower door manufacturer. An example software can be found in reference [2] to automatically control the blower door for multipoint tests. Typically, 100 data points at each of 8 different pressures between 15 and 50 Pa are used to determine the relationship between pressure and leakage rate for the test home. The equivalent leakage area is based on the leakage rate at a 4-Pa pressure difference, which is determined by a curve fit to the blower door test data at various pressures. The equivalent leakage area can then be used in conjunction with weather conditions at the home site to model the natural ACH at particular times and to estimate long-term or annual infiltration rates.

If attached units are being tested, guarded tests should be performed with adjacent units pressurized at the same level as the test unit to determine the leakage between units. A guarded test refers to a test with one or more adjacent units pressurized, which should eliminate any leakage between units. The leakage measured in a guarded test will be the leakage to outside and any unguarded adjacent units. Caution must be used when there are buffer spaces connecting adjacent units, such as a common crawlspace or attic. Such spaces can become partially pressurized during the blower door test, making interpretations of the data more difficult. Specific guidelines on guarded blower door testing are available from blower door manufacturers such as the Energy Conservatory.

Lawrence Berkeley National Lab has developed a methodology called Delta Q that uses a blower door to measure both building envelope leakage and duct leakage to the outside [3]. Specialized software is required to perform the Delta Q test.

Application Notes

Quantities that can be measured using a blower door test include:

- Air change rate of the house at 50 Pa pressurization/depressurization
- Effective leakage area (or equivalent leakage area) of the house
- Effective leakage area between adjacent multifamily units
- Effective leakage area of a buffer space
- Duct leakage to the outdoors (using the Delta Q method).

Some limitations to using a blower door are:

- Localized pressurization caused by different systems within the house will influence the leakage area of a house. The uniform pressurization of the house by a blower door makes it impossible to see these effects.
- The distribution of leakage area in the building envelope can have a large effect on the infiltration rate of the house. The blower door test does not provide any information about where the leaks are located, or how large they are on average. Assumptions about leak distribution can be validated to some extent by comparing blower door results to tracer gas results under known weather conditions.
- Blower door measurements must be made during very still outdoor conditions. Breezy days can result in inaccurate measurements, and blower door measurements should never be made on windy days. To limit the effects of wind, at least four pressure lines of equal length should be routed to the four sides of the home's exterior and placed such that any breeze would blow perpendicular to the tubes' openings.

References:

1. The Energy Conservatory. 2022. *Model 3 Minneapolis Blower Door^{TM} System*, Minneapolis, Minnesota: The Energy Conservatory.
2. The Energy Conservatory. 2016. *TECTITE (Ver. 4.o – WiF).* Minneapolis, Minnesota: The Energy Conservatory.
3. Walker, I.S., D.J. Dickerhoff, and M.H. Sherman. 2002. "The Delta Q Method of Testing the Air Leakage of Ducts." Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy-Efficient Economy.

3.1.2 Powered Ducted Fan—Duct Leakage and Kitchen Exhaust

A duct pressurization test using a powered ducted fan is used to evaluate leakage of an air-distribution system, including the ducts and air handler cabinet. During the test, all supply and return registers are taped closed, and the pressurization fan is temporarily mounted to pressurize the taped-off duct system. A multipoint test can be performed to infer a leakage area, but it is more common to pressurize to a reference pressure of 25 Pa. The flow rate at this pressure is an indication of the leakage characteristic of the air-distribution system. The supply and return sections of the air-distribution system can be separately tested by inserting a blocking section in the air handler. An inference can be made as to the proportion of leakage to the outside under test conditions by pressurizing the house to the reference pressure using a blower door during the duct pressurization test. Because the ducts and house are then at the same pressure, any leakage from the ducts is assumed to be to the outside rather than to the house. The results of this test provide a useful benchmark for evaluating the general quality of the air-distribution system, but the test results do not directly indicate duct air leakage during normal operation of the system. For full details on operating procedures for a powered duct fan, see references [1,2]. For an example of an equipment manufacturer's operating manual see reference [3].

Figure 7. A duct pressurization test in process

Photo by NREL/PIX 04869

In addition to duct pressurization testing, this test equipment can be used to measure the flow rate of kitchen exhaust fans. Due to their geometry, it may not be possible to directly measure the airflow rate from many kitchen exhaust fans. Sometimes it may be possible to measure the flow using a flow hood on the outside of the building. Otherwise, the duct pressurization rig can be used. A temporary plenum (aka air capture box) can be built from cardboard or foil-faced foam insulation with a hole positioned for easy access. Tape the duct of the depressurization rig over the hole and put a pressure tap in the plenum. The fan should be positioned to blow OUT of the plenum. To measure the exhaust fan flow rate, turn the exhaust fan on, adjust the flow rate of the depressurization rig until the pressure difference between the plenum and the room is zero. Repeat for the different exhaust fan settings. (Note, a powered flow hood could also be used with this approach.)

Figure 8. A kitchen exhaust fan test setup using a custom air capture box and a powered ducted fan

Photo by Paul Norton, NREL

Application Notes

Quantities that can be measured using a duct pressurization test include:

- Total duct leakage at 25 Pa
- Duct leakage at 25 Pa for the house (supply to inside, supply to outside, return to inside, return to outside)
- Kitchen exhaust hood flow rate.

Similar to the limitations with the blower door test, the uniform pressurization of the ducts makes it difficult to see actual leakage present during normal operation. The Delta Q method referred to in the blower door section above may be suitable for measuring duct leakage to the outside in many field tests.

References:

1. American Society for Testing and Materials. 1994. *ASTM E1554, Standard Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization*. West Conshohocken, Pennsylvania.
2. Hancock, E.; Norton, P. and Hendron, R. 2002. Building America System Performance Test Performance Test Practices: Part 2, Air Exchange Measurements. National Renewable Energy Laboratory, August 2002. NREL/TP-550-30270.

3. Minneapolis Duct Blaster Operation Manual. Minneapolis, Minnesota: The Energy Conservatory.

3.1.3 Tracer Gas—Building Enclosure Leakage and Fresh Air Distribution

Blower door and duct pressurization tests provide measurements of the leakage characteristics of the envelope and air-distribution systems at elevated and uniform pressure differences but may not be accurate for predicting how much outside air actually enters a house under normal driving forces. Tracer gas measurements can provide such direct measurements [1]. Single zone tests measure the net whole-house air exchange rates under a variety of operating conditions. Multi-zone tests provide additional insight into how outside air is distributed room to room inside the house. Inside and outside temperatures, as well as outside wind speeds, should be measured during the tests because these are the main drivers of infiltration.

Ideal tracer gases should be detectable at low concentration, safe for humans, not naturally occurring, and have neutral buoyancy in air. The most common tracer gas for Building America projects has been sulfur hexafluoride (SF_6). SF_6 is a very potent greenhouse gas. It is reported to be about 22,800 times more effective at trapping infrared radiation than an equivalent amount of CO_2) and stays in the atmosphere for 3,200 years. Although very small amounts of SF_6 are used in a residential tracer gas test, alternatives to SF_6 are being explored. In certain instances, multiple tracer gases are used to detect multi-zone interactions. NREL developed a test protocol for multi-zone tracer gas field tests [3].

Single-Zone Tracer Gas Decay Test

During a typical field test, six sample points are installed throughout the house and SF_6 is injected in all areas of the house and mixed to a uniform concentration using the air handler or portable fans. The rate of decay in SF_6 concentration is used to calculate the air exchange rate, stated as air changes per hour (ACH), due to infiltration or intentional ventilation. For single-zone tests, a combination of small portable fans, ceiling fans, and de-stratification fans (for multistory homes) are operated to help maintain uniform mixing throughout the home. Portable heaters are used to control the interior temperatures during tests where operation of the space heating system is not desired such as natural infiltration or ventilation tests. The tracer gas concentration is sampled at six points throughout the house. The results from the six sampling points are averaged to calculate whole-house concentration at each time step. This method is documented in ASTM E741 [2]. For room-to-room distribution tests, interzonal mixing is not desired. The degree of mixing is inferred by examining the decay curves in each room under various test conditions. Mixing fans are used to create well-mixed conditions inside each room to ensure that the measured concentration represents the zone average.

A bump test is used to determine the change in whole-house air change rate caused by changing the operating state of a building system. Bump tests can be performed on the air handler or ventilation system during a period when natural infiltration is steady. During a tracer gas test, the air handler is turned on for a prescribed period of time, and an increase in ACH implies there are leaks in the ductwork going to and from the air handler to outside. Measuring the duct leakage during a tracer gas test in the form of a bump test should be more reliable than a duct blaster test because the system is operating under normal pressurization conditions. A bump test can also be performed with the home's ventilation system. For a balanced ventilation system, the increase in ACH should correspond to the volume rate of air being pulled out the house, but in unbalanced ventilation, the effective ventilation may not correspond to the volume of air being exhausted. A bump test on the ventilation system will measure the effective rate of ventilation in the home.

Application Notes

Quantities that can be measured using a single zone tracer gas test include:

- The natural infiltration rate of the house under a particular set of weather conditions.
- How infiltration is changed when the air handler is turned on in the heating/cooling/fan mode.
- How infiltration is changed when the ventilation system is operated.

Some limitations to a single-zone test include:

- Results cannot always be generalized to different weather conditions.
- The air handler bump test measures the change in air infiltration caused by pressure imbalances resulting from air handler operation, including the effects of supply and return duct leakage. Supply and return duct leakage cannot be easily separated from each other, or from local pressurization effects.
- The location of duct leaks can skew the results of the air handler bump test. For instance, take a situation where the ducts are located in a vented attic and there is a leak on the supply side. The tracer gas will leak into the attic and mix with that unconditioned air. If there are leaks on the return side with the return ducts in the attic, the air handler will also pull air from the attic in through the leak. This air will contain some tracer gas, but also will be coming from an unconditioned space, unlike the rest of the return air. It is difficult to tease these details out of the bump test results, and so the true effect of duct leakage on energy usage cannot be known precisely.

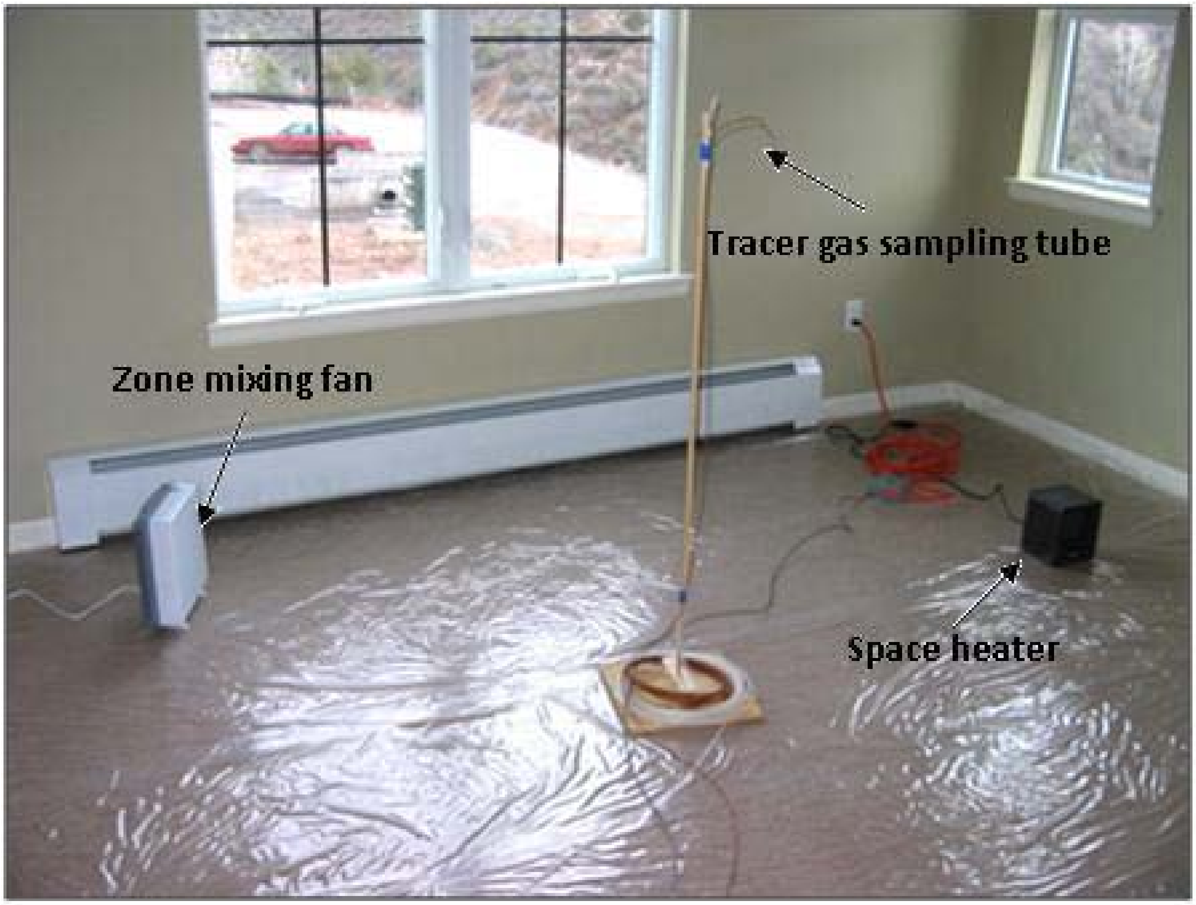


Figure 9. Tracer gas testing setup, including a space heater, a small fan, and a sampling tube

Photo by Ed Hancock, NREL

Multi-Zone Tracer Gas Decay Test: Reciprocal Age of Air

Outside air distribution (natural infiltration combined with mechanical ventilation) can be non-uniform within a home, causing ineffective dilution of contaminants and thus indoor air quality concerns in certain parts of the house. In evaluating the non-uniformity of outside air distribution within a home, a room-to-room tracer gas test can be performed to examine the concentration decay or "age of air" in each room. For a detailed description of this test, reference "A Test Protocol for Room-to-Room Distribution of Outside Air by Residential Ventilation Systems" [3].

Application Notes

A multi-zone tracer gas decay test provides the reciprocal age of air in each zone under a particular set of operating conditions and weather conditions. However, interzonal airflows, which are necessary to analyze pollutant control when sources are non-uniform, cannot be calculated from a multi-zone, single tracer gas test. A multi-zone, multi-tracer gas test is necessary to quantify interzonal airflows.

References:

1. Hancock, E.; Norton, P. and Hendron, R. 2002. National Renewable Energy Laboratory. NREL/TP-550-30270.

2. American Society for Testing and Materials 2000. *ASTM E741, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*. Conshohocken, Pennsylvania.
3. Barley, D.; Anderson, R.; Hendron, R. and Hancock, E. 2007. *A Test Protocol for Room-to-Room Distribution of Outside Air by Residential Ventilation Systems.* National Renewable Energy Lab. Golden, CO. December 2007. NREL/TP-550-31548.
4. ASHRAE. 2002. ANSI/ASHRAE Standard 129-1997 (RA 2002). *Measuring Air-Change Effectiveness*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Perfluorocarbon Ventilation Distribution

The perfluorocarbon test method [1] is a relatively simple, very approximate method of testing ventilation rates in a home. Up to six different types of tracer gas are continuously injected into the home via small, passive emitter capsules. Capillary adsorption tube samplers (CATS) detect the average concentrations of each tracer present at various sampling locations. Then, laboratory analysis of the CATS indicates the matrix of airflow rates among the emitter and sampling locations as well as the atmosphere (outside air).

The minimal apparatus is unobtrusive, allowing testing for long periods while the home is occupied. Thus, the effects of occupant behavior, as well as averaging over a variety of weather conditions and HVAC operating modes, can be included in the measurement. It is also an inexpensive way of diagnosing airflow patterns, such as entrainment of pollutants from a garage or crawl space into the conditioned space. However, despite the many advantages to a perfluorocarbon test relative to alternatives like tracer gas tests, it is a less accurate test method due to the many sources of uncertainty.

Application Notes

The perfluorocarbon method is subject to several significant sources of error, including:

- Miscalibration of the laboratory equipment that analyzes the CATS. This has been an issue in past field tests.
- Uncertainty in estimating the volumes of zones within the home, among which air is exchanged, with the assumption of uniformity within each zone. This is a rough approximation of actual tracer distributions throughout the volume.
- Possible contamination of the CATS during handling and storage. Errors may be larger in short-term perfluorocarbon tests than in longer-term tests, because of the lower signal-to-noise ratio in the CATS samplers (less of the tracer gas compared to the contaminants).
- Reciprocal averaging: Because ventilation rates are inversely related to tracer concentrations, the measurement of time-averaged tracer concentrations systematically underestimates the average air change rate when the rate varies significantly during the test. When considering indoor air quality, the reciprocal air change rate is regarded as more meaningful than the mean air change rate, because it more closely corresponds to the exposure of occupants to pollutants over the time period. However, for heating and cooling calculations, the actual average air change rate is more meaningful.

"Even avoiding the worst situations of assumption violations, [continuous-injection, long-term sampling] should be considered as having a something like a factor of two uncertainty for the broad field trials that it is typically used in." [2]

Because of these accuracy concerns, a recommended practice is to include a number of control samples with the test samples in order to analyze systematic and random error trends. The control samples may be exposed during side-by-side testing with tracer decay tests over several days in preliminary short-term testing. The tracer decay method is not subject to the same sources of error and is considered more reliable.

References

1. Dietz, R.N.; Goodrich, R.W.; Cote, E.A.; Wieser, R.F. 1986. *Detailed Description and Performance of a Passive Perfluorocarbon Tracer System for Building Ventilation and Air Exchange Measurements. Measured Air Leakage of Buildings*, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds. Philadelphia, PA: American Society for Testing and Materials, pp. 203-264.
2. Sherman, M.H.; Walker, I.S.; Lunden, M.L. 2014. "Uncertainties in Air Exchange using Continuous-Injection, Long-Term Sampling Tracer-Gas Methods." *International Journal of Ventilation*. LBNL-6544E.

