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Measure Guideline: Condensing Boilers—Optimizing Efficiency and Response Time During Setback Operation

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Consortium for Advanced Residential Buildings

February 2014

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Prepared for:

The National Renewable Energy Laboratory

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Office of Energy Efficiency and Renewable Energy

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Definitions

ACCA	Air Conditioning Contractors of America
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
CARB	Consortium for Advanced Residential Buildings
gpm	Gallons per minute
IECC	International Energy Conservation Code
kBtu/h	Thousands of British thermal units per hour
$T_{out,max}$	Maximum outdoor temperature on the boiler reset curve
$T_{out,min}$	Minimum outdoor temperature on the boiler reset curve, equivalent to the design heating temperature
$T_{s,max}$	Maximum supply temperature that will be delivered at $T_{out,min}$
$T_{s,min}$	Minimum supply temperature that will be delivered at $T_{out,max}$

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Abstract

Conventional wisdom surrounding space heating has told us a couple of things consistently for several years now: sizing the mechanical systems to the heating loads and setting the thermostat back at night for a period of at least 8 hours will result in energy savings. The problem is these two recommendations oppose each other. A system that is properly sized to the heating load will not have the extra capacity necessary to recover from a thermostat setback, especially at design conditions. The implication of this is that, for setback to be successfully implemented, the heating system must be oversized.

This issue is exacerbated further when an outdoor reset control is used with a condensing boiler, because not only is the system matched to the load at design, the outdoor reset control matches the output to the load under varying outdoor temperatures. Under these circumstances, the home may never recover from setback. Special controls to bypass the outdoor reset sensor are then needed.

Properly designing a hydronic system for setback operation can be accomplished but depends on several factors. The savings to be achieved and the response times possible depend on the climate, the heat capacity of the home (mass storage), the level of setback desired, and the controls available. Determining the appropriateness of setback for a particular project is the first step in the process. This is followed by proper sizing of the boiler and baseboard to ensure the needed capacity can be met. Finally, control settings must be chosen that result in the most efficient and responsive performance.

This guide is intended to provide step-by-step instructions for heating contractors and hydronic designers for selecting the proper control settings to maximize system performance and improve response time when using a thermostat setback. It is applicable to both new construction and retrofit applications.

Acknowledgments

Steven Winter Associates, Inc. acknowledges the U.S. Department of Energy Building America program and its funding and support for the development of this technical report as well as research that informed it. Steven Winter Associates Inc. would like to thank John Siegenthaler of Appropriate Designs along with all the manufacturers and product suppliers who donated their time, expertise, and equipment: Dave Davis from Heat Transfer Products, Dave Scearce from Peerless, Mark Handzel with Bell & Gossett, Bob Reimund from Grundfos, and Parker Wheat with Emerson Swan. A special thanks to Scott Reynolds with Ithaca Neighborhood Housing Services for his continued support and the use of his homes for this research.

Progression Summary

Designing for Operation with Thermostat Setback

Reasons for Setback. Using thermostat setback with boost controls for recovery can result in improved efficiency, reduced cycling, and less energy consumption than systems operated in constant temperature mode. The following are the steps required to ensure efficient operation and optimal comfort.

Proceed with caution if the home has one or more of the following:

- A non-condensing boiler
- Insulation levels significantly higher than the 2009 IECC
- High mass floors and/or walls.

Determine If Setback Is Right for the Project

1 **Step One:** Determine if the use of setback is right for the project based on climate, level of mass in the building, insulation levels, and occupant wishes.

Sizing the Boiler

2 **Step Two:** Properly size the boiler to meet the design load plus the energy required to recover from a thermostat setback. Perform load calculations in accordance with ACCA's Manual J, and determine the extra capacity needed to bring the house to the desired temperature after a period of setback.

Sizing the Baseboard

3 **Step Three:** As with the boiler, it is essential that the heat emitters are properly sized for the loads. An undersized delivery system can lead to poor performance and comfort problems. Calculate the necessary length to ensure efficient boiler performance while providing an acceptable recovery time.

Determine the Outdoor Reset Settings

4 **Step Four:** Reset controls are an essential part of a hydronic system. They can dramatically increase the efficiency of the system and can result in improved occupant comfort. Determine the control settings that will best accomplish both of these tasks.

Select Boost Control Settings

5 **Step Five:** Select the proper settings for the boilers boost control. This control allows the boiler to bypass the outdoor reset controller if the space is not brought to temperature in a reasonable time. Determine the incremental increase in temperature and the amount of time between increases.

Verify Proper Operation

6 **Step Six:** Before leaving the job, verify that the outdoor reset control and the boost controls are performing as intended.

1 Introduction

The combination of a gas-fired, modulating condensing boiler with baseboard convectors has become a common energy-efficient solution for space heating in cold climates. A typical system configuration can be seen in Figure 1, which includes a modulating condensing boiler, distribution piping that includes a primary/secondary loop for hydraulic separation, baseboard convectors (not shown), pumps, and an indirect tank for providing the domestic hot water. While the rated efficiencies of these boilers are high, it is imperative to understand that if the systems are not properly configured, these heaters will perform no better than their non-condensing counterparts.

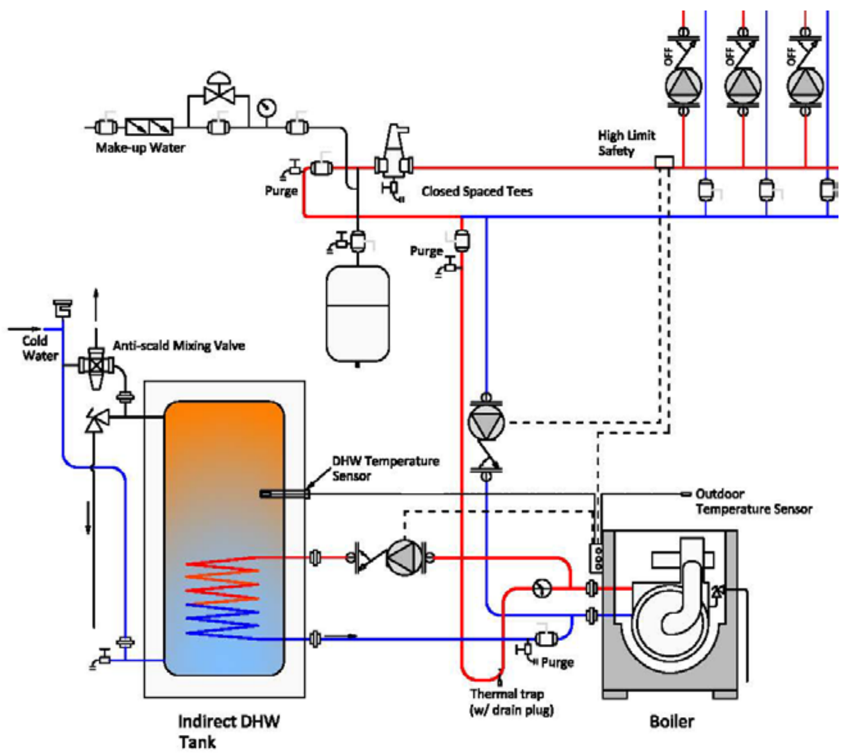


Figure 1. Condensing boiler with an indirect domestic hot water system and outdoor reset control

The reason condensing boilers achieve such high efficiencies is that they have the ability to recapture the latent energy from the moisture in the combustion gases when those gases condense. For condensing to occur, the boiler's heat exchanger surface temperature must be below the flue gas dew point. If the return water temperature is low enough, it will cool the heat

Latent Heat:

Latent heat is the heat that is added or removed due to a change in phase from a solid to a liquid or from a liquid to a vapor. In the case of a condensing boiler, it is the heat that is removed from the flue gases when the moisture changes from a vapor to a liquid.

exchanger below the dew point and condensation will occur. Therefore, strategies that lower the return water temperature will improve the boiler's efficiency.

The most reliable way to ensure that the return water temperature remains below the dew point is to install an outdoor reset control that modulates the boiler's output target temperature relative to the actual heating load. These controls consist of an outdoor temperature sensor and a special controller that communicates the current outdoor conditions to the boiler's standard controls. When using this type of control, the boiler's supply temperature decreases as the outdoor temperature rises, thus ensuring lower return water temperatures. For example, based on the standard factory reset curve shown in Figure 2, when the outside temperature is 5°F, the boiler supply temperature will be 180°F. But when the outside temperature rises to 50°F, the supply temperature is reduced to 120°F. The program that tells the boiler what temperature to deliver generally comes preset from the factory, but can be altered by the technician to optimize performance. A more detailed explanation of outdoor reset controls and how to program them can be found in the publication titled *Measure Guideline - Condensing Boilers: Control Strategies for Optimizing Performance and Comfort in Residential Applications* (Arena 2013).

