Synertech Systems Corporation

SYN TN 06-514 November 2006

Residential Energy Auditing Techniques

by

Larry Kinney
Gary Cler
Wyncia Clute
Tom Wilson

This technical note on residential energy auditing was prepared using material from a report by the authors written for Thistle Community Housing in Boulder, Colorado. Appendix A on air leakage was written by Tom Wilson of Residential Energy Services of Viroqua, Wisconsin. Some of the audit procedures in the Appendix C derive from audit processes developed by Bevilacqua-Knight, Inc. of Oakland, California. Synertech appreciates useful material, insights, and feedback from all parties, but we remain solely responsible for any shortcomings that may remain. Feedback should be addressed to Larry Kinney at the address and phone below, LarryK@SynertechSystemsCorp.com.

Synertech Systems Corporation ☼ 1335 Deer Trail Road ☼ Boulder, CO 80302 USA
303-449-7941 (V) ☼ 303-546-0343 (F) ☼ www.SynertechSystemsCorp.com

Table of Contents

Energy Saving Technologies and Audit Procedures

Many things affecting energy performance can go wrong in homes and apartments. An energy audit aims at identifying the factors that may contribute to energy waste and comfort problems. But it also examines issues that potentially or actually affect the health and safety of occupants and the well-being of the home's structure. The objective is to produce sound recommendations likely to improve the performance of the building cost effectively while lowering energy consumption.

A form is sometimes helpful in guiding the process of data gathering, supplying convenient places for recording observations, and to keep busy auditors from missing anything important. The focus of attention should be on understanding the dwelling and how energy flows, but forms are necessary as well. The form we find useful is reproduced as Appendix C of this document. The first page of the form is reproduced below (Table 1) as an indicator of the steps that should be taken in a thorough audit and as a guide to this document, since its discussion follows the same steps.

Table 1. Elements of a comprehensive energy audit

Section	**Actions**
1	Energy bills
2	Temperature and humidity measurement
3	Interview
4	Electrical tests and refrigerator monitoring
5	Inspection overview and safety tests
6	Convective losses and blower door tests
6.1	Finding leakage areas
6.2	Pressure differences indicate leakage
6.3	Convective loops
6.4	Estimating energy losses due to convection
7	Assessing duct losses
7.1	Estimating energy losses of duct leakage
8	Pressure testing
9	Insulation
10	Windows
10.1	Heat radiation
10.2	Conduction and convection
10.3	Modeling choices
11	HVAC auditing procedures
11.1	Furnace and boiler "house keeping"
11.2	Measuring furnace and boiler efficiency
11.3	Forced air systems
11.4	Thermostats controlling space conditioning
12	Domestic hot water systems
13	Lighting

14	Other appliances
14.1	Ceiling fans
14.2	Ventilation fans
14.3	Washing machines
14.4	Vending machines
15	Telling the story

It should be noted that not all steps must be taken and blanks filled in; many are not applicable to a specific circumstances so blank spaces are normal. On the other hand, the auditor sometimes finds energy or safety-relevant circumstances that are not anticipated by the audit form. These should be recorded carefully—and if they recur should help in producing the next version of the audit form itself.

It is important as one goes through the audit that most buildings, and apartments, are seen to have a story to tell. That is to say that the auditor may find a combination of conditions that make up the greatest source of energy loss, discomfort, and/or health risk in the dwelling. This will become the story of the audit, and will inform the first steps to be taken in the energy retrofit. In some buildings dramatic situations require repair followed by additional testing to find subtler problems and ensure an excellent energy retrofit. A classic example of such a situation is a home with major duct leaks into an unconditioned attic and a leaky fireplace chimney. When these problems are corrected, another blower door test may reveal patterns of air leakage that were dwarfed by the ducts and chimney problems.

1 Energy Bills

It is useful to know the energy content of electricity and gas versus costs. Electric energy is measured in kilowatt hours, which have a energy content in British Thermal Units (Btus) of 3412 Btu/kWh. A Btu is the energy necessary to raise a pound of water a degree Fahrenheit, about the energy that results from burning a kitchen match to a crisp. A million Btus is roughly the energy equivalent of a person year of labor. There are about 293 kWh of electricity per MMBtu. When electricity costs $0.10 per kWh, roughly the cost in Xcel's service area for residential customers, this amounts to $29.30 per MMBtu. Natural gas costs about $1.00 per therm, where a therm is 100,000 Btu. So gas costs about $10/MMBtu, about 1/3 the cost of electricity. This means that when there's an opportunity to save a given amount of energy, saving electricity saves three times as much money as does saving gas. Further, since over 80 percent of the electricity generated in Colorado comes from burning coal—a process that wastes about half a gallon of water per kWh produced—saving a kWh saves a half a gallon at the power station.

Apartments in our area use from 25 MMBtu/year to three times that number, the energy equivalent of 75 person years of labor per year. When they use that much, there is usually plenty of it wasted. And if that waste is found and treated, then energy is saved, money paid to the local utility is diminished, and apartments are usually substantially more comfortable.

For new structures, architectural drawings are routinely available. This is not generally true of older dwellings, but energy consumption information may be available and it can tell an important tale in identifying waste. Examining bills before an energy audit can enhance the efficiency of the audit itself because it can give strong hints about areas of waste—and areas not worth bothering with. How does energy use match with the apartment size? With household size? What patterns of month-by-month consumption are revealed and how do they follow weather? The school year? Holidays? Is their evidence of *ad hoc* electric resistance heating in an apartment whose primary source of heat is gas fired? What differences are discernable between one apartment and those close to it? Do insider apartments on lower floors show less consumption for space heating than do outsiders on top of the building? Are complaints correlated with high electric or gas bills? How do patterns of energy consumption vary when different tenants occupy the same space?

Answers to these questions are helpful both in guiding an audit and in designing energy education programming.

It is sometimes useful to develop an index of space energy consumption adjusted for weather and apartment size. The process entails separating space conditioning energy use from other uses by looking at a year of energy consumption information, taking an average of monthly consumption during the months in which there is no space conditioning energy use, then subtracting that figure from the amount of consumption during months in which space conditioning (particularly heating) is required. This yields an approximation of space conditioning energy use by month. This should be expressed in Btus, where a therm of gas = 100,000 Btu and a kWh of electricity = 3412 Btu. Divided by square feet of the living area, the result is Btu/ft^2, an index of the consumption of energy for space conditioning adjusted to apartment size.

The final step is to adjust for weather. Weather data is routinely collected by a number of organizations with information posted on the web (see, for example, http://www.engr.udayton.edu/weather.) The most frequently-employed technique for adjusting consumption to the severity of winter weather is the heating degree day, base 65. The heating degree days associated with a particular winter day are computed by taking the average temperature of the day (high plus low divided by 2) and subtracting the result from 65. To take an example, if the high is 30 and the low 10, the average is 20, so 65-20 = 45, the number of heating degree days on the day. The heating degree days for a given period are summed, and the result is divided into the Btu/ft^2 figure for the period, yielding the desired index of heating energy consumption, Btu/ft^2/HDD.

HEATING DEGREE DAYS:

Boulder = 5466
Denver = 6023
Cheyenne = 7315
Phoenix = 1444

ENERGY USE FOR SPACE HEATING

Below 5 Btu/ft^2/HDD: Low
5 – 10 Btu/ft^2/HDD: Average
Above 10 Btu/ft^2/HDD: High

When this weather and size-adjusted index of wintertime heating is below 5 Btu/ft^2/HDD, the likelihood of finding substantial opportunities for cost-effective retrofits addressed to space heating savings are small (although not zero). When the index is between 5 and 10, good opportunities are likely to be discovered. Numbers above 10 suggest the possibility of an energy savings triple or even a home run. Savings follow waste!

The average annual heating degree days for Boulder are 5466, and 6023for Denver. For reference, Cheyenne has an average of 7315 HDD and Phoenix 1444.

In the case of some apartment buildings, heating use is sub-metered with some degree of accuracy. If, for example, a number of apartments are served by the same boiler, it is possible to monitor the amount of time the thermostat in each apartment calls for heat by monitoring the elapsed time that the solenoid valve that controls the flow of hot water to radiators is actuated. If one knows the number of minutes all valves served by a boiler are open as well as the metered energy flow to the boiler (and one assumes that flow is constant and that the temperature of the water supplied is constant as well) gas usage over the period divided by total minutes per period yields a useful index of consumption, like Btu/minute. This index multiplied by each apartment's elapsed time of solenoid valve opening in minutes yields that apartment's consumption over the period. Thus, tenant consumption can be monitored, billed for, and compared with others.

2 Temperature and humidity measurement

It is useful on approaching an apartment to be audited to measure and note the exterior temperature and humidity, then the interior temperature and humidity. A simple digital meter that fits in the pocket is sufficiently accurate for such initial measurements (Figure 1).

3 Interview

Interview the homeowner, or in the case of multifamily dwellings, tenants, maintenance folks and/or on-site staff. The aim is to identify areas of concern in the particular unit. Information gathered will help the auditors vector in on the energy story of the dwelling as soon as possible. If the layout and square footage of the residence is unknown to the auditors, ask the interviewee to provide that information and to show you around initially.

Questions that will be helpful include:
Occupancy: How many people live here? (Given that the young, elderly and disabled people have differing comfort needs), what are the ages and health of the occupants that might affect energy use in the home? Is the dwelling unoccupied when people are at work? Does anyone in the residence have respiratory problems? Are there smokers living there?

Thermostat: At what temperature do you have your thermostat set in winter? In summer? What are your "set-back" practices? Is this done manually or do you use the automatic features of your thermostat? Do you know how to use the automatic features of the thermostat? Is it your sense that the thermostat works properly? Do you notice the heat coming on in frequent, short cycles?

Moisture and humidity: Use of humidifier? Dehumidifier? Areas of moisture damage? Condensation on windows?

Comfort: Where do you spend the most time? Are there cold rooms? Warm rooms? Any seasonal comfort concerns? Are room air conditioners or electric space heaters used (whether or not apparent today)? Do you open windows, summer or winter? Are there drafts, noise, related issues? Are kitchen/bath exhaust fans working? If so, how are they used?

HVAC: Is the furnace/boiler/domestic hot water system within the residence? Do the occupants adjust the controls on the units? Are furnace filters changed regularly? Are there closed or covered heating vents, supply or return?

Air quality: Odors? Dust? Pests? Where are cleaning supplies, craft supplies, and other volatile chemicals stored? Are combustion space heaters (gas, propane, wood, pellet) used? Is there an odor of sewer, natural gas or propane? Do any occupants suffer from chronic headaches or respiratory conditions? Does anyone have chemical sensitivities?

Ask if the interviewee has particular concerns about this residence. Follow up with questions you have about your initial observations and the interviewee's comments.

4 Electrical tests and refrigerator monitoring

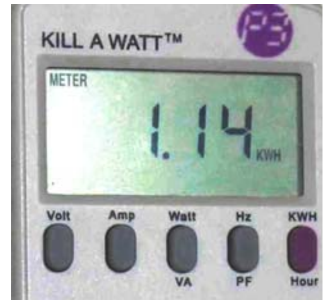
As soon as convenient upon arriving at an apartment, the circuit associated with the refrigerator is checked with a circuit testing meter that puts a 15 amp load on a circuit for a very short time and measures the voltage drop that results, expressing the result as a percentage. Voltage drops of more than 5% are considered abnormal, those above 8% call for remedial work. Usually tightening up connections in the outlet itself or other outlets between the outlet being measured and the circuit breaker box will solve the problem. If several outlets indicate similar readings, the problem could be the connection at the circuit breaker or in a junction box that cannot be easily accessed. In extreme cases, a line may need replacing. The "Suretest™" meter also measures wire resistance, the integrity of the neutral and ground, and several other parameters (Figure 2). All of the outlets in the apartment should be measured, but beginning with the outlet associated with the refrigerator enables initiating a test of the energy consumption of the refrigerator right away.

Figure 1. This humidity/temperature sensor fits in a shirt pocket.

Figure 2. Ideal circuit testerRefrigerators and freezers represent a substantial portion of the electric bill in many homes, nationally about 12%. Since many older units use 1,000 kWh/year or more—and new ENERGY STAR-rated units well less than 500 kWh/year—it is useful to measure their consumption toward estimating the cost effectiveness of replacement.

In the past, measuring electric energy use has required quite expensive instruments. However, a meter is now available that is both inexpensive and simple to operate. Called the "Kill A Watt™," the device is plugged into the wall outlet (or an extension cord), then the appliance to be measured is plugged into it. Buttons may be pushed to display a good deal of useful information:

- Button 1: Line
- voltage in volts
- Button 2: Current in amperes
- Button 3: Power in true watts or volt amperes (button toggles)
- Button 4: Frequency of the line voltage in Hertz and power factor (button toggles)
- Button 5: Electrical energy used in kilowatt hours (kWh) and the time over which the electrical energy has been consumed in hours and minutes (button toggles)



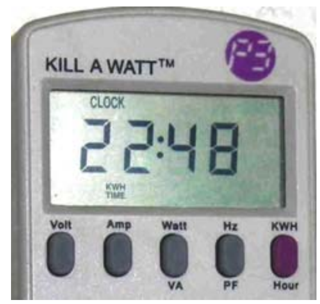


Figure 3. Sample readouts of the Kill a Watt meter.

Compressors on refrigerators tend to run about 1/3 of the time (more in summer), and it is best to wait until the compressor has stopped running before unplugging the refrigerator or freezer and connecting the meter. Sometimes turning the thermostat on the refrigerator to a warmer setting until the compressor stops is the only practical solution if one is pressed for time. Then the meter is put in series with the refrigerator plug and the wall outlet and the thermostat can be returned to its initial setting (Kinney and Belshe 2001).

The longer the meter is plugged in, the more accurate are estimates of annual consumption. A 24 hour period is best. (Be sure to take the readings before unplugging the meter, for data will be lost.)

Take both of the readings (elapsed time of monitoring and energy consumed) associated with Button 5, the colored one at the far right. Write down kWh and time. To estimate annual use, divide the number of hours in an average year (8766) by the monitoring time in hours and minutes expressed as a decimal, then multiply by the kWh used. The result is an estimate of energy the unit will consume over a year.

In the case illustrated, the elapsed time is 22 hours and 48 minutes. Divide 48 minutes by 60 to express minutes as a decimal (.8), then add the recorded hours (22). Divide 8766 by the time (28 hours) and multiply the result by 1.14 kWh. The result is 436 kWh/year, a good estimate of annual energy performance.

> Energy Use of Refrigerators
>
> Write down kWh and elapsed time.
>
> Divide number of elapsed minutes by 60 and add to the number of elapsed hours to express time in decimals.
>
> Divide 8766 (hrs/yr) by the elapsed time in decimal form
>
> Result is kWh/yr.

If the reading had been 3 kWh, for example, the result would have been 1153 kWh. In this case, a new refrigerator rated at (say) 375 kWh per year would save 778 kWh per year, or about $78 (at ten cents per kWh.) Depending on the cost of a new unit, this would represent a tax-free return on investment of 15 to 20%, much better than most stocks are doing these days.

5 Inspection overview and safety tests

Armed with insights from the tenant and given that measurements of the refrigerator (and freezer if applicable) are underway, the next steps are to take a quick look at the configuration of the apartment, the conditioned envelope, and its space and water conditioning systems. Where are the furnace and boiler? The air conditioning system? Fans and controls? The ducts (supply and return)? The radiators? The thermostats? The circuit breaker box? Where does water come in, where does it go? Where does gas come in and where does it go? The primary aim of this quick inspection is not analysis, but orientation, being sure to look at areas the tenant indicated may be a source of problems.

It may be helpful to make a sketch of the residence showing general layout, building orientation, situation of the unit within the building, placement and size of windows and HVAC supply and return registers for testing. The sketch page can also be used to note the location of any electrical outlets that fail the stress test.

During a site inspection, notes can be made regarding the type and condition of windows, external window treatment (storm windows, shutters), A/C unit including make, model, SEER, and condition, duct, vents and dampers as visible, shading/solar access, drainage and water damage.

Two specific actions accompany the initial inspection. First, a combustion gas detector like the TIF 8800 shown in Figures 4 and 5 should be used to detect any leaks in the gas system that feeds the furnace, hot water heater, stove, oven, clothes dryer, gas-fired fireplace, and any other gas-fired appliances. Best sensitivity is achieved when appliances are off, since the pressure in pipes is highest at this point. After a minute of warm- up, the sensitivity control on the detector should be adjusted so that its threshold is able to detect the breath of the inspector. Then the sensor should be run as close to pipes, connections, and (especially) valves as practical. The more substantial the leak, the higher is the pitch of the audio alarm from the sensor. Major leaks are cause to vent and clear the area right away, turning off cut off valves as practical. Maintenance staff should be contacted right away.

Figure 4. TIF 8800 combustion gas detector

Figure 5. Sniffing technique

All connections should be "sniffed" but valves are especially likely to leak.

The second action to be taken during the initial inspection are to turn off all gas-fired appliances so they cannot possibly come on during the blower door test, which is next. It is good practice to leave the keys to one's vehicle on top of a gas hot water heater to serve as a reminder to reset the controls (and relight the pilot if necessary) before leaving.

6 Convective losses and blower door tests

Energy losses in building are due to the transfer of heat via conduction, radiation, and convection. Convective losses are the result of the movement of air. Almost all buildings have openings between the inside and the outside of the "conditioned envelope" (the part of the building that is heated and/or cooled). When there is a driving force (a pressure difference) across these openings, air flow occurs. For each cubic foot of air coming into a building, there is a cubic foot that goes out, usually through a different opening. Pressure differences can be produced by the wind, by fans, by combustion appliances drawing in air to support flame, and by the greater buoyancy of warm air than cold air. The differences in air temperature cause what is termed "stack effect" infiltration/exfiltration. Except on very windy days, stack effect is the most powerful force causing convective losses in most homes during the winter. As illustrated in Figure 6, the greater the difference in temperature between the inside and outside of a building (and the taller it is), the greater the forces of infiltration that bring in unconditioned air at the bottom of the envelope—and the greater the forces of exfiltration that push it out at the top. These forces are at a maximum on the coldest day of the year.

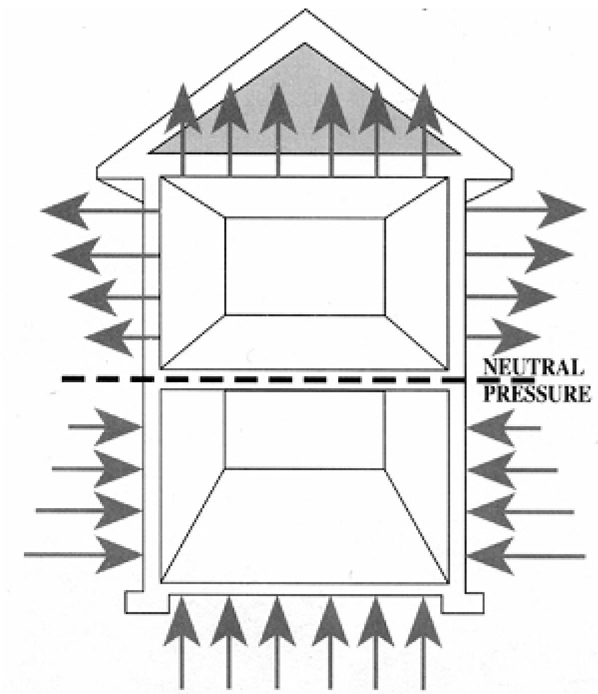


Figure 6. Stack effect infiltration/exfiltration.

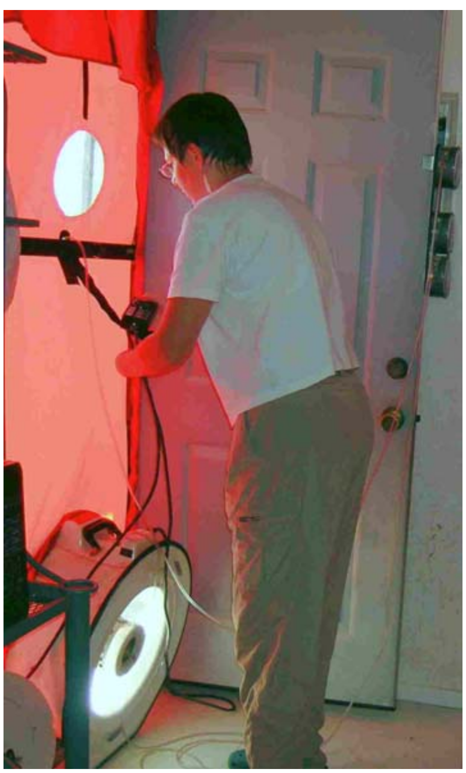


Figure 7. Blower door set up

It is interesting to note that there is a neutral pressure plane, typically toward the middle of the envelope where pressure differences are at a minimum. This means that in air sealing homes for energy efficiency, it is more important to air seal at the top bottom and top of the envelope than anywhere else. Stack effect losses show up within individual units of multifamily dwellings and through the building as a whole.

