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JOURNAL OF DESIGN INNOVATION FOR HYDRONIC AND PLUMBING PROFESSIONALS

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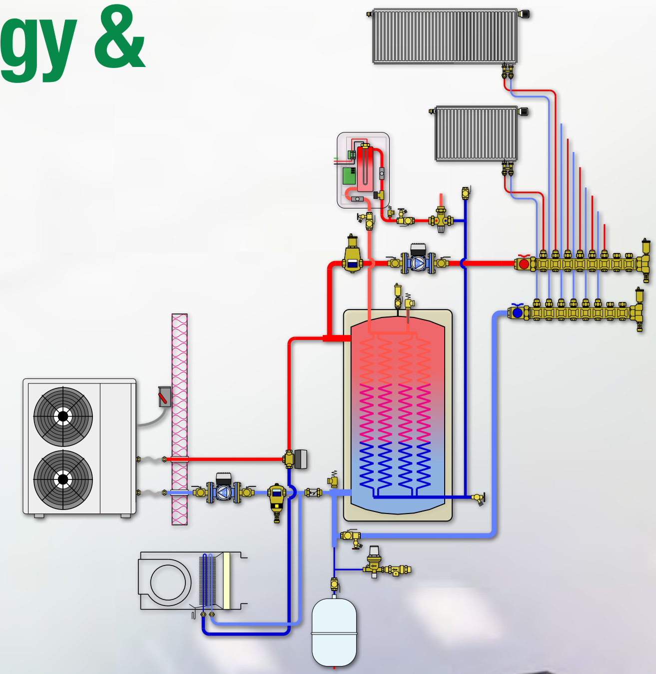
Hydronic Solutions

30
January 2022

Hydronics for Low-Energy & Net-Zero Buildings



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FROM THE GENERAL MANAGER & CEO

Dear Plumbing and Hydronic Professional,

In 2020, 75 percent of all new electrical power generation in the US was from solar photovoltaic and wind turbine systems. Wow! Renewably-sourced electricity is growing faster than I had imagined.

A societal shift toward decarbonization is underway.

I don't have an electrically powered car, but recently replaced my old chainsaw with a battery powered one. Same goes for the ice auger, leaf blower, weed trimmer, and pressure washer. And when our natural gas water heater finally succumbs, we'll likely consider replacing it with a heat pump water heater.... especially if time-of-day electrical rates become available in our area.

These are just a few examples of how shifting energy trends effect my daily life. You likely have had related experiences. Maybe you own an electric vehicle, have solar photovoltaic panels on your roof, or hydronic heating and cooling system supplied by a heat pump. Maybe you even remind your kids to *turn off the lights* like your parents did in the energy crisis 70's. If so, you are where the majority of the North American population is likely to be in the near future.

This issue of *idronics* describes the concepts and technical details for designing hydronic systems for low energy and net zero buildings. It stresses simple, cost effective, and resilient approaches that deliver the superior comfort hydronic systems have long been known for. Several system examples are provided that deliver heating, cooling, and domestic hot water.

We hope you enjoy this issue of *idronics* and encourage you to send us any feedback by e-mailing us at idronics@caleffi.com.

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Mark Olson

Mark Olson

General Manager & CEO

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from
CALEFFI NORTH AMERICA, INC
3883 W. Milwaukee Rd
Milwaukee, Wisconsin 53208
USA

Tel: 414-238-2360
FAX: 414-238-2366

E-mail: idronics@caleffi.com
Website: www.caleffi.us

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1. INTRODUCTION

For decades, the majority of the energy used to heat buildings has been supplied from fossil fuels, mostly in the form of natural gas, fuel oil and propane. During this time, the vast majority of hydronic heating systems were supplied by boilers burning these fuels.

The market for hydronic heating (and cooling) technology, like many other markets based on the beneficial use of energy, continues to be shaped by technological innovation, energy prices, public perception, government policy and economic competition.

As the 21st century unfolds, social attitudes and government policies around the world are increasingly focused on climate change, with a prevailing emphasis on reducing carbon emissions. One prominent example of this progression is the 2015 Paris Climate Accord, under which many nations have committed to bring their net carbon emissions from all energy use to zero by 2050. Another example is current or pending regulations that add a tax based on the carbon emissions from various fossil fuels such as natural gas, fuel oil and transportation fuels. Carbon taxes are already in place in Canada and are slated to increase substantially by 2030 to disincentivize the use of fossil fuels and encourage beneficial electrification. Several major U.S. cities, including Oakland, CA, and Seattle, WA, now have restrictions, or bans, on natural gas services for new buildings. More cities in both the US and Canada are expected to enact similar restrictions in the near future.

