

Building-Shell Heat Flow

Heat flows through the building shell by three mechanisms: heat transmission, air leakage, and solar radiation. Transmission and air leakage occur through four independent pathways: floors and foundations; walls; roofs and ceilings; and *fenestration* — windows and doors. Solar radiation occurs through all of these but the foundation and floor.

Heat transmission through the building shell depends on two factors: thermal resistance and surface area. Air leakage in cubic feet of air per minute (CFM) depends on the surface area of the shell's holes and the pressure differences between indoors and outdoors. Solar radiation depends on the climate, season, and the building's solar exposure.

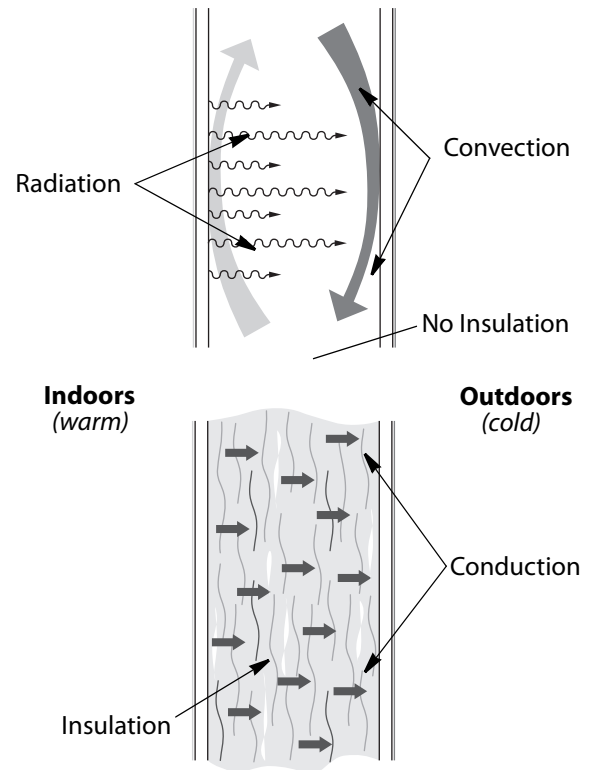
Windows are a special concern because of low thermal resistance, high solar transmittance, and significant surface area. Although they may be a comfort problem, doors have less energy loss compared to windows because their smaller surface area.

During winter, heat flows because of the indoor-outdoor temperature difference. During summer the main heat-driving force is solar radiation.



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Effect of Insulation



The uninsulated wall transmits heat through its air space by convection and radiation. In the insulated wall, heat must conduct through the tiny air pockets trapped by the insulation — a slower process.

Heat Transmission

Heat transmission is driven by the temperature difference between indoors and outdoors. A building's thermal resistance determines how much heat transmits through the shell.

When we say that insulation resists heat transmission, we mean it resists conduction, convection, and radiation heat flow through a building component. In the case of an uninsulated wall cavity, convection and radiation dominate heat transmission through the wall's empty cavity. Insulation, installed in that wall cavity, forces the heat to conduct from fiber to fiber and through the insulation's tiny air pockets — a slower heat-transmission process than convection and radiation.

See "Insulation Characteristics" on page 105.

Conductivity of building materials — A material's thermal conductivity describes how much heat in BTUs flows through a 1-inch-thick by 1-foot-square slab of that material each hour, when there is a 1-degree-Fahrenheit temperature difference between the slab's two surfaces. Thermal conductivity, denoted by the letter *k*, allows us to compare how well common building materials conduct heat.

Aluminum is the most conductive common building material: Its thermal conductivity is more than four times greater than steel, 900 times greater than wood, and 7,800 times greater than air. One square foot of steel, the next most conductive building material, conducts as much heat as 50 square feet of concrete, 200 square feet of wood, or 1200 square feet of glass wool, assuming all are the same thickness.

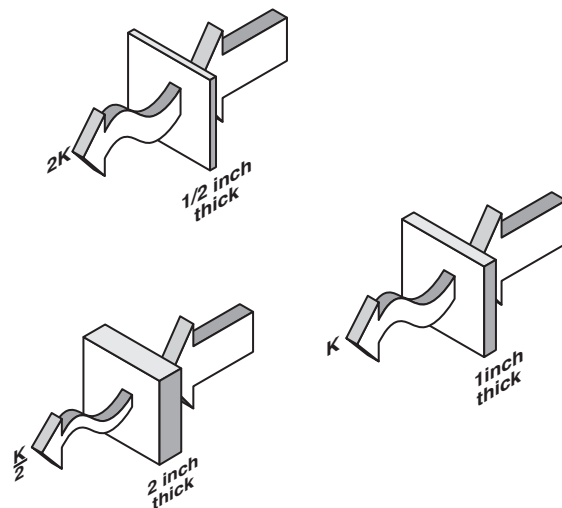
When very conductive materials are touching one another, heat flows rapidly through the building shell because even a small contact area can transfer heat rapidly. This phenomenon is called *thermal bridging*. Thermal bridging causes cold interior surfaces (such as aluminum window frames) during winter, and hot interior surfaces (such as west-facing masonry walls) during summer. Using less-conductive gaskets, called *thermal breaks*, between conductive materials such as glass and steel reduces this rapid heat flow.

Building-shell components, such as walls and roof assemblies, contain a variety of materials in their cross-sections. Depending on the location within a wall or roof, insulation or structural framing might be encountered. In a wood-framed wall, about 20% of the wall's surface area is solid wood and 80% is insulated stud space. The wall's average thermal resistance is an area-weighted average of these two different cross-sections.

Thermal Conductivity: Building Materials

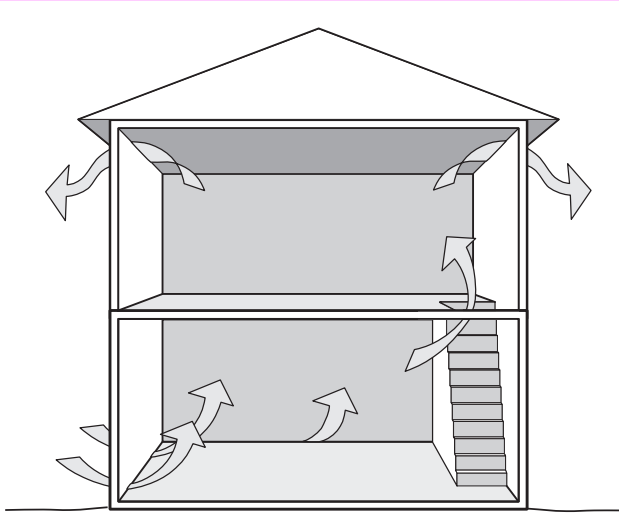
Material	Thermal Conductivity (k) BTU-in/hr·ft·°F
Aluminum	1400
Steel	310
Glass	7.8
Concrete	5.8
Brick	4.3
Wood	1.6
Rubber	1.4
Glass wool	0.26
Air	0.18

Thermal Conductivity: k-value



The k-value is the amount of heat (BTUs) that flows each hour through a 1-square-foot slab of material 1 inch thick, with a 1°F temperature difference between the slab's two sides. Heat-conduction rate depends on the material's thickness as shown here.