Holes in building envelopes are sometimes in unobvious places, and it is very difficult to tell how leaky a home is without using tools to extend vision. By far the most important of these is the blower door (Figure 7). The Energy Conservatory manufacturers the Minneapolis Blower Door which is both the best available on the market and the lowest in price. (MBD's documentation is also excellent and may be downloaded on at www.energyconservatory.com, Click on technical support, then manuals. There are half a dozen documents in pdf format that may be downloaded for free.)

A blower door is a device with a variable speed fan and meters to measure flow. It is temporarily set up in an outside door with the use of a frame and special shroud. After the home or apartment is configured for winter operations (all openings to the outside closed, internal doors open), **combustion appliances are off** and ash-containing fireplaces covered, the fan on the blower door is turned on to depressurize the dwelling by drawing inside air out of the building. The fan is brought gently up to a standard pressure, typically 50 pascals (Pa). A 50 Pa pressure difference roughly simulates the effect of a 20 mile per hour wind on all sides of the building at once. If the fan does not have to work very hard to achieve this 50 Pa difference, the dwelling is not very leaky. If it has to work quite hard to achieve this pressure difference, there are substantial openings between the inside and outside of the conditioned envelope.

A pascal is a small unit of pressure; atmospheric pressure at sea level under standard conditions is 101,325 pascals

Air flow is expressed in cubic feet per minute (CFM). When a dwelling is quite tight, it may measure 500 cubic feet per minute when depressurized to 50 Pa (CFM_{50}), expressed as 500 CFM_{50}. A leaky dwelling may measure 4000 CFM_{50} or even more.

In any case, with the apartment depressurized, air is brought into the dwelling via whatever openings it can find. Using the back of one's hand, it is frequently possible to feel blower-door-induced air leakage wherever it occurs. This aids significantly in being able to direct air sealing measures, for it reveals both where air infiltration occurs—and where it doesn't.

6.1 Finding leakage areas

There are a number of tricks that can make the infiltration-area-finding process more efficient.

Briefly closing a door to a room until it is open by only half an inch or so concentrates all of the flow from the space into the relatively narrow cross section of the space between the door and jamb. Air velocity through the narrow opening is increased substantially, making it easy to sense with the back of one's hand. If the flow is significant, more poking around in the room will be useful to pinpoint air leakage sites. If the flow is quite modest, the auditor can move on. This approach also works well when checking for infiltration in the cabinets under sinks where air frequently (but not always) leaks around plumbing penetrations.

Here is a list of some common areas where blower doors have revealed convective losses:

- Dropped ceilings and retrofit siding that may cover and hide problems--cheap cologne instead of badly-needed showers
- Dumb waiters, chimney ways, laundry chutes, pocket doors
- Plumbing and electrical ways, including recessed (can) light fixtures
- Balloon framing that may not have fire stops or top plates in the attic
- Some (which ones?) interior walls (sometimes evidenced by leaky outlets and switches)
- Party walls between adjacent units
- Stair wells
- Anything built in
- Foundation walls and sill plates
- Vented crawl spaces
- Ducts – both supply and returns
- Basement additions, attic additions, addition additions
- Subtractions (where spaces have been at least partly sealed off from the rest of the dwelling)
- Hatchways, doors, and other passages
- Windows (some of them, not all!)
- Crannies, nooks, and other unobvious and hard-to-get-to places

Some of these areas are depicted in the illustration in Figure 8 drawn by building scientist, Tom Wilson. Appendix A of this document identifies each of the kinds of air leakage areas called out in the numbers in this illustration and discusses techniques for sealing them most appropriately.

Source: Tom Wilson

Figure 8. Some areas where air infiltration/exfiltration may occur in a dwelling.

1 Staircase Ceiling
2 Recessed Light
3 Chimney Chase
4 Electric Wires and Box
5 Balloon Wall
6 Attic Entrance
7 Partition Wall Top Plate
8 Plumbing Vent Chase
9 Exhaust Fan
10 Dryer Vent
11 Plumbing/Utility Penetrations
12 Sill Plate
13 Rim Joist
14 Bathtub Opening
15 Basement Windows & Doors
16 Block Wall Cavities
17 Water Heater/Furnace Flue Connections
18 Ductwork
19 Plumbing Chase
20 Leakage Between Basement & Crawlspace
21 Floor Boards
22 Windows
23 Laundry Chutes
24 Stairwell
25 Kneewall/Framing Intersection
26 Built-in Dresser
27 Chimney Penetration
28 Built-in Cabinet
29 Holes in Plaster walls
30 Furnace Registers
31 Doors
32 Baseboards, Coves, & Interior Trim
33 Plumbing Access Panel
34 Sink Plumbing Penetrations
35 Dropped Soffit
36 Electrical Outlets
37 Electrical Fixtures
38 Porch Framing Intersection
39 Missing Siding & Trim
40 Additions, Dormers and Overhangs
41 Unused Chimney
42 Floor Joist

6.2 Pressure differences indicate leakages

Since the blower door puts a *total measured* pressure difference (ΔP)across the conditioned envelope (from the inside to the outside: $\mathbf{\Delta P_{in/out}}$), it also puts a *partial* pressure difference between the inside and some buffer zone ($\mathbf{\Delta P}_{in/buffer}$), like the attic or a porch. In such cases, the pressure difference between the buffer zone and the outside ($\mathbf{\Delta P}_{buffer/out}$) plus the pressure difference between the inside/buffer zone equals the full measured inside/outside pressure difference.

Symbolically, $$\Delta P_{in/out} = \Delta P_{in/buffer} + \Delta P_{buffer/out}$$

This relationship is quite convenient, since if one knows any two of the terms, it's quick and easy to determine the other. Let's imagine that an attic is vented to the outside and that the dwelling is depressurized to 50 pascals. Then we can measure the pressure difference between the inside of the dwelling and the attic with a manometer (pressure gauge) and draw some useful inferences. If the pressure difference from the inside to the attic is 50 pascals, then the attic area is effectively completely out of the conditioned envelope and there is no air flow across the attic floor and the rooms below. However, if the pressure difference is, say, 40 pascals, there are surely significant leaks that need to be air sealed.

$$\textbf{50 Pascals}_{in/out} = \textbf{40 Pascals}_{in/attic} + \textbf{10 Pascals}_{attic/out}$$

Areas that may be sealed in this process include attic doors or hatches, tops of interior walls, open chases, stairwells, ceiling light fixtures that penetrate into the attic, as well as plumbing, HVAC, and electrical penetrations. Effective techniques for sealing different kinds of leakage areas are discussed in Appendix A.

After the air sealing work between the attic and the interior is completed, the test can be repeated, and if the measured pressure has gone up to 47 pascals or so, the job is done.

Referring to the porch area in Figure 8, sometimes the porch ceiling is completely sealed from the rest of the home, and sometimes it is directly connected. In the latter case, leakage can cause substantial discomfort and energy loss to the second story rooms immediately above the porch. The blower door makes it easy to discover if the porch ceiling is connected to the house or not. As illustrated in Figures 9 and 10, inserting a probe from a manometer into a small hole drilled in the porch ceiling (or "borrowing" a hole from around a light fixture in the porch ceiling, for example), pressure can be read when the blower door is depressuring the dwelling to 50 pascals. If no pressure is read, the porch is completely outside of the envelope and no work is needed. However, if the meter indicates a reading of, say, 25 pascals, the porch is connected to the conditioned envelope and the sum of the holes from the inside to the porch ceiling is about equal to the sum of the holes from the porch ceiling to the external world. In this case, air sealing by blowing high density cellulose to fill the porch ceiling cavity is likely to solve the problem, increase comfort, and lower energy bills.

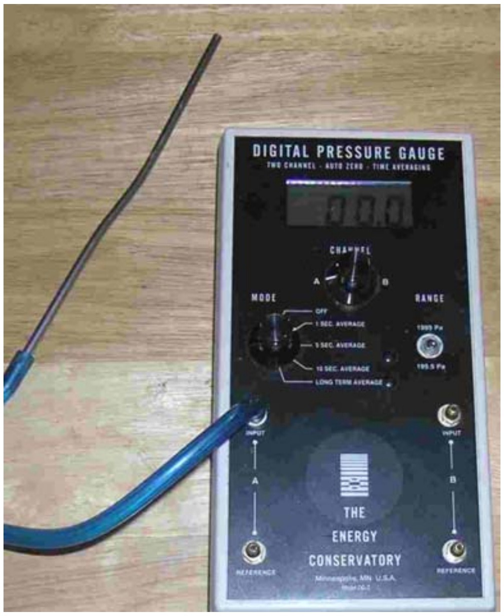


Figure 9. Digital manometer with metal probe to facilitate testing pressure differences without pinching the polypropylene tube.

Figure 10. Substantial pressure readings suggest that a porch may be effectively within the conditioned envelope.

6.3 Convective loops

Blower doors are quite useful tools, but they can not emulate what Mother Nature does and information flowing from testing procedures has to be tempered by knowledge of the myriad possible ways in which air moves. As a first approximation, the flow across an opening is proportional to the size of the hole and the square root of pressure difference across it, where the direction of flow is from high pressure to low. (Think about the test described above in which a door was closed to a crack so that the auditor could feel if there was air flow from a room during the blower door test. When the hole from the room to the rest of the house was made smaller by closing the door to a crack, the air velocity increased.) As discussed, through stack effect infiltration/exfiltration, wind, and fan use (particularly the distribution fan in the furnace), air is driven into and out of leakage areas all over a dwelling. However, the blower door does things to a home that Mother Nature never does: all holes become infiltration holes save for one large exfiltration hole where the blower door is temporarily installed. So there is a kind of distortion that can be somewhat misleading. Most of the action from stack effect is at the bottom and top of the envelope, and infiltration due to winds is routinely from the windward side of the structure. Further, blower door tests do not reveal any useful information about the degree of leakiness of the door in which it is installed (the measuring affects the measured to this degree).

Second, there is an important class of convective energy losses that blower doors do not demonstrate very clearly. Imagine an interior wall that is not very well sealed at the top where it is in contact with the attic. Balloon framed homes (in which studs extend from foundation to the attic of a two-story structure with few or no fire stops) and many others have either leaky or absent top plates covering the tops of interior walls. On winter days, when the vented attic temperature approaches outside air temperature, the cold attic air slides down the interior wall (because it is more dense than warm air), displacing warm air out through the top of the interior wall. This process, called thermo-siphoning, becomes quite pronounced on the coldest days, frequently causing interior walls to become substantially colder than insulated exterior walls. However, since these walls are not generally open to the inside of the envelope, the blower door does not reveal this situation very well. Nonetheless auditors should be on the lookout for such things. Sometimes outlets on interior walls are leaky when the blower door is running, and on cold days, sensing temperatures with the aid of a remotely-reading infrared thermometer can show that thermo-siphoning is taking place (Figures 11 and 12). The solution is to thoroughly air seal at the tops of interior walls and insulate at the level of the attic.

Figure 11. This spot radiometer takes temperatures at a distance. A laser that is bore sited with the center of the field of view of the instrument may be turned on to indicate precisely where surface temperatures are sampled.

Figure 12. A cold spot near the interface of a wall and a cathedral ceiling containing 10 inch batts of fiberglass indicates an area of air infiltration. Picture taken when outside temp was 10F and inside temp 65F; the area surveyed is at 23.5F.

Incidentally, thermo-siphoning also occurs in foundation walls made of concrete blocks, where the top rows of block are exposed to outside air. Although the bottom rows of block may be six or eight feet below grade, if the blocks are left hollow, the temperature of the bottom blocks will approach that of the top blocks via the mechanism of thermo-siphoning. The result is a basement that is cold in the winter via convective and radiative cooling from the inside surfaces of the concrete block. Insulating on the outside of the blocks with rigid foam rated for a moist environment or filling their voids with poured insulation or even sand will avert the thermo-siphoning problem.

6.4 Estimating energy consequences due to convection

Although blower doors do distort patterns of convective losses, it is possible to achieve a rough estimate of that portion of annual heating energy use in a dwelling associated with convection. Input information needed is the flow in cubic feet per minute at 50 pascals (CFM_{50}), local heating degree days, cost for heating fuel, and an estimate of the system efficiency of the furnace or boiler. An important assumption in the process is the conversion of CFM_{50} with a blower door to estimates of natural air exchange rates. Conventional wisdom holds that for "average" homes, natural air exchange rates are roughly CFM_{50} divided by 20 (plus or minus factors like how well shielded a home is and its height). For a somewhat well shielded home or apartment, we assume that natural air exchange rates are given by CFM_{50} divided by 25.

So annual convective losses = 0.018 x CFM50/25 x 60 x HDD x 24 Btu/heating season.

where 0.018 may be thought of as the heat transfer coefficient of air, CFM_{50} is the blower door measured flow in cubic feet per minute when the structure is depressurized to 50 pascals, 25 is the aforementioned factor to convert to natural air exchange rates, 60 converts cubic feet per minute to cubic feet per hour, HDD is the annual heating degree days in the area (which we take for 5466 in Boulder and 6023 in Denver) and 24 converts to heating degree hours. The result is expressed in Btu per heating season. Dividing by 100,000 yields the same data in therms of gas and dividing by 3412 yield kWh of electricity. Dividing this result by the assumed system efficiency of the heating system yields therm or kWh input to the heating season due to convective losses. Multiplying by the price per therm or kWh yields annual costs.

Cooling degree hours

Boulder = 7684

Denver = 5908

Estimates of convective losses associated with the cooling are calculated in similar ways, only using cooling degree hours (7,684 for Boulder, 5,908 for Denver), omitting the 24 factor for converting days to hours, and substituting an estimate of the coefficient of performance of the cooling season for furnace efficiency.

Natural Air Changes per Hour

ACH_{NAT} = (CFM_{50} x 60 minutes/hour) / ($20_{or\ N}$ x House Volume feet^3)

Finally, it is sometimes useful to express the air exchange rates as air changes per hour. This entails measuring the volume of air in the conditioned space of the building. Cubic feet per hour of air flow divided by the volume yields air changes per hour. Numbers above 0.5 natural air change per hour indicate substantial leakage; those below 0.2 air changes per hour suggest the need for ventilation.

A spread sheet for performing these calculations accompanies this document [tk click]. To take just one example, an electric resistance heated apartment on Goss Street in Boulder whose blower door measured CFM_{50} was 1900, the portion of the annual heating associated with convective losses alone are estimated to be 3944 kWh or $394. Curing obvious leaks shown by the blower door would almost certainly cut this by more than half.

7 Assessing duct losses

When the blower door is depressurizing the home, special attention should be paid to both supply and return ducts. With the air handler off and the blower door depressurizing the dwelling to 50 pascals, any air movement felt at the registers will by necessity be coming from the outside. If leakage is detected, a “subtraction” test should be done to estimate the magnitude of the duct leakage problem.

The blower door fan is turned off and all of the duct openings are sealed at the registers, both supply and return. A sticky-back plastic with perforations for tearing is available from vendors like The Energy Conservatory; this makes short work of the job. Of course, duct tape can also be used, with a combination of duct tape and garbage bags on large returns. After all registers are carefully sealed, the blower door test is repeated, measuring flow at 50 pascals. The flow at 50 is lower than with the ducts open by an amount reflective of the leakage through duct openings to outside of the envelope.

If duct losses are significant, it is useful to try to pinpoint where the major leakage areas exist. For this, the blower door is again run up to 50 pascals and the pressure between the inside of the dwelling and each individual register is measured with the particular register being measured sealed. Begin this test by removing all of the material sealing the supply registers and all but the largest return. Then insert a pressure probe from a manometer into a small hole in the material sealing the large duct and take a reading. Remove the plastic from this duct and move on to the next, sealing and measuring as you go.

A "pressure pan" is useful for quickly measuring the pressure at a register, as shown in Figures 13 and 14. The pressure pan can be fabricated of wood or other material. The edges have fat weather striping to air seal around the outsides of registers. A single hole is drilled into the pressure pan and is equipped with a fitting to connect to the plastic tubing to the manometer. The illustrations show pressure pans equipped with a swivel fitting that began life as a sanding disk of the kind used to finish dry wall.

Figure 13. Duct pan over large return indicates substantial leakage, 34 pascals

Figure 14. Smaller duct pan for supply ducts can also be used for taking other pressure measurements, in this case a drain in the basement floor suspected of a leaky trap.

In practice, registers are numbered starting with the registers nearest the furnace first and pressure pan tests taken with the blower door at 50 pascals and recorded. Higher readings are associated with being closer to leakage areas. Readings of several pascals are not worth bothering with, but sometimes double digit readings are found, or, in extreme cases, into the 30's or so. Repeating the tests after ducts are sealed (using mastic and fiberglass mesh, NOT duct tape!) is useful in assessing success (assurance.)

More detail on duct pans themselves and testing procedures is available on the web site of the Energy Conservatory, www.energyconservatory.com, which manufactures an excellent pressure pan. Click on technical support, then manuals. The "Pressure Pan Users Manual" is a pdf file.

7.1 Estimating energy losses of duct leakage

Estimating energy losses associated with *convective* duct leakage requires detailed simulation of a number of cases. Key elements in the simulation are the percentage of supply leakage outside and inside of the envelope and percentage of return leakage outside of the envelope. Other variables are heating and cooling degree days and the cost of electricity and gas. Table 1 shows the results of a simulation using Energy 10 software on a 1500 square foot structure in Denver. The table is useful for understanding the importance of air sealing ducts and the savings achievable by ensuring that losses to outside of the envelope are as small as possible.

Table Results of simulation of convective duct leakage under three scenarios of tightness in the Denver weather region (Kinney 2005)

Supply leakage outside of envelope (%)	**Supply leakage inside of envelope (%)**	**Return leakage outside of envelope (%)**	**Cooling season duct loss (kWh/yr)**	**Duct-leakage-related fan energy (kWh/yr)**	**Heating-season duct loss (therms/yr)**	**Duct-related cost for cooling and fan ($/yr)**	**Duct-related cost for heating ($/yr)**	**Duct-related annual cost heating and cooling ($/yr)**
20	10	20	479	697	573	$76	$527	$604
10	5	20	204	272	222	$31	$204	$235
2	2	2	40	49	37	$8	$34	$42

Insulation on ducts that are outside of the conditioned envelope is also important. Sometimes ducts are found in unconditioned crawl spaces or attics with little or no insulation. Table 2 shows the case of the same generic structure in the Denver weather region with ducts of various R values in the attic. Again, the principal value of the information is to illustrate the substantial savings achievable by enhanced insulation of ducts. Insulated ducting is available at R-4 and R-8 as are systems for adding duct insulation such as Ultimate R.

Table 3. Results of simulation of conductive duct losses in attics having 200 square feet of supply duct and 100 square feet of return ducts under three scenarios of insulating value in the Denver weather region (Kinney 2005)

Duct R value	Cooling season duct loss @5 cop (kWh/yr)	Heating season total duct loss @ 75% HVAC system efficiency (therms/yr)	Total annual costs due to conductive duct losses ($/yr)
4	68	137	$131
8	34	68	$66
30	9	18	$17

8 Pressure testing

As discussed above, measuring pressure differences under different circumstances of blower door operation can provide the energy auditor with a number of insights useful in pinpointing leaks in an apartment or its duct system. However, it is also useful to measure pressure differences when furnace fans and/or other appliance fans are operated, both with a view to energy efficiency and especially with a view to ensuring health and safety of the structure, especially after the dwelling is air sealed.

To illustrate the importance of these procedures, consider the following Thanksgiving story. Imagine a two-story apartment with well-designed ducts and fairly tight duct work within the insulated envelope. A single large return is located in the family room on the first floor, which is open to the rest of the first floor and the main stairway to the second. The apartment has recently undergone an energy saving retrofit that included both air sealing and insulation. This has resulted in better comfort than the family has experienced before as well as lower bills for space conditioning. The contractor checked for duct leakage, found it minimal, and decided not to include any duct-related work in the retrofit.

There are a dozen people at the dinner table on Thanksgiving Day. Family and friends enjoy a sumptuous meal, adequate drink, and animated conversations around the fireplace, which, although not used for most of the winter, contributes additional cheer for the festive day. When leftovers are put away and the weary family trundles off to bed, the fire is still burning, so the damper cannot be closed. Bedroom doors are all closed and deep sleep ensues.

As the flames in the fireplace give way to smoldering embers, both the home and the chimney cool down. In the wee hours, the thermostat calls for heat. When the 1200 cfm air handler in the furnace comes on, two pressure changes result. The main part of the home experiences strong negative pressures as centrally-located return air ducts draw air through the furnace heat exchanger. The bedrooms are strongly positively pressurized, both because good air sealing prevents the warm supply air from pushing out through openings AND because there is no "pressure relief" (air flow) from the bedrooms to the rest of the home when doors are closed. The negative pressure in the main part of the dwelling pulls air down the cooled chimney where it passes over the smoldering embers, which are now producing a good deal of carbon monoxide. The CO-laden air is swept through the return air system and heat exchanger of the furnace and directed through supply ducts into bedrooms, where it enters the lungs of the sleeping revelers. When they awake the next morning (indeed, *if* they awake the next morning), their headaches are not merely the result of the revelry the evening before, but also the result of CO exposure.