3.1.4 Passive Flow Hood

A flow hood is a device that measures the airflow rate into or out of a register while the air handler is operating. The flow hood channels the air through a short fabric duct containing thermal anemometers to measure the flow of air entering or exiting the register. During normal air handler or ventilation system operation, the flow hood is held over each supply and return register and the flow rate for that register is recorded. These measurements are used to check the total airflow for the house and room-to-room airflow balance. A flow hood is often used for these other airflow measurements:

- Bathroom exhaust flow rates at bathroom to ensure they are working properly.
- Kitchen exhaust fans if the hood can be positioned over the exhaust fan inlet in the kitchen or the exhaust port on the outside of the building. (If not, the exhaust fan flow rate can be measured with a powered ducted fan.)
- The difference between the sum of the flow rates at each supply or return register combined with the total flow rate at the air handler can provide estimates of the supply and return duct leakage.
- The supply and return airflows from each register of a heat recovery ventilation system can be measured to determine fresh air delivery or stale air exhaust from each room or zone.

Figure 10. Passive flow hood in use at a field test site

Photo by NREL/PIX 19616

Application Notes:

- Flow hood readings must be adjusted when taken at high altitudes.
- Accuracy of a passive flow hood is not very good (5%–10% in most cases).

Reference:

1. Hancock, E.; Norton, P. and Hendron, R. 2002. *Building America System Performance Test Performance Test Practices: Part 2, Air Exchange Measurements*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy02osti/30270.pdf.

3.1.5 Powered Flow Hood

A powered flow hood is a type of flow hood, primarily used for airflow measurement at a supply or return register. When properly used, it is able to provide a measure of airflow without altering the register pressure and flow as much as non-powered flow hoods can. Powered flow hoods are composed of a standard flow hood plus a fan, pressure gauge, and controller. The fan speed is set to ensure the register pressure is the same as the ambient room pressure. In that way, there is no backpressure from the flow measurement component (orifice plate or nozzle) on the duct system.

A powered flow hood should be used when a register is located near a duct branch or tee. The backpressure from a standard flow hood will reduce the measured flow on each side of that branch during the measurement, with the result being a strong underestimate of the volumetric flow.

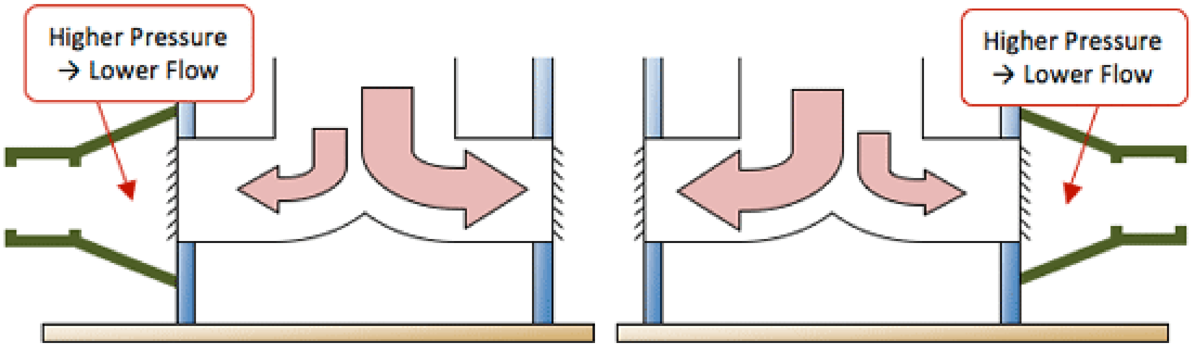


Figure 11. Flow measurement near a tee using a standard flow hood. Measuring on either side of a tee results in underestimates of the typical flow through these registers.

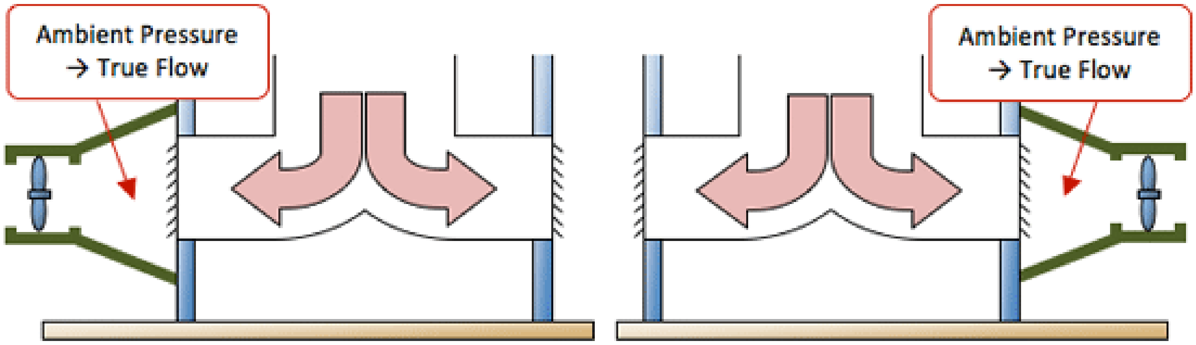


Figure 12. Flow measurement near a tee with a powered flow hood. Measuring on either side of a tee does not significantly change the typical flow through these registers, resulting in more accurate measurements.

Some powered flow hoods have an automatic fan speed controller, others have a manual dial. Powered flow hoods have been found to be much more accurate than standard flow hoods [1], and are the preferred method.

Powered flow hoods can also be connected directly to an air handler, or to ductwork. Equipment user manuals, such as [2], provide full details.

A blower door is a type of powered flow hood. Because it has different considerations and is used to measure different phenomena, it is described in its own section.

References:

1. Wray, C. et al. 2002. *Accuracy of Flow Hoods in Residential Applications*, Lawrence Berkeley National Laboratory. LBNL-49697.
2. ACIN Instruments Flow Finder 2 Manual, https://acin.nl/wp-content/uploads/2021/04/FFMK2_rev4-QuickStartManual8_EN.pdf.

3.1.6 Orifice Plate—Air Handler Flow Rate

An orifice plate, also known as a flow plate, is a calibrated airflow measurement device, typically used to measure return airflow at an air handler unit. It is placed in the filter slot and sealed to the sides of the air handler case. Round holes are located in a flat plate, and the differential pressure across the plate is measured while the air handler blower is operating. This pressure is correlated to the volumetric flow through the orifices.

Flow plates are typically provided with the necessary calculations and calibration factors to convert the pressure measurement to a flow in the field. Unless the orifice plate is damaged, it typically does not need recalibration. However, the pressure transducer used for this measurement should be handled carefully and be calibrated on a regular schedule.

Application Notes

Installation of the orifice plate will change the airflow and pressures in the air handler cabinet. The best practice method for using an orifice plate is as follows:

1. Install pressure taps in the supply ductwork after the air handler and in the air handler just after the filter.
2. Measure the differential static pressure across the blower and coils while the blower is running in the intended stage/mode.
3. Remove the filter and install the orifice plate.
4. Adjust the fan jumpers to achieve approximately the same differential pressure as above.
5. Measure the differential pressure across the orifice plate and calculate the airflow.
6. Remove the orifice plate, reinstall the filter (or a clean one), reset the fan jumpers, and verify the same differential pressure as before.
7. Cap the pressure taps, or seal them with mastic.

Note that different size and quantity of orifices may be needed, depending on the overall flow rate, so that underlying assumptions are valid. At extremely low and extremely high air speeds, those assumptions will become invalid. Consult the manufacturer's user manual for the range of use for your orifice plate.

Figure 13. Orifice plate in use

Photo by Ed Hancock, NREL

3.1.7 Pitot Tube—Air Velocity

A pitot tube is an instrument used to measure fluid flow rate and is typically used to measure airflow rate in a field test application. A pitot tube is a curved tube with an inlet that points toward the flow direction with no outlet, which is used to measure the total pressure of the flow. Often, there is a second pressure port on the side of the tube that senses the static pressure. The difference between the total and static pressure can be used to determine the velocity of the fluid. If this measurement is taking place in a duct or at an air vent, the cross-sectional area can be used to calculate the volumetric flow rate. Pitot tubes for airflow rate measurement can be found in a long-term installation configuration or in a handheld configuration.

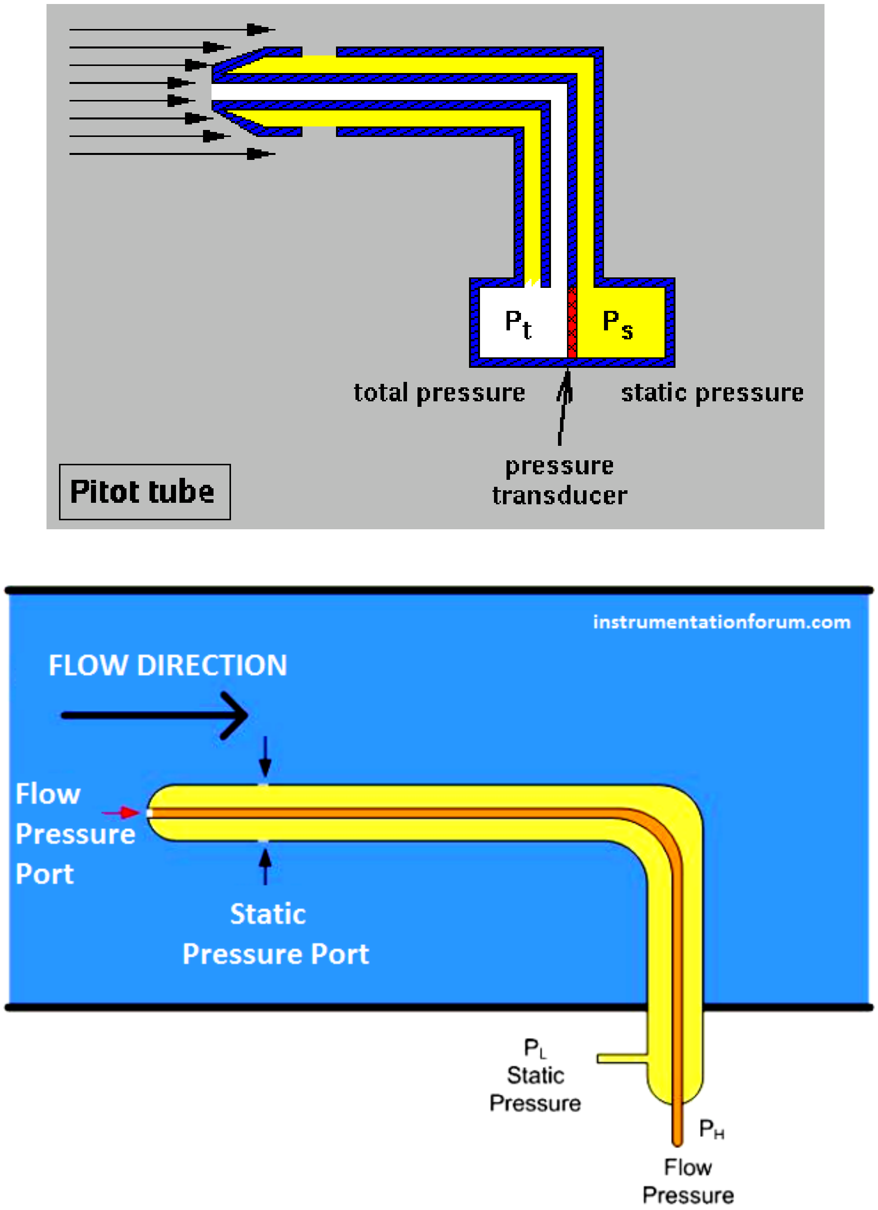


Figure 14. A diagram of a pitot tube flow meter

Image from PiaCarrot, Wikimedia Commons

3.1.8 Hot Wire Anemometer—Air Velocity

A hot wire anemometer, or thermal anemometer, is a device used to measure fluid speed. The wire is generally made of either platinum or tungsten and is heated by running current through it. The change in current required to maintain a constant wire temperature is directly related to the wire heat loss to the fluid. Based on convective heat transfer, the heat loss can be used to calculate the fluid speed.

Hot wire anemometers are typically available as handheld devices that could be used in an audit or short-term test. They are sensitive enough for very low flow rates from a vent or a bathroom fan. However, they are also fragile and will get dirty easily, so they should not be used when ducts are dirty. They will need to be calibrated often if dust is allowed to accumulate.

Figure 15. Hot wire anemometers used to measure airflow speed (installed on the left and handheld)

Photo by Paul Norton, NREL

3.2 Humidity

Humidity control and measurement are tricky to do accurately in a field test setting. There are different types of humidity sensors and hygrometers. A few things to keep in mind to ensure accurate measurement of humidity in a field test setting include knowing what parameters you will be measuring, choosing the correct instrument, avoiding external factors that will affect the measurement, and keeping good records of calibration, adjustment, and repairs.

3.2.1 Temperature and Relative Humidity Sensor

A temperature and relative humidity (T&RH) sensor is a simple, durable, and low-cost type of electronic hygrometer used in building science. Commonly available models use thin-film polymer technology. The dielectric properties of the polymer film change with ambient air relative humidity, and the capacitance of the sensor changes correspondingly.

The T&RH sensor directly measures temperature and relative humidity and calculates other psychrometric properties. Unlike a dewpoint hygrometer, which measures dewpoint, a T&RH sensor's relative humidity readings are significantly affected by ambient dry-bulb temperature. Therefore, it is important to maintain accurate temperature readings on a field test setting. Certain things such as condensation on the sensor probe, direct sunlight, body heat and humidity, non-representative sources of heat, or stagnant and/or non-representative air samples need to be avoided.

Figure 16. Example of a temperature and relative humidity sensor

Photo from Vaisala product website

T&RH sensor specifications on operating temperature ranges vary depending on application types such as ducted or wall-mounted, indoor, or outdoor application types. The widest range is between -40 to 60°C and 0 to 100% RH. T&RH sensor accuracy in general varies from ±1% to ±3% RH and ±0.2°C to ±0.6°C as common depending on the operating temperature range. However, for every 1% RH at 20°C the dewpoint temperature varies by less than 0.2°C. A device with an accuracy of ±2% RH and ±0.2°C is able to measure dewpoint temperature to better than ±0.5°C.

Figure 17. Additional example of a temperature and relative humidity sensor

Photo by Ed Hancock, NREL

Application Note

These sensors come pre-calibrated with manufacturer-listed total uncertainty limit. But over time, the RH readings will drift, and lab and in-field calibration are required. Good records need to be kept of T&RH calibration, spot-checking, and maintenance. It is common in a field test setting to do some salt-based spot checking on high and low RH setting such as 11% and 75% RH or check the reading against a recently calibrated handheld sensor.

3.2.2 Moisture Content Sensor

For long-term monitoring of moisture content in wood frames to detect mold or decay, it is common to measure the resistance of wood and convert that to a moisture content reading [1][2]. Capacitance-type T&RH sensors are not commonly used in these situations, because they often fail after extended exposure to high relative humidity environment.

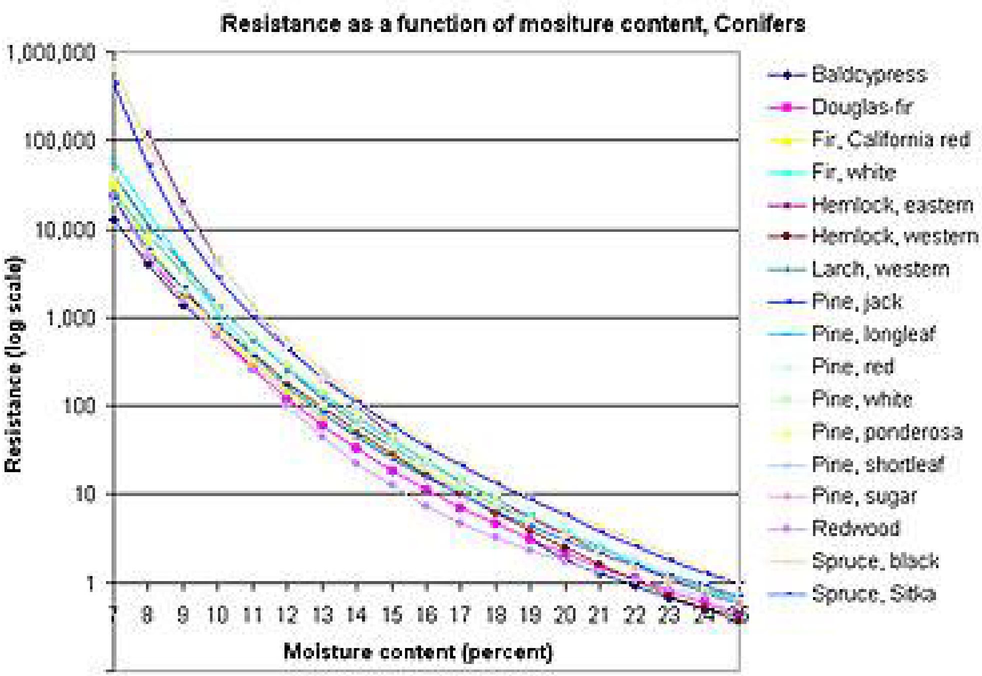


Figure 18. Electric resistance versus moisture content for different wood species

By reading the electrical resistance using a DAS, the moisture content can be derived from moisture content and resistance correlations for the specific wood species. Corrections for temperature and other species or species group can also be obtained [1]. The detailed methodology is detailed by Straube et al. [2].