Stack Effect



Warm air rises and leaves the home through holes near the ceiling. Cold air enters near the floor to replace it.

Air Leakage

Air leaks into and out of buildings through penetrations in the building shell's interior and exterior skins. Although you'll find obvious air leaks around windows and doors, large hidden penetrations often dominate air leakage. Air leaks are either direct, penetrating all the way through the shell at one location, or indirect, entering at one location and exiting at another.

On continuous areas of the shell, an effective air barrier should border and touch the insulation. Without an effective air barrier, migrating air can move through the insulation, convect heat from the insulation's surface, or carry heat around the insulation. The leakage rate for building materials is measured in CFM per square foot of surface area or CFM per linear foot for joints between materials.

Existing buildings usually have several partial air barriers, rather than one single component designed as an airtight air barrier. For example, a home's wall has interior paneling, insulation, exterior sheathing, and siding — all of which resist airflow but don't stop it. Any airtight and continuous building component — exterior

sheeting, interior sheathing, air-barrier building paper — can be an effective air barrier if installed in an airtight manner.

Irregularities in the building's exterior shell — such as protrusions and penetrations — promote air leakage and may harbor a concentration of joints between building materials. These areas create insulation and air-sealing problems even for builders who understand the desirability of continuity at the thermal boundary.

See Chapter 3 Air Leakage.

Fenestration

Windows give natural light and views to rooms and are necessary for the resident's mental health. However, windows are often a built-in thermal flaw. The best new windows have R-values up to R-20, but most windows remain between R-1 and R-3. Windows are often the major source of solar heat gain during summer. Window glass transmits from 20% to 84% of the sun's heat depending on whether it is clear glass, low-e glass, reflective glass, or heat-absorbing glass. The building's window surface area, R-value, and solar transmittance determine the comfort and energy-efficiency of windows.

Windows affect comfort more directly than other building components because of their low thermal resistance and high solar transmittance. During winter, windows cool sensitive human body parts directly by radiation. Cold window glass cools air near its surface, causing this air to move downward, creating cool convection currents. Air leakage through windows adds to the feeling that windows are a major energy problem. In summer, a window's solar heat warms the room's furniture, flooring, and other surfaces, driving radiant and ambient temperatures up, causing discomfort, and consuming electricity for air conditioning.

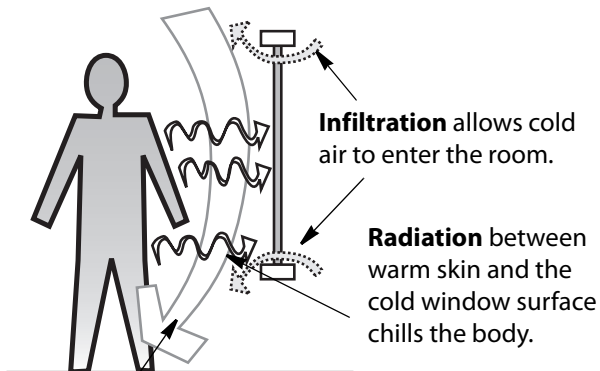
Many people assume window air leakage is a major energy and comfort problem, but in fact, most of the discomfort comes from windows' low

radiant temperature and convection currents created by their high heat transmittance. Many buildings have poor air quality due to their relative airtightness and lack of mechanical ventilation. Windows allow some incidental air leakage, which provides minimum ventilation to rooms with windows. To satisfy residents' need for fresh air, some new windows are manufactured with adjustable openings designed to admit ventilating air continuously.

Doors have a small surface area compared to other building components, making them relatively less important. Comfort, rather than overall energy loss, is generally the motive for weatherizing doors. Leakage around door frames causes discomfort, depending on a door's location, but a door's heat loss is comparatively small.

See Chapter 5 Windows and Doors.

Winter Window Comfort Factors



Convection currents form when air near the cold window surface cools, becomes denser, and flows downward, creating a continuous flow pattern.

Windows create three wintertime comfort problems.

Building Inspection and Diagnosis

Before you propose energy retrofits, a trained energy auditor should inspect and diagnose the building. The energy auditor must consider all major issues relating to energy conservation, health and safety, and building durability.

The inspection and analysis may include diagnostic equipment such as blower doors, infrared scanners, and heating-efficiency testers. This evaluation often incorporates utility-bill analysis and energy-savings predictions. Calculations determine the size of heating and cooling equipment, if replacement is a retrofit option.

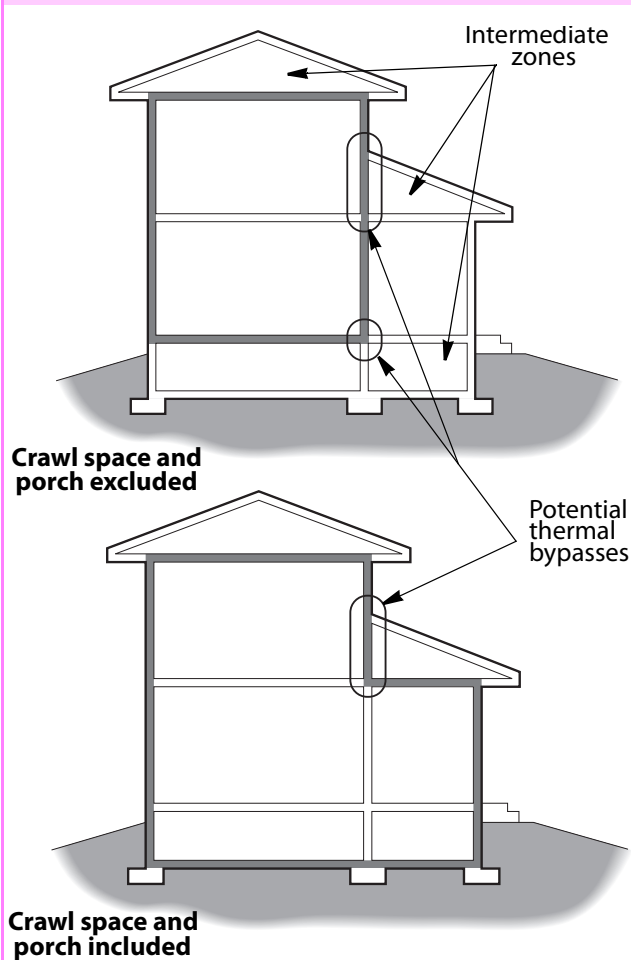
See "Finding Air Leaks" on page 86 for more information on actually locating air leaks.