Meanwhile the failure to pressure relieve the bedrooms contributes to other problems in the dwelling. Depressurizing the main portions of the home contributes infiltration of outside air as the HVAC system attempts to draw in air through central return ducts. The pressurized bedrooms have exfiltration problems which are potentially more serious. Moisture-bearing warm air will tend to be forced into the structure of the walls, where moisture may be released as the air is cooled below dew point, a circumstance that can cause major structural damage. Finally, the pressure differential will lower the flow of conditioned air through the ducts supplying bedrooms with closed doors. Accordingly, these rooms may be uncomfortably cool in the winter and hot in the summer. Adjusting the thermostat in the main part of the house to help alleviate the problem will result in overheating the main portion of the home in winter (and overcooling it in summer), with consequent energy waste.

There are a number of ways to prevent such unhealthy and potentially calamitous circumstances, only a few of which are genuinely elegant. It is always possible to leave homes (or ducts) leaky, to open bedroom windows, or to leave bedroom doors open. The first two options waste energy, and the third is inconsistent with privacy. Installing air-tight doors on the front of the chimney is a good idea and may resolve the CO problem, but not the pressure differential issue described above.

Solutions for the pressure difference problem include 1) designing each space to have a dedicated return air duct, "jump ducts" through attics between closed rooms and open hallways with access to the return air system, 2) installing transfer grilles which allow the closed rooms to "breathe", or 3) undercutting the bedroom doors.

In all events, the very first action is for the auditor to run the air handler of the furnace with all doors open, then systematically check the pressure between a hallway that is connected to the main return and each living space that becomes isolated by closing a door. The auditor merely inserts the probe of the manometer under a closed door and reads the pressure of the closed space with respect to the hallway, which will usually be positive unless the space has greater return duct area than supply. Pressures of less than 2.5 pascals are sufficiently small to be ignored, whereas larger pressures should be treated by some measure (or combination) that achieves pressure relief.

> Pressure Relieve Doors when a closed room has a positive pressure of greater than 2.5 pascals with the HVAC system running

A second class of pressure testing has to do with ensuring that no combination of appliance or fan operation coupled with door openings can possible cause enough negative pressure in the area of combustion appliance that backdrafting of products of combustion can occur. A "combustion appliance zone"(CAZ) is defined as an area with one or more combustion appliances such as a natural gas (or propane) hot water heater or furnace. Measure the draft of each combustion appliance from first firing until well after the air handler comes on (in the case of a furnace). It should be negative (indicating that products of combustion go up the chimney) under all circumstances. It is important to create worse-case circumstances during this test by opening and closing interior doors and turning on all exhaust fans (including the dryer). Under no circumstances should the pressure of the CAZ to the stack of a hot water heater or furnace go positive. If the draft becomes weaker in a furnace when the air handler comes on, this is an indication that leaks in the HVAC return air system outstrip leaks in the supply air system. *Always* repair the return air ducts first to avoid backdrafting..

9 Insulation

Insulation retards the flow of conductive heat transfer by functioning as a thermal resistor. As with electrical resistors which retard electrical current flow, the higher the value of the resistor, the greater the reduction of flow. The insulating value of a material is expressed as its R-value (resistance to conductive heat transfer, which in the US has units of hour-ft^{2o}F/Btu). The inverse of thermal resistance is thermal conductance (U value), so 1/R = U in units of Btu/hour-ft^{2o}F. The U value of a material is referred to as its heat transfer coefficient. If one knows the U value of a wall section, the hourly conductive losses (Q) across the wall section are the product of the U value of the wall section, the area of the section in square feet (A), and temperature difference across the section in degrees Fahrenheit (**ΔT).**

$$\mathbf{Q = U \times A \times \Delta T}$$

Where Q = the flow rate of energy in Btu/hour, A = the area of the opening in square feet and ΔT = the difference between inside and outside temperature.

Heat Transfer Resistance (R value) of an Exterior Wall is typically made up of the combined R values of the following parts of the wall:
Outside surface of still air along the external finish;
The siding or other external finish;
Insulation directly under the external finish;
External wall sheeting;
Insulation between studs, posts, or supporting units;
Interior wall sheeting and finish; and
Inside surface of still air.

For example, consider a wall section consisting of an outside surface of air under average wind conditions (R = 0.17), lapped siding (R = 0.81), an inch of rigid foam insulation (R = 4), 3.5 inches of fiberglass batts (R = 13.0) between 2 x 4 pine studs on 16 inch centers (R = 4.38), half inch gypsum wall board (R = 0.45) and an inside surface of still air (R = 0.68). Assuming that installation of these components is ideal, the composite R-value of the wall is 14.82. Accordingly, the U value of the wall is 1/14.82 = 0.067 Btu/hour-ft^2 Thus on an hour when the indoor air temp is 70 ºF and the outdoor air temperature is 20 ºF, the heat transfer across 1000 square feet of this wall surface will be:

Q = 0.067 x 1000 x (70 – 20) = 3350 Btu/hr

To estimate wintertime losses across the same surface, substitute heating degree days times 24 (hours per day), so the formula for annual conductive heat loss becomes:

Q = U x A x HDD x 24 Hrs/Day = Btu/heating season

In the present case for Boulder, Colorado

Q = 0.067 x 1000 x 5466 x 24 = 8,789,328 Btu/year or 87.9 therms/year or 8.79 MMBtu/yr.

It is useful for the energy auditor to have a good intuitive sense of the R values of various materials and also get a feeling for what happens when there are voids in insulation, due to its absence (mistakes in installation, settling over time) or deterioration (due to moisture build up, for example). Table 4 gives R values of commonly-found materials in construction for thicknesses listed.

Table 4. R values of typical building and insulating materials (from ASHRAE 2005)

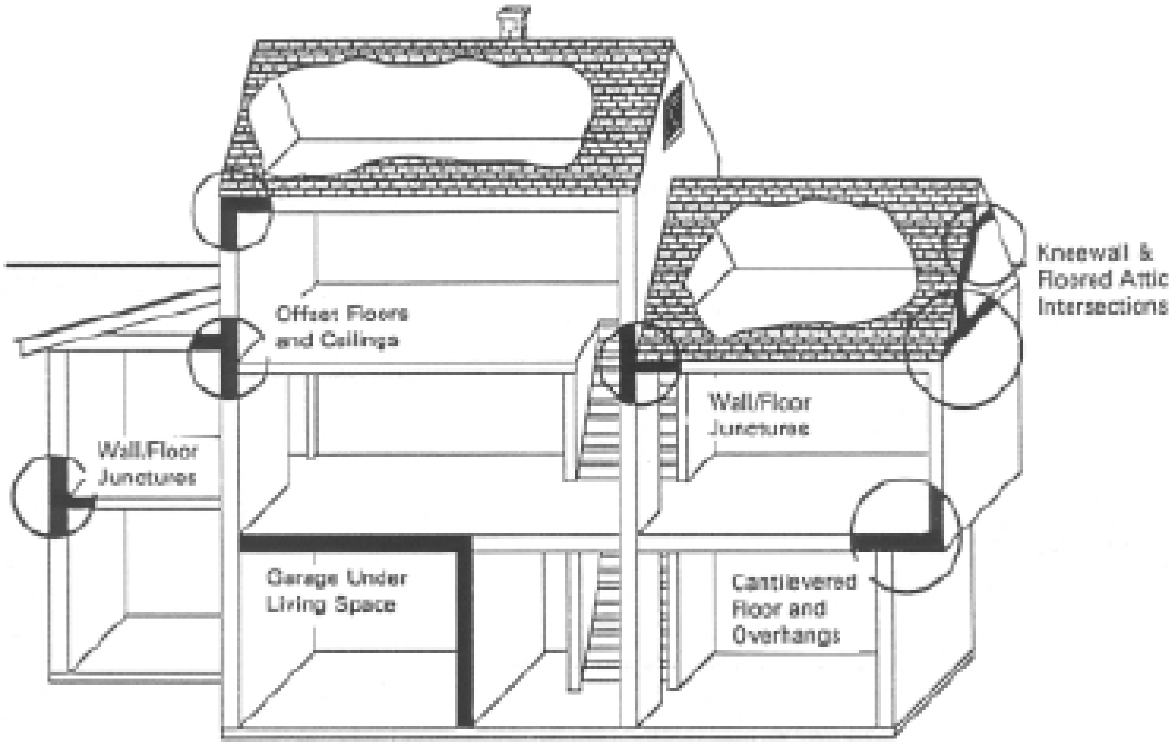
Material	Thickness (in)	R for thickness
Brick	3.5	0.1
Concrete block	8	1.0
Gypsum board	0.5	0.45
Gypsum board	0.625	0.56
Plywood	0.5	0.62
Plywood	0.75	0.93
Particle board	0.625	0.82
Carpet + fibrous pad		08
Carpet + rubber pad		1.23
Tile (linoleum, vinyl, ceramic)		0.05

Fiberglass	3.5	11
Fiberglass	6	19
Cellulose	3.5	12
Expanded polystyrene	2	10
Urethane	2	12
Polyisocyanurate	2	12
Vermiculite/expanded Perlite	2	5

It is clear that masonry materials are poorer thermal resistors than conductors, not so good for preventing heat loss in winter. The R value of different insulating materials varies by a factor of almost 5 from poured vermiculite to high R sheathing products. Furthermore, research at the Oak Ridge National Laboratory has shown that the effective R value of fiberglass diminishes as temperatures lower, whereas that of cellulose increases slightly as the temperature gradient across it increases.

It is also important to understand that many insulating materials do little to impede the flow of air under most common circumstances. For example, fiberglass blown at low density into attics (and to a lesser extent, batts placed between joists) will allow air from any bypasses to flow through it, thereby lowering the effective R value of the insulation. On the other hand, cellulose blown tightly (at high density) into wall and ceiling cavities not only provides good insulation but also impedes convective losses. Frequently, blower-door-measured air leakage between before and after blowing cellulose at high density into walls is lowered by a factor to two or even more by that measure alone. Choosing high-density blown cellulose is a good idea in most cases.

While inspecting a home, a combination of blower door and infrared scanning detective work can reveal insulation voids, some of which can occur in unobvious places (Figure 15). Note that the use of infrared scanning to find insulations problems will work best when there is a large difference in temperature between the inside and outside of the building. It is of little use in auditing when the inside of the building is not being heated or cooled.



Source: Tom Wilson, Residential Energy Services
Figure 15. Areas in construction frequently found to be uninsulated. These areas can also be sources of convective losses.

Insulation voids cause cold spots in winter which not only mean energy losses over the area, but also can translate into moisture problems. Warm air in a home cooled by cold spots can reach the point of saturation, thereby depositing moisture that can become a happy home for mold and mildew. Areas like bathrooms and kitchens where the local humidity may already be high are particularly vulnerable to this problem, so scanning for insulation voids in these areas is especially important.

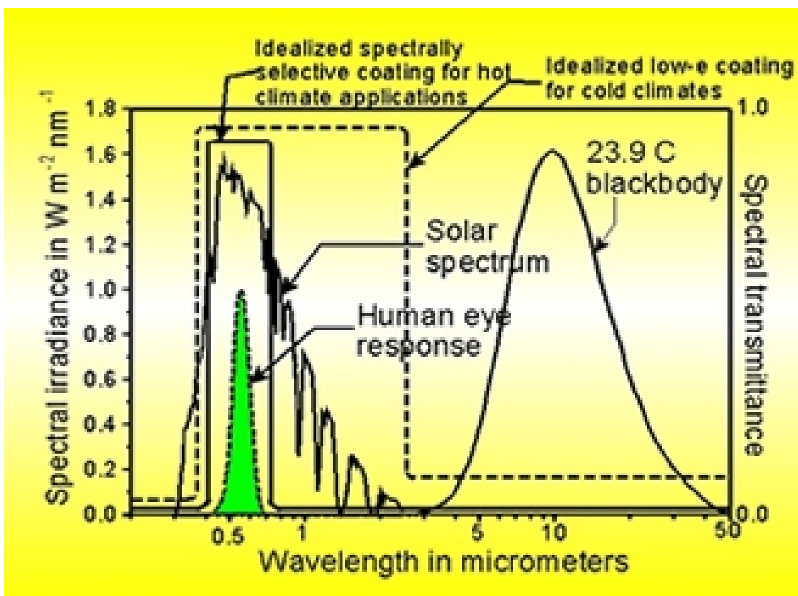
Scanning at the tops of walls where insulation may have been poorly installed or where it may have sunk over the years sometimes reveals voids that can be taken care of with tactical methods such as insulating foam. If the problem runs deeper, blowing cellulose to high density may be the best choice in a retrofit job. The result can save energy by limiting not only conductive losses, but also convective ones, since air movement will be impeded as well. This in turn can extend the life of a structure by diminishing the amount of moisture that migrates into walls and ceilings of a structure.

10 Windows

Windows are wonderful devices—they enable us to see outside of our homes, provide natural light, and may be opened to provide ventilation. But windows—particularly inefficient ones—are effectively holes in the insulated envelope through which a great deal of energy can flow. This tends to make energy meters run faster, ultimately resulting in higher utility bills. If a well-insulated wall (R = 25) has 15% of its area glazed with conventional insulating, double-glazed glass windows (R = 2), conductive losses through the windows are 2.2 times the conductive losses through the remainder of the wall. If the windows are not protected from direct beam sunlight, summertime heat gain through windows can be many times greater. In climates with substantial cooling energy needs, even fairly energy-efficient windows can account for 25% of total energy use for space conditioning—40% or more if clear glazing is un-shaded (Kinney 2004).

10.1 Heat radiation

Windows transfer energy by radiation, conduction, and convection. Under many conditions, radiation predominates. Our eyes see only a narrow range of wavelengths, slightly less than half of the solar spectrum. Figure 16 depicts the irradiance from the sun as a function of wavelength after it has been filtered by passing through the atmosphere. Note that the peak of our eye's sensitivity curve (around 0.68 micrometers which we call yellow) corresponds closely with the peak of the sun's output.



Source: Ross McCluney, Florida Solar Energy Center

Figure 16. Irradiance of the sun versus wavelength

Over the last several decades, manufacturers have developed the means to produce windows that selectively filter portions of the spectrum. The technique involves depositing very thin layers of metal on a surface of glass or a plastic substrate. First generation systems resulted in "low-E" coatings or films that are highly reflective of long wavelength radiation associated with room temperatures. Windows with conventional low-E coatings thus let through most of the sun's radiation, but reflect radiation from room temperature sources (75ºF is illustrated in the figure, with dashed lines illustrating the filtering action of low-E coatings.) The result is good performance of the window system in the wintertime since it lets in the whole spectrum of solar radiation yet keeps radiation from objects around room temperatures from escaping.

Newer "second generation" window technology can be much more carefully tuned to filter just the wavelengths desired. For example, it is possible to filter only the infrared and ultraviolet portions of the spectrum while allowing most of the visible portions to be transmitted. This "spectrally selective" property is illustrated by the solid line in Figure 16. The resulting window performance is much better adapted to the Denver/Boulder area, where cooling concerns are important. This style of window keeps out a large portion of the radiation that would result in heat that the air conditioner would have to remove, while allowing unobstructed viewing and substantial daylighting of the interior.

These considerations give rise to two useful terms:

- **Solar heat gain coefficient** (SHGC) is the fraction of solar heat transmitted through a window system (plus energy absorbed by the glazing itself that ends up supplying heat to the inside) with respect to the amount of solar heat that would flow through an unimpeded opening of the same size. It is a dimensionless number that can range between 0 and 1. SHGC's of clear single and double-glazed window systems run from 0.7 to 0.9, whereas windows with spectrally- selective glazings typically run from 0.2 to 0.5.

- **Visual transmittance** (V_t) is the fraction of visible light transmitted through a window system with respect to the amount of visible light that would flow through an unimpeded opening of the same size. This is an indication of what one can see through the window. It is also a dimensionless number that can range between 0 and 1. V_ts of clear single and double-glazed glass run from 0.8 to 0.9, whereas heavily-tinted glass can have a V_t of 0.1 or even lower. Double-glazed spectrally-selective glass typically runs from 0.4 to 0.7 V_t.

A typical spectrally-selective window system suitable for east and west-facing windows in the Denver/Boulder area might have a V_t of 0.55 and a SHGC of 0.35. This window would perform over twice as well at keeping out solar heat than a conventional low-E window system, and is sometimes referred to as "double low-E," "southern low-E," or "low solar gain low-E" window systems. Here, we adopt the latter convention. **A check of the SHGC is the best way of being sure that a window is indeed a low solar gain, low-E unit**. This has become easy to do owing to the window and door labeling process of the National Fenestration Rating Council (NFRC; see NFRC.org). Sticky-backed labels are prominently displayed on doors and windows and include five figures of merit related to energy performance. On the other hand, if southern exposures can be shaded in the summer, it is much better to choose windows with high SHGC to take better advantage of passive solar warmth in the heating season.

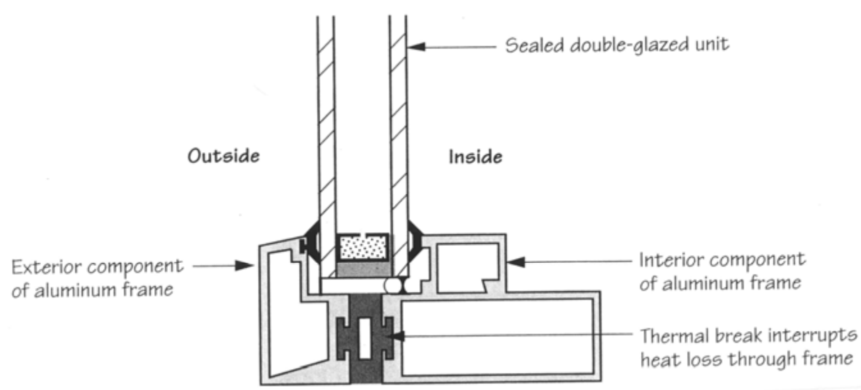
10.2 Conduction and convection

Windows also lose energy by conduction and convection. As discussed above, insulation performance in walls and ceilings, for example, is usually given as an R-value, which is a measure of the resistance to heat flow that occurs because of the temperature difference across the two sides of a surface. During cold weather, windows with high insulation values are significantly warmer on the inside surface than are windows with low insulation values. This provides several benefits: moisture from condensation is reduced or eliminated, occupant comfort is increased, thermostat set points can be lowered, and the home's heating system may be downsized. During the summer, well-insulated windows (particularly those that also have low SHGCs) are more comfortable, thereby allowing for higher thermostat set points and downsizing of the cooling system.

The conductivity of window systems, the U-factor, is the measure of choice in rating window systems. The lower the U-factor, the better. The U-factor is the reciprocal of R-value and is the rate of heat loss through a window *system* (which counts its frame) measured in Btu per hour per square foot per degree Fahrenheit (Btu/h-ft^2°F). U-value has the same units, but refers to the conductivity through the center of glass only. Unlike the ratings for insulation products, window U-factors and U-values include the effects of indoor and outdoor surface air films.

Glass itself is a fairly good conductor (a bad insulator), so its U-factor is quite high (and R-value low). When part of a single-glazed window system, most of the R-value of the system results from the still air layer immediately next to the pane on the inside and the not-so-still air space on the outside. Adding more layers of glazing (or suspended film) adds more still air spaces. Replacing the air between glazings with an inert gas with a low heat transfer coefficient lowers the U-factor of the space even more.

In addition considering the type of glazing, the energy auditor should evaluate the material that makes up the frame and its condition. Window frames are typically built of steel, aluminum, vinyl, wood, or a combination of several materials. Steel is mainly used in commercial and institutional buildings, although some older multifamily buildings also have windows with steel frames. A number of manufacturers use wood that is "clad" with aluminum or vinyl at critical points to ensure smooth sliding and extend the life of the window system. Aluminum is light, lasts a long time, can be painted, and can be extruded inexpensively to form complex profiles. Accordingly, low-cost aluminum window frames are in wide use in Colorado. However, aluminum is an excellent thermal conductor, so windows with aluminum frames which are not "thermally broken" result in both energy waste and discomfort. Happily, there are several techniques for achieving aluminum frames with a strategically-placed thermal break, thereby lowering the U-values of frame members by a factor of more than three over non-thermally broken frames (Figure 17).



Source: Carmody et al, 1996

Figure 17. Thermally-Broken Aluminum Window Frame. The complex aluminum extrusions shown include clamp-like elements that accommodate a low-conductivity hard vinyl shape. This

shape firmly holds the inside extrusion to the outside extrusion without sacrificing mechanical integrity.

10.3 Modeling choices

There are a number of manufacturers that produce middle-of-the-line wood, vinyl-clad wood, and vinyl windows aimed at the production home and replacement markets. Although their product literature does not emphasize energy features, the differences in cost between new windows unlikely to perform well in Colorado and those which will perform reasonably well is quite small. For example, Pella produces an attractive 15 square foot double-glazed wood window with a U-factor of 0.54 and a SHCG of 0.61 which Lowe's sells for about $200. The same model with an argon fill and spectrally-selective coating has a U-factor of 0.36 and a SHGC of 0.33 costs about $230, just over $15 per square foot. The extra $1.40 per square foot will have reasonable payback periods (3.3 years in Denver, where the less expensive and higher SHGC window is used on the south for better passive solar performance in the winter) and produce substantially better comfort.