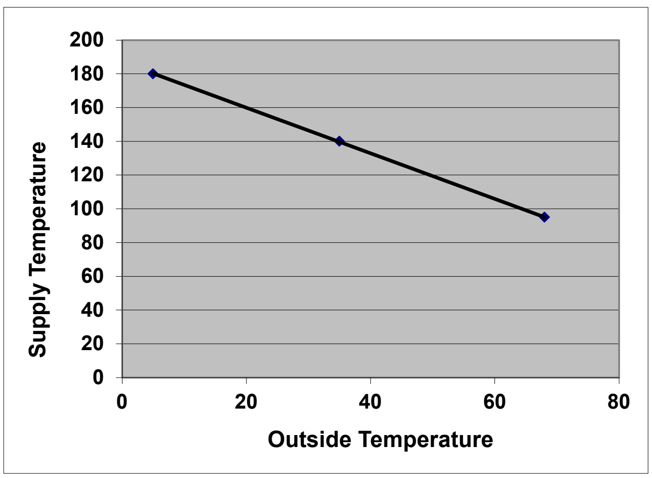


Figure 2. Linear boiler reset curve

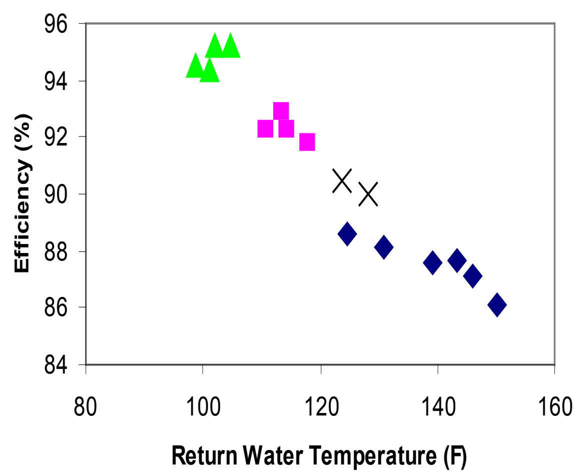


Figure 3. Combustion efficiency versus return water temperature

The desired outcome is the matching of space heating needs with the heat delivered and improved combustion efficiency. The effect of return water temperature on combustion efficiency can clearly be seen in the laboratory data displayed in Figure 3. As the return water temperatures were decreased, the combustion efficiency of the boiler clearly increased (Butcher 2011).

Additional efficiency gains can be realized if the thermostat setting is reduced at night and during unoccupied hours. This strategy is known as "setback" operation and has been shown in numerous field studies to save energy. It can also reduce system cycling, which reduces wear on the boiler. However, when the system has to raise the temperature in the space several degrees ("recover" from setback) in addition to satisfying the normal operating load, it may not have the required capacity. This is particularly true of systems that have been properly sized to meet the design load according to industry-recommended guidelines, especially if the system operates under the control of an outdoor reset. The reset control will only keep the supply temperature at the level required to meet the normal load based on the current outdoor conditions. Because of this, the system will not be able to provide the additional capacity needed to satisfy the demand from the setback. This will seriously hinder the system's ability to raise the temperature in the space. In fact, recovery from setback in previous studies was found to span several hours, and in some circumstances was not achieved at all.

Despite these issues, there are occupants who prefer a setback strategy to constant temperature operation. Many people prefer their bedrooms to be cooler at night for comfort reasons. Cost savings from reducing the indoor temperature during unoccupied periods are also often quoted as a reason for turning the thermostat down.

Facts About Setback:

- For an 8-hour nighttime setback period, every 1°F setback will result in ≈ 1% savings in energy consumption.
- The colder the weather, the greater the energy savings from thermostat setback.
- Savings are generally greater during periods of nighttime setback than during periods of daytime setback.

If a setback strategy is desired, controls to speed up recovery may sometimes be necessary. Some boilers employ controls that respond to lags in recovery by boosting the supply temperature and bypassing the outdoor reset controller. Once the thermostat in the conditioned space is satisfied, the system defaults back to the outdoor reset control. While the system efficiency will be reduced slightly during the recovery period, response time and comfort will be improved. Available options for a boost strategy are: (1) boiler controls that automatically raise the boiler output target temperature if the thermostat setting in the conditioned space is not satisfied within a set time frame; (2) an indoor sensor that would work in conjunction with the outdoor reset control to compensate for lags in response based on the difference between the interior temperature and the thermostat set point; or (3) a simple manual override switch. In addition, oversizing the baseboard and possibly the boiler may be necessary to meet the additional load during periods of setback recovery.

While these controls are widely available and commonly installed, it is apparent from previous research efforts that these types of systems—condensing boilers paired with baseboard convectors—are typically not designed and installed to achieve maximum efficiency and performance (Arena 2010). It was found that there is a significant lack of information for contractors on how to configure the control systems to optimize overall efficiency. For example, there is little advice on selecting the best settings for the boiler reset curve or how to design the system to quickly and efficiently recover from periods of thermostat setback.

This guide is intended to provide step-by-step instructions for heating contractors and hydronic designers for selecting the proper control settings to maximize system performance and improve response time when using thermostat setback.

2 Decision-Making Criteria

In a prior research study, using thermostat setback with boost controls for recovery resulted in improved efficiency, reduced cycling, and less energy consumption than systems operated in constant temperature mode. In order to ensure efficient responsive operation, however, careful design and planning are necessary. Extra capacity is required to overcome the additional load resulting from temperature setback, and controls that ensure quick response should be incorporated.

The following sections describe the key steps in determining the optimal system settings and control strategies for providing satisfactory response times and maximum overall system efficiency when thermostat setback is feasible and desired.

2.1 Cost and Performance

Thermostat setback is accomplished with a standard thermostat, programmable or not, and can result in reduced operating time, reduced wear on the boiler, and decreased energy use. Field studies have shown that setback operation can result in savings ranging from 5%–17% over constant temperature operation (Tariku et al. 2008; Arena 2013).

The basic system setup recommended in this guide includes a modulating condensing boiler (or similar heating appliance) coupled with baseboard convectors, both of which have been sized to provide the necessary capacity to recover from thermostat setback. In some circumstances, this may mean selecting a boiler larger than originally intended. With respect to baseboard, since the conventional practice is to oversize, there may not be any additional costs involved. If the contractor did size the baseboard to the design load, an increase in baseboard will likely be needed.

In addition, an outdoor reset control, a programmable setback thermostat, and boost controls to bypass the outdoor reset are recommended. Fortunately, both outdoor reset and boost controls are becoming standard features with condensing boilers and generally do not result in additional installation costs. Increased costs come primarily from the need for increased boiler and baseboard capacity.

2.2 Risk Identification

The risks associated with operating a hydronic heating system with a setback are primarily linked to occupant comfort and satisfaction. An outdoor reset controller won’t damage the boiler, but it can drastically affect response time if setback is used. A boost control installed to combat this problem may result in short periods of reduced efficiency, but again, will not result in damage to the equipment. If the baseboard is sized properly, this reduction in efficiency can be minimized.

When considering whether or not to employ these strategies, consideration should be given to the boiler’s capacity, the baseboard’s capacity, and how the occupants expect the system to behave. Information on how to deal with these risks can be found in Section 4 of this report, in works like Burdick 2011 and 2012; Butcher 2011, 2009, 2006, and 2004; and in the publication titled, *Measure Guideline - Condensing Boilers—Control Strategies for Optimizing Performance and Comfort in Residential Application* (Arena 2013).

Important:

Setback can have a sizable impact on peak heating loads because setback recovery occurs during the early morning hours on top of the peak heat loss.

2.2.1 Oversized Heat Sources

Conventional wisdom states that heating systems should be sized no larger than 110% of the design loads. Under constant temperature operation, following this practice should result in decreased short cycling, increased life of the equipment, and increased efficiency. However, operation of hydronic systems with thermostat setback actually requires capacities much higher than 110% of the design load to recover. And, as the mass of the home increases, the oversize factor must also increase. For example, a home built to the latest energy code may require a system that is 100% oversized to recover from a night setback of 8°F, as compared to an uninsulated, old home of the same size and location which may only need a system that is 50% oversized. These calculations are discussed in more depth in Section 3.

2.2.2 Undersized Baseboard

While installing an oversized boiler can be bad for comfort and efficiency, the exact opposite is true for baseboard. Undersized baseboard will result in reduced response time, reduced efficiency, increased cycling and reduced life of the boiler. Properly sizing the baseboard to handle the added load of the recovery period is critical to performance and overall system efficiency.

2.2.3 Effects of Setback on Indoor Relative Humidity and Building Moisture

Reducing the interior temperature in the home may increase relative humidity above desired levels, thereby increasing the negative effects associated with elevated moisture levels. In addition, the temperature of the surfaces in the home will decrease during periods of setback increasing the potential for condensation on windows and building envelope components (Tariku et al. 2008; CMHC 2009). Before recommending setback strategies, an evaluation of existing moisture issues and the expected interior moisture levels should be conducted.

2.2.4 Outdoor Sensor Placement

Where outdoor reset is used, the boiler supply temperature is dependent on the outdoor reset sensor. Therefore, proper placement of this sensor is critical. For example, if placed in a location where it is exposed to a heat source such as air from a dryer vent, in direct sunlight, or too near the boiler exhaust, the boiler will be fooled into thinking it is warmer outside than it actually is. This will result in lower supply temperatures to the space than are needed to meet the loads and can lead to comfort problems and/or drastically increased response times.

2.2.5 Specialty Components

Components that require a minimum supply water temperature, such as toe kick heaters, should be specified with the knowledge that boiler temperatures vary depending on the outside conditions, and supply temperatures may drop below that required by various components. For example, a fan coil unit may have a low limit control to prevent the fan from turning on if the supply water temperature were below 140°F. If the outdoor reset control is set such that the boiler would operate under that temperature for a significant portion of the heating season, the occupants would be left without heat in that area of the home.

3 System Interactions

This section discusses a few typical interactions that need to be considered when installing a hydronic system that will be controlled with an outdoor reset control and operated with a temperature setback.