Application Notes

Wood normally has a very high resistance. A standard circuitry used for a DAS system reading or a handheld multimeter is normally as follows:

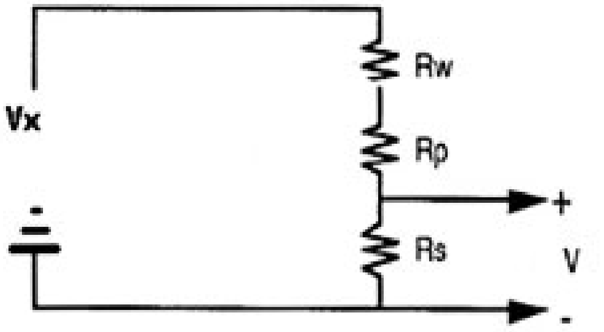


Figure 19. Circuit used to measure wood moisture

During short-term investigation, a handheld multimeter that works on the same electrical resistance principle is often used. These multimeters have ±2% accuracy with moisture content in the range of 7%–25%.

Figure 20. Handheld moisture meter

Photo from Extech website

1. Garrahan, Peter, "Moisture meter correction factors." Proceedings of In-Grade Testing of Structural Lumber, USDA Forest Products Laboratory, Madison, WI.
2. John Straube et.al. 2002. "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures." *Journal of Thermal Env. & BLDG. SCI.*, Vol. 26, No. 2.

3.3 Natural Gas Flow Rate

Gas flow measurement involves measuring the volume flow rate and/or total volume over time of fuel gases (e.g., natural gas or propane) to determine the energy consumption of an appliance or system. To understand combustion appliance in-use efficiency, it is important to properly measure natural gas flow rate into the appliance. Gas volumes vary with pressure and temperature, so it is common to have a gas meter with temperature compensation features. Many times, long-term monitoring is required to determine installed efficiency for furnaces and boilers or gas water heaters, so robust and reliable gas meters are required. To properly calculate the amount of heat delivered to the combustion appliance, the local heating value must be adjusted properly.

3.3.1 Utility Gas Meter

A utility gas meter is a common type of gas meter used in Building America field tests. A utility gas meter is a diaphragm/bellows type meter and is rugged and reliable for indoor or outdoor use. It is generally installed downstream of the house utility gas meter in Building America field tests. No upstream or downstream piping clearance is required. Utility gas meters normally come with a temperature compensation feature that adjusts gas volume flow rate reading accordingly.

Figure 21. Typical residential utility gas meter

Photo by Paul Norton, NREL

Utility-type gas meters can be fitted with pulse output devices that yield pulses at a resolution of approximately 1 to 1,000 pulses per cubic foot. The internal mechanism of gas meters provides an output to the dial index (and pulser) that is not quite uniform (i.e., each rotation of the smallest dial may not represent exactly the same amount of flow). Therefore, the use of data representing less than a few cubic feet of flow should not be taken as quantitatively accurate. For example, to capture the in-use efficiency of a condensing tankless water heater, hot water draw profiles are commonly implemented or monitored at a 6 seconds-to-1-minute interval. Having a meter at 1 cubic foot resolution will not work. Other types of gas flow meters with higher resolution will need to be installed.

Installation of a gas meter requires cutting into gas lines, which is a hazardous operation. It must always be performed by a technician trained and licensed to perform work on fuel gas systems.

Application Notes

Be sure the electrical signal produced by the pulse output device is compatible with the DAS or pulse counting device.

3.3.2 Meter Clocking to Estimate Gas Consumption Rate

Directly measuring natural gas consumption of water heaters and furnaces and other natural gas appliances can be expensive and requires hiring a professional when gas pipes need to be cut to insert a gas meter. However, it is possible to approximate gas flow consumption by manually reading an existing utility gas meter. When the fuel input rate of an appliance such as a furnace or water heater is fixed (e.g., the appliance does not have a modulating burner), obtain a one-time measurement of the fuel input rate. Once the gas input rate is known, that can be combined with monitoring of the time the gas valve is open to obtain total fuel use over time. The meter clocking approach uses a stopwatch to clock the speed of rotation of the finest dial on the meter.

Procedure

1. Locate gas meter, prepare timer, note volume indicated by one turn of “smallest” (highest resolution, fastest moving). Note the volume represented by one revolution of this dial (it should be marked on the meter; e.g., ¼ or ½ cu ft).
2. Disable gas appliances that are not to be measured (e.g., if water heater input is to be measured, turn down thermostat controlling furnace or boiler, and ask occupants to leave gas range off during test).
3. Fire appliance to be measured, and set thermostat high enough to keep it operating throughout test.
4. Start timer when the “smallest” dial crosses any index mark on dial face, and remember the location of the mark.
5. When exactly 4 full revolutions (or preferably a larger multiple such as 12 to 20) of the smallest dial are complete, stop timer.
6. Convert time to seconds. If gas volume during test is X cu ft, and time elapsed was Y seconds, gas input rate is (X cu ft) x (3600 sec/hr) / (Y seconds) = gas input in cu ft per hr. The heating value of natural gas varies somewhat, but it’s typically about 1,000 BTU/cu ft, so the input rate in BTU/hr is 1,000 times the value calculated here.
7. Turn appliance thermostat back to original position. Re-enable other gas appliances.

Two-stage appliances may also be monitored using this approach if the controls allow holding operation in one stage long enough to complete a test.

Pilot light gas flow is typically about 0.4 to 1 cu ft per hour, which means several hours of observation would be needed to complete meter clocking to provide a good estimate of the pilot light gas consumption. Clocking of a partial turn of the smallest meter dial can provide an approximate value for pilot flow.

Meter clocking itself is safe and does not require any special training or safety procedures. If gas leakage is noticed or gas can be smelled, however, the test should be stopped, and the utility contacted.

Application Notes

The internal mechanism of gas meters provides an output to the dial index that is not quite uniform (i.e., each rotation of the smallest dial may not represent exactly the same amount of flow). To be most accurate, this procedure should include at least 4 revolutions of the smallest dial on a meter, and preferably more. To avoid the effects of irregular dial rotation, this procedure should use an integral number of revolutions rather than reading fractional revolutions.

3.3.3 Monitoring Gas Valve Operation

For appliances with a single fuel input rate (e.g., non-modulating burner), the total gas consumption over time is simply the fuel input rate multiplied by burner run time. The gas input rate can be measured by clocking the gas meter, or the input rate may be estimated by calculation from burner orifice size or from the appliance nameplate rating. The burner run time can be obtained using a current switch and state logger. The current switch is activated by current flow through a conductor, and the state logger records the time at which the switch closes and opens (i.e., when the gas valve turns on and off).

Gas valves in most residential furnaces and boilers operate on 24 VAC, and the conductors are generally individual wires, allowing for easy installation of a clip-on current sensor. The current draw of gas valves is typically 0.2 to 1.0 Amp, and current switches should be selected to operate at a level below 0.2 A.

The state logger should ideally allow verification of operation of both the current switch and the logger by displaying the status of the input. One typical choice for a state logger is the HOBO UX90-001from Onset Computer. (This information is included as an example; we do not endorse this or any other product.)

Procedure

1. Identify the conductors to the gas valve. With the thermostat turned down, clip the current switch to one of the gas valves’ wires, and connect to state logger. Clip an ammeter to the same wire.
2. Force appliance into heating mode. In order to observe the startup sequence without leaving the appliance area, a helper or occupant can be asked to operate the thermostat or

the power switch on the appliance, or a safety switch on the blower compartment access panel may be used to power up the appliance with the thermostat already set high.

3. The state logger should indicate an open current switch until the gas burner fires and then should indicate a closed switch within a second. The clamp-on ammeter should indicate no current until the gas valve opens.
4. If the current through the gas valve wire is too low to operate the current switch, the wire may be wrapped around and passed through the current switch a second time, doubling the effective signal that the switch senses.
5. Allow the heating cycle to run to completion or turn the thermostat down. Note the sequence. The ammeter should show the gas valve current going to zero when the valve turns off, and the state logger should indicate switch open within a second.

If there is current flowing on the selected wire before or after the gas valve is operating, investigate other wires at the gas valve.

Application Notes

Note that in many modern heating systems, monitoring the thermostat call (signal) for heating is not a good substitute for direct monitoring of gas valve operation. When the thermostat calls for heat, the system responds by going through a sequence of turning on draft fans and opening vent dampers, if present, then opening the gas valve. The thermostat call may precede gas valve operation by 30 seconds or so. An exception to this is when monitoring systems with a two-stage thermostat; monitoring the second (higher output) stage thermostat signal may be a good method for capturing second stage operation.

Similarly, circulation blower operation doesn’t generally correspond to gas valve operation, and blower monitoring is not a good substitute for gas valve monitoring.

The gas valves in most residential water heaters operate on internally generated, low voltage DC current and cannot be monitored using this technique.

A detailed example of gas valve monitoring on a single-stage furnace is given in Appendix 1.

3.4 Electric Current, Power, and Energy

In many field tests, the electrical energy consumption of the house as a whole or a specific component is a focus of the project. As we move more toward all-electric homes and electrification of gas loads in existing homes to reduce CO_2 production, measuring electricity use in the home becomes even more important. In homes with photovoltaic (PV) systems and/or behind-the-meter batteries, electricity production, charge and discharge of the battery, and export to the grid are also of interest. For grid-interactive efficient buildings, the timing and magnitude of the interaction between energy use by home appliances utility control signals may be another motivation for electrical measurements.

Electrical power is calculated by combining two measurements: current and voltage. A research-grade watt meter (aka power meter) uses current transducers and voltage inputs (aka voltage taps). The watt meter measures the current, voltage, and phase angle between them to calculate true root mean square (RMS) power. Energy is the sum of power over time.

3.4.1 AC Current Transformers

Current transformers (CTs) measure alternating current (AC) current by induction. When a current-carrying conductor is passed through the CT ring along its cylindrical axis, a magnetic field is induced in the CT core, which in turn induces a current in the secondary coil that is proportional to the current through the ring. CTs allow measurement of AC current flow without interrupting the circuit of interest. They are commonly used in buildings field testing where inserting an ammeter in series with the circuit is impractical. A CT that measures AC is made of a toroidal (or similar) magnetic core with a length of wire wrapped around the torus to form a secondary winding.

There are three main varieties of CTs that we encounter in residential field testing:

- Solid-core CTs
- Split-core CTs
- Clamp-on CTs to be used with digital multimeters.

Solid-core CTs are approximately toroidal in shape and require the circuit being measured to be disconnected from the breaker during installation. They are more accurate than split-core CTs but are often not a practical solution for field work in residential circuit breaker panels because it is necessary to physically disconnect each current line to install the CT. Solid-core CTs can be a good choice for permanent installation if you have the opportunity to install the CTs while the circuits are being wired up for the first time.

Figure 22. Solid core CT

Photo from Ekmmetering website

Split-core CTs are very common in residential current monitoring because they can be installed without disconnecting wires from the breakers. Though convenient, they are generally more expensive and less accurate than solid-core CTs, but high accuracy versions are available. Some split-core CTs have a section of the CT that is removed for installation, but many have a section that opens on a hinge as shown below.

Figure 23. Split-core CTs

Photo by Paul Norton, NREL

Clamp-on CT probes allow non-contact current measurements using a digital multimeter or other instrument without interrupting the circuit under test. Not all CT probes work for both direct current (DC) and AC. Clamp-on CTs are commonly used for one-time measurements, rather than long-term monitoring.

Figure 24. Example of a clamp-on CT, aka Amp Clamp

Photo by Paul Norton, NREL

Application Notes

CTs are always marked to indicate which side must face the source and which side must face the load. The source direction is toward the utility power for loads and toward the inverter for solar PV systems. The load is toward the appliance being powered or a circuit breaker. Because current is directional, polarity matters when making measurements; take care that the electrician installs the CT in the correct orientation.

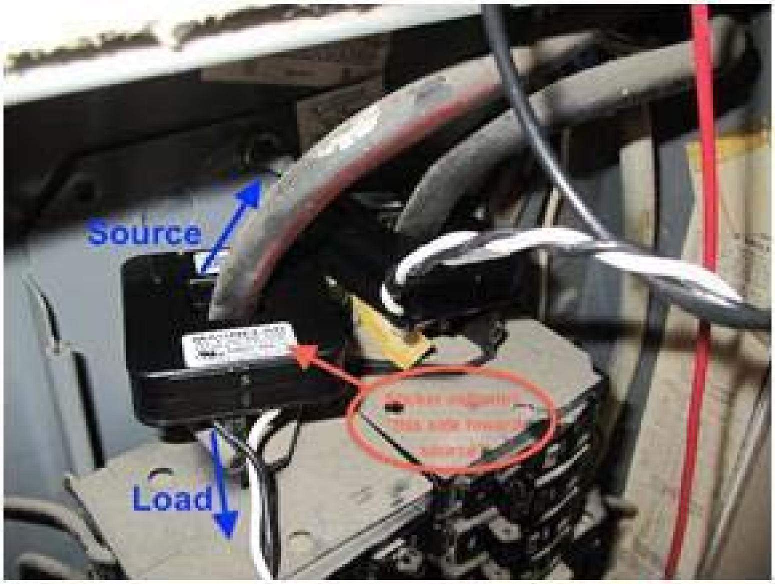


Figure 25. A split-core CT measuring the current of a load. Note the orientation of the CT.

3.4.2 Watt Meters

There are a variety of watt meters (aka power meters) available for residential energy monitoring. A watt meter monitors the current, voltage, and the relative phase angle between the two in a circuit to determine true RMS power delivered to a load. This information can be reported as a DC voltage, or a current or pulse signal proportional to the measured power and used as an input to a data logger. Other watt meters report the measurements by Modbus or directly to an internet proxy server.

For residential circuits, there are “single phase” 120V loads and “two phase” 240V loads. Single phase loads can be measured with a single CT. To accurately monitor the consumption of a two-phase load requires two CT—one on each phase. The practice of measuring a two-phase load by measuring only one phase and multiplying the measurement by two should be avoided. Two phase loads are often not balanced; in other words, the load is somewhat different on each phase due to singe phase loads within the two-phase appliance.

3.4.3 DC Current Measurements

Most electric loads in homes use AC. However, there is increasing interested in the use of home batteries and the use of DC to reduce or eliminate transformer losses. DC loads can be measured with shunts and Hall effect current transducers.

A shunt is simply a calibrated resistor for DC measurements. A shunt can be used to measure direct current with high precision. The current of interest is passed through a resistor of known resistance, *R*, and the voltage drop *V* is measured across the resistor (per Ohm's Law, $I=V/R$). These types of measurements may be required when investigating the energy use characteristics of a DC component within a system. For example, you could use a shunt to measure how much power the fan is drawing inside of a furnace.

Figure 26. Shunts used for measuring DC current

Photo by Paul Norton, NREL

A Hall effect current transducer is similar in appearance to an AC current transformer, but operates on a different principle and can measure both AC and DC current. The current carrying wire passes through a hole in the Hall effect current transducer, which can be solid core or split core. A Hall effect current transducer senses the strength of the magnetic field generated by the current in a wire and produces a signal proportional to the current.

Application Notes

Unlike an AC current transformer, a Hall effect current transducer requires a power supply to operate.

Figure 27. Hall effect current transducer for measuring DC current

Image from CR Magnetics website

3.4.4 End-Use Electrical Energy Measurements

Submetering at the appliance level may be straightforward or complex, depending on whether the appliance is powered via a dedicated circuit, shares a circuit with other loads, or is plugged into a wall outlet. If the appliance is on a dedicated circuit, the electrical energy use can be measured at the breaker. In the other case, where the appliance in question is not on a dedicated circuit, there are several options. If the appliance plugs into a standard 120V socket, there are several power meters that can be plugged in *between* the appliance and the wall socket. If the appliance is hardwired (lighting fixtures, for instance, are often hardwired but not on dedicated circuits), there are still options, but they usually require a modification to the wiring between the breaker panel and the appliance.

An appliance that plugs into a wall socket is often referred to as a "plug load." There are a wide variety of plug load watt meters that are installed between the outlet and the load to be measured. Many of these devices are inexpensive and simple to use, but do not have data storage or transfer capabilities, so they are mostly useful for spot checks, rather than long-term data acquisition. The memory is volatile (i.e., erased each time you unplug it), so if you are interested in the cumulative energy use data, you must be sure the read and record the display before unplugging the device from the outlet. An example of this type of meter is shown below.

Figure 28. Example of a plug load monitor

Photo by Paul Norton, NREL

Other plug load monitors can store and download time series data but cannot be used to feed data to a multichannel DAS. One example of this type of plug load meter is shown below.