These considerations are useful in considering replacing existing windows—or adding storm windows. Single-glazed windows with aluminum frames are worse case in terms of energy, but paybacks on energy savings grounds alone are nonetheless fairly long to replace them unless they are also quite leaky, something a blower door test will illustrate. Nonetheless such bad windows are a substantial source of discomfort, so replacing them can make an apartment more attractive to potential tenants—or a home more attractive to potential buyers. In general, the best choices for new windows on the north and south are those which have low U values (0.35 or lower) and high SHGCs (above 0.5), providing that overhangs on the south can keep the south-facing windows shaded during the height of the summer. Usually two feet of overhang is adequate for this purpose. For east and west-facing windows, low U windows with lower SHGCs are best, on the order of 0.4 or even lower. Of course, moveable devices that shade from the outside are best, like Synertech's exterior insulating shutters which optimize window performance in all seasons.

RESFEN (for "residential fenestration") is a user-friendly software available for free from the Lawrence Berkeley National Laboratory (http://windows.lbl.gov/software/resfen/resfen.html) It computes the energy use and cost of various windows specified by users or those from an extensive library of windows available on the market. The output is in the form of energy and dollars for the climate area and energy costs of choice.

Table 5 contains a description of the energy properties of five window types modeled with RESFEN software in the Denver region.

Table 5. Five window systems modeled

Case	Description	U factor	Solar Heat Gain Coefficient
1	Single-glazed clear	0.93	0.78
2	Double-glazed clear	0.55	0.59
3	Double-glazed Low E	0.36	0.53
4	Double-glazed Low EE	0.34	0.34
5	Triple glazed Super Alpen	0.12	0.29

We assumed that windows of these descriptions were on a 2,000 square foot dwelling in the Denver weather region with 75 square feet of glazing on each façade. The annual energy used (and its associated cost) having to do with the window alone is shown in Table 6. Figure 18 shows cost comparisons.

Table 6. Modeled results of energy use and cost of five window systems in the Denver area

	North		East		South		West		Totals			
Case	Cool kWh	Heat MBtu	Cool kWh	Heat MBtu	Cool kWh	Heat MBtu	Cool kWh	Heat MBtu	Cool kWh	Heat MBtu	Cool $	Heat $
1	249	9.19	671	1.15	616	-4.62	589	4.44	1509	10.16	$151	$112
2	195	5.72	500	-0.75	452	-5.39	437	1.81	1132	1.39	$113	$15
3	180	3.41	450	-45	405	-6.73	393	-0.19	1023	-5.96	$102	-$66
4	107	4.04	263	-0.16	233	-3.02	234	1.41	604	5.77	$60	$63
5	97	0.76	226	-77	198	-5.29	202	-1.52	723	-8.82	$72	-$97

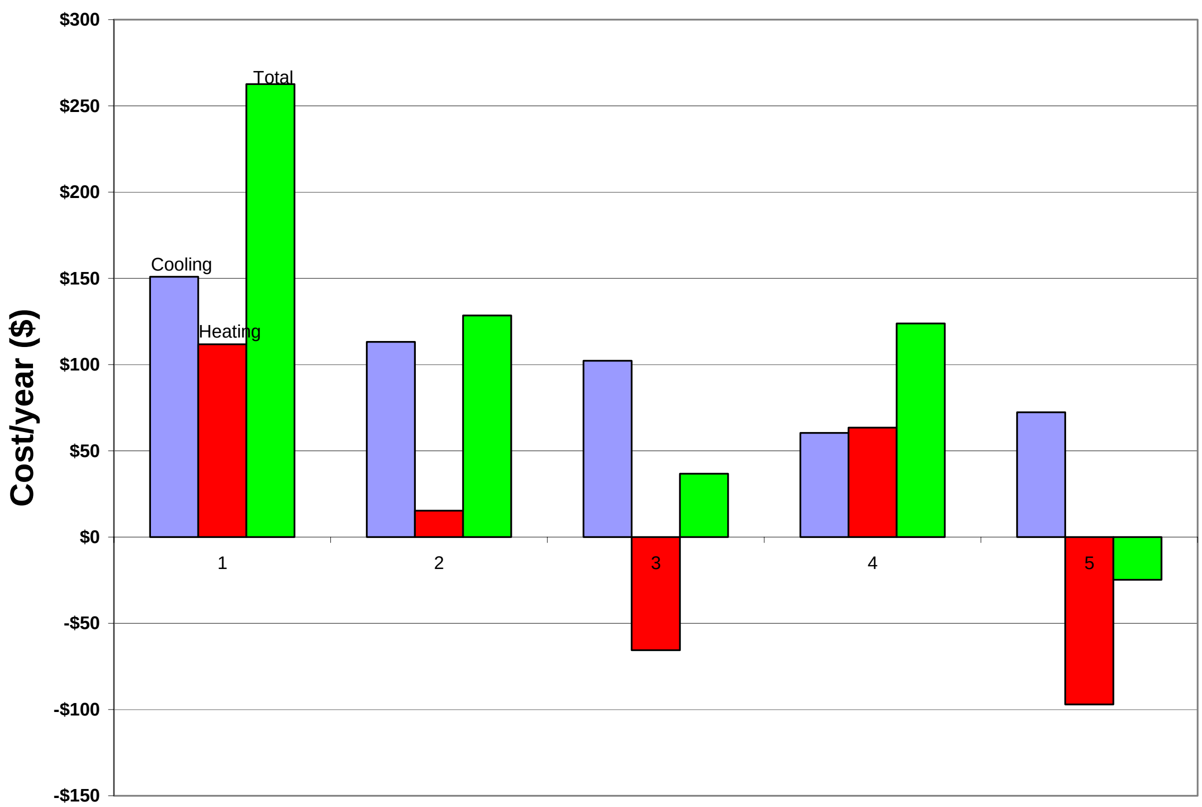


Figure 18. Annual cost comparisons of the five window systems, a total of 300 square feet of glazing distributed evenly on four facades.

Note that the single glazed case is by far and away the most wasteful of energy. Case 5, the triple glazed super Alpen unit, gives the best overall performance, but Case 3, the low E double glazed unit, probably yields the best cost effectiveness since it is substantially less expensive than the Alpen unit.

Concerning retrofitting, it is always useful to examine opportunities for tightening up the frames of wooden windows, installing strategic weather stripping, ensuring that sash locks work to pull the sashes together, and the like. Installing double glazing where single glazing was before is also feasible, but labor intensive. The process entails removing windows, stripping the frames, repairing them, routing frames to allow more space for double glazing, installing the glazing, installing appropriate putty, painting the units, and re-installing them. If one goes to this much trouble, it is usually worthwhile ordering low E glazing that has a krypton inert gas filling since it gives the lowest U value with the least space between panes of glass.

If new windows are installed, careful attention to air sealing and insulating the spaces old windows used for counterweights is critical, as is making certain the new windows are air and water sealed.

11 HVAC auditing procedures

Most conditioned spaces are heated by either forced air or hydronic systems fueled by fossil fuels. Both system types have their strong points and drawbacks—proper application minimizes weaker points while showing-off stronger ones. When auditing residential dwellings, whether stand-alone, single-family housing or multi-family apartments and condominiums, the procedures are generally similar. Of course, multi-family buildings with central heating systems have larger equipment, perhaps more equipment, and very likely more controls.

Testing for gas leaks was previously mentioned. From a safety standpoint, the importance of this testing can not be over stressed. The concern about gas leakage becomes even more important as the air leaks in the building are identified and sealed. Every audit and service call should include a gas leak check. This process takes just a few minutes and should not be skipped just because "there were no leaks last time…"

Hydronic distribution system auditing is parallel to duct testing: looking for leakage, proper insulation and the associated energy and financial costs. Care should be taken to ensure water distribution piping in hydronic systems is well insulated, especially when piping passes through unconditioned spaces. Uninsulated pipes within conditioned spaces lose heat in an uncontrolled manner. While the heat does enter the conditioned space and is therefore not completely wasted, it is possible to overheat one area while another remains too cool.

Damp insulation does very little good in reducing heat loss and may actually increase heat loss due to the evaporative cooling effect and since the insulation increases the surface area of the piping there is a larger area for this cooling to take effect. The cause of any wet insulation should be tracked down and repaired. It is most likely the result of a system leak:

- Perhaps from a frozen pipe. Yes, this is possible even in conditioned spaces.
- Damaged valve packing or loose gland nuts around valve stems

- Wear caused by pipes sliding in their hangers over many years of small movements that result from thermal expansion and contraction
- Pumps seals that wear over time
- Damaged or cracked gaskets in flanged connections.

Last, but definitely not the least important, before we look at the equipment, is carbon-monoxide (chemically, one carbon and one oxygen atom, CO). Not only is this gas deadly, it is odorless, colorless, and tasteless. CO can accumulate in any dwelling or facility where combustion appliances are operating. CO is the result of the incomplete combustion of carbon-based fuels. Ideally, the combustion (oxidation) of natural gas (typically over 90% methane (CH_4) and much smaller quantities of larger hydrocarbon molecules) in oxygen results in the formation of carbon-dioxide (CO_2) and water (H_2O). Since we use air (~20% oxygen, 79% nitrogen, 1% other gasses) instead of pure oxygen in the combustion process, we end up with oxides of nitrogen (NOx), and in fuels with sulfur (mostly oils and coals), we also get oxides of sulfur (SOx). Additionally, when the combustion process is not complete, when the surfaces are cool, and for a variety of other reasons, the carbon and oxygen reaction does not always proceed to CO_2, a harmless gas, but stops at CO, a poisonous gas. When the heating system is functioning properly any CO formed goes up the flue and out of the dwelling.

Carbon-monoxide problems can arise from several different causes. **Backdrafting** is the most common. This can occur under several different situations including:

- Improper installation of the flue. The flue may not extend the proper distance through the roof or not high enough above the surrounding roof ridgelines.
- Unusual winds can, even in properly-installed systems, occasionally cause backdrafts.
- Multiple appliances incorrectly connected to the same flue can also cause problems when one is operating and others are not.
- A gas-fired furnace is operating in a zone where return air leaks from the distribution are much greater than supply air leaks, thereby negatively pressurizing the zone. Ventilation fans and fans on dryers in the area can also contribute to negative pressures. These circumstances can backdraft a hot water heater in the zone or even the furnace itself.

Leaks in the flue, either at the connections of pipes and fittings or caused by condensation of the combustion gases corroding the vent pipe, can allow the products of combustion to enter the living space. The use of correct flue pipe materials and proper installation largely eliminate these issues but slight movements in the structure and very small amounts of condensation can, over time, loosen joints or corrode through the pipe, thereby requiring repairs.

In the event of a **cracked heat exchanger** in a furnace, CO can enter the dwelling. Air moved by the blower past the heat exchanger can create a low pressure area, pulling combustions gasses from the combustion side of the heat exchanger, through the crack (or hole!) to the other side and distributing them throughout the dwelling. This problem is much less of an issue in newer furnaces than in the past (and it was typically only a minor issue occurring at the end of the furnace's life. if ever) as a result of improved materials, forming processes, and welding technologies. Soot streaking the walls at supply registers may indicate this problem.

While carbon-monoxide problems are quite rare, when problems do occur the results can be very unfortunate—deadly. CO sensors are readily available, low cost, easy to install. and are required in many locations. These devices function similarly to smoke detectors—they seem to do nothing most of the time, until the battery starts loosing power and the unit "chirps" (usually in the middle of the night) indicating that battery replacement is needed. However, when the units do sense CO, they, like smoke detectors sniffing smoke, have a loud alarm. And knowing they are installed invites a better sleep at night.

11.1 Furnace and boiler "house keeping"

Furnaces and boilers should be inspected and cleaned annually. This involves a visual inspection of the unit, looking for leaks, damaged or frayed wiring, loose electrical connections, etc. The unit should be run and any unusual noises noted, their source identified, and corrective action taken. While new furnaces have blowers and motors that are typically direct drive and have sealed bearings, older units may require oiling of both the motor and blower bearings and should be accomplished per the manufacturer's specification. Inspection and replacement of cracked, frayed, and otherwise damaged belts during routine service and inspection can avoid the late night service call that results from a broken belt. With the service panels removed, the exposed area of the furnace or boiler should be vacuumed to remove any accumulated debris.

Forced air furnaces have integral air filter racks on the return air side. These filters are typically disposable and remove pet hair, dust, dirt, and other debris that enters the return air duct before it passes through to the heat exchanger and is delivered to the occupied space. Filters should be replaced according to manufacturer's specifications or every one to two months depending on usage. Providing a year's supply of filters (about 4 – 6) and showing the occupants how they are replaced and when to do so can be a cost-effective approach to getting filters replaced regularly.

As stated previously, "…showing the occupants…" really means to explain to the occupants what is happening, how it serves them, demonstrating and observing them doing it because *they* change the filter. With the newly-acquired confidence that they, indeed, can change the filters, and with a supply of filters that are on hand, the likelihood of the replacement actually happening is greatly increased.

11.2 Measuring furnace and boiler efficiency

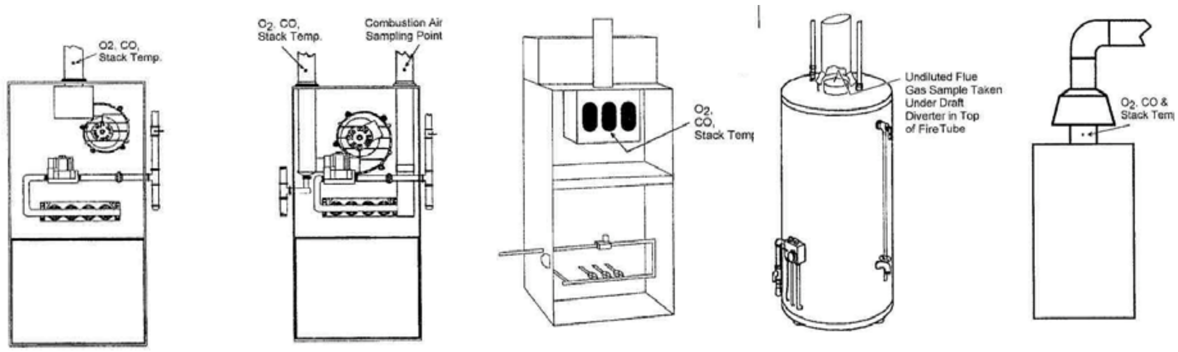
Prior to using any combustion gas analyzer, the tool should be allowed to warm to the surrounding temperature, within reason the warmer the better. Best results are obtained when the tool and hose have warmed as this reduces the likelihood of water from the combustion process condensing in the hose. Heated hoses are available for some analyzers if outdoor use is anticipated.

Steady-state furnace and boiler efficiency is straight forward to determine with modern hand-held combustion analyzers. The procedure for furnaces, boilers, water heaters, and other combustion appliances is similar with a few minor exceptions, described later. Figure 19 shows a Bacharach, Inc., Fyrite Tech. It costs about $600 and measures stack and ambient temperature, oxygen, and carbon-monoxide. With these measurements the unit calculates combustion efficiency, carbon-dioxide, and excess air. The unit is battery powered, and weighs about one pound, making it a very portable device.

Figure 19. Bacharach furnace tester measuring stack temperature and % steady state efficiency (left) and parts per million of CO and % oxygen in the stack gas (right)

When analyzing combustion gasses, the meter is started and allowed to go through a purge cycle. This takes about a minute and a timer counts down to the user know when the purge is complete. There are a number of fuels (natural gas, fuel oil, LPG, and kerosene) that can be tested with this unit and the correct type may be selected by scrolling through the options shown on the display.

The wand or probe, which contains a thermocouple, is connected to the handheld part of the unit by a hose. The probe must be inserted directly into the combustion gas stream of the operating appliance. Hold the probe as close to the center of the flue pipe as possible as this will provide the most accurate readings. Depending on the appliance there may be an opening available, such as under the draft diverter on a water heater. Otherwise a small hole can be drilled into the stack that will allow insertion of the probe (Figure 19). Once the probe is inserted, the thermocouple located at the end of the probe will begin to warm and the current temperature reading is displayed on the handheld part of the unit. When the temperature stabilizes (several minutes are typically required), the desired readings can be taken by scrolling through the available displays. When all desired data has been written down the probe can be removed from the stack. The probe is HOT. Use caution, do not touch, and avoid setting the probe on flammable materials or items that can be damaged by heat.



80% eff fan assisted vent	90% eff condensing furnace/boiler	Atmospheric burner furnace	Water Heater	Atmospheric boiler

Figure 20. Proper locations for the combustion gas analyzer probe to be inserted into the flue stack.

When an opening such as a draft diverter is available the probe must be inserted into the combustion gasses upstream of the diverter since air will enter and mix with the exhaust gas at the diverter. This increase the oxygen level being measured and also reduces the temperature of the gas, both of which adversely affect the accuracy of the readings.

When an appliance that heats water or the space within the dwelling's envelope with sealed combustion air is being analyzed, a temperature probe must be inserted into the pipe providing this air as its temperature is likely different from the ambient temperature surrounding the appliance—especially during the winter. Again, if no port is available, one must be drilled into this pipe. When testing is completed, both this hole and the one in the flue must be properly sealed with a metal tape with heat-tolerant adhesive. This is critical when a powered exhaust fan is part of the system as it can blow exhaust gasses through the hole and into the occupied space.

At the completion of the test, allow the unit to continue running until the oxygen reading reaches approximately 20.9%, the ambient O_2 level. Failure to do so can shift the calibration of the sensors leading to erroneous results in later tests.

11.3 Forced air systems

Natural-gas-fueled, forced-air furnaces are prevalent in the US with over 36% of the market. Hot water/steam boilers fueled by natural gas and electric warm air furnaces are roughly tied for a distant second place with about 9% each.

Steady-state efficiency

The US Environmental Protection Agency sets minimum efficiency standards for appliances, furnaces, air conditioners and similar equipment. These standards affect only equipment that is to be sold, not that which is already installed. Many older furnaces still in operation and functioning well have efficiencies between 70% and 75%. More recently, as of 1992, furnace efficiency must be greater than 78%. Modern, state-of-the-art equipment has efficiencies in the mid-90% range. However, these very high furnace efficiency numbers only tell part of the story. A 1992 ASHRAE study found that systems with a 95% efficient condensing furnace can have system efficiencies as low as 62% largely due to duct leakage, uninsulated ducts, and frequent unit cycling. The point being, prior to replacing an existing furnace with a higher efficiency unit, verify that the existing *system* is functioning properly, then purchase the most efficient furnace appropriate for the application. In a climate such as Colorado's, this will likely be a condensing furnace.

> Savings from replacing an existing furnace
>
> Where η = furnace efficiency:
>
> $1 - (\eta_{old} / \eta_{new})$ = percent of heating energy that can be saved by the new furnace.

When evaluating the benefits of replacing an existing furnace with a new, more efficient model, a quick estimate of the energy savings can be calculated by: Percent energy savings = $1 - (\eta_{old} / \eta_{new})$ where eta (η) is the Greek letter used to represent efficiency.

If the existing furnace is 65% efficient and the new units being considered are a standard 80% efficient model ($\eta_{standard}$) and a high 93% efficient model (η_{high}), the estimated savings are:

Percent energy savings $\eta_{high} = 1 - (65\% / 93\%) = 30\%$
Percent energy savings $\eta_{standard} = 1 - (65\% / 80\%) = 19\%$

So if the cost to heat a dwelling is currently $400 per year, the η_{high} furnace would save about $120 per year ($400 x 30%) while the $\eta_{standard}$ furnace would save about $76 per year ($400 x 19%). The economic benefit of the high efficiency furnace would be a savings of $44 per year.

The return on investment for replacement may be calculated by simply dividing the annual savings by the first cost.

To estimate the cost effectiveness of choosing a more efficient versus less efficient model, installation costs can left out of the analysis.

The average price for sixteen models of 92% to 93% efficient condensing furnaces and sixteen models of 80% efficient furnaces were obtained from various web sites. The average price for the high efficiency units is $1,305 while that of the standard efficiency units is $921. Therefore the incremental cost of the more efficient units is $384. With the estimated annual savings of $44 per year between the new options the simple payback on the higher cost, higher efficiency furnace is on the order of 8-9 years with an annual return on investment (ROI) of about 11.5%--at current fuel prices, a very conservative estimate for a product expected to last 25 years. Assuming 3% fuel escalation over the 25 year life of the furnace, the price of natural gas will double. The average price will be approximately 1.45 times the current rate. Using this number the ROI increases to over 16%.

Furnace controls

Modern furnace controls offer important energy savings compared to older units, which were generally either off or on, zero heat or 100% of the unit's capacity. Today's state-of-the-art controls communicate more with the thermostat (discussed later) to provide just enough heat energy to satisfy the load. In doing so, the controls neither allow the furnace to overheat the dwelling, nor let it cool unduly before providing another shot of heat. Instead, the furnace controls modulate the heat output either in multiple steps or continuously over its operating range.

Several benefits are achieved by this strategy. First, the output more nearly matches the load and therefore the dwelling stays at a more steady temperature. Second, since less heat is being delivered to the space most of the time, the blower can operate at a lower speed. The benefit of this is less power consumption and much quieter operation due to reduced air noise. Last, when warm air is delivered to a space at lower velocities there is typically less stratification, the warm air stays lower rather than shooting straight to the ceiling. While there is still some stratification it is reduced and comfort is higher with less energy use.