3.1 Setback and the Need To Oversize

As noted earlier, studies show that thermostat setback results in decreased energy use compared to systems operated at constant indoor temperatures. However, added capacity is needed to recover from that setback as opposed to operation under constant temperature. The extra capacity needed depends on the heat capacity, or thermal mass, of the building.

Heat Capacity (Kreider and Rabl 1994):

- The heat capacity of the building is the energy required to raise it 1°F.
- The effective heat capacity of walls, floors and ceilings is roughly 40%–80% of the static heat capacity, assuming typical construction.

The heat storage capacity of the building includes the heat flow into or out of the mass of the building, including the furnishings and air in the space. This depends on the rate of heat transfer and on the frequency. The static heat capacity can be calculated by multiplying the volume of the materials by their specific heat and density, as shown in Table 1. The effective heat capacity is usually calculated as 40%–80% of the static heat capacity, assuming typical wood frame construction (Kreider and Rabl 1994). The effective heat capacity is generally used for materials not directly coupled to the space such as framing members and insulation behind drywall and subfloors.

Table 1. Effective Heat Capacity of a 1200-ft^2 Home Built to 2009 IECC[a] in Climate Zone 6

	Area (ft^2)	Thickness (ft)	Volume (ft^3)	Specific Heat (Btu/lb·°F)	Density (lb/ft^3)	Heat Capacity (Btu/°F)
Drywall, Ceiling	1,276	0.04	53.2	0.26	78.0	1,074
Drywall, Walls	1,689	0.04	70.4	0.26	78.0	1,422
Plywood Floors	1,276	0.06	79.8	0.29	34.0	786
Furniture	same as floors					786
Air	1,276	8.00	10,208.0	0.24	0.08	184
Studs	805	0.458	369.0	0.45	31.0	3,088
Cellulose	3,960	0.458	1,814.8	0.33	2.20	791
Total Effective Heat Capacity[b]						8,131

[a] International Energy Conservation Code

[b] Only 60% of the heat capacity of the studs and insulation is included in the total, hence the term *effective heat capacity*.

The example in Table 1 applies to a 1,200-ft^2 single family home located in climate zone 6 built to the 2009 IECC. The extra capacity required to bring this home back to temperature from a 5°F setback in 1 hour would be 5°F × 8,131 Btu/°F = 40,655 Btu/h. If a 2-hour recovery period were acceptable, 20,328 Btu/h additional capacity would be needed. Considering the design load for the home is approximately 15,000 Btu/h, the capacity of the system would have to be doubled to recover from a 5°F setback in 2 hours under design conditions.

The negative effects associated with oversizing are actually minimized when combined with setback operation. This is due to the fact that the temperature difference between the emitters and the space is much greater than when operated under constant temperature control. During the recovery period, more heat is emitted to the space, resulting in lower return water temperatures, longer system runtimes, and reduced cycling. Simply operating the system for fewer hours per day (as is the case for setback operation) results in reduced cycling. Combining this with boost controls also reduces cycling by further decreasing the system runtime.

3.2 Greater Heat Capacity Equals Longer Recovery Periods

Table 2 lists the effective heat capacities for three different homes—a super insulated home with double-stud walls, a code level home insulated with cellulose, and an old, uninsulated home. Each home is assumed to be equipped with a heat source that is twice the design load. The recovery times show that similar size buildings with lower heat capacities warm up or cool down faster under similar climatic conditions.

Table 2. Recovery Time for an 8°F Setback for Three Homes Insulated to Different Levels With 100% Oversized Boilers

Efficiency Level	Heat Capacity (Btu/°F)	Design Load (Btu/h)	Boiler Size (Btu/h)	Recovery Time (hours)
Super Insulated	10685	8,540	17,080	6.9
2009 IECC	8131	15,441	30,882	3.4
Old, Uninsulated	6600	44,030	88,060	1.0

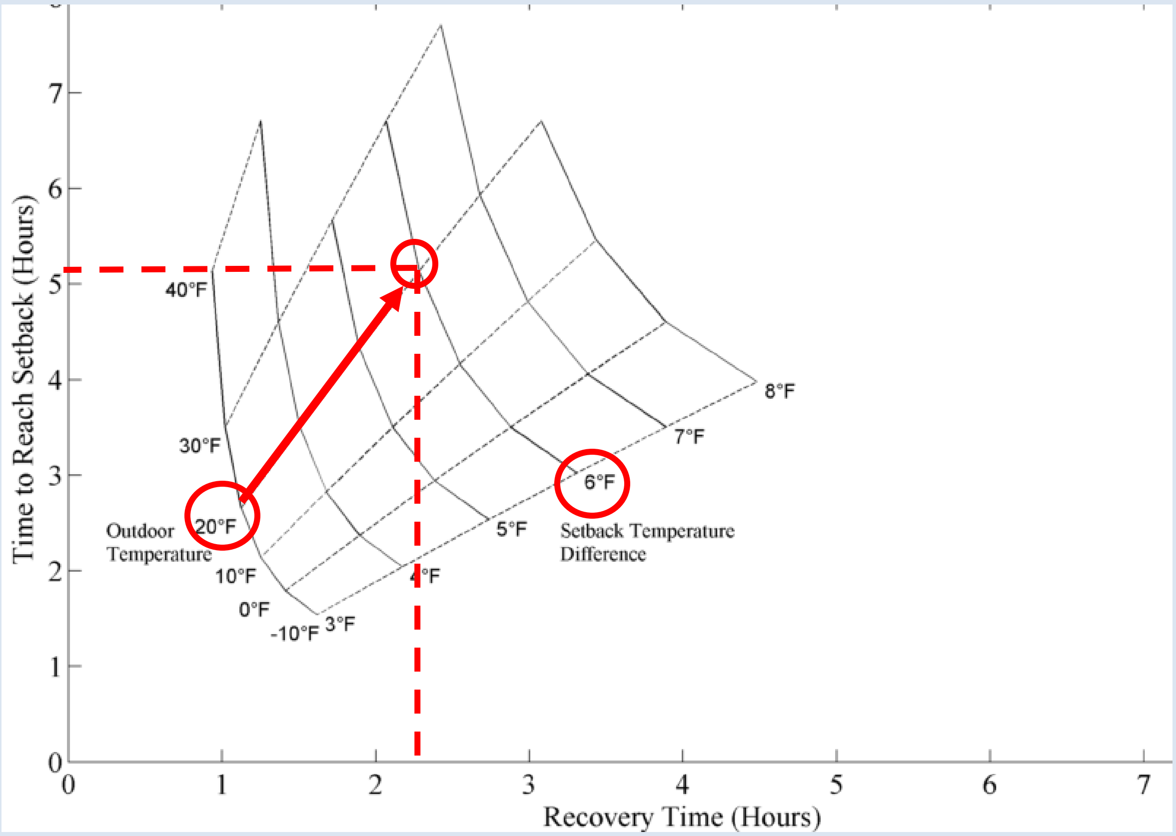
Figure 4 through Figure 6 show the recovery time versus the time it takes to fall to the setback temperature for the three homes listed in Table 2. The charts are read as follows:

1. Find the appropriate outdoor temperature on the left side of the plot in the body of the graph.
2. Follow the line to the right and up until it intersects with the setback desired.
3. Draw a line vertically to the bottom axis and read the number of hours expected to recover from setback given that outdoor temperature, setback, and an input equal to twice the design load.
4. Draw a line horizontally to the left to determine the number of hours that it will take for the house to fall to the setback chosen.

The following example illustrates the use of these charts.

Example
(A) How long will it take for a home built to code to recover from a setback of 6°F if the outdoor temperature is 20°F? (B) How long will it take for the home to drop those 6°F?

Answer Part A:
From Figure 4 (see below), find 20°F along the left side of the plot.
Follow the 20°F line up and to the right until it intersects with the 6°F setback temperature.
Drop straight down until the line intersects with the horizontal axis and read the number.
The answer to part A is approximately 2.25 hours to recover from a 6°F setback.



Answer Part B:
Draw a line horizontally to the left until it intersects with the vertical axis and read the answer. It would take just over 5 hours for the home to drop 6°F.

Figure 4 shows a home that is super-insulated. Note that the outdoor temperature goes to only 20°F and the maximum setback shown is 6°F. This is due to the fact that the home loses heat much more slowly and would not see an 8°F drop in temperature in less than 8 hours, even at –10°F outside. At 20°F outside, the temperature would drop only 3°F. While these low heat loss conditions are desirable, note that to recover from a 3°F setback at 20°F outside it would take 4 hours with a heat input twice that of the design load. This indicates that setback for a super-insulated home should be avoided. The added costs of tripling or quadrupling the heating system output capacity to decrease the recovery time would far outweigh the savings for a home with such a low heat load. It could be argued that the smallest boilers available would satisfy even 4 times the load of the super-insulated house without any additional expense to go to the next size, however, the baseboard would also have to be quadrupled. Based on how small the heating loads are, the potential savings from operating in setback mode would be miniscule compared to the extra cost of the baseboard.

In contrast, Figure 6 represents a very old, uninsulated home with plaster walls. With a heat input rate twice that of the design load, this home recovers from an 8°F setback in less than 1.5 hours at –10°F outside.