Defining the Thermal Boundary

A thermal boundary should surround the conditioned space. Insulation and an air barrier are located at this thermal boundary. The conditioned space includes the building's heated or cooled areas. Heat transmission through the shell depends on the insulation's thermal resistance and the shell's surface area. Air leakage depends on building pressures and hole sizes — two factors determining the CFM-airflow between the building and outdoors.

Many buildings' total enclosed space is conditioned space, while other buildings contain areas that are neither heated nor cooled. These unconditioned spaces include attics, crawl spaces, and attached garages. Some places, such as furnace and boiler rooms, are warmed by waste heat. These are called unintentionally conditioned spaces. Unintentionally conditioned spaces and unconditioned spaces — also known as intermediate zones or buffer zones — are located between conditioned spaces and outdoors, slowing the building's heat flow.

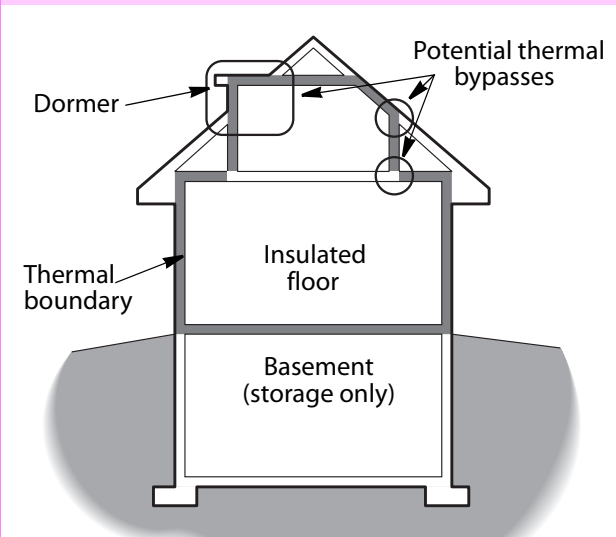
Thermal Boundary Decisions



The energy auditor and technicians choose thermal boundaries when they decide where to insulate. Those decisions are based on how the home's spaces are used and on practical considerations like access and cost of materials.

Defining the conditioned space includes evaluating the air barrier and insulation at the thermal boundary. The building may not have insulation or an air barrier totally surrounding the conditioned space. In that case, the energy audit should consider the cost-effectiveness of completing the air barrier and insulation, to surround the building entirely. A thermal boundary may surround only conditioned spaces, or it may include unconditioned spaces also. Factors involved in selecting the thermal boundary's location include:

Story-and-a-Half Home



This story-and-a-half home, with an attic converted to rooms, has thermal weaknesses above and beneath the knee walls, where air from an unheated attic can enter building cavities.

- ◆ The shell's existing insulation location and R-value.
- ◆ The effectiveness of existing air barriers.
- ◆ Incorporating potential areas of future use within the thermal boundary.

Energy auditors inspect the continuity of the air barrier and insulation. They develop a strategy for adding insulation and for sealing air leaks in the chosen air barrier, be it the building's interior surface, its exterior surface, or some other potential air barrier.

The air barrier and the insulation should be very close together. Air flowing against, around, or through the insulation is one of the most common energy wasters. Convecting air carries heat from one surface to another across air spaces. Airflow carrying heat across the thermal boundary and around the insulation is called a thermal bypass. When wind-driven air flows through the insulation, reducing its thermal resistance, this is called wind washing.

Though they may be outside the building's conditioned space, central forced-air furnaces, central air conditioners, and ducts are connected to the conditioned space. The cabinets of furnaces or air conditioners and the entire surface area of ducts outside the conditioned space must be considered to be inside the thermal boundary because the building's indoor air circulates inside the ducts. This is why ducts and furnace cabinets, located in unconditioned spaces, should be air-sealed and insulated.

See "Where to Insulate" on page 116, "Air Leakage Through Construction Materials" on page 77, and "Simple Air-leakage Diagnostic Methods" on page 87.

Unoccupied basements and crawl spaces

— The specific example of unoccupied basements and crawl spaces illustrates the decision-making complexities facing an energy auditor. No general rule applies when you consider whether to include a home's unoccupied basement or crawl space within the thermal boundary by retrofit insulation and air-sealing. This decision depends on climate, ground dampness, and the presence of ducts and pipes within the space, among other factors.

The most important practical consideration affecting this decision is the ease and cost of air sealing and insulating the floor versus air sealing and insulating foundation walls. For example, installing floor insulation can be a miserable job in a shallow crawl space; foundation insulation can be expensive when the foundation is built of rubble stone. Another important factor is that either the floor or the foundation may already be a good air barrier. If so, install the insulation at the most airtight location to reduce the effort needed for air sealing.

Energy auditors should consider potential energy-savings, moisture issues, and practical concerns when deciding whether to place the basement or crawl space inside or outside the thermal boundary.

Colder climates favor insulating the floor between the house and the crawl space (putting the crawl space outside the thermal boundary) because the cold ground causes greater heat loss through the floor compared to warmer climates.

Warmer climates favor including these partially subterranean areas within the thermal boundary. Heat loss through the floor in warmer climates is less compared to colder climates. The floor's heat loss to the cooler ground may aid in cooling the home during hot weather.

In a warm climate, it may not be cost-effective to insulate the floor or foundation walls. However, the energy auditor may decide to isolate a crawl space and the ground underneath it to mitigate existing moisture problems. This retrofit would include sealing the vents and installing an airtight ground-moisture barrier.

See "Basement and Crawl Space Insulation" on page 120.

Arguments favoring inclusion of unused basements and crawl spaces within the thermal boundary include these.

- ◆ Possible future occupancy of a basement.
- ◆ Waste heat from the furnace and water heater reduces heat loss through the floor above.
- ◆ Floor insulation can be difficult to install.
- ◆ The possibility of pipes freezing in cold climates if insulation and air sealing measures are installed between the house and basement.

Arguments favoring exclusion of unused basements and crawl spaces include these.

- ◆ Waste heat should be reduced at its source by insulating ducts, water heaters, pipes, and so on.
- ◆ Lacking heat sources, the basement or crawl space stays between ground temperature and outdoor temperature, which is usually above freezing.

- ◆ The floor is sometimes easier to air seal than the foundation because you can seal it from above or underneath or both.
- ◆ Floor insulation is inexpensive and often easy to install.
- ◆ In dry temperate or cold climates, comfort increases with floor insulation.
- ◆ Installing heating cable on pipes is often cheaper than heating an unused space to keep pipes thawed.