The benefits of operating at a lower level are achieved only if the duct system is tight and well insulated, and the entire system is balanced so no area is pressurized and none depressurized. If these conditions do not hold, then the instantaneous air exchange rate of the dwelling increases whenever the air handler comes on, sometimes quite dramatically (a factor of two or even three). In any case, it is important to seal the ducts and verify that all areas of the buildings are balanced, but when installing a system that has longer air handler run times, it is crucial.

Supply air temperature

Furnaces typically provide a "fixed" temperature increase to the air being heated, rather than heating it to a specific temperature. The design temperature increase depends on a number of factors including the total capacity, current specific heating output, and steady-state efficiency. In addition to the temperature rise designed by the manufacturer, the installation and system can also have a significant effect on the temperature rise. Ducts that are too small, closed registers, blocked return air grills, and any other restriction in air flow—*including dirty filters*—tend to increase the temperature rise. These blockages reduce the air velocity allowing it to spend more time in contact with the heat exchanger. The results are increased flue gas temperatures and a loss in furnace efficiency since the hot combustion gasses can not "give up" their heat energy as effectively.

Checking the temperature rise across a furnace is a straightforward process. The auditor allows the unit to come to steady-state operation, inserts a thermometer or thermocouple into the air stream in the supply and return ducts and reads the two temperatures. The temperature rise is the difference in these two temperatures. However, the real questions are what is the meaning of these temperatures and how this information is used. Many furnaces have an average temperature rise of between 52°F and 55ºF, with the lower end of this range corresponding with lower efficiency furnaces (80%) and the upper end with higher efficiency units (94%). This average came from furnaces with temperature rises ranging from 25ºF to 80ºF depending on the operating conditions, firing rate, blower speed, etc. Ideally, the manufacturers' specifications are available to fully commission new furnace installations.

At high-fire, the temperature rise is much tighter, ranging from 55ºF to 80ºF, still a large spread. If the temperature rise is outside this range during full load operation something is likely amiss and should be looked into, the problem(s) identified, and corrective action taken.

Combustion air and exhaust venting

Many new furnaces allow for two-pipe sealed combustion and venting or a single pipe for venting and using indoor air for combustion. Condensing furnaces can, and often do require PVC piping or an equivalent, non-corroding pipe since the condensate can be slightly acidic. *Always follow the manufacturer's recommendations for the exhaust venting.* This includes appropriate materials, vent total length, number of elbows and fittings, pipe diameter, grade in horizontal sections, and other specifics set forth in the installation instructions.

Open combustion systems spill cold air into the dwelling requiring additional heat to warm it. System efficiencies may be reduced several percentage points by the strict requirement for combustion air supply pipes in open combustion systems. Accordingly, when possible, sealed combustion systems are desirable for the efficiency increase in the system as a whole. Many code jurisdictions require very large combustion air supply pipes, often 2 – 8" diameter ducts delivering ambient temperature air to the furnace. Sealed combustion furnaces of 40,000 Btu/hr to 120,000 Btu/hr range typically require piping of only 1½" to 3" diameter.

Frequently the home's water heater is co-located with the furnace. If a sealed combustion furnace is used there may still be a code requirement for outside combustion air for the water heater unless it too is a sealed combustion unit. If open combustion air is used in the furnace and DHW heater, the colder air temperature in this space will also increase heat loss from the water heater tank and pipes. Under certain circumstances, freezing can occur.

11.4 Thermostats controlling space conditioning

Thermostats on walls that control space temperatures may be usefully divided into two classes, mechanical and electronic. Each in turn has two classes: those which typically operate with central systems work on 16 volts alternating currant (Vac) to 24 Vac and those which operate high voltage heaters directly that typically handle 240 Vac.

Mechanical thermostats simply close a single pole/single throw switch to actuate a solenoid valve that allows gas to flow to the burner of a furnace or boiler. They usually have a bimetallic coil that expands when heated and contracts when cooled. When the bimetallic coil is sufficiently cold to call for heat, a tube holding a small quantity of mercury tilts up enough to allow the mercury to short between a pair of wires in the bottom of the tube. If a pair of safety switches is also closed, the solenoid valve on the furnace opens, gas flows, and the burner ignites. (One safety switch closes when a sensor verifies that the pilot is lit and the other safety switch closes when the hot air plenum temperature is safely below its high limit set point, typically 190 F.) When the plenum temperature reaches 110F to 130F, depending on the fan control set point, the furnace fan comes on, pulling air from return ducts through a filter and the heat exchanger of the furnace and pushing the heated air through the supply ducts into the home. This warms spaces, including the space where the thermostat is located. When the temperature associated with the set point of the thermostat is sensed by its bimetallic coil, it tips the tube so that the mercury no longer shorts between the two wires. The solenoid valve closes, gas flow stops, and the furnace stops firing. The furnace fan continues harvesting energy from the hot heat exchanger until the temperature reaches the fan cutoff temperature, typically around 90F to 110F. This completes a heating cycle. In general, setting the fan switch so that it comes on at 110F and goes off at 90F achieves energy efficiency with no loss in comfort.

Most mechanical thermostats employ an "anticipator," a tiny electric resistance heater that supplies an equally tiny amount of heat in the vicinity of the bimetallic strip while the thermostat is calling for heat (Figure 21). If it is adjusted appropriately, it fools the thermostat into thinking that the air is at the set point a degree or so before the surrounding room temperature is quite that high. However, since there is warmth in the heat exchanger that will be harvested after the burner goes off, the net result is that the room temperature is more stable. The temperature swing over a typical furnace run will be a degree or two less than it would be the case without an anticipator. The result is adequate comfort and slightly lower average indoor air temperature, resulting in an annual savings of heating fuel of perhaps a percent or two.

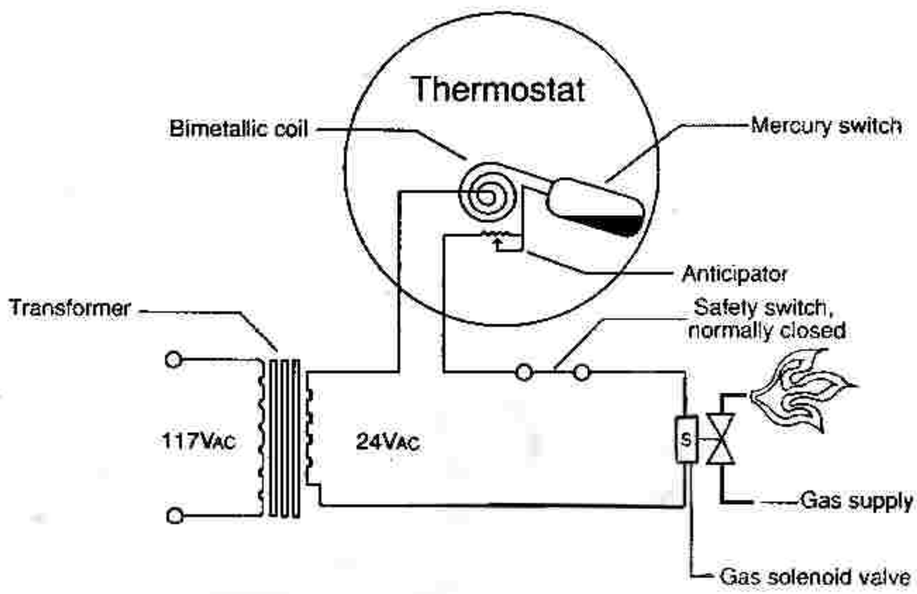


Figure 21. Diagram of thermostat and its connection to low voltage a/c and a solenoid valve

However, anticipators that are inaccurately set can cause problems. How much energy comes off the miniature electric resistance heater called the anticipator varies as the square of the current drawn by the solenoid valve that controls the flow of gas at the furnace, typically between 0.2 and 1.2 amperes. Accordingly, behind the cover of typical thermostats is a shorting strip calibrated from 0.2 to 1. If the anticipator is set too high for the actual current drawn, its action is quite modest. In this case, it allows the variation in room temperature from the beginning of the firing cycle until its end to be quite large, resulting in poor comfort and no energy savings. If the anticipator is set too low for the current drawn by the solenoid valve, it heats up quickly, turning off the furnace prematurely. Since the room temperature is still below the set point of the thermostat, it soon calls for heat again, resulting in yet another short burn. This results in "short cycling" or "jack rabbiting" which is both irritating to the dwelling's occupants and wasteful of energy since the time the furnace is allowed to function at full steady state efficiency is typically quite low.

Given this, it is useful to check the anticipator by measuring the current drawn by the solenoid valve and setting the shorting strip to the appropriate value. The procedure is not complicated, as shown in Figure 2

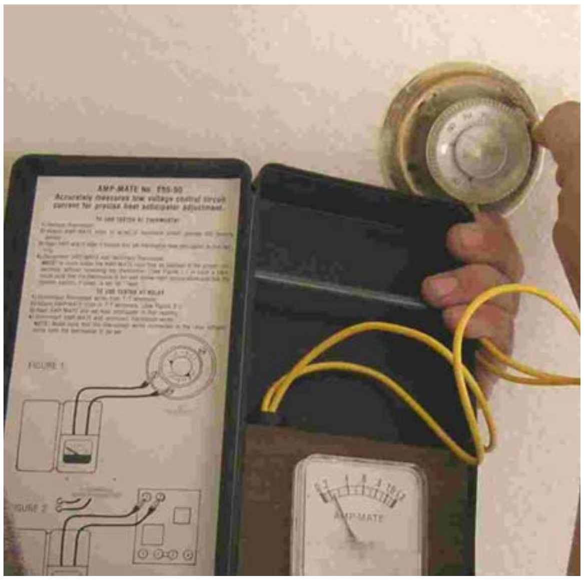


Figure 2 Measuring current drawn by a solenoid valve with an a/c ammeter. This one is called an "Amp-Mate Model E55-50" by Sid Harvey, but any a/c ammeter that reads up to 1.5 amps a/c will do.

Turn the thermostat down and locate the pair of screws that go to the furnace. It is easiest to use an a/c voltmeter to hunt until 16 to 25 Vac or so are found. Then use an a/c ammeter to go between those two terminals. This will fire the furnace temporarily, but also allow for sensing current. Note the draw in amperes. Withdraw the meter, set the anticipator to the reading measured with the ammeter, and replace the cover of the thermostat.

In some cases, the thermostat may control electronic circuitry in the furnace instead of the solenoid directly, so the current drawn will by too small to measure. If this occurs, the anticipator will not function no matter what its setting.

Electronic thermostats usually have some degree of anticipation built in to them which is not dependent on the current drawn by the solenoid valve—nor can it be set by the user.

Multi set back electronic thermostats are now widely available at modest costs. They are easy to install and for some residents can save a good deal of energy. The trick is to be sure to include resident training on the use of the thermostat, making it clear that energy (and money) can be saved automatically without causing discomfort. Be sure the residents can demonstrate how to operate the thermostat and how to reset it for special circumstances that may arise. Most thermostats have an override mode that recurs back to the normal set mode after a period of override. Thus if the thermostat is set to go down to 60F at 8 am on school days and back to 67F at 3:30 when kids come home from school, an override leaving the thermostat at 67F can be used on holidays or when a child is sick. However, the next day it should automatically return to the original program. Working with residents on these matters is very important in helping them to limit waste while maintaining comfort.

These same considerations apply to thermostats used to control electric resistance heaters, but typically, there are two or more in one dwelling. Accordingly, setting back needs to be accomplished carefully to ensure comfort and frugality. Testing and marking baseboard controls can help to overcome the ambiguity of devices calibrated as “Warmer and Cooler.” Pointing out that electricity costs about three times as much as does natural gas is sometimes useful in working with residents who employ electric resistance space heat to save on gas bills.

11.5 Fan control thermostats at the furnace

As explained above, many furnaces have a fan control thermostat whose temperature sensor is mounted close to the beginning of the supply plenum (Figures 23 and 24). There are small tabs that set the temperature where the **fan comes on** when the plenum is being heated at the beginning of a firing cycle and where the **fan turns off** after the burner is shut off and the fan has harvested residual energy from the heat exchanger. **We recommend setting the fan on at 110F and the fan off at 90F.** The other temperature setting turns off the burner in case the plenum gets too hot; it is the high limit switch. **We recommend setting the high limit safety switch at 190F. Whenever setting the tabs on this control, be sure to (1) turn of the electricity to the unit, and (2) hold the wheel steady in one hand while manipulating the tabs with the other.** This will avoid damaging the temperature sensor, a rolled bimetallic strip inside the plenum. When manufacturer recommendations are different from the setting recommended here, follow the manufacturer’s instructions.

> Recommended Fan Control Settings
>
> Fan On: 110F
> Fan Off: 90F
>
> Plenum Limit: 190F

Figure 23. Inside of furnace showing burners and fan control (at top)

Figure 24. Typical Honeywell fan control

12 DHW system

Domestic hot water is typically produced using either gas—natural or LP—or electricity as the energy source. Electric water heaters are less expensive to purchase and do not require a vent or combustion air supply but their operating costs can be substantially higher than gas-fired units. Whenever practical, gas-fired units are recommended. The only exception is when a solar hot water system provides almost all of the hot water needed. The few times per year when the solar system comes up short, it may not be cost effective to have natural gas or propane if the plumbing would be unduly complicated and expensive. Monthly service charges might far out-weigh the actual gas needs. Since electricity will already be installed for lighting and other appliances, this service charge is a "sunk cost" and using a bit more electricity adds only the cost of the commodity. However, when clothes driers and kitchen ranges can also be gas fired, these loads may shift the economics toward having a gas connection. Alternatively, even though propane is more expensive than natural gas, avoiding the monthly service charge may make this a cost-effective option. In some situations, such as apartment units with individual DHW units and no gas appliances, there may be a clean air and safety advantage to ***not*** bringing gas into the dwelling.

When auditing a facility with an electric water heater, consider the economics of replacing the unit with an efficient gas-fired unit if gas is already available at the facility.

When gas is used to heat domestic water all gas piping should be carefully checked for leaks as was discussed in the heating section. The importance of this task can not be overstated. The auditor should follow all as gas piping with an analyzer and trace around all fitting to pipe connections with care–especially valves and unions as these tend to be the fittings that are most troublesome.

When water heaters are located within a home or apartment, insulating the hot water pipe is always a good idea. However, insulation is critical to minimize heat loss when a central DHW heating system is used and water is circulated continuously. The circulation pump should use a high-efficiency motor and variable frequency (speed) drive (VFD) to control the flow rate of the hot water, typically based on the line pressure. As more simultaneous hot water draws occur, the line pressure will decrease requiring the pump motor to turn faster to maintain an adequate flow. Additionally, the return water temperature should be monitored since when there is no hot water draw, ideally from an energy stand point, the pump should stop. However, after several hours of no hot water usage the water in the pipe would cool and when a user at the far end of the building requires hot water, they could run the cool water down the drain for several minutes while waiting for hot water. This would likely be quickly followed by a call to the maintenance staff. A VFD will reduce energy requirements while eliminating the potentially long waits for hot water and associated water use and sewer costs.

When hot water is circulating through the distribution pipes 24 hours per day the VFD saves pumping energy but there is still heat loss through the pipes unless they are well insulated along their length and around all fittings–except valve handles. All elbows, tees, and other fittings to be covered with insulation and the joints and seams sealed by the method recommended by the insulation manufacturer.

Domestic hot water systems often store and deliver water that is too hot to use directly. It is then mixed with cold water either at the faucet or in an anti-scald device. In either case, fuel is used to heat the water only to have it mixed with cold water at the point of use. For most applications hot water of 125ºF, or less, is adequate. Adjusting the water temperature down also reduces standby losses through the storage tank walls and piping, even when these are insulated, while adding life to the boiler. The simple payback for turning down the water temperature is virtually immediate.

After the water has been reduced to an appropriate temperature, the flow rates at shower heads should be checked. This frequently presents an easy and inexpensive opportunity to reduce both water heating energy and water use. Many shower heads have flow rates in excess of 4 gallons per minute (gpm). If a typical shower lasts 10 minutes, that is 40 gallons of water down the drain. Using a 1.5 gpm shower head with a good spray pattern will provide a comfortable shower. During the same length shower, the water usage is reduced to 15 gallons, a 62% reduction.

Figure 25 shows a quick method of measuring the flow rate of a shower using a weir. Figure 26 illustrates dollar savings associated with changing shower heads which consume more than 1.5 gallons per minute with those which use only 1.5 gpm.

Figure 25. Measuring shower flow rate using a weir avoids needing a stop watch. Just wait until the water comes to the highest hole and read the flow rate on the side of the weir. The procedure only takes 15 seconds or so.

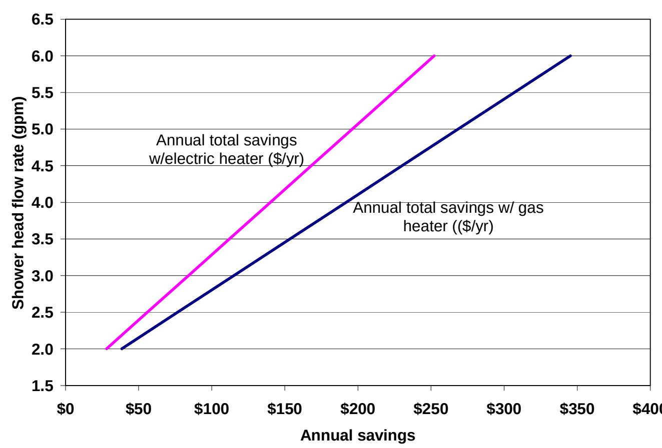


Figure 26. Annual savings of gas and water associated with changing existing shower heads for those that use 1.5 gmp. Assumptions are that the shower head costs $8 plus $10 for installation, and that two showers of six minutes duration are taken per day.

Table 7 illustrates details of the calculation in the figures above.

Table 7. Savings in energy, water, and dollars by changing out shower heads of flow rates from 2.0 to 6.0 gpm for those using 1.5 gpm assuming two showers/day @ 6 minutes/shower and a new shower installed cost of $18

Cost of Gas if used for DHW ($/therm)	Cost of Electricity if used for DHW ($/kWh)	Existing flow rate of shower (gpm)	Annual water savings (g/yr)	Annual hot water savings (g/yr)	Annual energy savings (therms/yr)	Annual energy cost savings ($/yr)	Annual water savings ($/yr)	Annual total savings ($/yr)	Simple payback (years)
	$0.10	6.0	19,724	15,497	94	$274	$71.00	$345.35	0.05
	$0.10	5.5	17,532	13,775	83	$244	$63.12	$306.98	0.06
	$0.10	5.0	15,341	12,053	73	$213	$55.23	$268.61	0.07
	$0.10	4.5	13,149	10,331	62	$183	$47.34	$230.24	0.08
	$0.10	4.0	10,958	8,609	52	$152	$39.45	$191.86	0.09
	$0.10	3.5	8,766	6,888	42	$122	$31.56	$153.49	0.12
	$0.10	3.0	6,575	5,166	31	$91	$23.67	$115.12	0.16
	$0.10	5	4,383	3,444	21	$61	$15.78	$76.75	0.23
	$0.10	0	2,192	1,722	10	$30	$7.89	$38.37	0.47
$1.10		6.0	19,724	15,497	165	$181	$71.00	$2521	0.07
$1.10		5.5	17,532	13,775	146	$161	$63.12	$224.18	0.08
$1.10		5.0	15,341	12,053	128	$141	$55.23	$196.16	0.09
$1.10		4.5	13,149	10,331	110	$121	$47.34	$168.14	0.11
$1.10		4.0	10,958	8,609	92	$101	$39.45	$140.11	0.13
$1.10		3.5	8,766	6,888	73	$81	$31.56	$1109	0.16
$1.10		3.0	6,575	5,166	55	$60	$23.67	$84.07	0.21
$1.10		5	4,383	3,444	37	$40	$15.78	$56.05	0.32
$1.10		0	2,192	1,722	18	$20	$7.89	$28.02	0.64

Incremental water rates in Boulder are $1.85/1000 gallons for Block 1, $3.60 for Block 2, $5.95 for Block 3. Block 2 rates of $5.95 per 1000 gallons used in calculation See http://www.ci.boulder.co.us/publicworks/depts/adminfleet/utbilling/current_rates.htm

When it is time to replace the water heater several options should be considered. In the case of some apartment buildings, a large boiler runs year round to provide hot water. Having a dedicated boiler for hot water, or several small modular boilers that are set up to run only when needed, increases system efficiency and reduces standby losses.

Tankless systems are quite efficient under steady loads and smaller applications. However, in larger applications and where loads can spike, go to zero, and suddenly spike again, a large system is required. In these cases a modest-sized storage tank can provide several benefits. First the heater capacity can often be downsized, reducing the first cost and possibly allowing the use of a smaller gas line, thereby reducing installation costs. Second, while the tank will have some heat loss, this is expected to be less than the heat loss of a large boiler that is used at its peak capacity on few occasions. Third, the storage tank can allow a low mass boiler or instantaneous water heater to heat the water in the tank and then turn off for a period of time, when the water cools or there is a large hot water draw, the heating unit would fire bringing the water up to temperature and then cycle off.