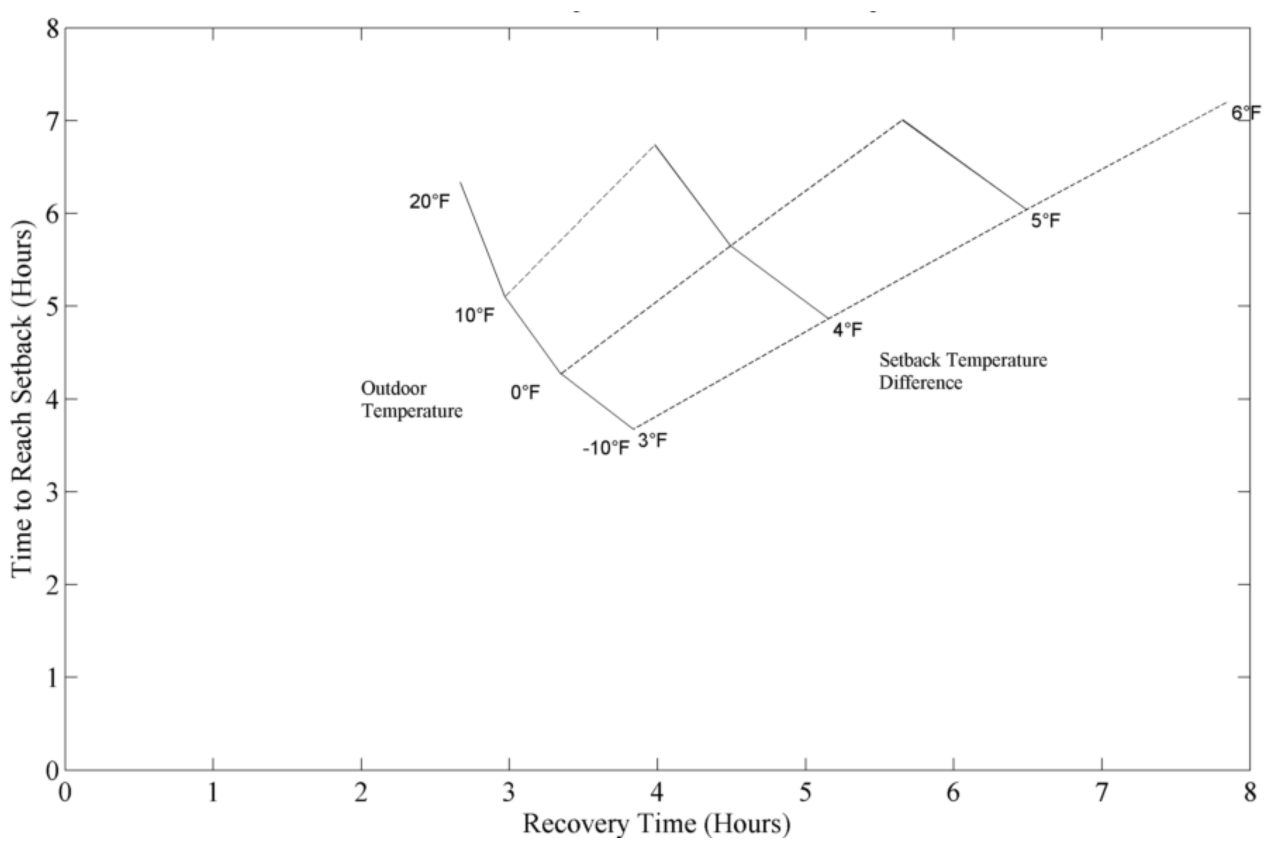


Figure 4. Recovery time from thermostat setback and time to fall to the setback temperature for a 1,200-ft^2 super-insulated home in climate zone 6 at varying setback intervals and exterior temperatures

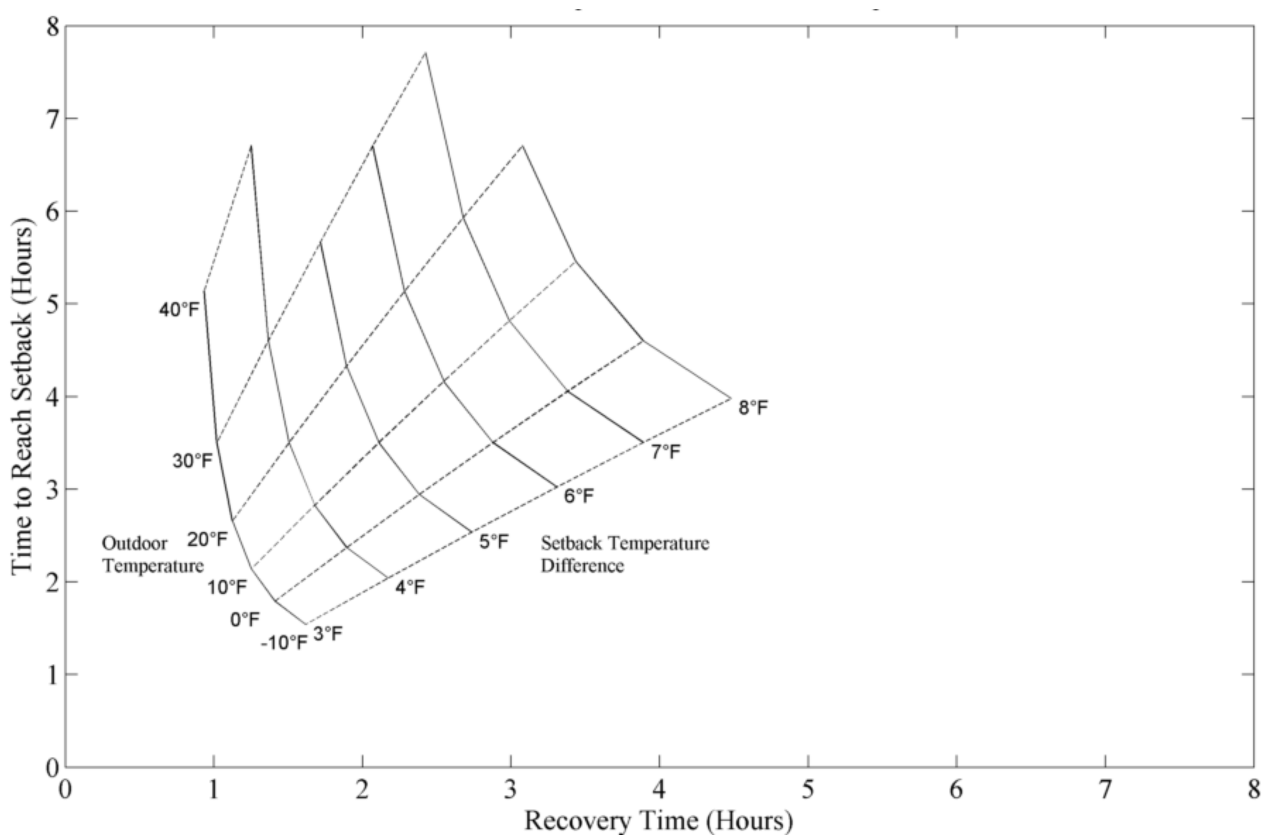


Figure 5. Recovery time from thermostat setback and time to fall to the setback temperature for a 1,200-ft^2 2009 IECC compliant home in climate zone 6 at varying setback intervals and exterior temperatures

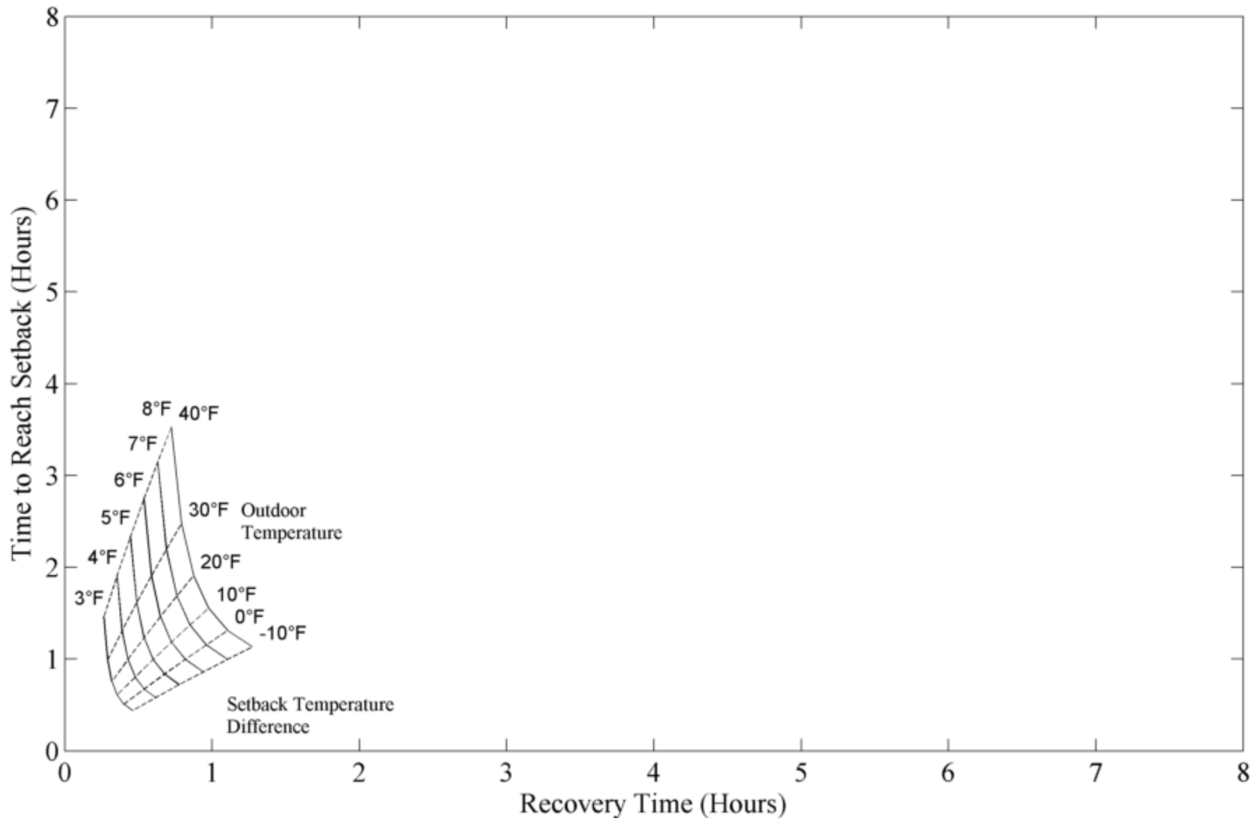


Figure 6. Recovery time from thermostat setback and time to fall to the setback temperature for an uninsulated, 1200-ft^2 home in climate zone 6 at varying setback intervals and exterior temperatures