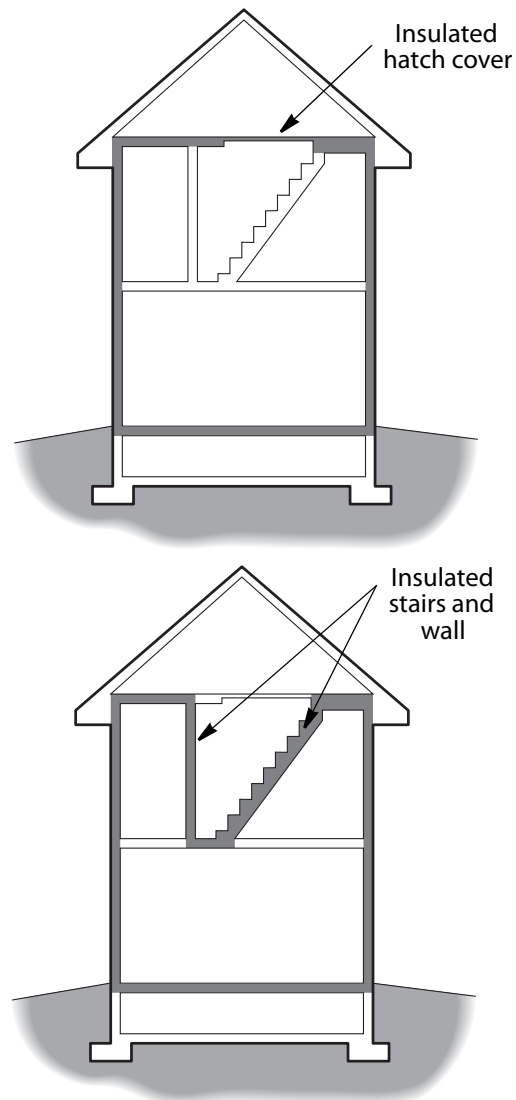
Consider the following specific examples.

House A's floor, over an unused basement in a cold dry climate, is easily accessible for insulation and air sealing. The ducts are fairly airtight, but uninsulated. The floor above the basement is a fairly good air barrier, but the foundation is leaky and difficult to insulate. A tight floor and leaky foundation walls favors air-sealing and insulating ducts, air-sealing and insulating the floor, blowing insulation into the walls of the basement's stairway, and installing electric heating cable on pipes close to the foundation's perimeter in very cold climates. The basement is placed outside the home's thermal boundary by these retrofits.

House B, located in a milder climate, has a pump and pressure tank in its crawl space. The ground under the house is covered by a moisture barrier, and the house has no moisture problems. Ducts are fairly leaky and lack insulation, but they would be difficult to insulate and air-seal. This situation favors sealing the crawl space vents and then insulating and air sealing the foundation walls and rim joist, thus including the crawl space within the home's thermal boundary.

As with any energy improvements, basement and crawl-space retrofits must compete with other energy improvements for available funds based on cost-effectiveness and practical feasibility. Insulating foundation walls or the first floor may not be cost-effective in the warmer U.S. climates.

Thermal Boundary Choices for Attic Stairs

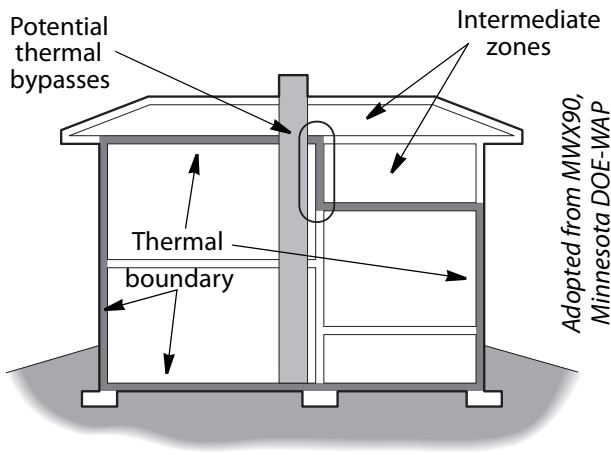


An insulated cover is the simplest way to define the thermal boundary around attic stairs. The alternative is to insulate and air-seal the stairs and surrounding walls. Stairs into an unconditioned basement present the same choice.

Visual Inspection

One way to learn about a building's construction is to inspect it thoroughly, including looking into floor, wall, and ceiling cavities. Experienced auditors know how buildings are constructed by having audited other buildings of the same type.

Split-Level Thermal Weaknesses



This split-level home has a thermal weakness where the chimney penetrates the ceiling, and also at the wall, where the uneven ceilings meet. These areas need careful inspection.

A thorough outdoor inspection may answer the following questions:

- ◆ What vertical shafts come through the roof (if visible from the ground)?
- ◆ Do the walls have protrusions or indentations, such as porches, bay windows, or cantilevered floors that break the continuity of the air barrier and insulation?
- ◆ Are there major seams between the building component elements? Are they deteriorated?
- ◆ Was the building built at one time, or in several parts? Is there an attached or built-in garage?
- ◆ Is the exterior shell airtight or leaky?

Answers to those questions help determine remedies for the building shell's energy and maintenance flaws.

Your interior inspection should identify the building's conditioned, unconditioned, and unintentionally conditioned areas. Determine insulation levels of the walls, floors, and roofs. Inspect the air barrier and insulation surrounding the conditioned space and notice voids, edge gaps, or

other flaws. Interior inspection involves checking basements, crawl spaces, attics, and other less visible areas for major air leakage sites. When inspecting the building visually from its interior, answer the following questions:

- ◆ What areas are used and unused?
- ◆ Where is the existing thermal boundary?
- ◆ What penetrations break wall, floor, and ceiling continuity?
- ◆ What indentations and shafts are intruding into the conditioned space from outdoors or from unconditioned spaces?
- ◆ What structures protrude from the building shell and are they currently conditioned or unconditioned?
- ◆ Are the insulation and air barrier continuous at the perimeter of the protrusions and indentations?
- ◆ What are the current and potential health and safety concerns?

See "Finding Air Leaks" on page 86.

Building Diagnostic Procedures

Visually inspecting all of a building's potential flaws can be difficult and time-consuming. A more practical, swift, and accurate way to diagnose building shell problems involves three diagnostic procedures: blower-door testing, infrared scanning, and duct-blower testing.

Since a large percentage of heat flow occurs at the building's thermal weak points, finding their locations is essential. Rather than seeking out each possible flaw and applying a prescriptive treatment, you can test and diagnose the problems and treat them in order of priority. Diagnostic equipment can reduce the time needed to find the important flaws in the insulation and air barrier.

In the 1970s, scientists and technicians began using blower doors and tracer-gas analysis to measure and locate air leaks. *Blower doors* are pressure-testing devices for the air barrier of a

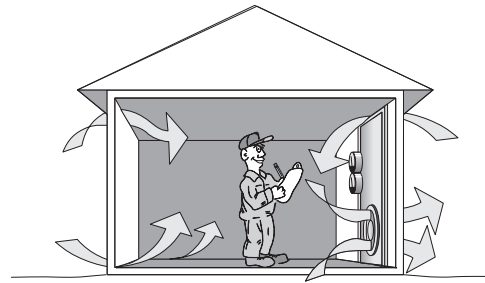
home. Infrared scanners allow the energy specialist to view heat flow through the building's thermal flaws.