When gas-fired tank water heaters are used a damper “valve” can be installed at the top of the tank to seal the opening at the top of the water heater when the gas valve is off. The pipe just below this opening is in direct contact with the hot water and is not insulated since heat from the combustion process is expected to transfer to the water being heated. When the burner is off the heat stored in the hot water is conducted through the pipe and natural convection carries heat energy out of the tank, causing substantial energy waste. With the damper closed natural convection is suppressed, reducing energy losses.

In the meantime, side-arm water heaters are effective at heating water, but unless well insulated, are also effective at loosing large amounts of heat energy from the water in the heater. Appropriate type and thickness of insulation, properly installed minimizes these losses.

13 Lighting

Most homes have lots of inefficient lighting. Nonetheless, energy-efficient lighting that is both attractive and cost effective has become widely available. It is time to adopt the best lighting technology and to integrate it into the new and existing dwellings when maintenance and auditing are done.

Toward understanding the energy consequences of lighting, it is useful to examine the amount of light produced by various lighting sources per unit of power required to produce it. This is called luminous efficacy, measured in lumens per watt, lm/W.

> *Luminous Efficacy* is measured in lumens delivered per watt of heat/energy (lm/W).
> Candles produce about 1 lm/W
> Incandescents produce about 15 lm/W
> New CFLs produce about 68 lm/W

Everyone knows that a candle puts out a lot more heat than light, but that is also the case for Edison's wonderful invention, the incandescent light. Large wattage incandescents may produce 16 or 17 lm/W, but smaller ones—like those in refrigerators—only 11 lm/W or so (Figure 17). Light sources that require a good deal of electrical energy to produce a given amount of light also produce considerable heat. The consequence of this inefficiency is starkly obvious in the case of lights in refrigerators, but it is also of concern in homes in the Southwest that require cooling for substantial portions of the year. Accordingly, using incandescent lighting costs twice: once for the lighting and a second time for the cooling system to remove the additional waste heat. The obvious solution is to use more efficient lighting in the first place (Kinney 2005).

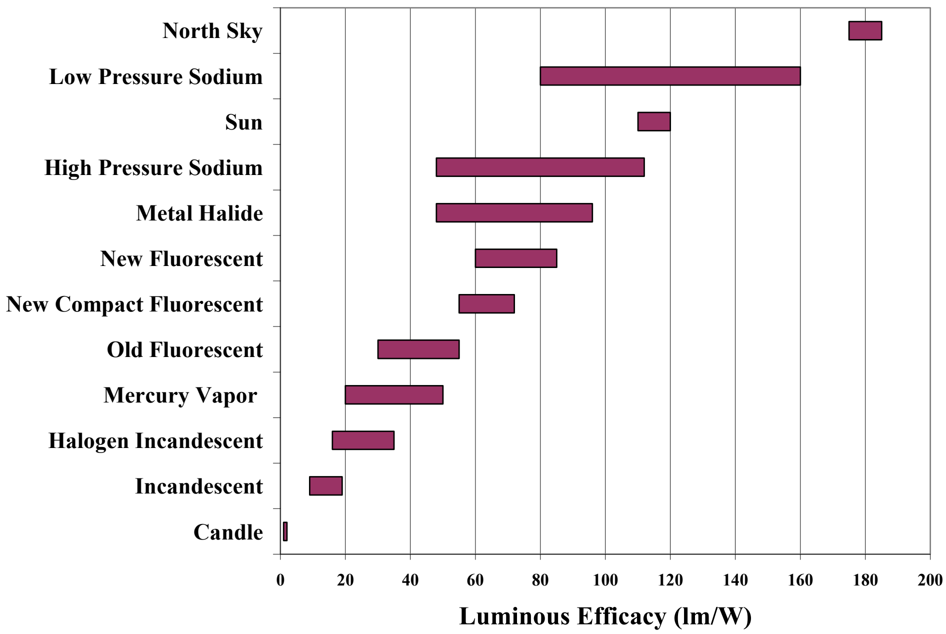


Figure 27. Range of luminous efficacy of various common light sources

Referring again to Figure 27, note that the modern fluorescent fixtures have a luminous efficacy on the order of four times greater than do incandescents. In addition, the best compact fluorescent lights (CFLs)—those recognized by ENERGY STAR®—have lifetimes that are typically longer than the lifetimes of incandescent lamps by a factor of 8 to 12. Note that high-intensity discharge lighting like metal halide and high-pressure sodium fixtures, which are used to provide exterior lighting for some residential and commercial structures, are more efficient by a factor of 5 than are incandescents, and have lifetimes that are 10 to 20 times longer.

In spite of the advantages of more efficient lighting, America's love affair with the incandescent light bulb is largely unabated. There are signs that more efficient lamps are making headway in the residential marketplace, but presently incandescents have a commanding portion of the residential lighting market.

Lighting Terms

In addition to luminous efficacy, several other terms of art in the lighting world are useful to understand. ***Color rendering index*** (CRI) is a figure of merit that ranges between 0 and 100 that expresses the degree to which a given light source renders "true" colors as seen by the human eye. Our sun is an almost perfect black body, which means that there are very few holes in its spectrum so its CRI is counted as 100. (Of course, the atmosphere sometimes selectively absorbs portions of its output, which is manifest at sunrise and sunset when sunlight traverses much more atmosphere on its way to observers than it does at midday.) At the other end of the spectrum, so to speak, are low-pressure sodium lights with a CRI of 0 to only 10. Our eyes are at their peak of sensitivity for the characteristic yellow radiated from low-pressure sodium bulbs, but the absence of other colors makes them fit only for illuminating junk yards and other such spaces. High-pressure sodium lamps have a CRI of 25 or so, but slightly less luminous efficacy. Incandescent bulbs, which include halogens, have relatively high CRIs that approach 100.

Good-quality fluorescents have CRIs in the 80+ (some as high as 98) range and the best metal halide lamps have a CRI of 94.

Color temperature is expressive of the characteristic color of a source of radiant energy we can see with our eyes. As a black body becomes hotter, it radiates more energy throughout the spectrum and increasing portions of its output are in the shorter wavelengths. Color temperatures are expressed in degrees Kelvin. A source with a color temperature of 2700K or below has a decided reddish feel to it, usually described as "warm." A crystal blue northern sky on a clear day may have a color temperature of 10,000K or higher, the sun at noon in the summer 5400K, and at sunset, 2000K. Most people enjoy color temperatures of around 3000K to 3500K or so for most visual tasks, although warmer temperature light tends to be more comfortable in romantic restaurants because it gives a rosy tint to the dinner companions.

It is interesting to pay attention to the *color* of an incandescent bulb as it is dimmed. It tends to go from white to yellowish to reddish as its filament gets cooler in the dimming process and its color temperature becomes lower. Figure 28 shows the effect of dimming a combination up-and-down torchiere-style lamp versus light from a north-facing skylight.

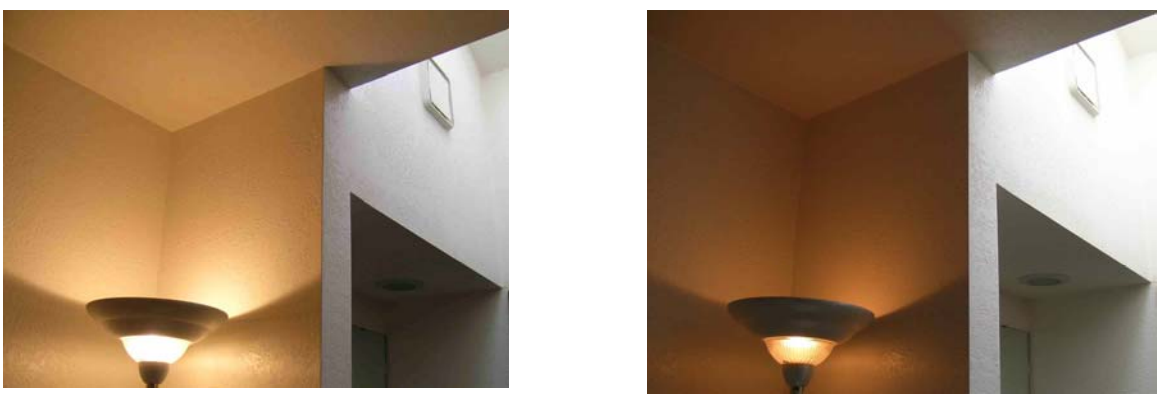


Figure 28. This torchiere has a 95 watt incandescent bulb that is drawing 95 watts in the left photo, but is dimmed to 48 watts in the photo on the right. The surfaces on the right are illuminated by a 4.5 square foot north-facing skylight on a clear day two hours before sunset. The walls are all painted with the same flat white paint. In principle, the color rendering index of both the sun and the incandescent source are both 100, but the color temperature of the incandescent is well below 3000K and that of the diffuse light from a northern sky is above 10,000K.

Evaluating Compact Fluorescent Lights (CFLs)

The Environmental Protection Agency's ENERGY STAR program evaluates a number of appliances, including CFLs. In order to qualify for an ENERGY STAR label, CFLs have to meet or exceed a number of performance characteristics. Current criteria for earning the ENERGY STAR label include having a luminous efficacy of 45 lm/W for bare bulb lamps of less than 15 watts and 60 lm/W for lamps of 15 watts and above. Reflector-type lamps of less than 20 watts must have a luminous efficacy of at least 33 lm/W and those of 20 watts and higher 40 lm/W. All lamps must have a CRI of greater than 80, a two-year guarantee, and a lifetime of more than 6,000 hours. Light levels fall off over time with all lamps, a phenomenon called lumen depreciation. ENERGY STAR-labeled lamps must have a lumen depreciation that retains 80% or more a lamp's initial lumens at 40% of its rated lifetime. Other performance criteria for CFLs are available on the ENERGY STAR web site, http://www.energystar.gov/index.cfm?c=cfls.pr_crit_cfls.

A list of CFLs that have been qualified under the ENERGY STAR program is available for downloading at http://www.energystar.gov/ia/products/prod_lists/cfl_prod_list.xls. There are over 1,675 products listed in the spreadsheet. In every case, the date on which a given product was listed is given, but there are two other columns that give dates when the product was taken off the list either because of being no longer manufactured (7%), usually because older models are replaced by newer models, or becoming disqualified (15%). Both consumers and manufacturers of high-quality products are benefited by EPA's diligence in taking lower-quality products off the list of ENERGY STAR-qualified CFLs.

The list also includes model numbers by manufacturer, packaging description, wattage, rated life, lumen output, color temperature, and type/design. In short, in making a decision to buy CFLs in quantity, only ENERGY STAR qualified CFLs should be chosen, the units should have good color rendering, a long lifetime, and low price.

ENERGY STAR also qualifies lighting fixtures designed to only utilize CFLs. In order to meet the demand set by California's Title 24 Efficiency Standards, multiple manufacturers have produced interior and exterior hard-wired fixtures with pin based ballasts and bulbs. This ensures that replacement bulbs will always be efficient since Edison socket (standard incandescent) bulbs do not fit.

CFL Economics

In assessing the cost effectiveness of CFLs, it is tempting to calculate simple paybacks that compare the CFL/incandescent option based on time of use. However, in all cases except those in which a bulb may be in a rarely-accessed attic, we believe it is more appropriate to ask the economic question based on lifetime considerations, to wit, "how much energy and money will this CFL save over its lifetime?" To illustrate, take an ENERGY STAR-labeled 23 watt CFL suitable for a floor or ceiling lamp, such are available at big box retail outlets for $2.50. This bulb has an output of 1600 lumens, slightly more than that of a 100 watt incandescent, but a luminous efficacy of 70 lm/W, 4.6 times that of the 100 watt incandescent at 15 lm/W. Over its lifetime, the CFL will consume 230 kWh, as compared to 1,000 kWh consumed by the incandescent, a savings of 770 kWh. At 10 cents per kWh, the energy savings is worth $77 (ignoring the time value of money). Of course, over the lifetime of the CFL, one must replace the incandescent on the order of 10 times. Ignoring labor, runs to the hardware store, and land filling 10 times as many burnt out bulbs, the first costs of the incandescents are slightly greater than the first cost of the CFL.

What is the 770 kWh savings at a coal-powered power plant? At 11,500 Btu/kWh, a factor that accounts for the carnot effect and line losses, it is almost nine million Btus, the energy equivalent of nine person years of labor. It's also associated with the mining, transporting, and burning of

Lifespan Savings of a CFL 23W CFL replacing a 100W incandescent 770 Watts of electricity $77 at 10 cents/kWh 10 replacement incandescents 633 pounds of coal 385 gallons of water 0.75 tons of airborne CO_2

633 pounds of coal, the evaporation of over 385 gallons of water at the power station and the release of 0.75 tons of CO2. Expressed in terms of gasoline, the energy savings are equivalent to 71 gallons of gas, enough to drive from New York to San Francisco in a Prius.

This analysis applies to the savings associated with the lifetime of a single 23 watt CFL replacing a 100 watt incandescent. The average American home contains 37 incandescents. Assuming that half are replaced by 23 watt CFLs and the other half by 13 watt CFLs, the lifetime savings will be 23,560 kWh of electricity, $2,391 at current electricity costs.

In short, it makes sense to change every single bulb or fixture in all of the dwelling units audited, being cautious to install CFLs that are specified for dimming on dimming circuits.

Problems with Can Light Fixtures

The efficiency of lamps interacts with heating and cooling costs, but so does the efficiency of light *fixtures* in the case of recessed downlights ("cans") in ceilings. Cans are becoming the light fixture of choice for many builders, and over 20 million are sold each year. The Pacific Northwest National Laboratory (PNNL) estimates that there are at least 350 million currently installed in US homes. Sadly, only a tiny fraction of the recessed downlights in new homes have CFLs installed, probably less than 2 percent.

Many cans are installed in the ceiling of the top story where they interact with a dwelling's thermal envelope. As discussed above, during the winter, the most powerful force that causes convective leaks is called "stack effect." Warm air is less dense than cool air, so it tends to rise. This puts a negative pressure on the bottom of the home's thermal envelope and a positive pressure on the top. The magnitude of the force of stack effect depends on the difference in temperature between inside and outside of the building and its height. As we have learned, the pressure differences due to stack effect are greatest at the top and bottom of the envelope. Further, flow across an orifice is proportional to both the size of the hole and the difference in pressure from one side to the other. Accordingly, in most homes, holes at the bottom and top of the thermal envelope account for more infiltration/exfiltration problems than anywhere else.

Savvy builders and practitioners of residential retrofit understand this and make it a point to spend most of their efforts at air sealing in the basement/crawl space and in the attic. They know that putting leaky can lights in ceilings is an open invitation for costly air leaks and a challenge to fix (Figure 29). The problem is made worse in several ways by inefficient lights. First, they raise the temperature of the air and objects in their immediate vicinity, thus increasing the force of stack-effect induced air leakage. All other factors being equal, a 13 watt bulb increases infiltration through a leaky can by 60% when it's on, a 50 watt by 170% and a 100 watt by 400% (Bennett and Perez-Blanco, 1994). Second, they heat up the can itself to the point where placing insulation on top of it may risk fire (Figure 30). The result is conductive energy losses as well as convective ones, an unhappy combination that raises energy costs and may cause discomfort as well.

Figure 29. Can light in a kitchen ceiling with a blower door depressurizing the home.

Smoke blowing downwards indicates openings to the vented attic above.

Source: Rana Belshe, Conservation Connection

Figure 30. Charred insulation due to a hot

Figure 31 shows a can light being scanned by infrared thermometer. Figure 32 shows a snowy roof with leaky cans in the attic below.

Figure 31. Kitchen light in a home heated to 68ºF, outside air temperature of 34ºF, blower door depressurizing the home drawing in the cold attic air.

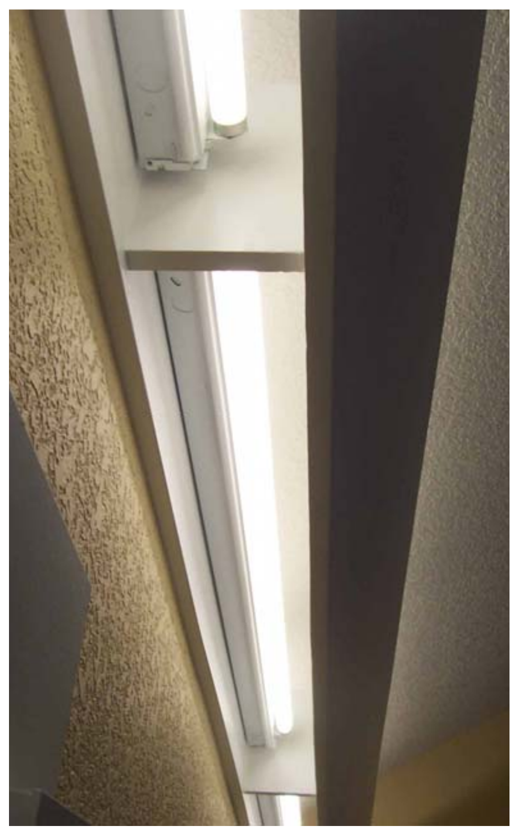
Figure 32. The two melted areas in the snow above the skylight correspond to recessed can lights that are almost never turned on. Melting is due only to air exfiltration from the conditioned space below the cans and the lack of insulation on top of them. The larger melted hole in the snow to the left of the vent pipe is due to a similar can above the shower which has a 250 watt infrared bulb in it. This light is on a timer and on average is illuminated about 12 minutes a day.

In many homes, can lights cause quite significant energy losses. Since they allow warm, moist air to enter the attic, they can cause moisture problems, ice damming, and premature roof failure in addition to energy waste and discomfort.

So what is the solution to the problem? Avoiding can lights altogether comes easily to mind, particularly can lights that penetrate the thermal envelope. Wall sconces are widely available at prices similar to those of can lights. They produce nice light and can be fitted with CFLs.

McStain Neighborhoods, Inc., a progressive production builder in Boulder, Colorado, has started to use four foot long 32 watt T-8 florescent bulbs with electronic ballasts as wall and ceiling "washers." The bulbs are mounted in simple fixtures McStain fabricates on site from wheat board. Wheat board is a renewable resource that comes in 4 x 8 foot sheets and costs about $1 per square foot. After fabrication, the fixture's interior is painted with a white semi-gloss low VOC interior latex paint. The fixture's exterior may be painted to match the walls or trim.

As shown in Figure 33, the result is nice diffuse light that washes walls and ceilings without causing glare. In addition to energy savings of both electricity for lights and gas for space heating, McStain avoids the use of cans that produce visual hot spots in the ceiling, sharp shadows, and glare.



Source: Jeff Medanich, McStain Neighborhoods

Figure 33. This wall washer is simple to build yet yields excellent, efficient, glare-free light.

All of the over 400 homes McStain builds each year are ENERGY STAR® rated; many have a Home Energy Rating System (HERS) rating of 90, 20% better than needed to qualify as an

ENERGY STAR home. They are built "tight and right" and are 100% inspected with blower doors and duct blasters. In consequence, annual energy use for space conditioning has become a relatively small portion of the whole. A recent analysis of typical 1800 square foot McStain homes showed annual energy costs of $251 (33%) for space conditioning, $221 (29%) for hot water, and $288 (38%) for lights and appliances (Wilson 2005).

Retrofit
If cans already exist, the retrofitter has four choices:

- Remove the can and seal up the hole, insulating above the sealed-up space;
- Seal up the space, insulate, put a plug into the electric socket, and install a surface-mounted fixture in its place;
- Use the existing can, but build a large fireproof box around it in the attic, then seal and insulate the box; or
- Replace the old can with one that is sealed and can be insulated with impunity, or install a retrofit device over the old can that achieves the same result.

The surface-mount-fixture option
Autocell Electronics is a California company that manufactures and markets a range of energy-efficient lamps and fixtures, all of which are ENERGY STAR approved. Figure 34 shows a fixture designed to get power via a screw-in plug from the electrical outlet in an old can, but to be mounted so that it covers the hole. It uses a 32 watt circular fluorescent bulb, which, with an electronic ballast, achieves a luminous efficacy of 68 lm/W and is rated for a 10,000 hour lifetime. Equally important, it allows for sealing and insulating the old can.

Figure 34. Autocell ceiling-mounted fixture. Both acrylic and alabaster glass cover are available.

The add-a-box option
Since 1995, the Model Energy Code and its successors (in particular, the International Energy Conservation Code which is in force in Boulder and Denver) have included language allowing a box to be made of metal or ½-inch gypsum board that is installed in an attic surrounding a recessed can whether it is leaky or not. The box must be made so that it keeps combustible material at least three inches away from the can. As a matter of practice, this is not always easy to do since there are typically no small number of accoutrements associated with cans in attics. These include mounting hardware, an electrical box, and Romex® wire. The trick is to build and install a box that will meet the three-inch constraint while being as well sealed as possible. Once fitted and sealed—ideally with a high-temperature caulk—the box can be insulated.