Although response times for the super-insulated home look very long under design conditions and an 8°F setback, only a fraction of the heating season will see those conditions. As temperatures increase outside, response times will be faster if using a boost control. In addition, during warmer conditions, the home will not fall to the full setback temperature which will also decrease the recovery time. While design conditions should be evaluated, decisions to use setback versus constant temperature control would be best evaluated at average low temperatures for the project location, not necessarily design conditions.

Another interaction that should be noted is the effect of house size on recovery rate. As can be seen in Figure 7, recovery time actually increases as house size increases. All five homes evaluated were located in the same climate zone and have the same configuration and insulation levels. The reason the recovery time increases is because the increase in heat load is smaller than the increase in the heat capacity as the house increases in size.

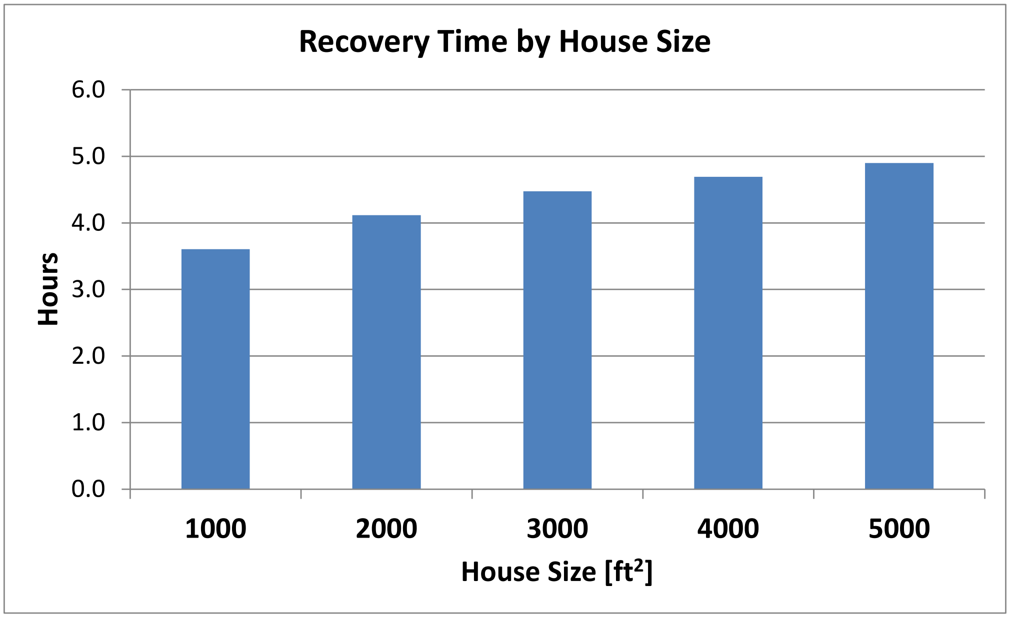


Figure 7. Recovery times for an 8°F setback for five different size homes built to the 2009 IECC in climate zone 6. Heat input is assumed to be twice the design load.

3.3 Increasing Heat Loss and Decreasing Baseboard Effectiveness

Assuming a constant outdoor temperature, response time will be affected by the fact that the heat loss from the conditioned space will increase as the indoor temperature increases, but the output of the baseboard will actually decrease. This is because the temperature difference between the baseboard and the room air has decreased. This is mostly a concern if the added capacity in the system is coming only from additional length of baseboard and not from increased supply temperatures that would result from using a boost control. Fortunately, most baseboard ratings are based on 65°F room air. Therefore, for room air temperatures under that baseline, the output should be higher than rated. This will offset the lower-than-rated output once the house temperature rises above 65°F.

3.4 Milder Outdoor Conditions and Decreased Recovery Time

As temperatures increase outside, temperatures in the home may not fall to the setback temperature resulting in quicker recovery times (if using a boost control). Considering that the design heating condition occurs for only 1% of the heating season, the evaluation of recovery time should be conducted for a more common operating condition. A recommendation would be to look at the average low temperature for each of the three coldest months, and use that temperature to determine the extra capacity needed.

3.5 Using Added Baseboard Capacity To Recover Without Boost

Another option for recovering from setback is to oversize the baseboard and supply warmer water so that the heat input to the space under design conditions is greater than the load. For example, if the design load were 15,000 Btu/h, install enough baseboard to supply 30,000 Btu/h under design conditions. For maximum efficiency, assume a supply temperature at design that will result in condensing operation. Typically systems are designed so that there is a 20°F difference between the supply and return to the boiler at design temperatures. Under these conditions, the maximum boiler supply temperature should be set to 150°F on the outdoor reset curve, and the baseboard should be sized to provide 30,000 Btu/h at an average of 140°F water.

Caution:

When relying solely on added baseboard length to recover from setback (without the aid of a boost control), baseboard effectiveness will be reduced as:

- The temperature in the home increases but the baseboard temperature remains constant; i.e., outdoor temperature is constant and boiler has reached programed supply temperature.
- The outdoor reset control reduces the boiler supply temperature as the exterior temperature increases.

Both of these conditions result in extended recovery times. Baseboard should be sized accordingly.

The downside to this approach as opposed to using a boost control is particular to using outdoor reset. As noted earlier, as the outdoor temperature increases the boiler supply temperature will decrease. Unfortunately, the baseboard output at lower temperatures is not proportional to the decreased load. Baseboard is less efficient at lower temperatures. Recovery times will actually increase as the outdoor temperatures increase and the boiler supply temperature decreases. Therefore, while increased baseboard is recommended under design conditions for the most efficient steady-state operation when the house is already at the desired temperature, it should be used in conjunction with a boost control to more efficiently and quickly recover from setback.

4 Measure Implementation

Scope of Work

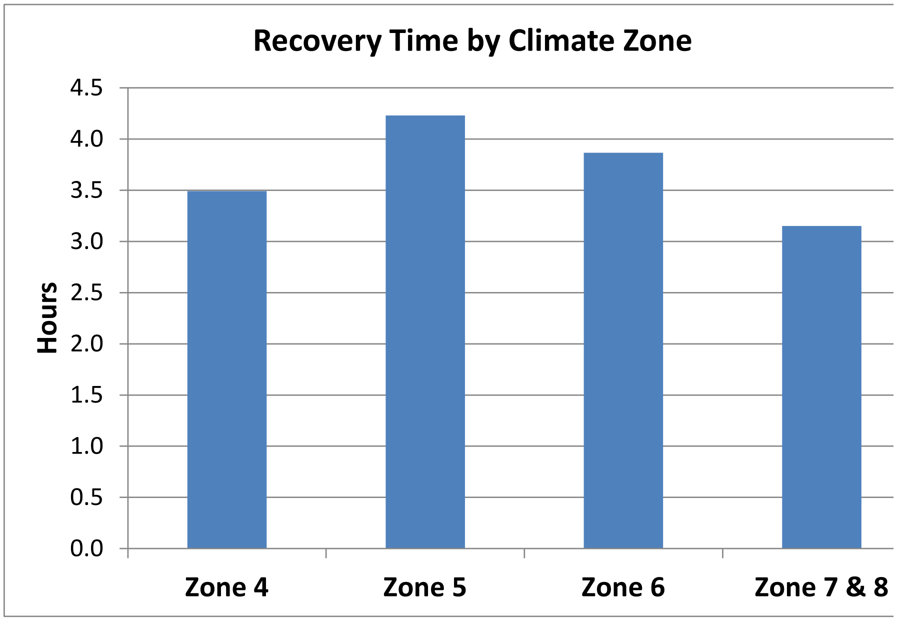
A. Determine if the project is right for thermostat setback operation.
B. Size the boiler to provide the capacity needed for recovery from setback.
C. Size the baseboard to provide the capacity at low supply temperatures and to recover from setback.
D. Determine the proper settings for the outdoor reset control
E. Determine the proper settings for the boost control.

4.1 Determine If Setback Is Appropriate for the Home

4.1.1 Evaluate Climate Zone

This guide is applicable to all climate zones where space heating is required. Setback operation can result in savings in all zones. Actual savings will be greatest in colder climates; however, savings in milder climates are a larger percentage of the overall load (Tariku et al. 2008).