Still, widely varying opinions remain on how “decarbonization” should be accomplished. They range from complete dismissal of any need to act on the subject, to proposals that would radically change how an average person would eat, remain comfortable in their home or workplace, travel, or even use their leisure time.

Figure 1-1

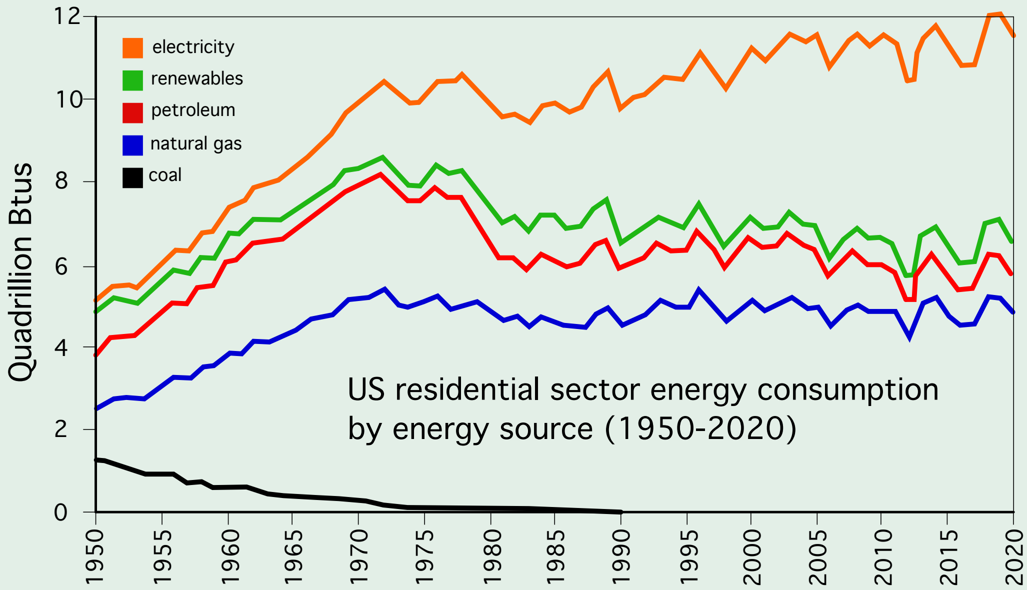
Figure 1-2

Regardless of such opinions, the scope of the decarbonization issue, both within North America and globally, is certain to affect the future of hydronics technology. Those effects will be based on actions beyond what any individual or company can control. The likelihood of reduced reliance on fossil fuels is contrasted by *emerging opportunities for hydronic-based heating and cooling systems* that operate on electricity obtained from sources other than fossil fuels.

The shift toward electrification is based on increasing availability of renewably sourced electricity. During 2020, utility-scale solar photovoltaic systems, such as those shown in figure 1-1, as well as utility-scale wind turbine systems, as shown in figure 1-2, accounted for more than 75 percent of all new electrical generation in the U.S.

Figure 1-3 shows the overall growth in residential energy use, as well as the increasing percentage of that energy supplied by electricity over the last several decades.

Figure 1-3



Data source: US Energy Information Administration (May 2021)

- Electricity excludes losses in generation and deliver
- Petroleum includes fuel oil, propane & kerosene
- Renewables include wood, geothermal, and solar energy

Other developments that continue to influence the market for hydronic systems are evolving building technology and regulations that significantly reduce building heating and cooling loads relative to those common during the 20th century.

During the latter half of the 20th century, it was common for single family homes to have design heating loads in the range of 30-35 Btu/hr/ft^2 of floor area. A typical 2,500 square foot home would require a heat source with a capacity of 75,000 to 88,000 Btu/hr. A home with an 88,000 Btu/hr design load, in a cold winter climate (7,000ºF•day and -5ºF outdoor design temperature) would require about 128 million Btu (128 MMBtu) of delivered heat to maintain an average indoor temperature of 70ºF over an average heating season.

State and provincial energy codes, in combination with steady improvement in the efficiency of heating and cooling equipment, and energy conservation standards such as EnergyStar, LEED and R-2000, have drastically reduced the energy required for space heating and cooling.

Today, a 2,500 square foot house built to one or more of these standards could have a design heating load in the range of 10-15 Btu/hr/ft^2 of floor area, approximately 1/3 that of a similar-sized home built 50 years ago.

Figure 1-4

Courtesy of Rachel Wagner

Figure 1-5

The growing availability and increasing efficiency of air-to-water heat pumps (Figure 1-5) and geothermal water-to-water heat pumps, will also significantly influence the market for hydronic systems. *Unlike boilers, nearly all these heat pumps can provide chilled water for cooling.* This characteristic alone opens many opportunities that were previously impractical. As 2022 and the years following unfold, heat pumps will gain an increasing portion of the hydronic heat source market. The flexibility of modern hydronics technology allows informed designers to craft systems that allow heat pumps to operate at peak performance.