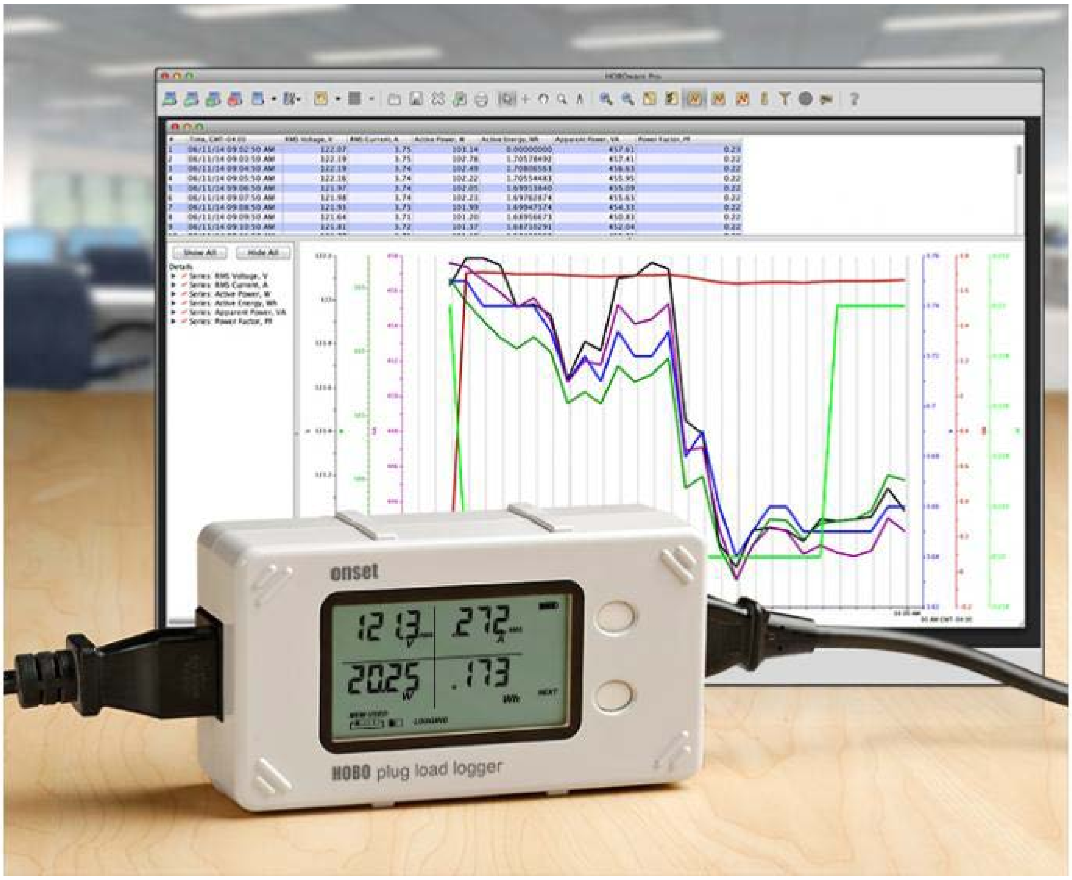


Figure 29. Stand-alone plug load logger

Photo from Onset website

None of the plug load monitors mentioned above are stand-alone systems that are designed to be used in conjunction with a multichannel DAS. One way to measure plug loads using a DAS is to install a watt meter in a compact electrical box. A cord with a standard male plug is run into the electrical box. This wire is used to provide the voltage taps for the watt meter and power to a cord with a standard female plug that is fed out the opposite side of the electrical box. One or two CTs (depending on whether the load is 120V or 240V) are installed around the live wire(s) inside the enclosure and connect to the watt meter. A separate low-voltage sensor wire is run from the watt meter output to the DAS. This type of setup should be inspected by a licensed electrician before being put into service.

Using the Utility Meter for Whole-House Energy Consumption

If the home is equipped with an advanced metering infrastructure meter, it may be possible to collect the information from the meter via a wireless home area network connection to an automated home energy management system. Some manufacturers of automated home energy management devices allow connection to automated meter reading type utility meters as well, using a translator box. There are pros and cons to each approach. Relying on wireless communication from the meter head avoids the hassle of having to hire an electrician to work in the breaker panel; however, the sample rate of the data will be limited by what the meter is capable of reporting. Device selection will depend on the resolution requirements of the analysis approach you plan to take as well as logistical considerations for the test site (space and access issues, for example).

Application Notes

Electrical power is the product of the current and the voltage. Because both the current and the voltage may be varying, a watt meter must sample the current and voltage and multiply them together at a high frequency to calculate energy. These high frequency energy calculations are then summed and stored at some time series interval. Summing current and voltage independently over a long time interval and subsequently multiplying the sums to calculate energy can lead to large errors in the result.

3.5 Occupancy

Occupants introduce realistic loads to a house system. Occupants introduce sensible and latent load through their body heat. In-house activities, such as turning lights on and off and using home appliances and miscellaneous electrical equipment, also introduce sensible and latent load. Opening and closing of windows brings in natural ventilation.

Occupant behaviors, because they're varied and difficult to predict, also create the biggest uncertainty and challenge in testing, monitoring, and analyzing building system performance. You may want to simulate occupancy in a test house to test the performance under controlled conditions. This is also useful when you need to test a new system that may not provide adequate comfort conditions.

When doing research in occupied homes it can be useful to monitor the occupancy. There are two common types of occupancy sensors: ultrasonic and infrared. Ultrasonic sensors detect sound, while infrared sensors detect heat and motion. Each technology alone is not totally reliable, which can cause inconvenience when using the sensors to control lights. Combining sound, heat, and motion detection can potentially generate decent savings without causing complaints.

The opening and closing of windows and doors can have a significant impact on ventilation rates and heating needs. Stand-alone and wireless sensors are available to monitor the opening and closing of windows and doors. These generally work by using a magnet to close a switch when the window or door is closed. An example is shown below.

Figure 30. Example of a stand-alone door open/closed sensor/logger

Photo by Paul Norton, NREL

Application Notes

Some smart thermostat manufacturers are now offering wireless door, window, and occupancy sensors that connect to the thermostat. Data time series from these sensors may be available for download through the internet.

3.6 Pressure and Pressure Difference

This information applies to pressure measurement in fluids, such as air, other gases, and water, as required in a variety of buildings research applications.

Pressure measurements fall into three categories, depending on what the measured pressure is compared to:

- Absolute pressure—the pressure of the fluid compared to a vacuum with no pressure.
- Gauge pressure—the pressure of a fluid compared to the air pressure in the immediate surrounding environment.
- Differential pressure—the difference between fluid pressures at two locations as determined by particular measurement needs. Differential pressure measurements always take the form of P differential = P (location a) - P (location b). When measuring differential pressures, it is critical to be clear which measurement location is a and which is b. This is especially important when the higher pressure can occur at either a or b (e.g., when measuring pressures across a building enclosure). In such cases, the sign of the result is critical information and cannot be assumed. We recommend using statements like “Pressure a wrt (with respect to) Pressure b” or “Pressure a - Pressure b.”

The pressure of a fluid independent of any flow is the “static pressure.” A sensor placed so that the moving fluid flow impinges on it will sense an additional pressure (“dynamic pressure”) related to the momentum of the flow. See the application notes for guidelines on measuring static and dynamic pressure.

Common units of pressure include pascals (Pa) for air pressure, inches of water (in H_2O) for gas pressure and air pressure, and pounds per square inch (psi) for refrigerants, water, and atmospheric pressures.

Table 1. Common Building Research Pressure Measurement Categories and Applications

Category	Why Measured?	Differential, Gauge, or Absolute	Typical Range	Notes
Building internal operating pressure ($P_{outdoor} - P_{indoor}$)	For investigating the pressurization effects of ventilation or HVAC fans, or for characterizing likelihood of depressurization that may cause combustion products spillage. Possibly, for quantifying infiltration driving forces.	Diff	-10 to +10 Pa	Direct exposure to wind may yield much higher values
Atmospheric combustion appliance draft pressure ($P_{vent} - P_{room}$)	As an indicator of vent spillage ("backdrafting") and (though not absolute) of direction of vent flow	Diff	-50 to +20 Pa	Usually measured as vent wrt room
HVAC system pressures ($P_{duct} - P_{room}$, or $P_{duct1} - P_{duct2}$)	For estimation of blower flow rates, characterizing system pressure drops, or estimating leakage rates	Diff	-300 to +300 Pa	Note distinction between static and dynamic pressure
Refrigerant line pressure	To establish operating conditions of compression cycle refrigeration system	Gauge	0 to 500 psi (or higher)	Requires knowledge of compression refrigeration systems
Water line pressure	For estimation of flow rate through a valve or system of known characteristics, or to screen for adequate line pressure in a system	Gauge	15 to 150 psi	Requires "wet" design (internals exposed to water)
Gas line pressure	To check proper adjustment and operation, or for estimation of flow rate through a device of known characteristics (e.g., a pilot light orifice)	Gauge	Up to 15 inches of water	Warning: hazard of fire and explosion
Barometric pressure	To calculate exact density of air, sometimes needed for precise calculations of fan flow rate, energy transfer, and relative humidity	Absolute	14 to 15 psi	

Note: Always select sensors that can withstand the maximum pressure that can be expected in your application.

Sensor and Transducer Types

Pressure transducers are widely available from many manufacturers, with linear (analog) voltage output or 4 to 20 mA (analog) current output. Some come equipped with visual displays.

Pressure transducers in general may be sensitive to temperature changes. Consult the manufacturer's specifications for model-specific information.

3.6.1 Low-Level Differential Pressure

We use the term "low-level" for pressure transducers with full-scale ranges of less than 500 Pa. Differential pressure transducers are either uni-directional or bi-directional. Uni-directional models provide an output only when the "high" pressure input is at a higher pressure than the "low" pressure input. Bi-directional models can provide an output with either input at a higher pressure. The fittings on low-level pressure transducers are most often barbed fittings that are compatible with flexible tubing (or "hose") of the correct size. PVC and urethane are common tubing materials used in these applications.

Application Notes

Some typical connections for differential pressure transducers used for building pressure, duct pressure, and water heater draft are shown at the end of this subsection.

Low-pressure differential pressure transducers in particular may be temperature sensitive, and the output may drift significantly as operating temperature changes. All manufacturers should provide specifications on the expected errors that can be introduced by temperature drift. Some designs include temperature compensation to reduce this effect. Some models of handheld differential pressure sensors include an automatic re-zeroing routine, in which valving takes the pressure transducer offline momentarily. Though not simple to implement, similar re-zeroing valving arrangements can be used in monitoring systems.

Orientation of the transducer may affect output in some cases. Run a trial, or check with the manufacturer if this could affect your results.

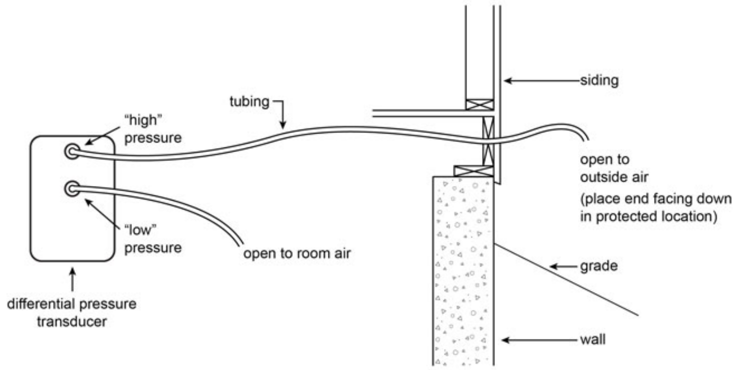
Pressure sampling tubes that are exposed to outdoor air may become occluded with rainwater, snow, or condensation. The weight of even a small water drop (if it fills the tube) is enough to render building enclosure pressure data completely useless. To protect against this, the outside end of the tube should be protected from direct falling or wind-driven rain and snow, and be far enough off the ground to prevent entry of splash water. Tubing exposed for prolonged periods should be checked for condensation. Clear tubing has an advantage in allowing visual inspection for water.

Wind can cause large swings when measuring outdoor-indoor differential pressures, and adequate wind shielding is important.

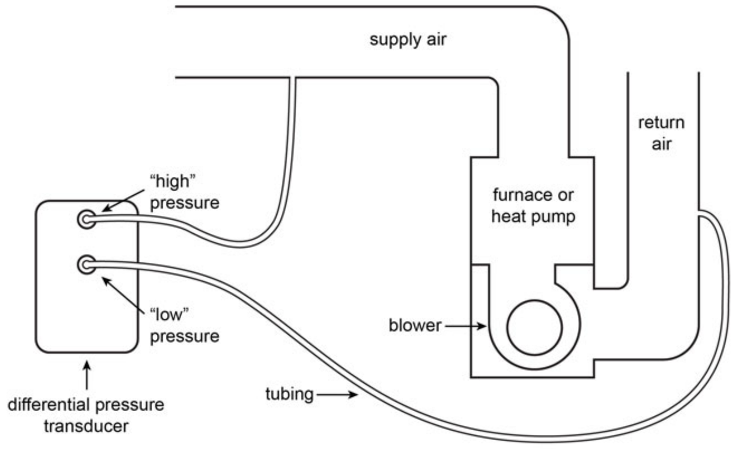
Static and Dynamic Pressure

Most duct pressure measurements are intended to be static pressure measurements. To measure static pressure, the orifice where pressure is sensed should face perpendicular to fluid flow. Dynamic pressure is used to estimate flow velocity of a fluid, and can be measured using a differential measurement of the pressure "looking into" the flow (i.e., with the sensor orifice facing the flow stream), with respect to the static pressure in the same flow stream. The pitot tube is designed to perform exactly this function.

Differential Pressure: OUTSIDE AIR wrt INSIDE AIR



Differential Pressure: SUPPLY AIR wrt RETURN AIR



Differential Pressure: VENT wrt ROOM ("Draft Pressure")

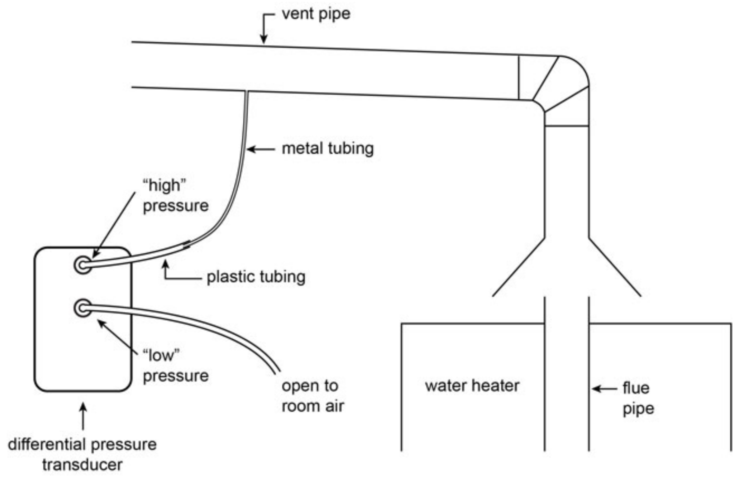


Figure 31. Typical connections for differential pressure transducers

3.6.2 Differential Pressure Gauge

In Building America field tests, a differential pressure gauge (aka digital monometer) is a very useful tool. Coupled with other gadgets, it can be used for precise differential pressure control required on blower door test, duct blaster test, exhaust fan airflow, supply fan airflow measurement tests, and similar testing. The differential pressure gauge normally comes with two independent pressure measurement channels (Channel A and Channel B).

3.6.3 Refrigerant Line Pressure

Refrigerant line pressure measurement can be used in establishing the operating conditions of a compression-cycle heat pump or air conditioner, and in determining whether the system may have a refrigerant over-charge or under-charge. Refrigerant pressures may range up to 500 psi and even higher for some refrigerants (e.g., up to 800 psi for R-410a).

Application Notes

Any connection to a refrigerant system must be done by a trained and certified technician. U.S. Environmental Protection Agency (EPA) regulations covering ozone-depleting materials (including chlorofluorocarbons [CFC] and hydrochlorofluorocarbons [HCFC] refrigerants) require technician certification for almost any type of work on systems (e.g., attaching and detaching hoses and gauges to and from the appliance to measure pressure within the appliance).

Most technicians working on refrigerant systems carry gauge sets for on-site pressure measurement but are not equipped to install pressure transducers for longer-term monitoring. It is important to determine the type of fittings available on the refrigerant lines and pressure transducers in advance, to find fittings that allow a positive and leak-free connection, and to test the connections for leakage after installation. Any leakage that occurs has the potential to alter the conditions of the test being done and might be a violation of EPA regulations.

3.6.4 Water Line Pressure

Water line pressure measurement may be useful in estimating flow rates or checking the pressure drop in domestic water systems. Typical water pressure in buildings on a municipal system is about 50 to 110 psi. Extremes may be lower or higher. Typical water pressure in buildings on private wells is about 30 to 50 psi.

Application Notes

- Internal parts must be compatible with water. If used in potable domestic water systems, tubing and fittings must be acceptable in potable water systems.
- Observed water pressure will vary with the elevation of the sensor relative to the point of intended measurement. If possible, mount the transducer at the elevation of the intended measurement. An elevation difference of 1 foot yields a pressure difference of about 0.43 psi if the connecting tube is filled with water.

3.6.5 Gas Line Pressure

Pressure measurement in fuel gas systems may be of value in estimating flow rates through pilot light orifices or other components, or in validating adequate pressure during operation.

Installation of a pressure transducer in a gas system (e.g., natural gas or propane) requires opening gas lines, which is a hazardous operation. It must always be performed by a technician trained and licensed to perform work on fuel gas systems.

Application Notes

Gas valves on appliances such as water heaters and furnaces have internal pressure regulators that control main burner manifold pressure. Burner gas flow rates should not vary greatly as long as gas line pressure remains within appliance specs.

Pilot light gas flow can be estimated from measured gas line pressure and the pilot light orifice size.

3.6.6 Barometric Pressure

Barometric pressure is used in detailed psychrometric calculations and in calculation of the density of air and can be important in accurate determination of heat transport via airflow. Barometric pressure is by definition an absolute pressure measurement. Alternatives to direct measurement of local barometric pressure include:

- Obtaining weather data from a nearby weather station
- Using a fixed value for barometric pressure (adjusted if needed for elevation)
- Barometric pressure transducer.

Barometric pressure values reported by weather stations are altitude adjusted (i.e., corrected to the pressure that would be observed if the station were at sea level).

The resolution of barometric pressure transducer output can be increased by selecting models with ranges corresponding to expected atmospheric pressure. Table 2 provides guidance on pressure range selection.

In Building America field tests, barometric pressure is usually calculated from the test site elevation, using the following equation:

$$P = P_0\,x\,(1-(Lxh)/T_0)\hat{}(gM/RL)$$

Table 2. Approximate Minimum and Maximum Expected Local Atmospheric Pressure at Varying Elevations

Elevation (ft)	Approx. Minimum Expected Local Atmospheric Pressure (psi)	Approx. Maximum Expected Local Atmospheric Pressure (psi)
Sea level	14.2	15.2
2,000	13.2	14.2
4,000	12.2	13.2
6,000	11.3	12.2
8,000	10.5	11.3
10,000	9.7	10.5

Extreme conditions, especially those created by hurricanes and typhoons, can generate pressures well outside these ranges. The lowest (sea level) pressure ever recorded was about 12.62 psi, and the highest about 15.84 psi.