Recovery times from setback will vary from climate to climate, with size of the home, and with differences in the levels of mass in relationship to the load. The recovery times for a similar size home in climate zones 4 through 6 are displayed in Figure 8. All homes were modeled with 2009 IECC insulation levels. The increase in recovery time from climate zone 4 to climate zone 5 is due to the increase in lumber in the walls and the increase in insulation levels. Homes in zone 4 were assumed to be constructed with 2 × 4 walls, while homes in zones 5 through 8 are assumed to have 2 × 6 walls. The thermal mass in the homes in zones 5 through 8 are fairly similar, but the heat loads are quite different. This results in shorter recovery times as the climate gets colder. Essentially, there is more heating capacity available per square foot of mass because the heating system is larger the colder the climate, but the heat capacity of the building changes very little. No climate zones need be excluded from setback operation.



> Burner Modulation:
>
> Burners in newer natural gas and propane boilers typically have the ability to supply a fraction of the total capacity by modulating the burner.
>
> This feature is often referred to as the *turndown ratio*. A modulation rate of 20% equates to a 5:1 turndown ratio.

Figure 8. Comparison of recovery times for climate zones 4 through 8 for similar size homes built to the 2009 IECC

4.1.2 Who Shouldn't Use Nighttime Setback

For any home with a hydronic heating system, if the answer to any of the following questions is "yes," the project is probably not right for nighttime setback and should be maintained under constant temperature operation.

1. Does the home have a boiler that cannot modulate its output?
2. Is the home insulated to levels significantly better than the 2009 IECC?
3. Is the heat emitter radiant flooring or radiant panels?
4. Are the walls or floor of the conditioned space constructed with concrete? If yes, is that concrete uninsulated to the interior?
5. Do the occupants expect/desire a recovery time shorter than 1 hour?

4.2 Design and Install Procedures

The following steps are necessary for proper design and installation of a hydronic system intended to be operated with a nighttime thermostat setback. An example is provided for each step and is based on a 2000-ft^2 home located in climate zone 6 built in compliance with the 2009 IECC. The home is assumed to be two stories of conditioned space over an unconditioned basement.

4.2.1 Size the Boiler for Setback Operation

The very first step in a good design is proper sizing of the mechanical equipment. A right-sized heating system provides the desired occupant comfort and runs efficiently. Even though oversizing is necessary for recovery from setback, the design load must be determined first. Then the proper capacity needed to recover from setback can be determined and the boiler can be selected based on those two pieces of information.

In order to properly size the boiler, accurate heating loads must be calculated. These calculations should be performed in compliance with the Air Conditioning Contractors of America's (ACCA) standard protocols as outlined in the most recent version of *Manual J: Residential Load Calculation* (ACCA 2009a).

For constant temperature operation, it is ideal if the highest modulation rate of the boiler matches the design load of the home, leaving plenty of room for the unit to reduce its firing rate for the loads during non-peak times. However, for setback operation, the boiler should be approximately twice the design load for a code compliant home to about 1.5 times the heating design load for an old inefficient home.

Example 1:
The buyers of new spec home in Ithaca, New York would like to install a condensing boiler with baseboard convectors. They desire to use a nighttime setback in their new home because they are accustomed to sleeping in cooler temperatures. The home will be 2000 ft^2 and will be built in compliance with the 2009 IECC. The design load on the house was calculated using Manual J and is approximately 25,000 Btu/h. What size boiler should the contractor install?

Answer:
Ideally, the contractor should install a boiler with that has a capacity equal to twice that of the design load:

2 × 25,000 = 50,000 Btu/h

The boiler should also have a modulation rate of at least 5:1 (typically the best ratio available in residential boilers) resulting in a low output of between 10,000 and 15,000 Btu/h.

Note: If this were a very old inefficient home, the contractor would only have to oversize the boiler by 50% or 1.5 × 25,000 = 37,500 Btu/h

Additional Resources:

- ACCA Manual J V.8: Residential Load Calculation (ACCA 2009a)
- ACCA Manual S V.3: Residential Equipment Sizing (ACCA 2009b)
- Heating and Cooling of Buildings (Kreider and Rabl 1994)
- Condensing Boilers: Control Strategies for Optimizing Performance and Comfort in Residential Applications (Arena 2013)

4.2.2 Size the Baseboard for Setback Operation With a Boost Control

Installing sufficient capacity to transfer the heat to the conditioned space is imperative. An undersized distribution system will lead to all the same troubles as an oversized boiler—slow response, increased cycling, and reduced efficiency.

If the baseboard is unable to deliver enough energy to the space, the return water temperature to the boiler will be higher than desired. This can result in reduced condensing which in turn results in lower system efficiencies. Additionally, many boilers compare the temperature difference between the supply and return water. If the difference is too small, the burner shuts off. If the baseboards are undersized, the system will short cycle (even if the boiler is properly sized) because it simply cannot release enough heat to the space.

Manufacturers of baseboards publish output capacities for their equipment at varying temperatures. Table 3 lists some generic baseboard capacities for different flow rates and element diameters assuming only one pipe passes through the baseboard. To use the chart, determine the average baseboard temperature at design conditions, the flow rate and the size of the element to be installed. For example, if the boiler supply temperature at design is 150°F, assume a 20°F difference between the supply and the return, which would result in an average water temperature of 140°F in the baseboard. Assuming the size of the element will be ¾ in. and a 1 gpm flow rate through the system (unless 4 gpm or higher can be verified), the baseboard output from Table 3 would be 290 Btu/h/linear foot.

Determining Baseboard Capacity in an Existing Home:

1. Measure the length of the baseboard (length with fins).
2. Determine the manufacturer.
3. If manufacturer is unknown, compare the dimensions of the casing, fins, and pipe diameter to those of several manufacturers. Pick the one that is closest.
4. Determine the boiler supply temperature at design and subtract 10°F (assuming the system was designed for a 20°F temperature differential) to get the average water temperature.
5. Look up the output listed in the manufacturer's tables.
6. Multiply the length by the capacity.
7. Verify that the baseboard capacity is greater than the peak heating load.
8. If setback operation is desired and the boiler does not have a boost control, double the length of the baseboard if possible or increase the supply temperature to a setting that will result in double the output capacity of the baseboard.

Table 3. Generic Baseboard Capacities/Linear Foot for Different Flow Rates and Element Diameters

		Btu/h/ft Based on Average Temperature Listed								
	Flow	140°F	150°F	160°F	170°F	180°F	190°F	200°F	210°F	220°F
¾-in. Element	1 gpm	290	350	420	480	550	620	680	750	820
	4 gpm	310	370	440	510	580	660	720	790	870
½-in. Element	1 gpm	310	370	430	490	550	610	680	740	800
	4 gpm	330	390	450	520	580	640	720	780	850

Evaluating the baseboard's ability to meet the design load is only one part of the equation. If the boiler is oversized compared to the design load, oversizing the baseboard will help reduce short cycling of the boiler. This may be the only option in situations where the smallest boilers are too large for the design load or there are several zones, all of which have very small loads compared to the boiler's capacity. In these cases, oversizing the baseboard will reduce cycling, improve response time and increase efficiency. In the case above, if the lowest modulating rate on the boiler was 30 kBtu/h, installing enough baseboard to regulate the system would require installing 103 linear feet of baseboard (30,000 Btu/h ÷ 290 Btu/h·ft). For those homes where space is limited, high output baseboards or buffer tanks should be considered to counter the negative effects of severely oversized equipment.

Example 2:
For the home in Example 1, determine the length of baseboard needed to provide the capacity needed to recover from setback (50 kBtu/h). The maximum boiler temperature is 180°F, and the maximum supply temperature on the outdoor reset curve is programmed at 150°F to ensure 130°F return water temperatures at design conditions. Assume a flow rate of 1 gpm and ¾-in. elements. The occupants wish to set back their thermostat 8°F at night. Size the baseboard assuming the boiler has a boost control and can supply water up to 180°F.

Answer:
If the supply temperature is 180°F and the system has been designed for a 20°F temperature difference at design conditions, the average baseboard temperature would be 170°F. Therefore, the capacity at 170°F should be used to size the baseboard. Determine the length at 170°F average temperature at the design load of 50 kBtu/h:

50,000 Btu/h ÷ 480 Btu/h·ft = 104 ft

To make sure this length can meet the design load once the home is up to temperature, determine the length of baseboard needed when the system is running at the temperature dictated by the outdoor reset curve—150°F. Assume a 20°F temperature difference which would result in an average baseboard temperature of 140°F at the design load of 25kBtu/h:

25,000 Btu/h ÷ 290 Btu/h·ft = 86 ft

To meet the additional load from setback, 22 additional feet of baseboard would have to be installed. At $10/ft, this would result in an additional cost of $220. If the savings due to the setback were 1% for every 1°F, the homeowners would save approximately 8% annually. Assuming $1200/yr for heating, the savings would be ≈ $96/year and would have a simple payback of 2.3 years.

4.2.3 Size the Baseboard for Setback Operation Without a Boost Control

As noted earlier, recovery from setback can be met with the use of a boost control by oversizing the baseboard and selecting a boiler supply water temperature that results in heat input to the space which is greater than the load. For maximum efficiency, assume a supply temperature at design that will result in condensing operation. But, because the baseboard is less efficient at lower temperatures, recovery times will actually increase as the outdoor temperatures increase and the boiler supply temperature decreases.