The confluence of these trends for electrification, building heating/cooling load reduction, and heat pump technology, presents an unprecedented opportunity for use of modern hydronics technology, one that could significantly increase market share and better meet consumer expectations.

This issue of *idronics* describes the concepts and technical details of how to craft hydronic systems for modern low-energy and net-zero buildings. It stresses simplicity, repeatability and resilient approaches that deliver comfort without the complexity and cost that has, in some cases, stigmatized the use of hydronics in such buildings. Several examples of systems that deliver heating, cooling, and domestic hot water will be provided.

2. CHARACTERISTICS OF A NET-ZERO BUILDING

The first step in designing any heating or cooling system is to understand the building the system will supply. It could range from a 200-year-old building with little or no insulation, single pane windows and high rates of air leakage, to a contemporary structure built to the latest energy conservation standards.

For most buildings, and over many decades, customary practice was to decide on the fuel source, select the type of heat emitters to be used, and then size a heat source to maintain a selected interior air temperature (typically 68-72ºF) under the coldest expected outdoor temperature. Although this approach has led to acceptable installations, it often did not address issues such as ideal comfort, reducing emissions or energy use strategies that could be mutually beneficial to the consumer, the energy supplier and the environment.

The long-standing "customary" approach to building heating and cooling is changing. Modern building designers are employing increasingly wholistic strategies that consider more than the simple thermodynamic balance of matching heating or cooling source equipment to building loads.

Because buildings represent approximately 40 percent of the total energy used in North America, energy conservation efforts, both voluntary and mandatory (in the form of building codes and other regulations) have accelerated over the last decades. These efforts have resulted in buildings that can maintain comfortable interior conditions, such as those based on ASHRAE Standard 55, while using less a 1/3 the energy per square foot of floor space that was required 50 years ago.

Other wholistic design considerations include increased attention to indoor environmental quality, adaptive use of renewable energy and reducing carbon-based emissions.

Collectively, these new design considerations allow contemporary buildings, as well as rehabilitated structures, to serve their intended purposes with minimal environmental impact. Extrapolating these advancements into the future suggests that buildings may eventually be environmentally benign as well as energy self-sufficient.

WHAT IS "NET-ZERO?"

There is no single definition or current standard the specifies exactly what constitutes a "net-zero" building.

The original concept was a building that could produce all the energy it required over a typical year using various combinations of onsite generation, energy storage and "feedback" of surplus electrical energy to a utility grid. The energy required included that used for heating, cooling, domestic water heating, as well as for lights, appliances, cooking, etc.

The only practical way to create such a building was to incorporate onsite electrical energy generation using solar photovoltaic modules.

During the 1970s, the cost of solar photovoltaic modules was in the range of $1,000 per peak watt. This limited their use to very specialized situations such as power for spacecraft, satellites and critical use applications such as remote mountaintop communications equipment.

Over the last 50 years, the price of solar photovoltaic modules has decreased by orders of magnitude. Today, the retail cost of solar photovoltaic modules is typically between $1 and $2 per peak watt. The reliability and service life of solar photovoltaic modules has also improved significantly over this time. These advances now make it practical to create onsite electricity in a wide range of climates ranging from tropical to arctic. The life-cycle cost of energy provided by modern solar photovoltaic modules and balance of system components is now competitive, and in some cases, lower than that of utility-supplied electricity. Solar electric systems are now widely used to supply electricity to buildings ranging from single family homes to large industrial facilities.

Solar PV systems are an integral subsystem in most net-zero buildings. In many cases, the solar PV array is