Application Notes

- For most building-related measurements, the specific location of a barometric pressure transducer in or near a building isn't important. The fractional change in absolute air pressure is roughly 0.3% for a 100-foot elevation change.
- Barometric pressure transducers are typically not sensitive to orientation.

3.7 Solar Irradiance

Irradiance refers to the power of solar radiation per unit area on a surface. Global irradiance on a horizontal surface is composed of direct irradiance and diffuse irradiance. On a tilted surface, the reflected irradiance from the ground also contributes to the total global irradiance. Generally, solar irradiance is called insolation.

Solar radiation affects many systems in the house and can vary considerably within the same town. On-site, solar irradiance is a particularly useful measurement if there is a PV system or solar thermal system installed at the field test location. Also, if space conditioning is a focus of the field test, solar irradiance is an important measurement as solar radiation has a large effect on heating and cooling load requirements, electrical lighting demand (daylighting), and envelope performance.

There are three types of sensors can be used to measure irradiance, all with a specific purpose: pyranometers, pyrgeometers, and photometers.

3.7.1 Pyranometer

A pyranometer is a device used to measure solar irradiance, or insolation, both direct and diffuse on a planar surface. Pyranometers are typically passive devices, requiring no power to operate.

Pyranometers use a black-coated thermopile that will absorb all solar radiation across a wide wavelength range. A glass dome limits the radiation to the short-wave range only. The thermopile generates a voltage signal that is proportional to the incident solar radiation. Alternatively, a silicon PV detector can be used to measure the incoming radiation for certain wavelengths, which generates a current signal that is converted to a voltage signal using a potentiometer. The variable resistance of the potentiometer is used to calibrate the sensitivity for the PV sensors.

Figure 32. Thermopile-type pyranometer (left), and PV detector-type pyranometer (right)

Photo by NREL/PIX 15537 (left); photo by Lieko Earle, NREL (right)

Pyranometers are a common sensor for field tests, especially when PV panels are installed at the house, or cooling loads are a main subject of the field test. Typically, two pyranometers will be installed: one mounted on a horizontal surface and a second affixed to one of the PV panels (if applicable) in order to measure the available short-wave radiation in the plane of the collector. The horizontally mounted pyranometer should be leveled using adjustable feet and the level sensor (shown in the photo above, right) and should be located where it will not be shaded by the building or surroundings. Pyranometers can be used to determine the installed efficiency of PV systems, since the available solar radiation in the plane of the PV panels will be measured. Additionally, insolation can have a large effect on the cooling and heating loads in the house and capturing the on-site insolation, in addition to outdoor temperature and humidity, will help complete the picture of the environmental effects on the home's HVAC system.

For a detailed description of a test procedure for measuring the performance of a residential PV systems see Barker, G. and Norton, P. *Building America System Performance Test Practices: Part 1 – Photovoltaic Systems*. National Renewable Energy Laboratory, May 2003. NREL/TP-550-30301.

3.7.2 Pyrgeometer

To measure radiant heat transfer, such as night-sky radiation or the sun hitting a solar thermal system, use a pyrgeometer. A pyrgeometer is a passive device used to measure far infrared radiation. A thermopile sensor detects infrared radiation, but a coated silicon shield over the sensor blocks the short-wave radiation. Short-wave radiation is measured with a pyranometer. Pyrgeometers output a voltage signal that is proportional to the radiation exchange between the sensor and the sky. They provide an averaged measurement across the field of view, which would include effects of partial cloud cover, etc.

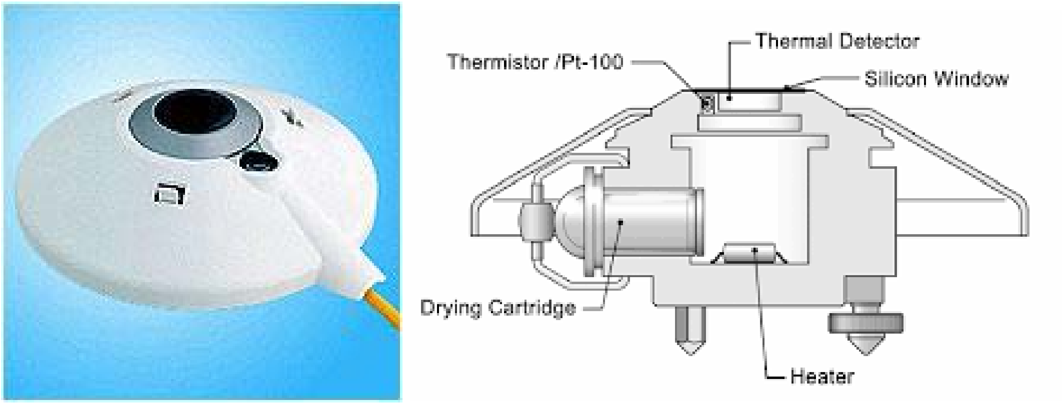


Figure 33. An example of a pyrgeometer (left) and a schematic of the main components of a pyrgeometer (right)

Images from Kipp & Zonen

The temperature of the sensor is needed to calculate the net incoming or outgoing infrared radiation, so an integrated temperature sensor measures body temperature of the sensor. Depending on the pyrgeometer manufacturer, the temperature compensation may automatically be taken into account or may be a separate calculation done by the researcher. In the latter case, the pyrgeometer will output a voltage signal from the thermopile and from one or more thermistors used to measure sensor temperature. A manual for two common pyrgeometers, the Eppley PIR and the Kipp Zonen Pyrgeometer, are included in the related documents section below.

Pyrgeometers are an important field test instrument when a measurement of the available thermal radiation is needed, such as when a solar thermal system is installed. Typically, one pyrgeometer will be affixed to the solar thermal collector to measure the infrared radiation in the plane of the collector. Additionally, the pyrgeometer should be mounted in an unshaded location, away from any heat sources. Among other things, these measurements can be used to calculate the installed thermal efficiency of solar thermal systems.

3.7.3 Photometer

Photometers, also referred to as light meters or lux meters, are used to measure light intensity inside a building. Handheld photometers are often used to spot check the light levels in a room or on a particular surface. Photometers can also be installed as a part as a lighting control system to automatically dim the lights based on the amount of daylight.

Figure 34. A handheld lux meter

Photo from Tilt u, Wikipedia Commons

Figure 35. A researcher checks the quantity of daylight and the accuracy of the lighting sensors

Photo by NREL/PIX 05171

Photometers can be used in a variety of ways in a field test. Photometers could be installed as a means of detecting occupancy. Photometers could be installed in several rooms in the house and when lights are turned on, occupancy can be inferred. For that application, the light meters should be installed on a wall without direct sunlight, so changes in natural light will not trigger the light sensor.

Another application for light meters in a field test is for verification of a lighting control system. Sophisticated lighting control systems use photometers to adjust room lighting levels as the natural light entering the room changes. To verify that the lighting control system is working as intended, the photometers for the field test should be installed by the researchers next to the photometers used for control. If the appropriate lighting levels (as prescribed by the lighting control system) are being maintained, the control system is working as intended.

Figure 36. Light sensor for daylighting in NREL's Research Support Facility

Photo by Dennis Schroeder, NREL

Figure 37. Field-test grade photometer

The handheld photometers generally do not produce an analog output. They could be used for a quick verification of a lighting control system, but would not be suitable for occupancy detection, which would require a long-term installation and an output signal. There are other options for photometers that send an analog signal that can be read by a data logger. Figure 37 shows a photometric sensor that uses a silicon photodiode that produces a µA signal that is proportional to the incident light intensity.

For more information about lighting control using photometers, see:

Guglielmetti , R.; Scheib, J.; Pless, S. D.; Torcellini, P.; Petro, R. 2011. "Energy Use Intensity and its Influence on the Integrated Daylighting Design of a Large Net Zero Energy Building: Preprint." National Renewable Energy Laboratory. NREL/CP-5500-49103.

3.8 Temperature

There are two distinct categories of practical methods for measuring temperature of a building component: contact and non-contact.

A contact measurement is taken with a sensor from the following instrumentation list:

- Thermocouple
- Resistance temperature detector (RTD)
- Thermistor.

Contact temperature measurements allow the researcher to measure the temperature of the body (solid, liquid, or gas) immediately adjacent to the instrument. Care is needed in many cases to prevent heat transfer from other nearby bodies from affecting the measurement.

A non-contact measurement relies on remote means to determine temperature. The primary buildings tool is an infrared camera. Non-contact measurements rely on radiant emissions from a body to infer its temperature. Infrared thermography is the most common used in building applications.

Table **3** summarizes some basic characteristics of the temperature measurement devices most commonly used in buildings research. Pricing for temperature sensors depends strongly on sensor packaging and cabling terminations. Thermocouple sensors that do not require protection (e.g., when used for air temperature measurement) can be fabricated by soldering or brazing the two wires together to form a junction.

Table 3. Types of Temperature Measurements

Sensor Type	Sensitivity in Typical Application (mV/F)	Typical Usable Temperature Range
Thermocouple (Type T)	0.077	-300 to +570°F (-185 to +300°C)
Thermocouple (Type J)	0.099	+30 to +1,380°F (0 to +750°C)
Thermocouple (Type K)	0.073	+30 to +2,010°F (0 to +1,100°C)
Thermocouple (Type E)	0.122	+30 to +1,470°F (0 to +800°C)
RTD	2.7	-150to +840°F (-100 to +450°C)
Thermistor	12	-110 to +300°F (-80 to +150°C)

3.8.1 Thermocouple

A thermocouple is composed of two dissimilar materials (usually metallic wires) bonded together. The junction between the wires forms a microscopic region where voltage is induced between the wires. As the temperature of the junction changes, the voltage will vary in a repeatable, controlled manner, and can be measured at the other end of those wires.

For building science purposes, T-type thermocouples, made of copper and constantan with a temperature range from -200 to 350°C, are always appropriate. Shielded thermocouple wire is strongly preferred to limit noise from power wires being inferred over the thermocouple's microvolt signal.

Accuracy of a thermocouple depends on the material properties, and uniformity of those properties. It is strongly recommended that researchers always purchase thermocouples and extension wire with lowest uncertainty. The preferred extension wire will be labeled "special limits of error" or SLE, and typically has a ±0.5°C accuracy limit. This is half the error range of standard thermocouple wire. SLE wire cost is minimally higher than standard, but may require a slightly longer lead time in purchasing.

Accuracy of a thermocouple measurement also depends on the temperature, and thus location, of any junctions in the signal wiring. Often, a thermocouple is purchased with a connector attached from the factory. That connector creates two additional thermocouples (one for each pin/wire), called cold junctions. Where possible, the connector should be located to maintain similar temperatures to the data logger to minimize the impact of this intermediate cold junction on the measurement.

Several forms of manufactured thermocouples are available, for use in different applications.

3.8.2 Immersion Thermocouples

Immersed thermocouples are the preferred method for measuring the temperature of liquid flow in a pipe. They should be mounted in a plumbing tee where an elbow would normally be used. If there is no convenient spot where an elbow would normally be used, a u-shape can be plumbed-in to allow the installation of the tee.

Application Notes

The particular orientation for installation depends on the application, whether an elbow can be conveniently used, and the relative dimensions of the sensor sheath and the pipe.

For example, in the "Do NOT install like this" figure below, if a 1/8" diameter probe installed in a 1/2" diameter pipe, the conduction along the sensor stem may be non-negligible and could bias the measurement, depending on the liquid and ambient temperatures. In addition, it may be hard to know precisely where the measurement junction is located along the cross section of the pipe in this configuration. In contrast, the "DO install like this" figure illustrates a configuration where you can easily get more than 20 sheath diameters of immersion and not much exposed sheath. You can also be pretty sure that the thermocouple junction is along the centerline of the pipe. If you are making measurements where the pipe diameter is much greater than the sheath diameter (e.g., 2" ID pipe, 1/16" sheath), you could disregard this advice.

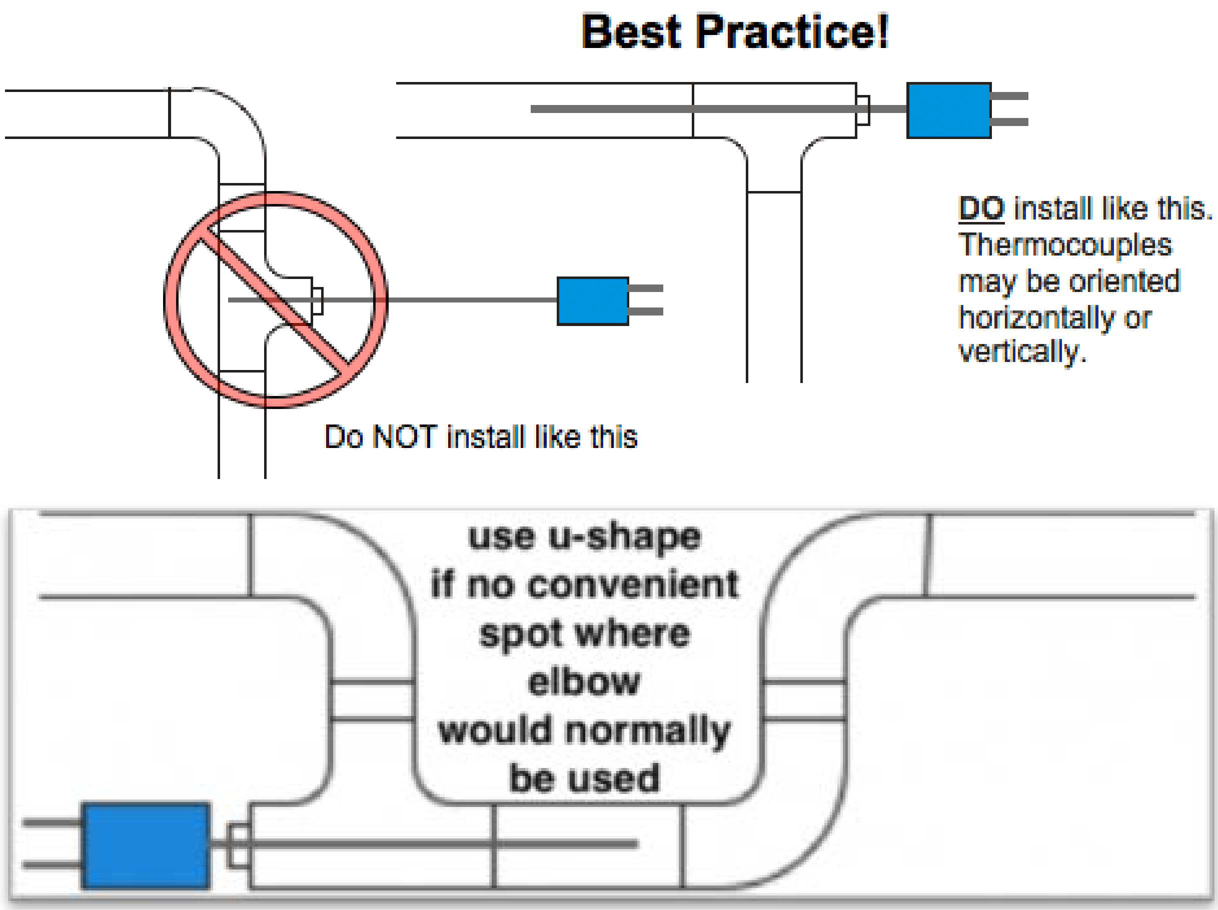


Figure 38. Installation details for immersion thermocouples

In general, we recommend 1/16” ungrounded thermocouples be used, along with 1/16” compression fittings with 1/8” National Pipe Thread (NPT) tapered thread.

If possible, the thermocouple should be oriented along the normal flow direction, and the measurement located downstream of the T-bend (the T will help mix the liquid if it is not thermally uniform). If pointed against the normal flow, a 1/16” thermocouple could risk bending and touching the pipe wall, depending on the pipe ID and liquid flow rate. Pointing the probe downstream reduces this risk.

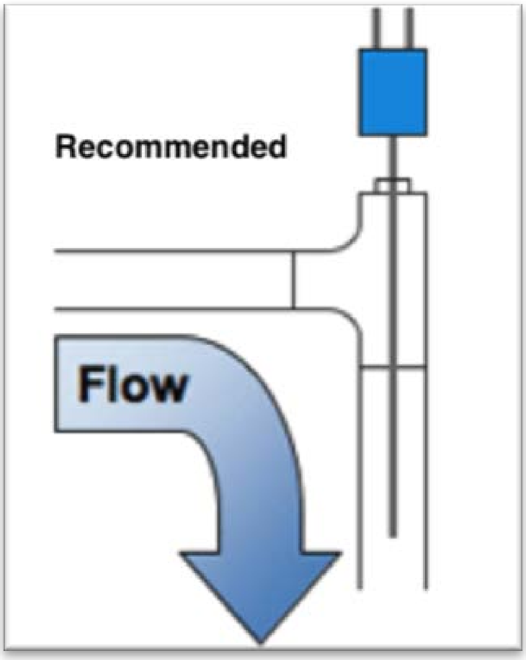


Figure 39. Recommended orientation for an immersion thermocouple installation

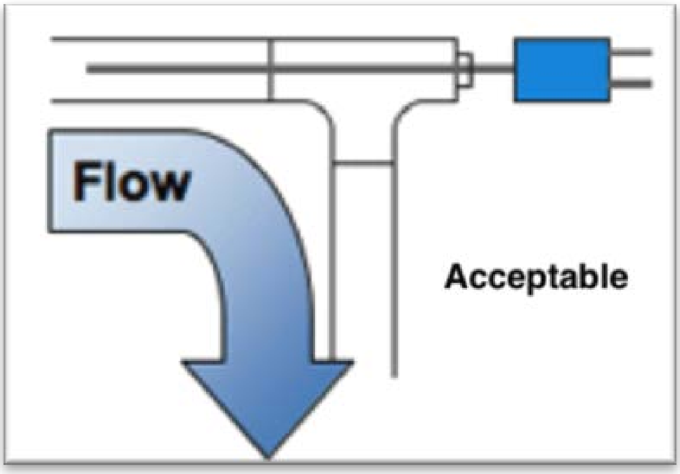


Figure 40. Acceptable orientation for an immersion thermocouple installation

One thermocouple and a compression fitting are required at each location. Plumbers and builders can be asked to supply other fittings as needed. Before you head into the field, ensure each compression fitting has a ferrule; these are sometimes missing from the factory and are easy to misplace.