Ducts, because they are full of indoor air, should be inside the thermal boundary. Tests on homes with ducted forced-air distribution systems generally indicate more air leaks than homes without ducts. Testing shows that ducted forced-air systems, when switched on, increased air leakage up to five times more than when those same systems were not operating. Special duct testing devices — called *duct blowers* — are often necessary to diagnose and correct duct air leakage.

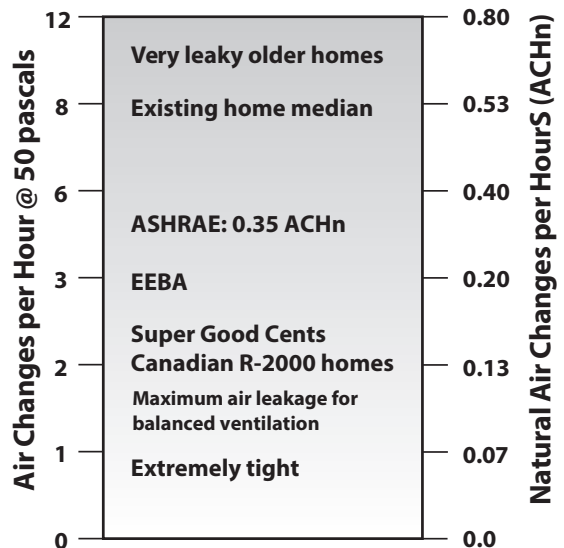
Blower-door testing is a practical and effective technique for estimating air leakage in homes. The blower door consists of a panel with a built-in fan that fits an open doorway. The fan pressurizes the home to a standard pressure. Gauges then measure the air leakage.

Blower-door testing helps energy professionals determine airtightness and decide if air-sealing work is necessary. If the building needs air-tightening, a blower door also helps locate specific areas in the home that allow air leakage. See “Blower-Door Testing” on page 82.

Blower-Door Testing

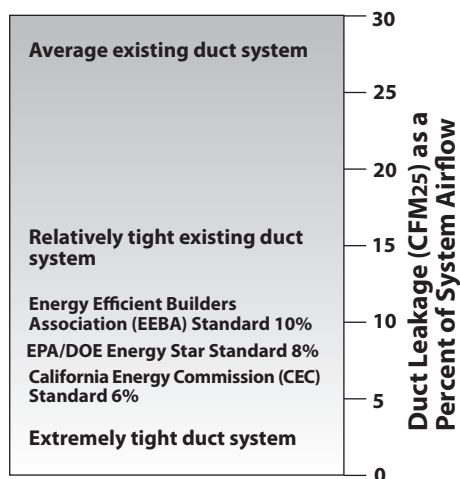


An instrument called a blower door measures and helps locate air leaks in homes.



The blower door's measurements are used to set shell leakage standards and compare homes to one another. (Assumes an n-value of 15)

Duct Leakage Comparisons



Duct blower measurements allow technicians to set standards and compare duct systems.

Duct blowers are actually small blower doors connected to the duct system. Duct blowers measure the severity of duct leakage and help locate leaks. See “Duct-testing Strategies” on page 91.

Infrared scanners are optical viewers or cameras that reveal temperature differences. (Standard cameras reveal differences in light brightness.) Using infrared scanners, energy auditors can detect heat transmission and air leakage. Finding hidden air leaks is possible using the blower door and infrared scanner together. See “Infrared Scanners” on page 89.

Calculating Building Heat Loads

In a building, there are three primary modes of heat transfer to consider when calculating space-conditioning loads: heat transmission, air exchange, and solar radiation. These losses and gains are collectively referred to as heating and cooling loads. The purpose of calculating these loads is to size heating and cooling equipment and to determine annual heating and cooling energy consumption.

Consider the following factors when calculating a building's heating and cooling loads.

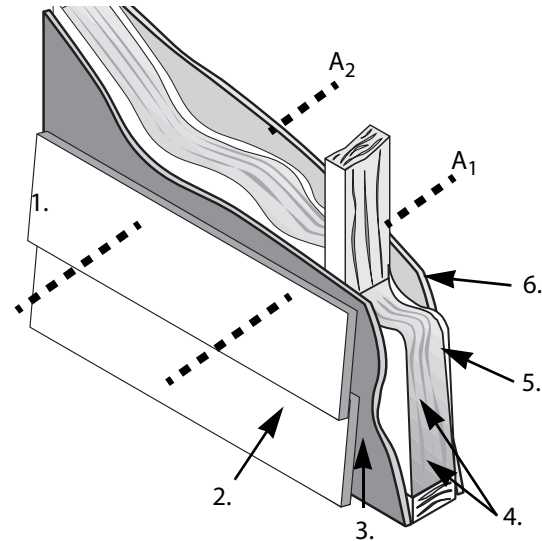
- ◆ Heat transmission through walls, floors, ceilings, windows and doors
- ◆ Air leakage and ventilation
- ◆ Solar radiation through glass
- ◆ Solar radiation falling on roofs and walls
- ◆ Buffering effect of heat stored in building components (mass)
- ◆ Internal heat gains
- ◆ External and internal moisture (latent) loads
- ◆ Local climate
- ◆ Indoor temperature

Computer-based energy modeling programs greatly simplify load calculations. However, users of these programs should have a basic understanding of underlying concepts in order to achieve accurate results.

Utility- and government-sponsored conservation programs often require computer-based energy modeling since this standardizes the evaluation process and may help to maximize the energy saved per dollar invested.

Heat transmission — The amount of heat that flows through a building assembly such as a wall depends on the indoor-outdoor temperature difference, the exposed surface area, and the thermal resistance or R-value of the materials that make up the assembly.

Wall U-factor and R-value Calculations



Numbered Wall Component	R (A ₁) Framing	R (A ₂) Insul.
1. Outside Air Film	0.17	0.17
2. Lapped Wood Siding	0.81	0.81
3. OSB Sheathing (1/2")	0.62	0.62
4. Framing or Insulation	*4.38	13.0
5. Gypsum Wall Board (1/2")	0.45	0.45
6. Inside Air Film	0.68	0.68
Total R	7.11	15.7
U-factor	0.14	0.063
Percentage of total wall area	0.25	0.75

* R-value of 3.5-inch wood stud

Calculation: Area-Weighted Average U-Factor

$$U = (A_1 \times U_1) + (A_2 \times U_2)$$

$$U = (0.25 \times 0.141) + (0.75 \times 0.0637)$$

$$U = 0.0830$$

Calculation of R-value from Average U-factor

$$R = 1/U = 1/0.0830 = R-12.0$$

U-factors for the framed (A₁) and insulated wall (A₂) areas are blended by an area-weighted average. The inverse of this averaged U-factor is the average R-value.

Building assemblies usually contain layers of materials. You can calculate the thermal resistance of the structure by adding the R-values. For example, if you install R-4 insulated sheathing on an R-15 wall, the total R-value for the wall becomes R-19.

See “Materials/Building Assembly R-Values” on page 278.