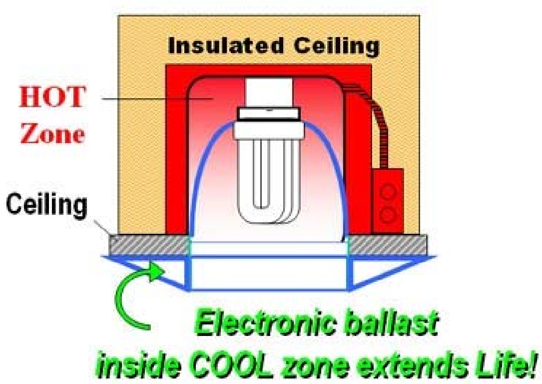
One practical consideration for retrofitters is that some old-style wiring has a temperature rating that is only 60ºC (140ºF), far below the temperature rating of modern Romex (typically 90ºC, 194ºF) as well as below the temperature of the high temperature limit switches typically installed in cans. If this is found to be the case, the most prudent options would be to select another method for retrofitting or do some rewiring. Choosing another option is likely to be more cost effective unless new wiring is desirable for other reasons.

The install-a-better-can option
Given the popularity of recessed downlights, it is desirable to develop can/lamp products that maintain the integrity of the thermal envelope of the home while supplying efficient, long-lasting illumination. Hot spaces—which small, well-insulated cans with lights in them can easily become—tend to shorten the lifetime of both CFL bulbs and (especially) their electronic ballasts. Accordingly, the design problem is not trivial, and few companies have solved it.

Toward stimulating the development of products that meet the criteria of safeguarding the integrity of the thermal envelope while delivering light efficiently over the long term, scientists at the Pacific Northwest National Laboratory (PNNL) initiated a Recessed Downlight Project (www.pnl.gov/cfldownlights). The project solicits lighting companies to submit their products for testing at the lab. The lab verifies that lighting systems tested meet the ENERGY STAR specifications and a sub-set of specifications specific to CFL downlights. "Insulated Ceiling" (IC) cans and associated pin-based CFLs and ballasts are tested in a special facility designed for the job. The primary aim is to stimulate the development of an energy-efficient solution for the hundreds of millions of recessed cans already installed as well as the millions of new ones added every year.

One test is designed to determine if the temperatures in the can ever exceeds some specified maximum—typically the warranted temperature rating of the electronic ballast—even when left on for 12 hours while covered by insulation rated at R-45. A longer-term test measures fixture performance and longevity as well as lumen depreciation over a year period under the stress of being turned on for three hours, then off for 20 minutes, then on again for three hours, etc. As of the spring of 2005, several vendors have had their products pass these tests, two of which are currently available in the market, PowerLux Corporation (www.powerlux.com) and Technical Consumer Products (www.tcpi.com).

PowerLux® solves the problem by keeping the small electronic ballast in a rim outside of the can itself (Figure 35). The advantage of this approach is that the ballast stays quite cool, only slightly warmer than the air at the ceiling. Thus, the ballast never approaches its rated maximum temperature, with the consequence that its lifetime is quite long. A general rule-of-thumb in the electronics industry is that the life of electronic ballasts is doubled for each 10 degrees C it is operated below its maximum rated temperature (McCullough 2005.)



Source: Powerlux®

Figure 35. The PowerLux system keeps the ballast outside of the can. Replaceable CFLs that fit the system are available in 18, 26, 32, and 42 watts, and in color temperatures of 2700, 3000, 3500 or 4100K. All have a color rendering index of 82 and 12,000 hour lifetimes. Initial luminous efficacy ranges from 67 to76 lm/W. All with ANSI/IEC standardized lamp base configuration. Costs for the fixture, bulbs, and ballasts range from $56 to $100 with volume discounts.

Note that the PowerLux system simply installs in an existing can, whether IC rated or not. Importantly, it seals air leaks to the attic even better than called for in Washington State energy codes and ENERGY STAR 4.0 for IC-rated cans, which is less than 2 CFM (Cubic Feet per Minute) at a pressure of 75 Pascals. (PowerLux has been tested in accordance with ASTM E283 with a leaky non-IC can and showed a result of 0.83 CFM, 60% better. Lau 2005) All cans manufactured after 1983, whether IC rated or not, must have high temperature limit switches mounted in them (Figure 36), so according to PowerLux, the retrofitted can may have insulation installed directly over it. To be sure, while the PowerLux product renders an IC or non-IC substantially airtight, only an IC-rated can be covered with insulation. PowerLux electronic ballast has a built-in EOL (End- of-Life) protection and shut-down circuit. In the unlikely event that the can with an energy-efficient CFL in it does overheat, the high temperature limit switch opens the circuit when it senses temperature reaching 90ºC (194ºF).

Figure 36. Can showing the high temperature limit switch which opens at 90ºC (194ºF) and closes again at 80ºC (176ºF). Other models have the limit switch above the light socket. Note the leakage area between the edges of the can and the hole in the gypsum board ceiling. This is quite common. According to the new Title 24 code energy code in California, this area must be caulked or be fitted with a gasket to prevent air leakage. Some can manufacturers supply a doughnut-shaped annulus of sticky-backed foam with their products. This should be installing before fixing the rim in place.

14 Other appliances

14.1 Ceiling Fans

Ceiling fans are found in a number of homes. Most use inefficient motors with inefficient blade design which means that they are very inefficient at moving air, do not produce much comfort when they do, and many include incandescent bulbs that should be retrofitted with CFLs. The figure of merit of overhead fans is the ratio of air moved in cubic feet per minute to electric power for each speed (cfm/W). For all fans, whether efficient or not, the higher the speed, the less efficient they are. So keeping a fan at low speed is wise.

If it is deemed important to replace an existing fan, several very energy efficient overhead fans are now available in the market place. Invented at the Florida Solar Energy Center by building scientist Danny Parker, these are marketed under the brand name of Gossamer Wind and are available at such outlets as Home Depot. (See http://www.ceiling-fans-ceiling-fans.com/resources/Types_Gossamer-Wind.htm). In addition, ENERGY STAR rates ceiling fans according the above-mentioned figure of merit. The Casablanca Fan company has a model called "Concentra" which produces almost 300 cfm per watt at low speed, far and away the best performance of the fans listed on the ENERGY STAR website (http://www.energystar.gov/ia/products/prod_lists/ceiling_fans_only_prod_list.xls).

14.2 Ventilating fans

Ventilating fans remove odors and moisture, when operating, but are a hole in the conditioned envelope when they are not. The trick is to make sure they are well designed to do their job well, efficiently, and quietly; that they are controlled property to run when needed (and not when not); and that they are installed properly so they functions as designed, yet may be maintainable. The other critical detail is to ensure their dampers are well designed and work well.

In practice, the auditor often sees very dirty fans whose installation was never right. It is important to vent fans completely outside, not merely into the attic, and to air seal the penetration of the exhaust duct from the fan as it passes through a sidewall or attic. Finally, keeping both the damper and fan clean is important to functioning, as is working with the resident to ensure the fan in the kitchen is operated when the stove is and that the fan in the bathroom is turned on before the shower starts and run until 10 minutes after it ends.

In shopping for ventilation fans, it's important to ensure the fan meets mechanical needs, but is also ENERGY STAR rated (http://www.energystar.gov/index.cfm?c=vent_fans.pr_vent_fans). Kitchen, bathroom, and utility fans rated by ENERGY STAR are quieter and more efficient (both the fan and motor that runs it) than average fans. In the case of those which include lighting, typically no units using inefficient incandescent bulbs carry the ENERYG STAR label.

14.3 Washing machines

Very substantial advances in energy efficiency and water use have been made in the world of washing machines available to Americans in recent years and the cost is coming down. As with much else in energy programming. the benefits integrate across the laundry system. If people presently wash with cold water and hang laundry out, the payback is elusive. If they wash in warm or hot water and utilize a clothes dryer, the combined energy savings may be as great as 50%. This energy use is defined by a Modified Energy Factor (MEF) which includes the energy needed to run the machine, heat the water, and fuel the clothes dryer. The higher the MEF, the more efficient the machine.

The primary consideration in either front or top-loading ENERGY STAR qualified machines is the reduced use of water—18 to 25 gallons per load compared to the 40 (or more) used by a standard machine. While savings depend on sufficiency and cost of supply and waste treatment, EPA has developed a Water Factor to help shoppers. It expresses the gallons of water used per cycle based on the washer size in cubic feet. For example, a 3.0 cubic foot washer using 27 gallons per cycle has a water factor or 9. The lower the Water Factor, the better.

Front loading machines are by nature more energy and water efficient, and modern units may be purchased which cost very little more than wasteful units and that save substantial water and electricity while producing clean clothes (Figure 37).

When recommending appropriate units to apartment dwellers, or re-equipping laundry rooms, examining the useful information produced by ENERGY STAR on the subject prior to buying makes good sense. The qualified product list can be accessed through the web site and shows both Modified Energy and Water factors. Both residential and commercial washers are available including ones that are coin operated.
http://www.energystar.gov/index.cfm?c=clotheswash.pr_clothes_washers.

Figure 37. This new front loading washing machine costs little more than machines that do not carry the ENERGY STAR label.

ENERGY STAR-rated clothes washers use less than half of the energy of standard washers and 20 to 25 gallons of water per wash as compared with 40 by standard machines.

Finally, using cold water as much as possible saves the energy associated with heating water, while nonetheless achieving effective clothes washing.

14.1 Vending machines

Vending machines are energy consumers that are hidden in plain sight (Figure 38). They typically operate 8,760 hours per year. Electrical energy consumption for refrigerated drink vending machines is on the order of 4,000 kWh per year due to the refrigeration compressor motor and lights. This electricity is paid for by the host site, hidden among the lighting, HVAC, and other electric loads of the facility.

A product called Vending Miser™ can reduce energy consumption of refrigerated vending machines by about 45% and depending on the model selected at a cost of about $165. It connects between the plug and the machine where it can monitor current flow and has an occupancy sensor that detects movement in the immediate vicinity. If it has detected no movement for 15 minutes and the machine is not presently in a compressor run cycle, it disconnects the vending machine. As soon as motion is detected, it reconnects the machine. If no movement is detected for two hours, it also actuates the machine, allowing it to have a compressor run, then turns it off again if no motion is detected. (Information on Vending Miser is available at http://www.usatech.com/energy/vendingmiser_overview.php, telephone: 800-770-8539/303-296-9800; Web: www.usatech.com.)

Figure 38. This vending machine is outside of a laundry room at an apartment complex in North Denver. It is exposed to direct beam sunlight.

15 Telling the Story

The testing done, measurements recorded, and the equipment back in the vehicle, the energy auditors are ready for a break. Knowing that notes are already recorded on the audit form and that some additional calculations will be done later, it seems like a good time to move onto the next job. Nonetheless, this can be a very useful moment for the auditors to pause to discuss their impressions and compare findings. Even using one recording file, some observations may be missed, and the interactions are best fleshed out through discussion.

This task is satisfying to the auditors who have been energy detectives collecting evidence during the audit. Now they bring all the suspects together and solve their case. Like the game *Clue*, the team decides "who done it"; not the butler in the pantry with a kitchen knife, but return air register in the living room with a dog bed on it. When the team discovers a series of culprits, the solution to the puzzle is most satisfying.

The story of the dwelling is what emerges from this auditor task. While working in the building the team has probably determined what the greatest retrofit target will be. Through the story-telling task, methods for the retrofit that will best serve the job, perhaps solving multiple problems at once, emerge. The extended vision of the many instruments and the various team members are brought together while fresh in memory.

During the storying task, assignments are made regarding additional research, writing up the report, retrofit recommendations, suggested post-retrofit re-testing, and issues for resident and staff education.

Consider problems that may recur in similar units. Often an energy retrofit becomes much more cost effective if it can be performed on a number of similar structures, whether in single family homes or multifamily residences. Although some problems (and recommended retrofits) are likely to be similar from those seen before, it's important to be ever alert for new, unobvious problems and special circumstances.

The rewards of the energy audit come when the retrofit work is done. When residents are comfortable, in healthy homes that cost less live in, the housing team feels good—and Mother Nature is pleased.

Appendix A

ByPass House

Real problems in real houses that cause real convective energy losses— And how to deal with them

by Tom Wilson

Used with permission of author. Feedback is most welcome. Comments may be sent to:

Tom Wilson
Residential Energy Services
Outreach and Training Specialist
Wisconsin Focus on Energy
Home Performance with ENERGY STAR®
Suite 201 Landmark Center
500 East Jefferson Street
Viroqua, WI 54665
Phone/fax 608/637-3356
resenergy@mwt.net

ATTIC

1 Staircase Ceiling
Cover opening with sheetrock or reinforced cardboard (or plywood for large openings) caulked and nailed to joists, taking special care to seal ends with similar material. Insulate to standard depth. Alternately, fill cavity full with blown insulation.

2 Recessed Light
Replace with surface-mount U.L. approved I.C. recessed fixture for use under insulation (may require services of licensed electrician).
3 Chimney Chase
Seal opening at ceiling level with metal flashing caulked and nailed to joists and attached to chimney with high temperature caulk. Establish barrier at least 2 inches from chimney to hold back any insulation.

4 Electric Wires and Box

Fill wire holes through framing members with siliconized acrylic caulk or urethane foam. Seal boxes that penetrate ceiling. Flag boxes before insulating for later maintenance. Junction boxes should have covers - do not fill with insulation.

5 Balloon Wall

Fill exterior walls with high density blown insulation. Some can be reached from the attic. Interior walls can be sealed with cardboard caulked and stapled in place or walls may be sealed top and bottom with fiberglass-filled plastic trash bag "pillows". In some cases interior wails can be blown full of insulation.

6 Attic Entrance

Weatherstrip with appropriate material and use hardware to secure door. Caulk trim on interior.

7 Partition Wall Top Plate

Seal seams at plate and plaster/sheetrock with urethane caulk (or urethane foam if gaps are large).

8 Plumbing Vent Chase

Seal around pipe with clamps and special neoprene collars designed for that purpose or use plastic mechanically fastened around pipe and sealed to ceiling with staples and acoustical caulk.

9 Exhaust Fan

Extend vent hose through gable end or roof and install quality backdraft damper/vent hood. Seal edges of fan unit to ceiling with urethane or siliconized acrylic caulk.

BASEMENT OR CRAWL SPACE

10 Dryer Vent

Replace vent hood with improved design unit. Seal penetration with urethane caulk.

11 Plumbing/Utility Penetrations

Fill large openings with mortar patch. Seal penetration with urethane foam or caulk.

12 Sill Plate

Seal to foundation with urethane caulk.

13 Rim Joist

Caulk all leaking gaps with siliconized acrylic or urethane caulk.

14 Bathtub Opening

Block air movement with reinforced cardboard, caulked and stapled to floor members.

15 Basement Windows & Doors

Make operable but air seal as you would doors and windows in living space.

16 Block Wall Cavities

Fill tops with urethane foam or mortar plaster.

17 Water Heater/Furnace Flue Connections
Replace deteriorated pipe. Assure connections with sheet metal screws. Seal at chimney with non-asbestos furnace cement or high temperature caulk.

18 Ductwork
Mechanically close open seams and reconnect open ducts, boots, and registers. Clean with alcohol solution and seal with dead-soft aluminum tape or a combination of duct mastic and fiberglass mesh tape.

19 Plumbing Chase
Seal around pipe with urethane foam, duct wrap, or polyethylene as practical.

20 Leakage Between Basement & Crawlspace
Seal as appropriate with urethane foam, caulk, hatches, etc.

21 Floor Boards
Support floor insulation with high tensile strength air barrier material (Tyvek®, Typar® etc) sealed carefully around edges with acoustical sealant and battens. Protect barrier material from ultra-violet radiation. Alternately seal floor from interior by putting down a new floor surface (plywood, vinyl, etc.) over building paper/air barrier.

LIVING AREA

22 Windows
Repair as necessary. Adjust stops. Install sash locks. Replace broken glass. Weatherstrip only if required. Caulk on interior with clear siliconized acrylic caulk. Caulk exteriors with urethane caulk for water penetration protection.

23 Laundry Chutes
Seal with appropriate gasket material.

24 Stairwell
Caulk risers, treads and sidewall junctions as needed. Consider blowing inaccessible stairwell sections with high density insulation.

25 Kneewall/Framing Intersection
Isolate kneewall from living space with tight-sealing door or panel. Insulate sloped roof/ceiling section with high density blown insulation. Insulate vertical kneewall with fiberglass bans. Insulate floor with dense-pack blown insulation being sure to seal off floor cavity under living space with tightly packed insulation.

26 Built-in Dresser
In unconditioned space, build bureau with cardboard or plastic stapled and caulked to drawer-guide framing members. Insulate and seal at roof rafters.

27 Chimney Penetration

Seal with high-temperature caulk and sheet metal.

28 Built-in Cabinet
Caulk perimeter of cabinet and interior hardware slots with siliconized acrylic. Alternately, remove cabinet, seal wall chase and replace cabinet.

29 Holes in Plaster walls
Patch smaller holes with Durabond patching plaster or fiberglass reinforced patch kit. Large deteriorated sections can be covered with sheetrock screwed through to framing members.

30 Furnace Registers
Reinforce large gaps with sheet metal and screws. Clean surfaces with alcohol solution and seal with J-channel, dead-soft aluminum tape or duct mastic

31 Doors
Repair as necessary and install appropriate hardware. Weatherstrip as required with rigid materials and sweep to achieve good seal. Caulk trim on interior with clear siliconized acrylic caulk. Caulk exteriors with urethane caulk for water penetration protection.

32 Baseboards, Coves, & Interior Trim
Caulk on interior with clear siliconized acrylic caulk.

33 Plumbing Access Panel
Weatherstrip if possible. If not, caulk with silicone caulk using bond-breaker tape on one surface and screw in place.

34 Sink Plumbing Penetrations
Seal with urethane foam. If appearance is important, cover opening with scrap linoleum tile cut to fit snugly around pipe and caulk seam and back.

35 Dropped Soffit
Caulk all open seams from interior or try to seal from above with board stock and urethane foam or caulk. If covering is impossible, consider filling with blown insulation (Not if light fixtures are present).

36 Electrical Outlets
Place gaskets behind cover plates as required.

37 Electrical Fixtures
Caulk fixtures to interior surfaces with clear siliconized acrylic caulk.

EXTERIOR

38 Porch Framing Intersection
Gain access and blow all connecting cavities with high density blown insulation.

39 Missing Siding & Trim
Replace and caulk for water penetration.

40 Additions, Dormers and Overhangs
Take special care to understand framing details and fill all cavities with high density blown insulation. Seal interior surfaces as required.

41 Unused Chimney
Stop airflow with fiberglass/polybag stuffed down to ceiling line. Cap off top with sheet metal. Seal at bottom as appropriate.

42 Floor Joist
Dense pack with high density blown insulation as part of wall insulation job.

Appendix B

Useful Tools for the Energy Auditor

Good audits require instruments, the most important of which are located between the ears of the energy auditor. A description of other instruments and tools—and where to secure them—follows in the paragraphs below:

General

Professional Equipment
800-334-9291 voice: 888-776-3187; web: www.professionalequipment.com Technical support to help choose the right equipment for the job. Supplies a wide range of energy auditing diagnostic tools, has catalog that appears quarterly and details on the web.

The Energy Conservatory
2801 21st Ave. South, Suite 160, Minneapolis, MN 55407
Voice : (612) 827-1117 ; Fax : (612) 827-1051 ; web www.energyconservatory.com
Sells blower doors, duct blasters, duct pans, digital and analog manometers, infrared scanners, etc. Has a number of excellent "how to do it" documents on web site, downloads free.

Teledynamics LLP
2200 Wheless Lane, Austin, TX 78723
Toll free: 1-800-847-5629; Fax: 1-800-847-5675;
Email: info@teledynamics.com; www.teledynamics.com;
Kill A Watt electric energy meter (P3-P4400) costs $17.75

Ideal Industries, Inc
Becker Place, Sycamore, IL 60178 USA
Toll free: 800-435-0705; Fax 800-533-4483 ;
E-Mail: TestersandMeters@idealindustries.com; www.testersandmeters.com.
Sells Suretest® Circuit Analyzers through distributors. In Denver, try GE supply, GE supply 303-572-7100; in Portland Platt Electric at 503-224-1919, EOSS Electric at 503-222-9411, or Graybar electric at 503-249-1300.

Testo Inc.
35 Ironia Rd., 07836 Flanders NJ.
Voice: 973-252-1720; Fax:973-252-1729 ; E-Mail: info@testo.com; www.testo.com
Has wide range of combustion testing equipment and other measuring tools.

Bacharach, Inc.
621 Hunt Valley Circle, New Kensington, PA 15068-7074 U.S.A.
Voice: 724-334-5000; Fax: 724-334-5001; Toll Free: 1-800-736-4666;
E-mail: help@bacharach-inc.com; www.bacharach-inc.com.

Quality Instruments, Inc.