Grounding Considerations

The reason for using *ungrounded* probes is that you want to avoid creating ground loops. If you have the probe installed in a plastic pipe there is likely a partial electrical connection between the probe and the fluid, which in turn may be coupled to ground somewhere else where it flows through a metal pipe. You can’t count on this for a good ground connection, so you will need to ground the thermocouple elsewhere, which could lead to ground loops. To be confident that you have only one point for ground, best practice is to use an ungrounded probe and ground the measurement explicitly at, and only at, the data logger.

3.8.3 Surface-Mounted Thermocouples

Surface-mount thermocouples are used when equipment cannot be penetrated. Measuring refrigerant temperature is an example of appropriate surface-mount thermocouple usage; there is no reasonable method for immersing a thermocouple in the refrigerant flow path. Surface-mount thermocouples are also used to measure solid surface temperatures.

In the case of measuring refrigerant temperature, the temperature of the solid surface is being measured, and care must be taken to ensure it is the same temperature of the underlying refrigerant in the example above.

Types

Surface-mount thermocouples come in two varieties. The pre-formed type with bonding material can be used directly. Alternatively, you can solder your own thermocouple wire into an on-site thermocouple.

Installation

Surface-mount thermocouples may be mounted using a bonding material, or with mechanical means. The bonding material is usually an epoxy material or glue. The surface must be relatively clean and free of dirt, dust, and oil for the bonding to be reliable. Emery cloth can be used to buff a small spot clean prior to bonding. Mechanical methods of fastening include pipe clamps and various types of tape.

Isolation

Because surface-mount thermocouples are exposed to the surrounding environment, they often need to be isolated. Sunshine, airflow, and nearby heat sources can significantly affect these measurements. Therefore, it is best to place insulation over all surface-mount thermocouples. For pipe-mounted thermocouples, usually an 8-12” length of pipe insulation is sufficient. The insulation should be chosen to prevent conductive, convective, and radiant heat transfer from affecting the measurement. Pipe insulation and spray foam are two methods to insulate surface-mount thermocouples.

It may also be necessary to protect the thermocouple from corrosion, such as in outdoor environments. This is only necessary for long-term monitoring.

3.8.4 Bare Thermocouples

In building applications, bare thermocouples are used for measurement of air temperatures. While they can be used for other measurements, the best practice is to use one of the other thermocouple types (immersion or surface-mounted thermocouples) for measuring liquid or solid temperatures. Bare thermocouples are just that—a soldered or welded junction of copper and constantan where the sheathing has been stripped or pulled back from T-type thermocouple wire. This is an inexpensive thermocouple that can be field-fabricated using a soldering iron and either lead or silver solder.

Isolation

Since bare thermocouple junctions are exposed to the surrounding environment, they often need to be isolated to ensure an accurate measurement. Sunshine, airflow, and nearby heat sources can significantly affect these measurements. Therefore, the application of a bare thermocouple must be considered, and other heat transfer paths blocked.

Examples of isolating a bare thermocouple can be seen in surface-mounted thermocouples for liquid temperature measurement, and aspirated shield for room air temperature measurement.

It may also be necessary to protect the thermocouple from corrosion, such as in outdoor or humid environments. Typically, this is only necessary for long-term monitoring.

3.8.5 Resistance Temperature Detector

In building applications, bare thermocouples are used for measurement of air temperatures. Resistance temperature detectors (RTDs) are an alternative to a thermocouple where accuracy and repeatability are of highest importance. An RTD is a resistor whose resistance varies directly and linearly with temperature. It is more expensive and has a slower response than a thermocouple, so is not as appropriate for general temperature measurements. Data logger capabilities and requirements should be considered when planning to use an RTD in a field test.

Typically, a current is applied to an RTD, and the voltage drop measured (or vice versa) to calculate resistance. Care must be taken to keep the current below manufacturer stated limits, to prevent RTD self-heating.

Most RTDs measure at 100Ω at 0°C, with a measurement slope of 0.00392/°C. RTDs are very stable over time. Check the calibration sheet with your RTD to ensure the measurement is converted correctly. The signal wiring has a resistance as well, so it should be carefully chosen and measured at installation to ensure that resistance does not skew your measurements. Due to this, 2-wire RTDs are less accurate than 3- and 4-wire RTDs.

Application Notes

Unlike thermocouples, you must supply power to an RTD.

3.8.6 Thermistor

Thermistors are devices in which electrical resistance changes with temperature. Resistance is readily measured by providing a known excitation voltage and measuring the current flow (usually by sensing the voltage drop across a separate known resistance). The usable temperature range of most thermistors is less than that of thermocouples, with a typical range being about -110 to 300°F (-80 to 150°C).

The high sensitivity of thermistors makes them less susceptible to noise-induced errors. Thermistors can be useful for measuring small temperature differences, and for use with data acquisition equipment that does not have a good ability to measure millivolt signals. Thermistors, like other temperature sensors, are available in a wide variety of packages appropriate to various measurement requirements.

Because thermistors dissipate power when energized, they are susceptible to self-heating errors. This error is influenced by the ability of the surrounding fluid to carry away the heat produced. Thermistor manufacturers can provide information on the effect of self-heating in various fluid environments. A common approach to reducing self-heating is to energize thermistors only briefly before making a measurement.

Thermistors come in several varieties. They are commonly specified by the nominal resistance at 25°C (77°F), e.g., a “10K Ohm” thermistor will have a resistance of about 10,000 Ohms at 25°C. There are variations in thermistor types even within a single nominal resistance category, (due to chemical “mix”), and users should be sure to obtain the resistance versus temperature table or curve for the device purchased.

3.8.7 Aspirated Shield

Sometimes making temperature measurements can be a challenge. Thermocouple measurements can be biased due to undesired heat transfer effects (i.e., a nearby hot surface). Further, a thermocouple only measures at one point in space. To get around these limitations, you can use an aspirated shield. This assembly is useful for protecting sensors while measuring outdoor temperature or estimating a room’s average air temperature.

An aspirated shield is composed of several parts:

- A thermocouple, to make the measurement
- A radiant shield, to block radiant heat transfer from sunlight, or hot/cold objects in the vicinity
- A fan to draw air across the thermocouple and encourage some level of mixing, and
- A stand to suspend the assembly in the air being measured.

Figure 41. A commercially available passive shield on the left and a commercially available aspirated shield on the right

Photo by Paul Norton, NREL

Figure 42. A custom fabricated aspirated shield in use

Photo by Ed Hancock, NREL

Indoor aspirated shields can be purchased or fabricated inexpensively. Two pieces of thin polyvinyl chloride (PVC) pipe can be used, the smaller of which fits within the larger diameter pipe with an air gap. The cylindrical surfaces that face each other should be coated with a shiny material such as aluminum tape or aluminum foil. The pipes can be supported using bolts, screws, or metal or plastic rods. A thermocouple is located at the center of the inner pipe. The fan, such as a computer case fan, is located to blow outward at the exit of the tubes. In that way, the fan heat does not affect the measurement. This assembly can be screwed to a tripod or hung from the ceiling. Outdoor aspirated shields can be purchased from many sources.

3.8.8 Infrared Camera

Infrared imaging, or thermography, is a useful diagnostic tool. All materials emit infrared radiation at levels, dependent on their temperature. An infrared camera is able to capture this radiation in the same way a standard camera captures visible light. Like a digital camera color calibration, infrared cameras must be used carefully if accurate temperatures are desired. But less care is required for relative measurements, such as looking for cold sections that represent lack of insulation within a wall's stud cavities.

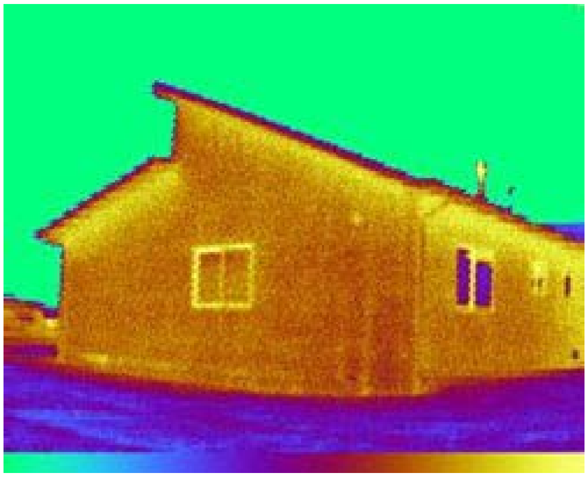


Figure 43. Infrared thermograph showing the exterior of a home

Photo by Ed Hancock, NREL

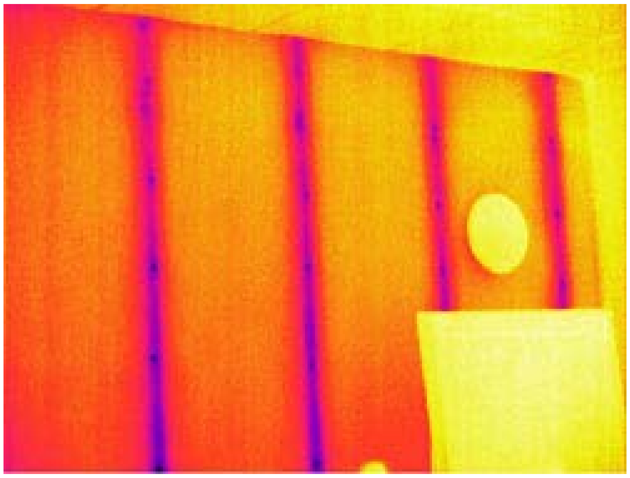


Figure 44. Infrared thermograph showing studs and drywall screws in an exterior wall

Photo by Ed Hancock, NREL

Thermography can yield very useful information in field tests. Some limitations of the materials being imaged can be easily addressed. For example, glass is largely reflective in the infrared range, so imaging of a window will be very strongly influenced by the temperature of reflected surfaces (such as the low temperature seen on the purple window areas in the right of the above image). Using a strip or two of blue painter's tape, a more accurate window temperature can be visualized. Other materials that are difficult or cause inaccuracies include thin objects, shiny objects of nearly any type, metallic surfaces, and ice.

Use of an infrared camera requires skill and practice. To achieve accurate temperatures of any building component, you must focus correctly on it. Most infrared cameras' auto-focus features will get you close, but not exactly where you need to be.

Recording an infrared image is somewhat slower than with a digital camera, so a tripod is often useful in the field. This also means that accurate temperature visualization of a rapidly heating or cooling body is not realistic. There are very expensive infrared cameras that provide this capability if it is necessary.

3.9 Thermal Comfort

Short-term thermal comfort evaluations are sometimes conducted in Building America field test houses to evaluate the thermal comfort effect on different types of windows, sliding glass doors, window shades and radiant heating and cooling systems. For windows, the measurement set is normally located 4 feet away from windows. For radiant heating and cooling systems, it is usually located at the center of the room. Long-term evaluation of thermal comfort is generally not recommended, because thermal comfort is generally not an issue in mild seasons and is likely to be a concern only under extreme weather conditions. It is also recommended to avoid placing the measurement set in direct sun light, which causes local discomfort that does not truly reflect the building components and systems performance and cannot be evaluated effectively by the radiant asymmetry sensor.

The thermal comfort variables are mean radiant temperature, air temperature, air velocity, relative humidity, clothing level, and metabolic rate. The thermal comfort instrument set that is usually deployed in the field includes: a mean radiant temperature sensor, a radiant shielded dry-bulb temperature sensor, a T&RH sensor, a hot wire anemometer, a radiant asymmetry sensor, and a data logger with software calculating thermal comfort with user input clothing level and metabolic rate. The sensors are located in series on a rack, as shown in Figure 45. The short-term measurement will generate predicted mean vote and percent of people dissatisfied, as the most comprehensive index of human object thermal comfort [1].

Alternately, in the retrofit context, operative temperature measurement using mean radiant temperature and air temperature may be used to as a metric for partial thermal comfort prediction. In high-performance homes, operative temperature measurement does not have much value, as its operative temperature readings always normally come close to air temperature readings.

Figure 45. Thermal comfort instrument set during a field test

Photo by Ed Hancock, NREL

References:

1. ASHRAE. 2004b. *ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

3.10 Wind Speed and Direction

Wind primarily affects the infiltration in a house, so measuring wind speed and direction in a field test is particularly important if natural infiltration is being measured. Tracer gas tests, for instance, are very sensitive to outdoor conditions and wind speed should always be measured when tracer gas tests are performed. Wind speed is measured using an anemometer, pictured below. Wind direction is typically measured separately by a wind vane or weathervane. Wind direction is not always measured in past field tests, even if wind speed is measured. The measurement set is normally located 4 feet away from windows.

Figure 46. Three-cup anemometer at a field test site

Photos by Lieko Earle, NREL

The cup-type anemometer, as pictured, directly measures wind speed by measuring the rotational speed of the cups. The three-cup anemometer is the most common configuration for cup-type anemometers, since it responds more quickly to large gusts than four-cup anemometers. Weathervanes are designed to rotate freely on the vertical axis so they can respond to small changes in wind direction. The weight on either side of the vertical axis is equal, but the surface area is much larger on one side. That side will catch the wind if the pointer is not pointing directly in line with the wind. Weathervanes typically send the wind direction to a data logger using a potentiometer; as the vane rotates, the resistance of a potentiometer changes.

3.11 Water Flow Rate

Measuring the volumetric flow rate of a liquid, usually water, is a common practice in field tests. Applications for measuring liquid flow include measuring whole-house hot water use, hot and cold water use at individual fixtures throughout the house, and measuring the condensate generated by an air conditioner or heat pump. Due to the wide range of flow rates that these measurements may include, there are different types of flow meters. Due to cost issues, volumetric flow meters are typical even though there are flow meters that can measure mass flow rate directly.

Figure 47. A turbine flow meter, installed under a sink, is used to measure the hot water flow rate and total usage

Photo by Dane Christensen, NREL

Turbine flow meters come in a variety of size and resolution options and are typically used in conjunction with hot and cold water flows. Measuring condensate flow rate, however, is not a measurement that turbine flow meters do well. Condensate is generated at a very slow flow rate and is not necessarily a continuous flow. There are ways to measure condensate flow rate very accurately in a laboratory setting, but they are cost-prohibitive for a field test. A pumped reservoir is a type of flow meter that is appropriate for field tests when measuring very low liquid flow rates. A tipping bucket rain gauge is another device that can be used to measure condensate generation rate.

There are several other ways to measure liquid flow rate, some of which are not expected to be used often in field tests. The following list of flow meters includes those that are commonly used in field tests and some that are not.

Table 4. Types of Flow Meters

Measurement Method	Can Be Used for Data Acquisition?
Turbine flow meter	Yes
Pumped reservoir	Yes
Magnetic flow meter	Yes
Utility-type water meter (no pulse output)	No
Utility-type water meter (with pulse output)	Yes
Tipping bucket	Yes
Rotameter	No

3.11.1 Turbine Flow Meter

A turbine flow meter has an internal rotor that is spun by the kinetic energy of a fluid flowing through it. The rotational speed of the turbine varies linearly with the mean flow velocity of the liquid. The rotational speed of the shaft is often measured by monitoring a change in magnetic field. As the turbine rotates, voltage is induced in a magnetic pickup coil and as each blade passes the coil, a voltage pulse is generated. Each pulse corresponds to a known volume, which allows the flow rate to be measured. Another similar design for turbine flow meters uses a Hall effect sensor to measure the rotational speed of the rotor.

3.11.2 Hall Effect Flow Meter

A Hall effect turbine flow meter has two key components: a rotary wheel placed in the flowing stream, and an external Hall effect sensor that picks up the blade rotations. When there is positive fluid flow in the turbine, the magnetic materials embedded in the rotor blades trigger an internal circuit in the sensor to produce a square-wave pulse, which is reported as a low-voltage signal to a DAS. The sensor itself requires external power to operate and it can only measure positive fluid flow, so care must be taken to install the turbine in the correct orientation.

3.11.3 Hardware and Installation Considerations

Turbine flow meters come in a variety of sizes and material choices, making them suitable for a wide range of applications. Material compatibility, temperature, and pressure requirements should all be considered when choosing the material of the flow meter. Resolution and accuracy requirements must also be carefully chosen. The resolution of turbine flow meters is designated by a K-factor, which is the number of pulses per gallon produced by the flow meter. In low-flow applications, a higher K-factor will be more important to ensure that many pulses can be counted every time step. Turbine flow meters will have a maximum and minimum flow rate designated on their data sheets and the expected flow rate for the field test should be comfortably within that range.

Just as with any other flow meter, it is important to install turbine flow meters in a long, straight section of pipe to ensure well-behaved, laminar flow in the flow meter. The general rule of thumb is that there should be 10 pipe diameters upstream of the flow meter and 5 diameters downstream of straight pipe. For example, when installing a turbine flow meter in a ¾” diameter pipe, there should be 7.5” of straight pipe before the flow meter and 3.75” after the flow meter. This can often restrict where flow meters can be installed in a field test and should be considered before buying a turbine flow meter, as it may be possible to buy a smaller (shorter) flow meter to make installation easier. Most turbine flow meters can be installed horizontally or vertically, but the liquid flow direction must match the flow meter's orientation. This will be indicated on the flow meter, usually with an arrow.