The figure and table shown on page 68 demonstrate how to calculate the effective R-value for a wall, where studs and plates interrupt the insulation. In this example, the framing lumber occupies 25% of the wall while the insulation occupies 75%. This ratio is called the framing factor. Most energy modeling programs calculate area-weighted R-values and require the user to enter the R-value of the insulation and, in some cases, the R-value of the framing.

By convention, the thermal performance for windows, skylights, and glass doors is specified in terms of thermal transmittance, or U-factor, which is the inverse of the R-value. The U-factor is measured in BTUs per hour per degree Fahrenheit (°F) per square foot. A material with a thermal resistance of R-1 has a U-factor of 1, an R-2 material has a U-factor of 0.50, an R-4 material has a U-factor of 0.25, and so on.

Once you know the R-value (or U-factor) of a component, you can easily calculate its heat transmission (q) by multiplying the component's transmittance (U), exposed surface area in square feet (A), and temperature difference in °F (ΔT) together.

$$q \text{ (BTUH)} = U \times A \times \Delta T$$

The exposed surface area of a wall, ceiling or floor is typically measured to the outside edge of the framing. The surface area of windows and doors is typically based on rough opening dimensions. The ΔT is the difference between the indoor and outdoor design temperatures, described later in this section.

Air exchange — You must account for air leakage and ventilation when calculating heating and cooling loads. The impact of air exchange on heating and cooling loads depends on the temperature difference between the outdoor and indoor air and the rate of air exchange into and out of the building.

For every cubic foot of air that enters a building, a cubic foot escapes. The energy that heated or cooled the escaping air is lost when it leaves the building. You can limit ventilation or reclaim the escaping air's energy through a heat-recovery ventilator or an energy-recovery ventilator, to minimize the energy cost of ventilation.

See “ASHRAE Ventilation Standard” on page 251.

Air leakage is difficult to quantify without using a blower door. Air leakage is either expressed in cubic feet per minute (CFM) or air changes per hour (ACH), also known as the air exchange rate. CFM can be converted to ACH and vice versa if the volume of the space is known:

$$ACH = (CFM \times 60) \div \text{Volume (cu.ft.)}$$

$$CFM = (ACH \times \text{Volume cu. ft.}) \div 60$$

Each cubic foot of air that enters the home requires 0.018 BTU to change its temperature by 1°F. If you know the airflow rate (CFM) and how many degrees (°F) the outdoor air needs to change, you can estimate the amount of heat to be added or removed from the incoming air.

$$q \text{ (BTUH)} = CFM \times 0.018 \times \Delta T \times 60$$

Solar radiation — When solar radiation passes through a window or glass door, it heats the building. Solar heat gain reduces a building's heating load during the winter and increases the cooling load during the summer. The amount of solar gain depends on orientation, reflectivity, shading, and glass properties.

You must account for solar gain when calculating the annual heating and cooling loads. Solar gain is usually ignored when calculating the heating design load for equipment sizing since peak heating loads occur at night and during months when available solar energy is small. The exception is highly insulated buildings that are designed to be solar heated. Cooling equipment must always be sized to handle solar gain since peak solar gain coincides with peak cooling loads.

Solar heat gain calculations are complex and best performed by software programs. Solar heat gains through windows are the most important. The software user provides data for each window: the orientation, *Solar Heat Gain Coefficient* (from the window's energy label), and a *shading coefficient*. Most programs calculate the effect of overhang shading based on user inputs that define the geometry of the overhang.

Other Load Factors

There are some other factors to consider when calculating heating and cooling loads. The mass of building components, heat gains from things inside the building, and latent heat in moisture all contribute to the building's heating and cooling load.

Thermal mass — A building absorbs and releases heat in cycles as the outdoor temperature changes. Mass can have a significant buffering effect on heating and cooling loads, especially for buildings with masonry slabs or high-mass walls. Passive solar homes are optimized to maximize solar gain and heat storage during the winter and minimize solar gain during the summer.

The effects of thermal mass are typically ignored when calculating design loads for equipment sizing since the equipment must be able to handle peak loads during periods of prolonged cold or hot weather when a building's mass can become fully depleted or fully saturated.

In hot sunny climates, thermal mass and solar gain can greatly reduce the heating load. Likewise in cool climates, thermal mass can reduce or even eliminate the need for air conditioning. Unfortunately, established load calculation procedures don't account for the effect of thermal mass.

Internal heat loads — People, lights, and appliances all generate sensible heat. These internal loads are usually ignored when sizing heating equipment, but they must be included when sizing cooling equipment. Each occupant is assumed to generate 230 BTUH. Appliance, equipment, and lighting loads can be estimated based on their power ratings and frequency of use. Load calculation procedures include tables with typical internal load profiles.

Moisture loads — Air conditioners remove both sensible and latent heat from buildings. An air conditioner's latent load results from water vapor condensation on the evaporator coil. Air leakage is a major source of moisture in buildings, which depends on the air-leakage rate and the humidity of the outside air. Internal moisture generated by people, bathrooms, cooking, laundry, and plants add further to the latent load. The amount of moisture that an air conditioner removes depends on its latent capacity and the amount of moisture in the air. The energy required to condense this moisture must be included in the cooling-load calculations.

Calculating Heating Load or Input Rating

Transmission Heating Load

Transmittance	Area	Temperature difference	Transmissive Load
$U \frac{\text{BTUs}}{\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}}$	$\times A \text{ ft}^2$	$\times \Delta T \text{ } ^\circ\text{F}$	$= q \frac{\text{BTUs}}{\text{hr}}$
0.083	$\times 7000$	$\times 79$	$= 45,899 \frac{\text{BTUs}}{\text{hr}}$

Air Exchange Heating Load

Air's heat capacity	Air flow rate	Temperature difference	
$\frac{\text{BTUs}}{\text{ft}^3 \cdot ^\circ\text{F}}$	$\times F \frac{\text{ft}^3}{\text{hr}}$	$\times \Delta T \text{ } ^\circ\text{F}$	$= q \frac{\text{BTUs}}{\text{hr}}$
0.018	$\times 4500$	$\times 79$	$= 6399 \frac{\text{BTUs}}{\text{hr}}$

This simplified heat load (q) calculation assumes that a home in Madison, Wisconsin has a surface area of 7000 square feet, an average R-value of 12 ($U=0.083$), air leakage of 4500 cubic feet per hour (0.50 air change per hour). Madison's design temperature is -9°F , 79°F temperature difference (ΔT) from the 70° desired indoor temperature. Real heat load calculations employ separate calculations for walls, windows, ceilings, and floors with their different U-factors.