4315 Regnas Avenue, Suite "B", Tampa, Florida 33617, Phone (813) 984-7885, Fax (813) 984-8755 Toll-Free (888) 345-7885, www.extechproducts.com

Suggestions for items for energy auditors' items follow in the table below:

Item	Item #	Vendor	Manufacturer	Price
Combustible Gas Detector	G275	Professional Equipment	TIF	$210
Fyrite Pro 60 Combustion Analyzer	G499-05K	Professional Equipment	Bacharach	$595
Pen Style Thermo Hygrometer	M925	Professional Equipment	Mannix	$70
50:1 Laser Thermometer	52545	Quality Instruments	Extech	$224
Pocket Digital Thermometer	T405-1721	Professional Equipment	Fieldpiece	$20
Digital Light Meter	Q4100	Professional Equipment	AEMC	$200
Minnneapolis Blower Door	Model 3	Energy Conservatory	Energy Conservatory	$2,525
Digital Pressure Gauge	DG-500	Energy Conservatory	Energy Conservatory	$695
Duct Mask Register Sealing Film	6 rolls 8"wide, 200' long	Energy Conservatory	Energy Conservatory	$130
Weatherization Training DVD (4 hours)		Energy Conservatory	Energy Conservatory	$40
Pressure pan	12" x 14" x 4"	Energy Conservatory	Energy Conservatory	$65
Smoke Puffer		Energy Conservatory	Energy Conservatory	$45
Kill a Watt Electric Energy Meter	P3-P4400	Teledynamics LLP	Kill a Watt	$18
Suretest Circuit Analyzer	164	GE Electric	Ideal Industries	$230

Appendix C

Residential Energy Audit Check List

The following check list is substantially modified from a procedure developed by Dr. Bob Knight, President, Bevilacqua-Knight, Inc. (BKi), and his colleagues. The audit currently used by the Home Performance with Energy Star contractors in California resembles this document and may be obtained from BKi at the following address:

1000 Broadway, Suite 410
Oakland CA 94607
510-444-8707 ext 223
rknight@bki.com
www.bki.com

Users of this check list should note that it is not designed for every item to be filled out. Everything depends on what is found in the dwelling being audited. The checklist is, we hope, useful as a place to record findings in an orderly way and a reminder of items to at least think about during a careful audit.

Residential Energy Audit Check List

Concordance

Section	Actions	Page
2.1	Energy bills	1
2.2	Temperature and humidity measurement	4
2.3	Interview	2-3
2.4	Electrical tests and refrigerator monitoring	8
2.5	Inspection overview and safety tests	5-6
2.6	Convective losses and blower door tests	15
2.6.1	Finding leakage areas	15
2.6.2	Pressure differences indicate leakage	15
2.6.3	Convective loops	X
2.6.4	Estimating energy losses due to convection	15
2.7	Assessing duct losses	16
2.7.1	Estimating energy losses of duct leakage	16-17
2.8	Pressure testing	11
2.9	Insulation	19
2.10	Windows	6
2.10.1	Heat radiation	6
2.10.2	Conduction and convection	6
2.10.3	Modeling choices	6
2.11	HVAC auditing procedures	11 12
2.11.1	Furnace and boiler “house keeping”	11-12
2.11.2	Measuring furnace and boiler efficiency	11-12
2.11.3	Forced air systems	11-12
2.11.4	Thermostats controlling space conditioning	8
2.12	Domestic hot water systems	10
2.13	Lighting	18
2.14	Other appliances	9-10
2.14.1	Ceiling fans	9-10
2.14.2	Ventilation fans	7 & 16-17
2.14.3	Washing machines	9-10
2.14.4	Vending machines	X
2.15	Telling the story	21

Pre-Audit Information

Auditor: ______________________________ Date: ______________

Neighborhood/Complex Name ______________________________

Phone: ______________________________

Resident/Housing Manager: ______________________________

E-mail: ______________________________

Address: ______________________________

Fax: ______________________________

City: ______________________________

Cell: ______________________________

Resident/housing goal for audit: ______________________________

Directions to home: ❑ Mapquest print-out attached

____

❑ Resident/housing personnel will have house plans available

❑ Resident/housing personnel has 12 months of utility bills available

Heating degree days for location: (from bill when possible) [ ]

Cooling degree days for location: (from bill when possible) [ ]

Bill Analysis Results:

Gas Total	____________ therms		Electrical Total	____________ kWh
Heating	____________ therms		Cooling	____________ kWh
Baseload	____________ therms		Baseload	____________ kWh

Btu/hdd/ft² = ______________________________

Resident/Housing Personnel Interview

Interview Date: ____________________________________ Inspection Start Time: ______________________________

Interviewed by: ____________________________________ Inspection Completion Time: _________________________

Shoe policy:
____

Pets/pet doors:
____

Misc information:
____

Utility bills or history available? Y / N

Floor plans available? Y / N

Outside temperature: [ ]

Outside relative humidity: [ ]

Wind speed & direction: [ ]

Indoor relative humidity: [ ]

Type of thermostat

Set back practices

Summer thermostat settings

Winter thermostat settings

Number of occupants: _________________________________

Occupant ages: ____

Occupied hours: _______________________________________

Type of building: ❑ Attached ❑ Detached

House square footage: _________________________________

Number of floors: ______________________________________

Age of house: ____

Currant occupants since: __________________________________

Smokers in home: ______________________________________

Humidifier:

Customer concerns, questions and observations:

❑ Cold rooms? ❑ Stratification?

❑ Respiratory problems?

❑ Child or elderly health?

❑ Chemical sensitivities?

❑ Moisture damaged areas?

❑ Open windows?

❑ Storage of cleaning products?
❑ Condensation on windows?

❑ Hot rooms?

❑ Drafts?

❑ Closed rooms?

❑ Closed supply vents?

❑ Dust?

❑ Odors: gas, sewer, other?

❑ Humidity?

❑Additions, retrofit work, space conversions?

❑New Appliances?

❑Furnace ❑Boiler

❑Furnace filter change? #____per year

❑Gas fireplace/stove? #____Use frequency___

❑Wood fireplace/stove? #___Use Frequency___

❑Noise issues?

❑Pests? What kinds?

Type of thermostat(s)? Do you know how to use the set back features?

Summer settings and set back practice.

Does heat coming on in frequent, short cycles?

Use of humidifier? Dehumidifier? Areas of moisture damage? Condensation on windows?

Where do you spend the most time? Cold

Are room air conditioners or electric space heaters used?

Type of ventilation in kitchen and bathroom and how it is used? Are there timers?

Notes:

Outside Temperature_____ Outside Humidity______Inside Temperature________ Inside Humidity ______

Floor Plan: Sketch floor plan. Indicate position of doors and windows. Locater supply and return ducts. Mark and number HVAC supply and return duct grilles, #1 closest to heat source. Transfer numbers to list in ***Ducts and Vents*** section. ***Include ceiling height.***

Site Inspection

Orientation: ______________________

Solar shading: ______________________

Overhangs: ______________________

Trees: ❑ Deciduous ❑ Conifers

Landscaping close to house: ____

Water management:

❑ Gutters ❑ Downspouts ❑ Foundation drains

Annual precipitation: ____________________________

Site slope & barriers to drainage: ______________________________

❑ Sprinklers next to house

Sprinkler run times: _________________________________

Total inches: ____

Roofing fitness: _______________________________________

Roof type: _____________________________________

Water Damage on Exterior:

❑ Peeling paint ❑ Water stains ❑ Dry rot ❑ Mold

Windows:

Frame: _________ Condition:

Thermal Break: Condition:

Glazings:__________ Condition:

Winter/storm protection:

Square footage by Orientation:

North:

South:

East:

West:

Skylights:

Notes on Windows:

Doors Type*:* ___Patio doors _______French doors _______Vertical _______ Horizontal ______Fixed

Insulation: _____________
Glazings: ______________
Frame:

Notes re doors:

Condition:
House gutters: copper / galvanization

Crawl space: Y/N Basement: Y/N

Accesses: ____

Conditions noted:

Number of Vents/window ____________ ______

Vent sizes: __________________________

Vent Safety /External:

Check vent terminations

Clearances must be at least 24"

Building openings? Y / N   Above roof? Y / N

Obstructions? Y / N   All vents go outside? Y / N   Bushes by vent openings? Y / N

Notes:

____

Cooling Equipment:

❑ **Consider Replacement,** ❑ **Other Improvements**

Equipment:

Type: ❑Condensor ❑ Evaporative ❑Radiant
❑Room ❑Whole house ❑Ducted
❑Through the wall ❑Window ❑Roof top
❑Split ❑Heat pump ❑Other

Outdoor Unit Data Plate Capacity [______________] ***tons***

Outdoor Unit Model # ____

Outdoor Unit Serial # ____

Outdoor Unit Condition: fins clean, fin air flow ____

Equipment Age ____

Cooling Coil Model # ____

TXV Installed ____

Coil Condition: dirty, pan functional ____

Input Temperature [__________] **°F, Output Temperature** [__________] **°F, AC Δ T** [__________] **(15°F – 21°F)**

Measured Combustion Efficiency (from section 6) [________________________]

❑ **Needs Improvement,** Measure cooling total efficiency (cooling delivered at each supply grille wet bulb temperature and CFM – need a big table and an Enthalpy chart)

Total air flow with a flow plate (optional)

❑ **Needs Improvement,** Check refrigerant charge *(need information to do both superheat and subcooling),* (optional)

❑ **Needs Improvement,** Run-time % on hot day for AC sizing check (optional)

Electrical Service:

Make ___________________

Size [__________] Amps

Breakers Labeled: Y / N

Spare Breaker spaces: Y / N

Estimated Delivered Sensible SEER:

$$\frac{\text{Delivered Sensible Capacity * Nominal SEER}}{\text{Nominal Sensible Capacity}} = \text{Est. Del. Sens. SEER}$$ [__________]

Delivered Sensible Capacity = Delivered CFM * ΔT * 1.08 (delivered CFM & ΔT from section 10)

Nominal Sensible Capacity = Nominal Tons * 12,000 * 0.7

(duct leakage, duct conduction, refrigerant charge and line set sizing, low evaporator air flow, coil selection)

Thermal Looping:

Examine attic and basement for open causeways that would allow thermal loops.

Check interior wall temperatures.

Check cement block wall temperatures.

Gas Testing: **Check to see if natural gas or propane is used for heat, hot water, cooking, clothes drier, or elsewhere.**

Examine for gas leaks. Take immediate action if leaks found. ❑ Okay. No leaks.

Thermostat:

❑ Consider Replacement ❑ Other Improvements

Thermostat Make & Model ____________________

❑ Set back model ❑ Electronic

Heat Setting ____________________ Cool Setting ____________________

Heat Set back ____________________ Cool Set-back ____________________

❑ Anticipator. Check and adjust.

Electrical Outlet Stress Testing

Voltage Measured (fail if more than 132):

Failure Location	Flawed Ground	% drop >5

Electrical Appliance Inventory

Plug in refrigerator meters early in visit.

Appliance	**Model**	**kWh**	**Elapsed Time**	**kWh/yr**

Fridge 1				
Fridge 2				
Freezer				

Other Appliance Type	**Location**	**Fuel Type**	**Brand/model and notes**

Water Heater:

Water Heater Make ______________________

Water Heater Model ______________________

Storage Gallons _________________________________

Water Heater Btu/h input ____________________________

Water Heater Age __________________________

Signs of Deterioration (soot, rust, etc.)

____

Measured Hot Water Temperature__________________ *°F*

Measured Combustion Efficiency (%) [ ]

Recirculation Present Y / N

Pump Make, Model, Wattage

__________________________ Pump run hours [ ]

Water Flow Rates:

M. Shower [ ] gpm

M. Vanity [ ] gpm

M. Toilet per Flush [ ] gal

Bath 2 Shower [ ] gpm

Bath 2 Vanity [ ] gpm

Bath 2 Toilet per Flush [ ] gal

Kitchen Sink [ ] gpm

Other:

Consumer Education Opportunities & Appliance Operation Education:

Hot Water Set Temperature [ ] Mark setting with a pencil before moving in coordination with residents.

Other:

Heating Equipment:

❑ **Consider Replacement,** ❑ **Other Improvements**

Equipment Specifications:

Furnace Model ____

Furnace Serial ____

Equipment Age ____

Signs of Deterioration (soot, rust, etc.) ____

Furnace Size Btu/h input [   ]

Input Temperature [   ] ^{o}F, Output Temperature [   ] ^{o}F, Furnace Δ T [   ] (35^{o}F – 70^{o}F)

Measured Combustion Efficiency (from page 8) [   ]

Filter Visual Check:

Cleanliness:

Direction:

Connection to return plenum:

Notes:

Pressure Balance between Rooms: *Furnace Fan running.*

Notes:

Master Bedroom: ____________Pa ❑ *Pressure relief retrofit required*

Bedroom 2: ____________ Pa ❑ *Pressure relief retrofit required*

Bedroom 3: ____________ Pa ❑ *Pressure relief retrofit required*

Other room: ____________ *Pa* ❑ *Pressure relief retrofit required*

Other room: ____________ *Pa* ❑ *Pressure relief retrofit required*

Combustion Testing

First Step – Visual Inspection and Combustible Gas Sniffing Test (TIF)

Check for:

- ❑ Missing components
- ❑ Indicators of incomplete combustion (soot and aldehydes)
- ❑ Note and mark thermostat settings
- ❑ Close windows, open registers, open interior doors, close fireplace and damper

Test with TIF device; if leaks found:, describe and proceed only if very minor.

Second Step – Ambient Tests

House Ambient 1 – Center of house
All equipment in pilot only, 10 feet away from registers and equipment ☐ CO (PPM) (10+ PPM = fail)

House Ambient 2 – Same Location
Heater on for 5 minutes ☐ CO (PPM) (10+ PPM = fail)

House Ambient 3 – Closest supply register ☐ CO (PPM) Any increase over Ambient 2 test = fail

Furnace (or other space heater)

Name/ Location	CO PPM	Draft Tactile	Draft Smoke	Draft H2O	Eff. %	O2 %	Temp ˚F	Confined Space?		
___________		P / F	P / F					Y / N	:	❑ **Pass** ❑ **Fail**

Notes:

Water Heater

Name/ Location	CO PPM	Draft Tactile	Draft Smoke	Draft H2O	Eff. %	O2 %	Temp ˚F	Confined Space?		
___________		P / F	P / F					Y / N	:	❑ **Pass** ❑ **Fail**

Notes:

Other

Name/ Location	CO PPM	Draft Tactile	Draft Smoke	Draft H2O	Eff. %	O2 %	Temp °F	Confined Space?	
____________		P / F	P / F					Y / N	❑ Pass ❑ Fail

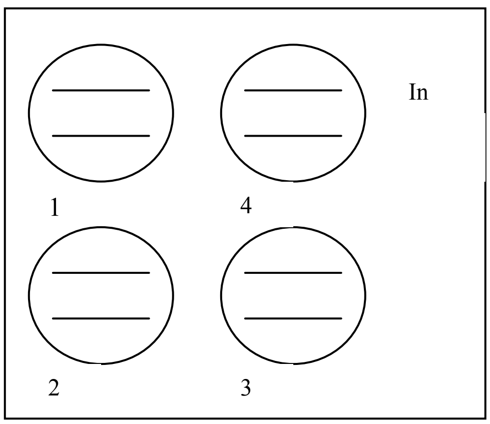
Notes:

Oven & Cooktop

Name/Location **Oven CO PPM**

________________ ❑ Pass ❑ Fail

Cooktop CO PPM



Other:

Name/Location **CO PPM**

________________ : ❑ Pass ❑ Fail

Fireplaces/Stove:

Location/fuel type **CO PPM**

________________ : ❑ Pass ❑ Fail

________________ ________________ : ❑ Pass ❑ Fail

Blower Door Test: Infiltration (Envelope Tightness)

Before testing configure building for winter. Double check to be sure combustion appliances are off and will stay off during testing.

Blower Door Test ____________ CFM_{50}

$ACH_{NAT} = (CFM_{50} * 60 \text{ minutes/hour}) / (20_{\text{or } N} * \text{House Volume feet}^3) =$ ____________ ACH_{NAT}

Rule-of-Thumb guidelines for an average tightness house: 1 CFM_{50}/square foot of floor area, 0.25 CFM_{50}/square foot of building surface area including the floor, 0.35 ACH_{NAT}.

Connected Spaces: With the house depressurized to 50 Pascals measure the pressure in all connected spaces with-respect-to outside.

Garage	____	Pascals	❑ Potential Repair ____________
Crawlspace	____	Pascals	❑ Potential Repair ____________
Attic	____	Pascals	❑ Potential Repair ____________
Porch Attic	____	Pascals	❑ Potential Repair ____________
____________		Pascals	❑ Potential Repair ____________
____________		Pascals	❑ Potential Repair ____________
____________		Pascals	❑ Potential Repair ____________

Blower door: All registers (supply and return) sealed: ____________ CFM_{50}

Duct leakage to outside (base test minus sealed register test): ____________ CFM_{50}

Notes & Potential Improvements:

(list areas that are candidates for air sealing, take digital photos)

Ducts and Vents

Duct: With blower door depressurizing house check each grille with pressure pan.

Room/Supply Duct # Grille size Pressure Pan

Vent Fans

Return Ducts

Others:

Ventilation Systems:

Kitchen:

Type: Ducted ___ Damper condition:_______________________________________

Filtered ____ Condition of filter: ____________________________________

Operation: Manual ___ Timer:____ Sensor: ________________Type:_____________

Bath 1:

Type: Ducted ___ Damper condition:_______________________________________

Filtered ____ Condition of filter: ____________________________________

Operation: Manual ___ Timer:____ Sensor: ________________Type:_____________

Bath 2:

Type: Ducted ___ Damper condition:_______________________________________

Filtered ____ Condition of filter: ____________________________________

Operation: Manual ___ Timer:____ Sensor: ________________Type:_____________

Whole House:

Type: Ducted ___ Damper condition:_______________________________________

Filtered ____ Condition of filter: ____________________________________

Operation: Manual ___ Timer:____ Sensor: ________________Type:_____________

Other:

Type: Ducted ___ Damper condition:_______________________________________

Filtered ____ Condition of filter: ____________________________________

Operation: Manual ___ Timer:____ Sensor: ________________Type:_____________

Lighting Inventory

Location	Type*	15 W	40 W	60 W	75W	100W	Other: describe	Improvements Recommended

* I = incandescent; CFL = compact florescent; T-12, T-8, T-5 = tube florescent type; H = halogen; LED = LED.

Insulation and Air Barrier Performance Inspection

Take photos to record condition as appropriate.

Ceilings: ❑ **Need Improvement,** ❑ **Perform Well,** ❑ **No Access**

		Ceiling Description	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Ceiling Description	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Ceiling Description:	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Ceiling Description:	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well			

Check areas that apply: Descriptions:

❑ Installation quality improvement
____

❑ Voids present
____

❑ Compressions at wiring, plumbing, ducting, etc.
____

❑ Interstitial spaces present
____

❑ Attic ventilation
____

❑ Access hatches size and insulation
____

❑ R-values, type, inches
____

❑ I.R. for R-value and air movement
____

❑ Framing size and on centers
____

Walls & Windows: ❑ **Needs Improvement,** ❑ **Performs Well,** ❑ **No Access**

		Wall & Window Description	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Wall & Window Description	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Wall & Window Description:	*Area*	*Existing R*

		Wall & Window Description:	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well			
❑ Needs Improvement	❑ Performs Well			

Check areas that apply: Descriptions:

❑ Installation quality improvement

❑ Voids present

❑ Compressions at wiring, plumbing, etc.

❑ Interstitial spaces present

❑ R-values, type, inches

❑ I.R. for R-value and air movement

❑ Framing size and on centers

Floors: ❑ Needs Improvement, ❑ Performs Well, ❑ No Access

		Description	*Area*	*Existing R*
❑ Needs Improvement	❑ Performs Well	Floor Description		
❑ Needs Improvement	❑ Performs Well	Floor Description		
❑ Needs Improvement	❑ Performs Well	Floor Description:		
❑ Needs Improvement	❑ Performs Well	Floor Description:		

Check areas that apply: Descriptions:

❑ Installation quality improvement

❑ Voids present

❑ Compressions at wiring, etc.

❑ Interstitial spaces present, balloon framing

- ❑ Access hatches size, rodent barrier

  ____

- ❑ R-values, type, inches

  ____

- ❑ Rodent presence or damage

  ____

- ❑ Odor present

  ____

- ❑ Moisture present

  ____

- ❑ Vapor present on soil

  ____

Post Audit Huddle

Good job! Now that we are thinking about what we have learned, the story of this house is….

Appendix D

References

ASHRAE Handbook of Fundamentals, 2005

Kinney, L. "Lighting Systems in Southwestern Homes: Problems and Opportunities." Prepared for the USDOE's Building America Program, July 2005. Available under *Daylighting* at www.SynertechSystemsCorp.com.

Kinney, L. "Duct Systems in Southwestern Homes: Problems and Opportunities." Prepared for the USDOE's Building America Program, April 2005. Available under *Energy Auditing* at www.SynertechSystemsCorp.com.

Kinney, L. "Windows and Window Treatments." Prepared for the USDOE's Building America Program, September 2004. Available under *Energy Auditing* at www.SynertechSystemsCorp.com.

Kinney, L. and R. Belshe. "Refrigerator Replacement in the Weatherization Program: Putting a Chill on Energy Waste." Special E SOURCE report for the Weatherization Assistance Program, September 2001. Available under *Energy Auditing* at www.SynertechSystemsCorp.com.