Figure 48. Omega FTB-4605 flow meter installed in a field test of a heat pump water heater

Photo by Lieko Earle, NREL

3.11.4 Sample Hardware Choices

An example of a turbine flow meter used in past field tests is the Omega FTB-4605 turbine flow meter. The flow rate range (0.15–13.0 gpm) is appropriate for residential hot water use and the price and accuracy are also both well-suited to field test application. This turbine flow meter uses a Hall effect sensor to generate the pulsed output. The connections for this flow meter are both male ½" NPT threads.

3.11.5 Nutating Disk Water Meter

Nutating disk water meters have an internal disk that "wobbles" as flow passes around it. Disk meters are a type of "positive displacement" meter and will respond to very low flow rates. Water utilities have traditionally used this type of meter, and they are sometimes called "utility meters."

The disk in these meters is connected to a magnet, which in turn drives the register that shows accumulated water use. Disk meters can be equipped with pulse output devices that are driven mechanically or coupled to the field of the rotating magnet. The resolution of pulse outputs on water meters is typically 50 to 200 pulses per gallon of flow.

The accuracy of disk meters drops off significantly at flows below about ¼ or ½ gallon per minute. However, they are capable of sensing much smaller flow rates, and can be used to identify leakage in domestic water systems. They will also produce output pulses when water flows in the reverse of the usual direction in systems. Small forward-reverse flow oscillations may be caused by thermal expansion (of water and/or water tanks), and by pressure changes (especially if there are air pockets in the system). The commonly used pulse output devices don't provide information on flow direction, and pulse data at low flow rates should be scrutinized to determine whether it represents positive water use or oscillating flow.

3.11.6 Pumped Reservoir Flow Measurement

Measurement of air-conditioner condensate flow is of interest in many field tests. The rate of condensate flow is often higher than can be accurately metered using low-flow meters, such as the tipping bucket, and lower than can be accurately measured using standard flow meters, such as turbine flow meters. Thus, for HVAC condensate flow, a pumped reservoir is recommended.

The basis for a pumped reservoir flow measurement is collection of condensate in a reservoir (or "sump"), which is pumped out with a known volume per pumping cycle. The condensate line must be rerouted to the sump. A float switch activates the pump when the water level gets to a certain level and turns it off once enough water has been pumped out. If you know the volume that gets pumped per cycle, you can monitor power consumption of the sump pump and count pumping cycles to measure incremental volume. Clearly, this is a "batch" measurement instead of a continuous one. For field tests, this typically provides satisfactory accuracy during annual monitoring. Higher accuracy may be attained if a turbine flow meter is placed in the outlet line of the pumped reservoir.

To be a useful measurement, this pumped volume must be repeatable. If condensate is flowing into the sump during the pumping cycle, a greater volume must be removed before the float switch is satisfied. Also, if the reservoir top is open then the condensate may evaporate prior to being pumped. This is particularly a concern in periods of minimal load. Also, correlation of the pumped volume to specific hours of latent load must be considered during low-load periods.

3.11.7 Magnetic Flow Meter

Magnetic flow meters are a type of volumetric flow meter that can only be used with conductive or water-based liquids. This excludes liquid hydrocarbons and distilled water, among other things. Magnetic flow meters have no moving parts, do not induce a pressure drop and have little need for maintenance.

Figure 49. A magnetic flow meter in use at a brewery

Photo from Wikimedia Commons

A magnetic flow meter measures flow rate by making use of Faraday's Law: E is proportional to $V \cdot B \cdot D$, where E is the induced voltage, V is the velocity of the liquid, B is the magnetic field applied to the fluid and D is the inner diameter of the pipe. By measuring the induced voltage, the velocity of the fluid can be determined. The velocity of the fluid and the cross-sectional area of the pipe determine the volumetric flow rate. There are in-line magnetic flow meters and insertion style magnetic flow meters. Either type can only be used with electrically conductive liquid. Water is generally electrically conductive, if it is not distilled or deionized, but its conductivity can vary. Magnetic flow meters are typically too expensive for field tests, but the lack of moving parts may be necessary for some applications.

3.11.8 Rotameters

Rotameters are a type of differential pressure flow meter used to measure (and sometimes control) the volumetric flow rate of liquids or gases. A rotameter consists of a tapered tube made of either glass or plastic and a float. When fluid is flowing through the tapered tube, the float rises until gravity is equal to the drag exerted by the fluid. The scale on the rotameter has been calibrated to reflect the appropriate flow rate. Some rotameters have a manually adjustable valve that allows the user to set the desired flow rate.

Rotameters are a simple flow meter and can provide flow control for a constant pressure fluid. Typically, the flow rate measured by a rotameter cannot be sent to a data logger, but some rotameters with magnetic floats can be combined with a sensor to sense the level change of the float. Depending on the application, it may be appropriate to use a rotameter during a field test. If a simple, one-time flow measurement is needed or if flow rate control is desired, a rotameter may be a good choice. Rotameters must always be installed vertically, and this should be verified with a level before using.

3.11.9 Tipping Bucket Rain Gauge

A common sensor for measuring rain or condensate is a tipping bucket rain gauge. Rain is collected in a funnel on the top of the assembly and is directed into the tipping bucket. The tipping bucket is shaped like a roof truss, with a fulcrum in the middle like a seesaw. The truss will tip when a preset amount of water is collected on one side and the other side will begin filling. This action will trip a reed switch sending a pulse to the data logger. Because the volume held in the bucket is known, the rate of pulses is used to determine the rate of rain falling or the rate of condensate production. This method works well for low flow rates and becomes less accurate for higher flow rates. As one example, the tipping bucket rain gauge made by Texas Electronics does not accurately capture flow rates higher than 1.5 liters/hour [1].

Figure 50. Tipping bucket rain gauge (left), and with the top removed to show the tipping bucket mechanism (right)

Photos from Cambridge Bay Weather

A tipping bucket rain gauge needs to be mounted on a level surface to achieve the best possible accuracy. It also needs to be mounted on a surface that cannot vibrate (like a porch) since even small vibrations could cause the bucket to tip prematurely. When used outside for rain collection, it should be in an open area away from trees and other sources of debris that can clog the collector. For measuring the rate of snow, heated tipping buckets are made to melt the snow in the funnel. The water is measured with the tipping bucket and the water is converted to an approximate amount of snow using an average snow density.

References:

1. TR-525 Series Rainfall Sensors User’s Manual, Texas Electronics

Appendix 1: Example of Gas Valve Monitoring

General Approach

1. Measure the time that the gas burning is on using an Onset HOBO logger
2. Measure the rate of gas consumption while the burner is on using meter clocking
3. Adjust the consumption rate for the altitude of the test site
4. Get the heating value of the gas from the utility
5. Multiplying the time that the burner is on (minutes), the altitude adjusted burn rate of the gas (ft^3/min), and the heating value (BTU/ft^3) yields the thermal energy delivered by the furnace.[2]

The gas use of the pilot is not accounted for in this example.

Safety Precautions

A residential natural gas furnace generally includes both 24 VAC and 120 VAC circuits. The procedure described in this brief must be performed by an individual trained and qualified to safely work with these conditions. The individual executing this procedure must independently determine the voltage present and take appropriate safety precautions.

Equipment Needed

- Onset HOBO motor on/off logger (UX90-004) **- *or* -** state logger (UX90-001)
- Onset DC Voltage Input Sensor (CABLE-DCVOLT)
- Onset Current Switch (CSV-A8) **- *or* -** a 24VAC normally open (NO) relay

(If you use a relay, you will need a way to connect the relay coil terminals to the furnace gas solenoid valve terminals.)

Figure 51. Motor on/off logger (UX90-004)

Photo from Onset website

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[2] This yields the thermal energy delivered to the ducts. If it is important for your project to know the thermal energy delivered to the living space, you will need to take the duct leakage to the outside into account. The duct leakage to the outside is usually measured using a blower door and a duct blaster or with a blower door alone using the DeltaQ software.

Figure 52. State logger (UX90-001)

Photo from Onset website

Figure 53. Current switch (CSV-A8)

Photo from Onset website

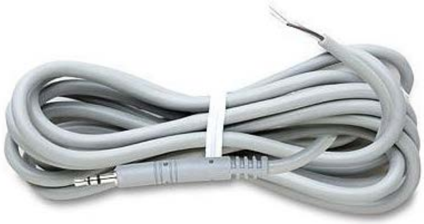


Figure 54. Voltage input sensor (CABLE-DCVOLT)

Photo from Onset website

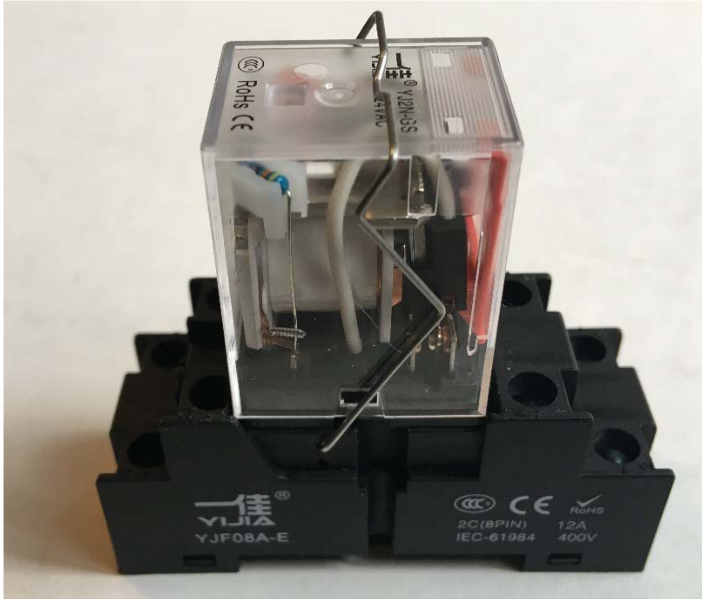


Figure 55. Example of a 24 VAC relay

Photo by Paul Norton, NREL

Step by Step Installation Instructions

1. Launch the Logger – Choose the ***external*** sensor to be logged and **do not** check the "Turn LCD off" box. Set the logger to record runtime. Make note of the battery level and logging duration.

2. Turn the thermostat down so the furnace will not turn on unexpectedly. With the furnace OFF, remove the low-voltage access panel from the furnace cabinet. **Avoid the high-voltage access panel**. In the example furnace shown below, the top panel accesses low-voltage circuitry, and the bottom panel access high-voltage circuitry.

3. Locate the gas solenoid valve. It will be located near the gas burner and will be plumbed into the gas line. There is usually an on/off switch on the solenoid valve.

> Always follow proper safety procedures and test for voltage present. In general, removing the top panel of a residential furnace may expose only 24V circuits, removing the bottom panel exposes 120V circuits. However, do not take this for granted—always test for voltage present.

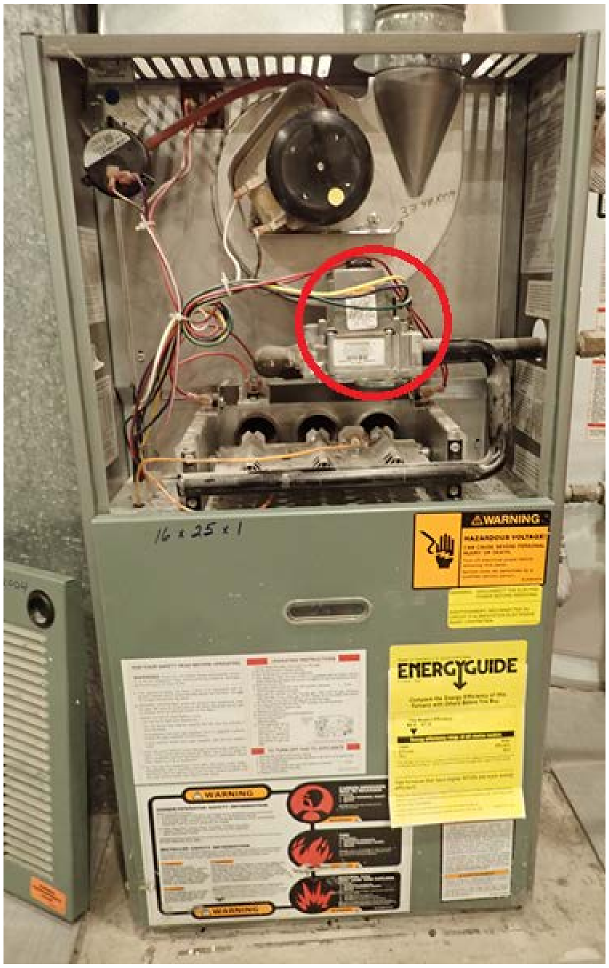


Figure 56. Example of the location of the gas solenoid valve in a residential furnace

Photo by Paul Norton, NREL

Figure 57. Close-up of the solenoid valve and wiring

Photo by Paul Norton, NREL

4. Identify the terminals on the gas solenoid valve that open the gas valve when energized. There are a couple ways to do this:

   Method 1—Use the circuit diagram. This is usually located on the inside of the bottom panel cover. The bottom panel generally contains 120V circuits. Before removing the bottom panel, turn OFF the breaker to the furnace and follow electrical safety procedures required by your organization such as appropriate lockout-tagout procedures and zero voltage confirmation. Examine the circuit diagram to determine the colors of the hot and return wires to the gas solenoid valve.

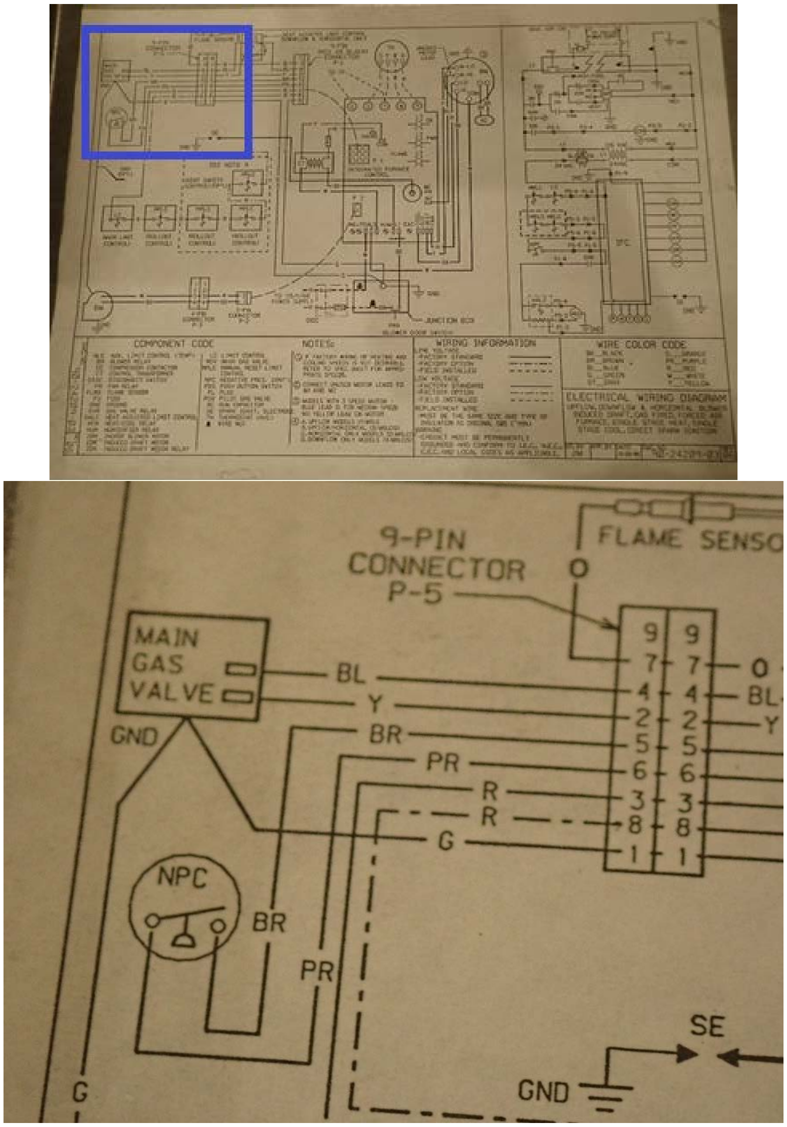


Figure 58. Example of a furnace wiring diagram and an enlargement of the upper left corner showing the main gas valve. The blue (BL) and yellow (Y) wires activate the gas valve solenoid.

Photos by Paul Norton, NREL

Method 2—Use a multimeter to determine the hot and return wires that energize the solenoid coil and open the gas valve. You may need to call for heat at the thermostat to get the gas valve to turn on in order to identify the hot 24 VAC and the return wire.

At this point you have the options of using an Onset current switch or a normally open relay with a 24 VAC coil. If you are using a relay, skip forward to the "Option 2—Using a Relay" section.

Option 1—Using an Onset current switch

5. Attached the Voltage Input Sensor cable to the terminal of the Onset Current Switch. Note that the cable may have two or three conductors—only two conductors are needed.
6. Open the Current Switch and clamp it around the hot wire of the gas solenoid valve.
7. Plug the Onset Voltage Sensor Input cable into the HOBO logger.