Calculating Heater Output and Input

$$q_{(\text{transmis.})} + q_{(\text{air})} = \text{Output Rating}$$

$$45,899 \frac{\text{BTUs}}{\text{hr}} + 6399 \frac{\text{BTUs}}{\text{hr}} = 52,298 \frac{\text{BTUs}}{\text{hr}}$$

$$\frac{\text{Output Rating}}{\text{Heating Efficiency}} = \text{Input Rating}$$

$$\frac{52,298 \frac{\text{BTUs}}{\text{hr}}}{.80} = 65,373 \frac{\text{BTUs}}{\text{hr}}$$

The difference between input and output is the heat wasted up the chimney and through the heater's cabinet. The heater's input rating is usually increased by 10% or more as a safety factor to insure customer satisfaction during the coldest weather.

Heating and Cooling Design Loads

When working with heating and cooling loads, don't confuse *design* loads with *seasonal* or *annual* loads. The design load, expressed in BTUH (BTUs per hour), is the predicted *rate* at which heat must be added or removed from a building at near-peak conditions, while the seasonal or annual load, expressed in MMBTU (millions of BTUs), is the amount of heat added or removed over the course of a season or a year.

Heating and cooling design loads provide a basis for sizing space conditioning equipment. Complete procedures for calculating heating and cooling loads are found in the ASHRAE *Handbook of Fundamentals* as well as *Manual J*, published by ACCA. ASHRAE is the American Society of Heating, Refrigerating, and Air Conditioning Engineers and ACCA is the Air Conditioning Contractors of America.

Ideally, equipment capacity should closely match a building's load at the design conditions. Design conditions include outdoor temperature, solar radiation, wind, indoor temperature, and relative humidity. Note that design conditions aren't the same as worst-case conditions. You don't need to size equipment based on worst-case climate extremes, and it isn't advisable.

ASHRAE maintains a climatic database for over 1,500 locations in the United States and Canada, last updated in 2009. This database includes statistical temperatures and other weather data. The 99th and 1st percentile temperatures are commonly used for sizing heating and cooling equipment.

The outdoor design temperatures for Baltimore are 17°F and 91°F . Over a period of decades in Baltimore, the temperature was at or below 17° for one percent of the hours, while exceeding 91° for one percent of the hours.

ACCA and ENERGY STAR have adopted the 99%–1% outside design temperatures. This means that space-conditioning (heating and cooling) systems are designed to operate continuously at these two

design temperatures. Due to the buffering effect of a building's mass, the indoor temperature is unlikely to deviate more than a couple of degrees from the thermostat setpoint when design temperatures are exceeded (low or high).

Indoor design temperatures for new homes are typically 70°F for heating and 75°F for cooling. In existing homes, consider the occupants' temperature preferences instead of these default temperatures. Indoor humidity is assumed to be 50% in most climate zones. Cooling system sizing is affected by both the sensible (dry bulb) and latent (wet bulb) design temperatures, while the heating system is only affected by the dry bulb temperature.

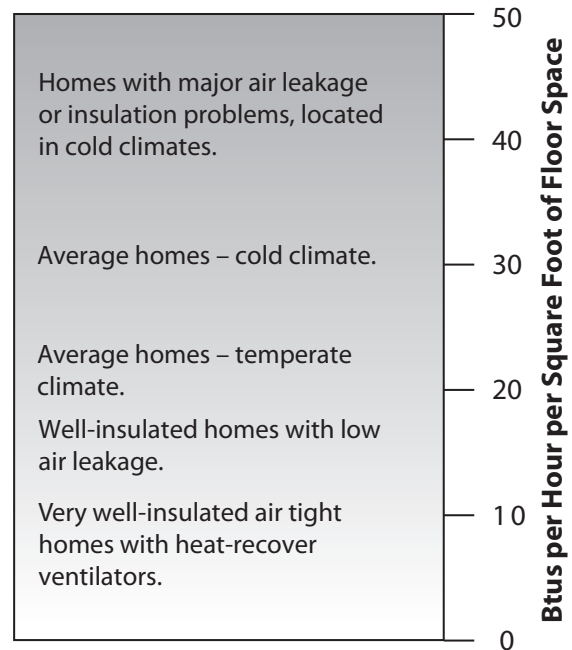
For definitions of wet-bulb and dry-bulb temperatures, see "Glossary" on page 257.

Benefits of right-sizing — Contractors and homeowners both should understand the importance of proper sizing, especially for air conditioners. Oversized HVAC equipment has the following disadvantages.

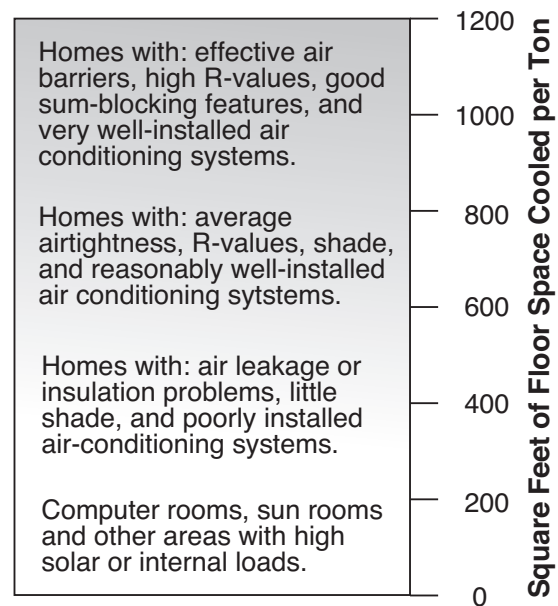
- ◆ Oversized equipment costs more and requires larger electrical circuits.
- ◆ Oversized compressors have a shorter life expectancy due to short cycling.
- ◆ Excess capacity results in comfort issues due to larger temperature variations.
- ◆ Oversized air conditioners remove less moisture, an issue in humid climates.
- ◆ Excess capacity compromises indoor air quality (less run time = less filtration).
- ◆ Excess cooling capacity increases potential for structural damage from moisture.
- ◆ Oversized equipment costs more to operate due to inefficient short cycling.

See "Sizing and Selecting Air Conditioners" on page 215.

Variation in Heating and Cooling Loads



The number of BTUH heating capacity needed by a building depends on climate, insulation levels, air leakage, and heating installation's quality.



The number of square feet of floor space that can be cooled by a ton of air-conditioning capacity depends on climate, shade, insulation levels, internal heat gains and air leakage.

Heating and cooling equipment efficiency

— Heating and cooling system efficiency is the output capacity divided by the equipment's instantaneous energy consumption (input). Efficiency losses include both energy waste and energy conversion losses, which are reflected in the equipment's rated output capacity. Therefore, equipment efficiency isn't necessary for the load calculation procedure. Rather, efficiency ratings play an important role in equipment selection.

See "Types of Efficiency" on page 148 and "Air-conditioner Efficiency" on page 214.

Heating and cooling distribution losses

— Duct efficiency losses include both heat transmission and air leakage. Heat transmission through the duct walls depends on the temperature difference, surface area, insulation R-value, and the amount of air flowing through the duct.