Example 3:
For the home in Example 2, size the baseboard assuming there is no boost and the maximum boiler supply will be 150°F to promote condensing. Use the baseboard capacities list in Table 3.

Answer:
Check the length required at 140°F average baseboard temperature at the design load of 50 kBtu/h:

50,000 Btu/h ÷ 290 Btu/h·ft = 173 ft

Compared to constant temperature operation, this option results in an additional $870 of baseboard and a simple payback of 9 years as opposed to $220 additional for setback operation coupled with a boost as determined in Example 2.

4.2.4 Determine the Set Points for the Outdoor Reset Curve

Determining the optimal settings for the reset curve is an iterative process. While the goal is to create conditions where the return water temperature is always below the dew point for the particular fuel being used, this could result in baseboard lengths that are too long for the space available. Therefore, several supply temperatures may need to be evaluated. This process is outlined in detail in the publication titled *Measure Guideline - Condensing Boilers: Control Strategies for Optimizing Performance and Comfort in Residential Applications* (Arena 2013).

Ultimately, the goal is to maximize the time the boiler is in condensing operation. Systems should be configured to condense at design conditions. This can be accomplished by supplying temperatures lower than the boiler's maximum supply temperature. Then, when recovery from setback is needed, the boiler can boost to higher temperatures to meet the added load. For modulating, condensing boilers, design the system to meet the design heating load such that the return temperature does not exceed 130°F. For loops designed for a 20°F temperature difference between the supply and return, this would equate to a 150°F boiler supply temperature and an average loop temperature of 140°F.

If using a condensing water heater, design the system to meet the design heating load such that the tank temperature does not exceed 130°F. Because the heat exchanger is submerged in the tank, the tank temperature will have a much greater effect on condensing than the return water temperature. If maintaining a temperature below 130°F, the supply temperature to the zones would be no more than 125°F assuming that there is a 5°F temperature loss in the heat exchanger. Figure 9 shows the reset curve for a condensing water heater where the supply temperature under design conditions was set to 140°F. Under these conditions, the tank must be kept at 145°F in order to supply 140°F water to the space heating zones. This means that the tank will be kept above the condensing temperature of 130°F until the outdoor temperature rises above 15°F.

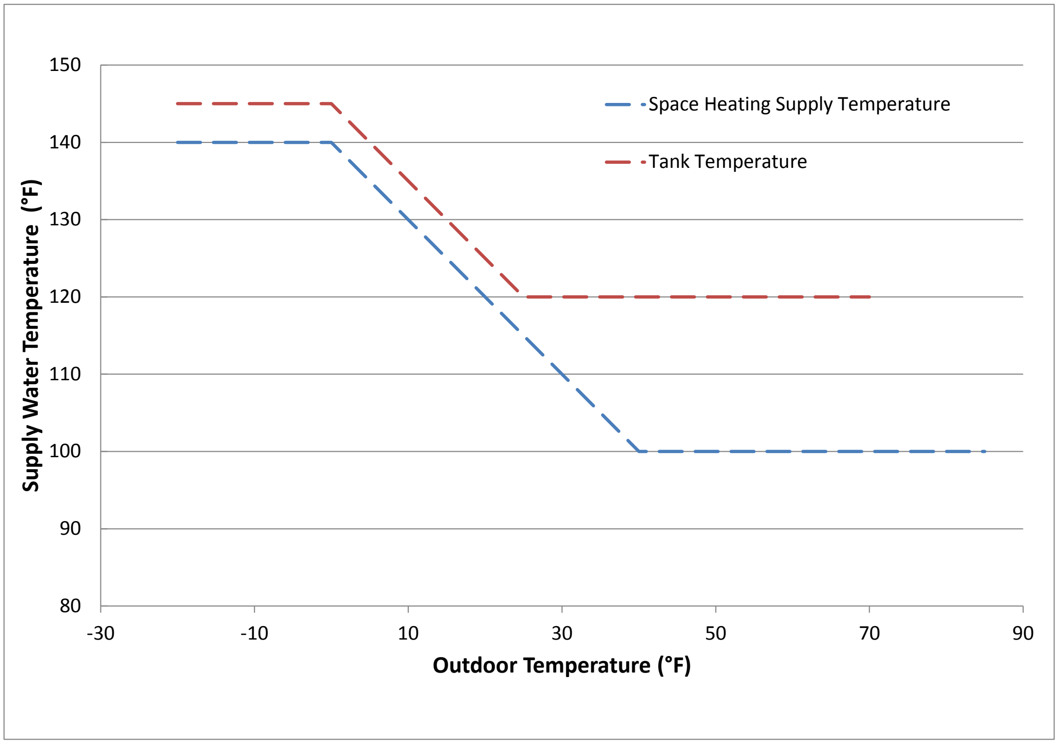


Figure 9. Reset curve for a condensing water heater if the supply temperature under design conditions is 140°F

If designed for a 20°F temperature difference between the supply and return under design conditions, the average loop temperature would be 115°F, and the baseboard should be sized accordingly. Capping the maximum supply temperature to 125°F doesn't only encourage condensing, it also reduces standby losses because the entire tank is kept at a lower temperature. Running the tank at a temperature higher than 130°F will result in efficiencies that are only in the mid to upper 80% range. Incorporating a boost with these systems would allow warmer supply temperatures for a short period of time, but would not require keeping the tank at higher temperatures once the space reaches the desired temperature. This would reduce the amount of baseboard needed. It is not recommended that condensing tanks are used for constant temperature operation unless that temperature is below 130°F.

4.2.5 Determine the Settings for the Boost Control

As mechanical systems are more closely matched to the loads, especially in higher efficiency homes, systems are less able to respond to large setbacks because excess capacity was not installed. Recovering from a setback of 8°–10°F can take several hours in homes when outdoor reset controls are used without boost, since these controls are specifically trying to very closely match the output of the system to the load.

Some boilers employ controls that respond to lags by boosting the output temperature to the zones and bypassing the outdoor reset controller. Once space heating is accomplished, the system defaults back to the outdoor reset control. Boost controls set to override the outdoor reset control work as follows: if a heating demand is not satisfied within *x* minutes, an offset of *d* degrees F is added to the target temperature of the boiler. Both of these values are adjustable based on selections in the installer menu.

Figure 10 illustrates how such a boost control would operate. “Lag” is the number of minutes (*x*) that would pass before the boiler’s supply temperature was increased, and “offset” refers to the number of degrees (*d*) by which the supply temperature would be raised. This process would continue until either the thermostat was satisfied or until the supply temperature reached the high limit setting of the boiler.

Assuming that $x = 20$ minutes and $d = 18$°F, if the outdoor reset algorithm calculates a target of 110°F and the central heating call exceeds 20 minutes, the target supply temperature would be increased to 128°F. If the central heating thermostat continues to call for another 20 minutes, the temperature would jump again to 146°F, and so on. The actual settings chosen can be adjusted based on response and occupant preference.

To determine the best setting for the boost control, the following should be considered:

1. The capacity of the baseboard at different temperatures. Some baseboard almost doubles in capacity with a 20°–30°F increase in supply temperature.
2. The heat capacity of the home. See Figure 4 through Figure 6 to determine the response time for the desired setback and building efficiency.

These two pieces of information along with the occupants’ desires will determine the necessary increase in supply temperature and the time lag between increases.

Note that the temperature will not exceed the maximum supply temperature dictated by the boiler’s safety setting.

Additional Resources

- Modern Hydronic Heating for Residential and Light Commercial Buildings, 3rd edition; John Siegenthaler, P.E. (Siegenthaler 2012)
- I=B=R Guide—Residential Hydronic Heating: Installation and Design, AHRI

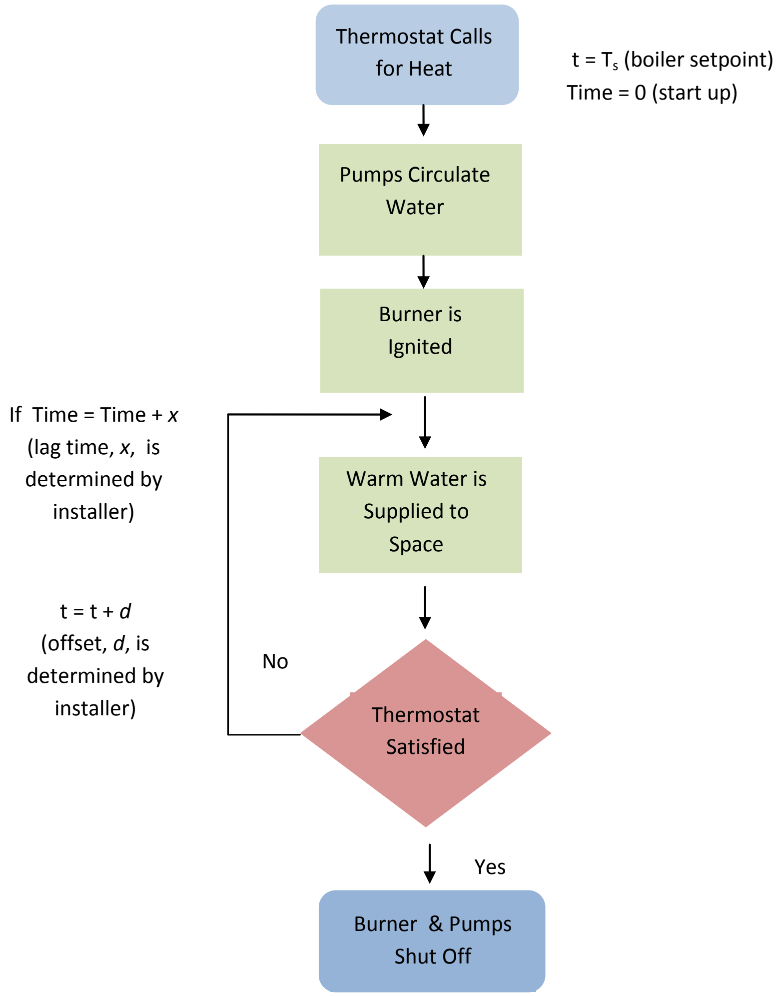


Figure 10. Flow diagram illustrating the effects of a boost control on the boiler supply temperature

Caution: Boost Controls

Care must be used when implementing this function in multi-zone systems as the boiler may boost to the highest temperature if calls from several zones overlap.