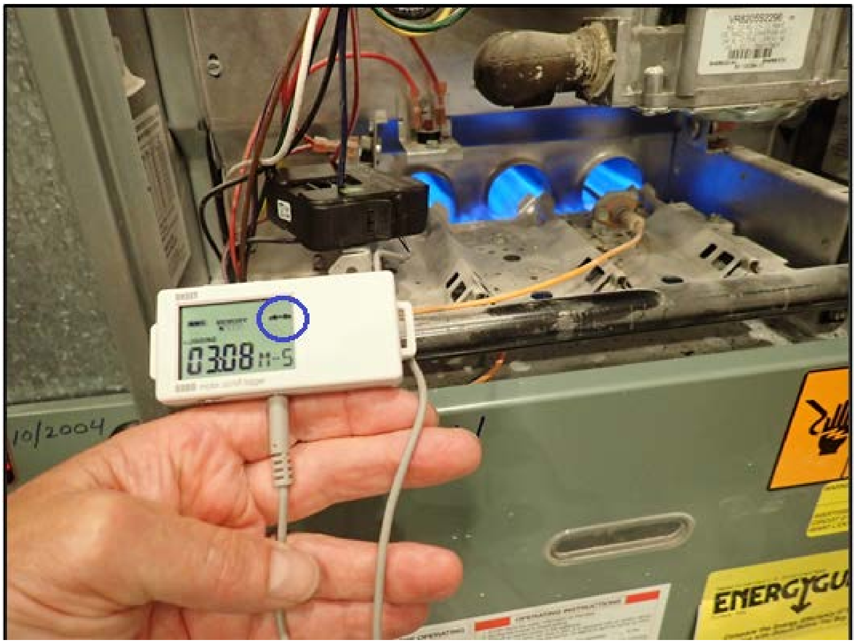


Figure 59. Example installation using an Onset Current Switch on the hot 24 VAC wire. Note that the gas is ON and the logger indicator (circled in blue) is in the closed position

Photo by Paul Norton, NREL

If you used option 1, skip to step 8 below.

Option 2—Using a Relay

5. Attach the relay coil terminals to the hot and return wires of the gas solenoid valve. These terminals are often ¼” spade connectors that can be quite close together. Take care not to short these terminals. If the spade connectors are exposed enough, you may be able to use an alligator clip on the exposed spade connector to make connection to the relay. If an alligator clip is not possible, you may be able to use a duplex spade connector or fabricate a connector as shown below.

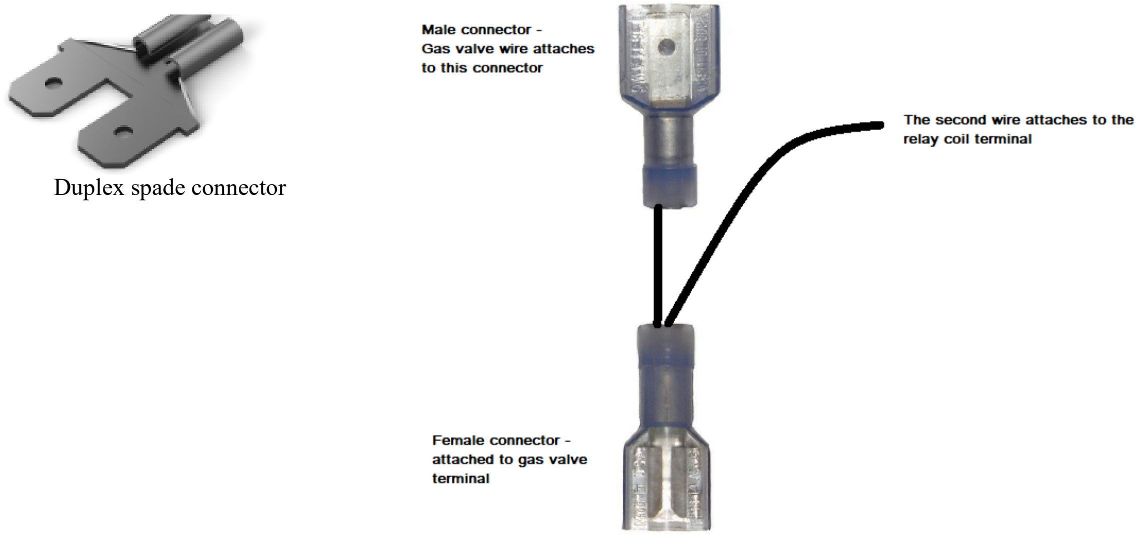

Duplex spade connector

Figure 60. Duplex spade connectors

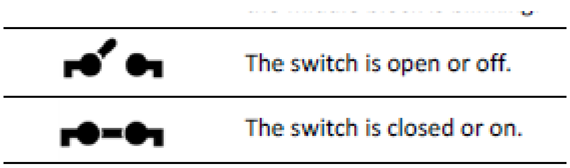
Photo by Paul Norton, NREL

6. Attach the Onset Voltage Sensor Input cable to the normally open terminals on the relay. Note that this cable may have two or three conductors—only two conductors are needed.

7. Plug the Onset Voltage Sensor Input cable into the HOBO logger.

8. Test the logger. Call for heat by turning up the setpoint at the thermostat. Observe the logger’s on/off indicator. The combustion exhaust fan will come on right away. After some delay there will be a loud click (the solenoid gas valve opening) followed by a quick series of softer clicks (the igniter), and the flame will ignite. You should observe the logger indicator close with the loud click of the solenoid valve. If not, check all the wiring and try again. If using the current switch, try adjusting the current needed to close the switch. You can also wrap the wire around the current switch to double the sensed current.

Logger open/close indicator



	The switch is open or off.
	The switch is closed or on.

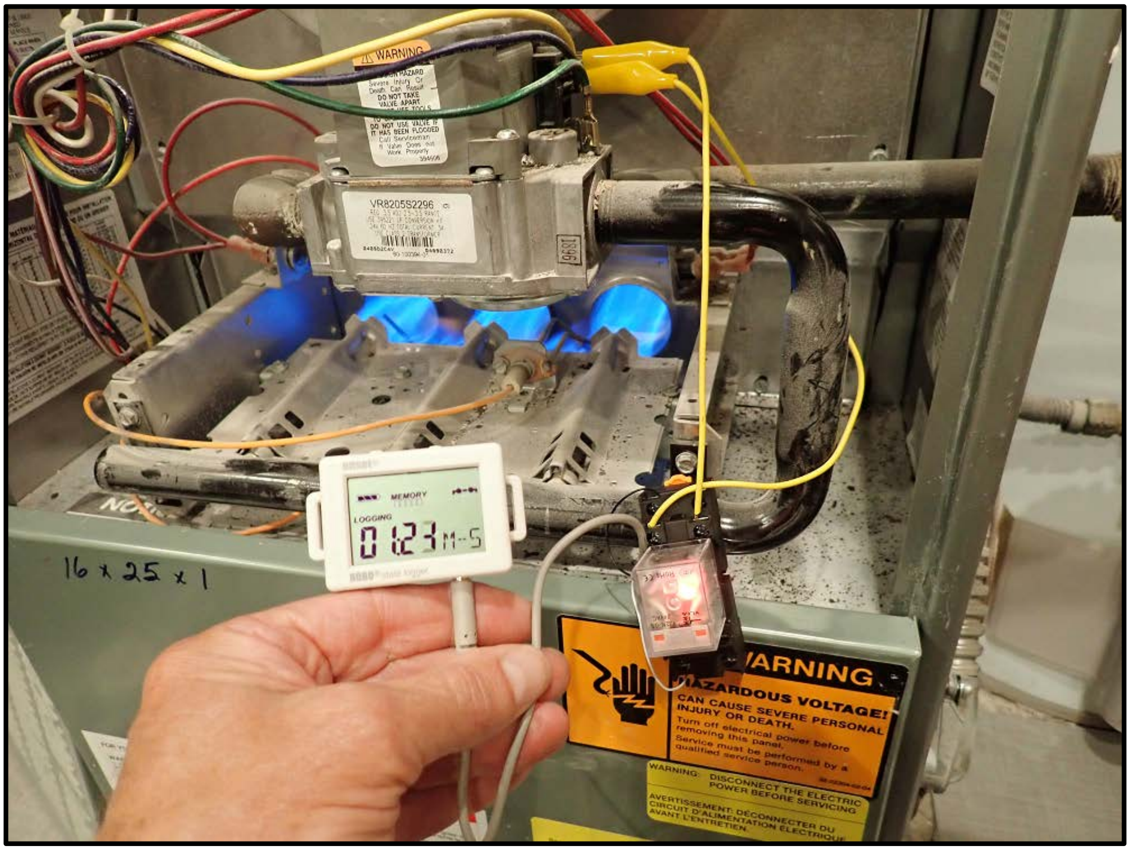


Figure 61. Duplex example installation using a relay with alligator clips on the low voltage gas valve solenoid and an Onset HOBO state logger. Note that the gas is on, and the logger indicator (circled in blue) is in the closed position.

Upper photo from Onset website, lower photo by Paul Norton, NREL

9. Find a location away from the heat of the gas flame to secure the logger.

10. Replace the top cover panel of the furnace.

The HOBO logger will provide you with time series data of when the furnace was running. We will now use this data to calculate space conditioning energy.

11. Measure the gas consumption rate using the utility gas meter. Set the thermostat high so the furnace turns on and stays on. Locate the utility gas meter outside the house. The gas meter has several dials; locate the one that is turning the fastest and make note of the cubic feet of gas per revolution noted on the dial. Count the number of revolutions the dial makes in one minute. Do this several times and take an average of the result. You can increase the accuracy of this measurement by counting the revolutions over a longer period of time and/or doing additional repetitions of the measurements and averaging. This measurement should be fairly close to the furnace rated output.

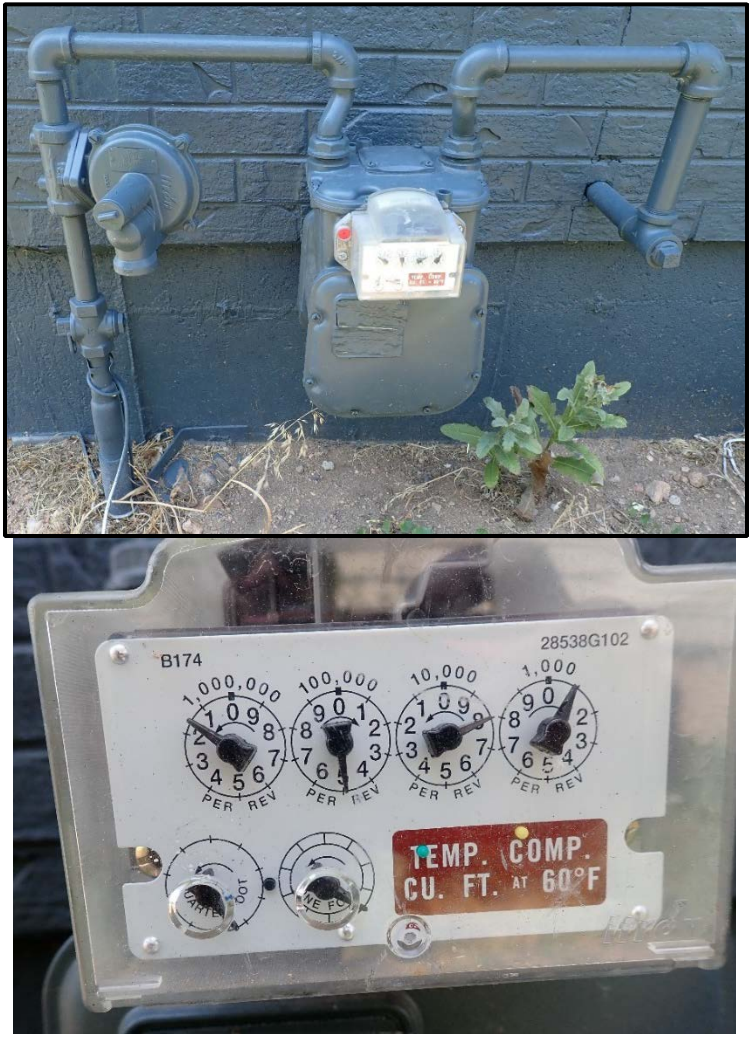


Figure 62. Example of a utility gas meter. In this case, the lower left dial measures ¼ cubic foot of gas per revolution. Note that the meter has temperature compensation and measures cubic feet of gas at 60˚F

Photos by Paul Norton, NREL

12. Determine the heating value of the natural gas. The heating value of a natural gas is the energy released upon combustion at standard temperature and pressure (STP). The heating value can be expressed in terms of either higher heating value or lower heating value, depending upon whether the available heat energy includes or excludes the energy

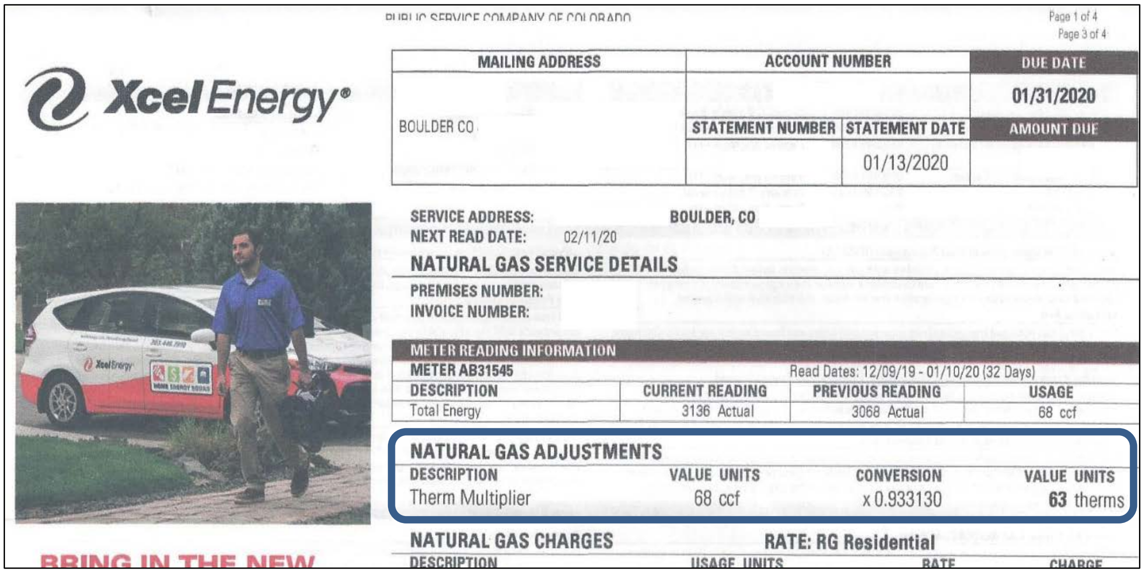
used to vaporize. Unless the furnace is a condensing furnace, the lower heating value should be used.

The primary constituent of natural gas is methane, which has a lower heating value of 910 Btu per cubic foot (Btu/ft^3) at standard temperature and pressure. However, the heating value of natural gas varies somewhat around the country due to the presence of gases other than methane. Therefore, you may want to find the heating value of natural gas at your test site. Contact the natural gas utility at your test site to get this information. In general, the lower heating value of natural gas is between 900 and 950 Btu/ft^3.

13. Determine the heating energy delivered to the home. The volumetric gas flow rate measured by the utility meter needs to be adjusted to account for the altitude of the test site and temperature to convert it to standard cubic feet. (Note that the gas meter shown above includes temperature compensation to 60°.)

    The International Standard Metric Conditions for natural gas and similar fluids are 288.15 K (15.00°C; 59.00°F) and 101.325 kPa (ISO 1344:1996) If the meter is already temperature compensated to 60°, altitude compensation is probably sufficient. Multiply the heating value by the ratio of atmospheric pressure at the test site (in kPa) over the standard pressure of 101.325 kPa.

    Some utilities provide the conversion factor from cubic feet of gas at the meter to energy delivered in therms. Below is an example from an Xcel Energy residential bill in Boulder, Colorado.



PUBLIC SERVICE COMPANY OF COLORADO

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MAILING ADDRESS	ACCOUNT NUMBER		DUE DATE
BOULDER CO			01/31/2020
	STATEMENT NUMBER	STATEMENT DATE	AMOUNT DUE
		01/13/2020	

SERVICE ADDRESS: **BOULDER, CO**
NEXT READ DATE: 02/11/20

NATURAL GAS SERVICE DETAILS

PREMISES NUMBER:
INVOICE NUMBER:

METER READING INFORMATION

METER AB31545 Read Dates: 12/09/19 - 01/10/20 (32 Days)

DESCRIPTION	CURRENT READING	PREVIOUS READING	USAGE
Total Energy	3136 Actual	3068 Actual	68 ccf

NATURAL GAS ADJUSTMENTS

DESCRIPTION	VALUE UNITS	CONVERSION	VALUE UNITS
Therm Multiplier	68 ccf	x 0.933130	**63** therms

NATURAL GAS CHARGES **RATE: RG Residential**

DESCRIPTION	USAGE UNITS	RATE	CHARGE

BRING IN THE NEW

In the example of Xcel Energy, they include the monthly "Therm Multiplier" in the utility bill. According to Xcel, "The Therm Multiplier, which is the product of the Altitude Factor, Temperature Factor and Energy Factor, adjusts your volumetric gas measurement to reflect the energy content of the gas supplied to your home or business." This Therm Multiplier can therefore be used to convert the cubic feet of gas as measured at the meter directly into energy in therms. A therm is equal to 100,000 Btu.

Figure 63. Example of utility-provided conversion factor from cubic feet of gas at the meter to energy delivered in therms

Figure from Xcel Energy

Discussion

- This approach is only as accurate as the visual measurement of the gas flow rate and the value used for the lower heating value of the natural gas.
- However, if the gas flow measurement is being used to measure a percent reduction in heating energy attributable to a retrofit measure, it may be possible to compare the gas flow rate before and after the retrofit directly without conversion to space conditioning energy. This assumes that the heating value of the fuel does not change substantially during the test period.
- It may be possible to use this same approach on condensing furnaces by using the higher heating value of the natural gas rather than the lower heating value.
- The approach described here is only applicable to simple single-speed furnaces, but it may be possible to adapt it to more sophisticated furnaces. Some two-speed furnaces have two sets of terminals and two solenoid values. Adding a second HOBO motor or state logger and using the utility meter to measure the gas flow at low speed and high speed may be possible. Multi-speed furnaces are more challenging. We would have to understand and measure the signal controlling the gas valve then correlate the measured signal to the gas flow rate.