For practical reasons, duct-efficiency losses are considered part of the building load. ASHRAE establishes procedures and equations for estimating duct efficiency losses, which then become part of the building load.

Duct air leakage is difficult to estimate without measurement using a duct blower. The impact of duct leakage depends on the amount of leakage and where the leaks are located. Leakage on the return side can increase or decrease the load, depending on the ambient temperature and humidity of the air entering the return ducts. Leakage on the supply side, when located outside the thermal boundary, always increases the load since the heating or cooling system must condition more air to make up for the conditioned air that escapes.

See "Duct Air Leakage" on page 89.

Air-handler cabinets also transmit heat and leak air. These heat losses and heat gains don't figure into equipment efficiency ratings because the cabinet is assumed to be located inside the ther-

mal boundary. When an air handler is located outside the thermal boundary, you should include cabinet heat flows for the load calculations.

Penetrations for refrigerant lines and condensation drains are often serious air leaks. When you conduct a duct leakage test, the cabinet is part of the tested duct system so any leaks are included in your duct-leakage measurement.

Whenever possible, mechanical equipment and duct systems should be located inside the thermal boundary. Efficiency losses associated with interior ducts are generally ignored when calculating heating and cooling loads. However, these losses affect the performance of the air distribution system and should ideally be reduced by air sealing and insulation.

Annual heating and cooling loads — The primary purpose of calculating annual heating and cooling loads is to predict savings from energy-efficiency improvements. Calculating these annual loads before and after an improvement estimates the savings provided by that improvement.

The heat loss (Q) in BTUs over any time period (usually a season or a year) can be calculated by multiplying the total heat transmittance (U), area in square feet (A), temperature difference in °F (ΔT), and time period in hours (t). This formula is as follows:

$$Q \text{ (BTU)} = U \times A \times \Delta T \times t$$

Degree-days combine ΔT and t in the above formula. Heating degree-days (HDDs) and cooling degree-days (CDDs) are typically based on a balance-point temperature of 65°F. The balance point, also called the base, is the outdoor temperature at which no heating or cooling is required. The degree-day base is typically set lower than the heating and cooling design indoor temperatures due to the effects of solar gain.

Heating degree-days are calculated by subtracting the average daily temperature from the base, while cooling degree-days are calculated by subtracting the base from the average daily temperature. (Ignore negative numbers because no space conditioning is required if degree days are zero or negative.) For example, if the high temperature on a particular day is 45°F and the low temperature is 15°F, then the average temperature is 30°F. In this case, 35 heating degree-days would accumulate for that day. Use the formulas below to calculate HDDs and CDDs.

$$\mathbf{HDDs = 65 - 1/2(T_{high} + T_{low})}$$

$$\mathbf{CDDs = 1/2(T_{high} + T_{low}) - 65}$$

The annual heating and cooling degree-days are the total degree-day values for an entire year. The average HDDs and CDDs for a location are based on historical climate records. For example, Caribou, Maine, experiences an average of 9767 HDD, while Wilmington, North Carolina, experiences 2347 HDD.

While degree-day calculations provide a rough estimate of annual heating or cooling loads, an energy-modeling program is an essential tool for making accurate and repeatable calculations. When analyzing existing homes, some energy-modeling programs can refine their predictions using historical energy usage from utility bills, which greatly improves accuracy. Some energy modeling programs prioritize suggested energy improvements based on their cost-effectiveness.

Seasonal Heat Load: Effect of Insulation

Transmittance	Area	Heating degree-days	Change days to hours	Annual heat loss
$U \frac{\text{BTUs}}{\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}}$	$\times A \text{ ft}^2$	$\times \Delta T \frac{\text{HDDs}}{\text{year}}$	$\times 24 \frac{\text{hrs.}}{\text{day}}$	$= Q \text{ Therms or Decatherms per year}$
Before insulation				
0.29	$\times 100$	$\times 5864$	$\times 24$	$= 40.8$ Therms or Decatherms per year
After insulation				
0.069	$\times 100$	$\times 5864$	$\times 24$	$= 9.71$ Therms or Decatherms per year

Calculation of Savings

$$40.8 \frac{\text{Therms}}{\text{year}} - 9.71 \frac{\text{Therms}}{\text{year}} = 31.1 \frac{\text{Therms}}{\text{year}} \quad \text{Savings}$$

$$31.1 \frac{\text{Therms}}{\text{year}} \times 0.805 \frac{\$}{\text{Therm}} = 25 \frac{\$}{\text{year}}$$

Cost of Wall Insulation

$$0.75 \frac{\$}{\text{ft}^2} \times 100 \text{ ft}^2 = \$75 \quad \text{Cost}$$

Payback and Annual Return

$$\text{Payback} = \frac{\text{Cost}}{\text{Savings}} = \frac{\$75}{25 \frac{\$}{\text{year}}} = 3 \text{ years}$$

$$\text{Annual Return} = \frac{\text{Savings}}{\text{Cost}} = \frac{25 \frac{\$}{\text{year}}}{\$75} = 33\% \text{ per year}$$

These calculations outline an economic analysis of installing R-11 insulation in an uninsulated wall. We first calculate savings in therms, then convert therms to dollars.

Manual J Computer Calculation of Room Heat Flows and Air-Handler Airflows

Room	Area (ft ²)	Heating load (BTUH)	Heating Airflow (cfm)	Cooling load (BTUH)	Cooling Airflow (cfm)
Living room	255	4670	188	4568	221
Dining room	224	4219	195	2271	188
Kitchen	144	3201	91	2456	119
Bedroom 1	158	4410	142	1799	98
Bedroom 2	106	1730	53	771	41
Bedroom 3	99	3941	151	2492	136
Bathroom 1	80	1532	65	1206	78
Bathroom 2	60	771	29	521	39
Totals	1126	24,474	914	16,084	920

Calculating Loads With Computer Programs

Many energy auditors and HVAC contractors use computer programs to make heat-load calculations easy. The programs perform only as well as the person who enters the data.

Utility and government conservation programs prefer computer programs because they standardize decision-making procedures and help maximize energy savings per dollar invested.

Computer programs designed to calculate heating and cooling load can do one or more of the following.

- ◆ Calculate heating and cooling loads by room, as in the table above.
- ◆ Calculate airflow or water flow needed to heat and cool the building at design conditions.
- ◆ Calculate duct sizes or pipe sizes for the heating and cooling delivery system.

Computer programs designed to calculate seasonal energy loads can do one or more of the following.

- ◆ Calculate heat loss and heat gain before and after a retrofit to estimate the cost-effectiveness of energy retrofits.
- ◆ Predict energy usage to compare with actual energy use. This comparison helps evaluate the calculation's accuracy and indicates whether the building has significant hidden problems.
- ◆ Simulate variable building operations to see how energy consumption changes. These programs are especially useful for analyzing large, complicated buildings.
- ◆ Manage and keep records of decision-making for weatherization and home-performance jobs.

See "Analyzing Annual Energy Costs" on page 277.