5 Verification Procedures and Tests

Before leaving the site, confirm that the desired operation of the controls has actually been achieved. The inspections outlined below should take only a few minutes. A field checklist has been included in the Appendix to assist in the verification and testing process.

5.1 Proper Functioning of the Outdoor Reset

Verifying that the boiler is operating as intended is not very difficult unless it is an extremely hot day when testing is desired. Under those conditions it may not be possible to get the boiler to fire if the thermostat cannot be set above the ambient conditions. Under these circumstances, it may be necessary to postpone commissioning until the weather turns colder.

To verify the outdoor reset control is set up as intended, increase the temperature setting on the thermostat so the boiler fires. Be sure to choose a temperature several degrees above the indoor condition so that the boiler runs for a few minutes. On the boiler's control screen, note the maximum supply temperature after it stops rising or at the time the burner shuts down (which may happen quickly if oversized for the load). Compare this temperature to the temperature from the boiler curve which coincides with the current outdoor temperature. The predicted and actual temperatures should be very close.

Caution: Ensuring Success

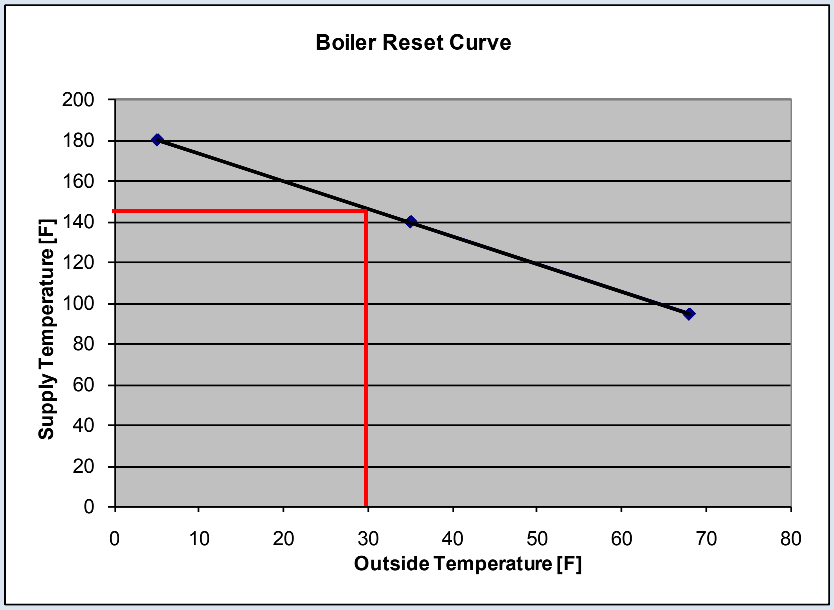
Items to verify:

1. The boiler is properly sized for recovery from setback.
2. Enough baseboard has been installed to deliver the capacity needed and ensure a minimum of a 20°F differential between the supply and return temperatures under design conditions.
3. The maximum supply temperature on the boiler reset curve is set to promote condensing at design conditions.
4. Warm weather shutoff is high enough to prevent no-heat situations during the swing seasons.
5. The outdoor reset sensor has been placed away from any exhaust vents, including kitchen, bath, dryer, and mechanical system vents and will not be in direct sunlight during any portion of the day.

Example 4:

Determine the boiler supply temperature for a system with a reset curve as shown in the figure if it were 30°F outside.

Answer:
Follow a straight line up from 30°F on the horizontal axis until you intersect with the reset curve. Then follow that point over to the left until you intersect with the vertical axis. The corresponding boiler supply temperature at 30°F outdoor temperature would be approximately 145°F.



5.2 Evaluate Boost Control

If a boost control is installed, allow the system to run long enough for it to kick in. Setting the thermostat several degrees above the indoor temperature will ensure that the boiler will run long enough. Don't assume that the system is shutting off if the burner shuts down. The boiler may just have met the current set point. If the pumps continue to run, the thermostat has not been satisfied yet, and the controller is keeping track of the time.

After the programmed time has passed, the boiler should increase the temperature of the supply water. Give the boiler a couple of minutes to increase the supply temperature and then compare that temperature to the set point noted from the previous test outlined under Section 5.1. It should be higher than the original set point temperature by the differential entered into the controller. If the boiler does not supply a higher temperature to the zones, the boost function is not operating properly.

5.3 Additional Resources

There are many different control and design strategies for optimizing hydronic system efficiency and occupant comfort. Those mentioned in this report are just a small subset. Following are a few resources that may be consulted for different control strategies and additional information:

- I=B=R Guide: Residential Hydronic Heating Installation & Design (AHRI 2009)
- Modern Hydronic Heating, John Siegenthaler, PE (Siegenthaler 2012)
- ACCA Manual S, Residential Equipment Selection (ACCA 2009b)
- ACCA Manual B, Balancing and Testing Air and Hydronic Systems (ACCA 2009c).

Verifying Setup

- Don't forget to reset any settings that you bypassed for testing.
- Verify the return temperature on non-condensing systems is not below the critical threshold.

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Appendix: Prescriptive Measure Checklist

Boiler Setup for Setback Operation: Field Checklist

Tool Box Items

Digital Thermometer Compass Tape Measure Boiler Control Manual

Where to Locate Information

BC—Boiler Controller MS—Manufacturer Specifications CV—Calculated Value MP—Measured Parameter

	System Parameters		**Comments/Suggestions**
	1. Determine if Setback Operation is Right for the Project		**Note: If the answer to any of the questions in this section is "yes", setback operation may not be appropriate for the job.**
	a. Does the home have a boiler that cannot modulate its output?	Yes No	A boiler that cannot modulate should not be used for setback because it will be significantly oversized leading to excessive short cycling.
	b. Is the home insulated to levels significantly better than the 2009 IECC?	Yes No	Homes with insulation levels much above current code generally contain higher levels of mass and respond slowly.
	c. Is the heat emitter radiant flooring or radiant panels?	Yes No	These types of systems contain a lot of mass and are meant to operate at very low temperatures.
	d. Are the walls or floor of the conditioned space constructed with concrete? If yes, is that concrete uninsulated to the interior?	Yes No	High mass homes respond very slowly and will not recover from setback in an acceptable amount of time.
	e. Do the occupants expect/desire a recovery time under one hour?	Yes No	Even the best designed systems are unlikely to recover in under 1 hour.
	2. Verifying Proper Sizing of the Boiler		
CV	a. Design Load	kBtu/h	Calculated according to ACCA Manual J
MS	b. Max output capacity of boiler	kBtu/h	
MS	c. Min output capacity of boiler	kBtu/h	If min output capacity > the design load, choose a smaller boiler or add a buffer tank to the system
	3. Assessing Baseboard Capacity		
CV	a. Average baseboard water temperature under design conditions	°F	Assume a 20°F temperature difference between the supply and the return for each zone
MS	b. Baseboard output capacity at average water temperature	kBtu/h/ft	
MP	c. Total length	ft	
CV	d. Total capacity (output x length)	kBtu/h	If baseboard capacity < design load, add more baseboard or choose a higher design supply water temperature
	4. Entering Control Settings		
MS	a. High limit	°F	
BC	b. $T_{s,max}$	°F	$T_{s,max}$ must be lower than high limit
BC	c. $T_{out,max}$	°F	
BC	d. $T_{s,min}$	°F	
BC	e. $T_{out,min}$	°F	

BC	f. Differential	°F	
BC	g. Warm weather shutoff	°F	This setting should be 2°F to 4°F higher than desired temperature for occupied periods
	h. Thermostat setting (s)	°F to °F	If no setback, enter only one temperature
	5. Sensor Placement		
MP	a. Side of house (North, South, East West)		
MP	b. Height off ground	ft	Verify that sensor is installed above the typical snow line
MP	c. Heat sources nearby	Yes No	If yes, move sensor
	6. Verifying performance		
MP	a. Outdoor temperature	°F	
CV	b. Predicted supply setpoint from boiler curve	°F	
BC	c. Actual supply temperature being delivered	°F	Predicted supply should be no more than a couple of degrees different than the actual
MP	d. Time for space to increase 1°F	min	If response is less than 5°F per hour, recommend reducing setback or installing a boost
	7. Evaluating the Boost Control (if applicable)		
CV	a. Predicted supply setpoint from boiler curve	°F	
BC	b. Lag time allowed	min	
BC	c. Intended temperature offset	°F	If the supply temperature did not increase after the lag time passed and the thermostat is still calling for heat, recheck the settings in the boiler's controller and consult the manufacturer's installation guide.

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