Figure 2-1

Figure 2-2

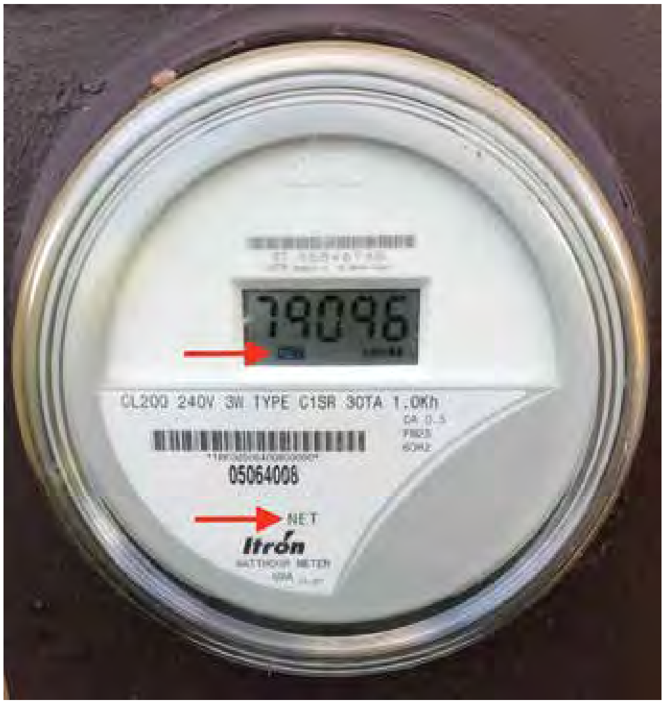
Courtesy of Revision Energy

located on the building, as seen in figure 2-2, or mounted close to it on the same site. In other cases, where site-mounted panels may not be practical, the PV array is centralized as part of a community solar electric system. Each client building is individually metered for the energy it draws from that system and billed accordingly.

NET METERING

Another technical as well as legal development that makes net-zero buildings possible is called "net metering." The fundamental concept is that the building owner is compensated by the utility for any surplus electrical energy generated on the customer side of the meter and fed back to the utility's electrical grid. Furthermore, each kilowatt•hour of electrical energy supplied by the customer to the utility grid is credited to the customer at *the same retail rate* as a kilowatt•hour supplied to the building by the utility. When this concept is in effect, the electrical grid becomes equivalent to a battery that is free, 100% efficient and practically infinite in size. Thus, it would be possible for a photovoltaic system to send surplus electrical energy into the grid during a sunny summer day, and "pull" an equivalent amount of electrical energy back from the grid on a cold winter night, without any net cost to the consumer. Electric utility meters that are certified for bidirectional energy flow are used to ensure accurate tallies for both ingoing and outgoing electrical energy.

Figure 2-3



Net metering, where it's available, provides a huge energy management advantage. It eliminates the classic quandary associated with solar thermal systems, where excess energy needs to be stored on-site, and in thermal form, until it is needed.

However, various electric utilities and their regulating bodies treat the concept of net metering differently. Some allow complete net metering as previously described. Others only pay an "avoided cost" for electrical energy sent into the grid from the solar electric system, which is akin to paying customers a *wholesale* rate rather than a retail rate. Others impose a tariff to customers with solar photovoltaic systems, or other forms of onsite electrical generation. The intent of the tariff is to compensate for grid maintenance and other expenses that would normally be present on invoices to customers with no onsite power generation. Some utilities do not allow any form of net metering. Regulations regarding net metering continue to evolve. Current regulations for all areas of the United States are available at the website **www.dsireusa.org**.

Some early approaches to net-zero buildings included the use of natural gas or other fossil fuels to meet a portion of the energy needs. Since these fuels cannot be regenerated on site, the energy they provided would have to be compensated for by surplus electrical generation from the building's solar electric system. Although possible, given a sufficiently sized solar photovoltaic system, this approach focuses solely on balancing energy use with onsite energy production. It doesn't necessarily encourage energy conservation measures, decarbonization, or the ability for the building to sustain operation under abnormal conditions, which have now become important considerations.

Contemporary approaches to net-zero construction aim to eliminate fossil fuel use within buildings. This stems from rising interest in reducing carbon emissions rather than only seeking a balance between energy use and energy production. This approach requires "all-electric" buildings, and thus limits the choice of hydronic heating sources to heat pumps or electric resistance boilers. If cooling is to be provided, the building will likely use a reversible air-to-water heat pump or geothermal water-to-water heat pump.

ELECTRICAL ENERGY STORAGE & MANAGEMENT

Another trend associated with modern net-zero buildings is called resiliency. It refers to the ability of the building to withstand unexpected events such as severe storms, earthquakes or floods that could create widespread and long-lasting utility power outages. Given that most or all of the energy needed within the building under such circumstances would be provided by electricity, the building needs battery energy storage and the ability to operate as an "island" completely independent of the utility grid.

Several companies now offer lithium ion battery storage systems and load management controls that enable such operation. Figure 2-4 shows one example of a residential scale battery-based energy storage system.

Figure 2-4

The integration of onsite battery storage into solar electric systems also allows for the possibility of utilities to draw energy from the batteries during peak demand periods. Such an arrangement would be governed by terms and compensation rates between the utility and building owner. When many buildings within a utility service territory have this ability, the utility can "aggregate" their capacity to create a virtual peak-shaving electrical generation effect. This can be mutually beneficial to the building owner — who is compensated for the energy withdrawn from their storage system —as well as the utility, which avoids the need to operate expensive peak power generators that are typically fueled by natural gas.

The load management controls now available for storage-equipped solar photovoltaic systems can also shift the operating times of certain appliances, such as water heaters, dishwashers, clothes washers and electric vehicle chargers, to reduce peak demands on the utility, or take advantage of lower retail electrical rates during low-demand periods.

Figure 2-5

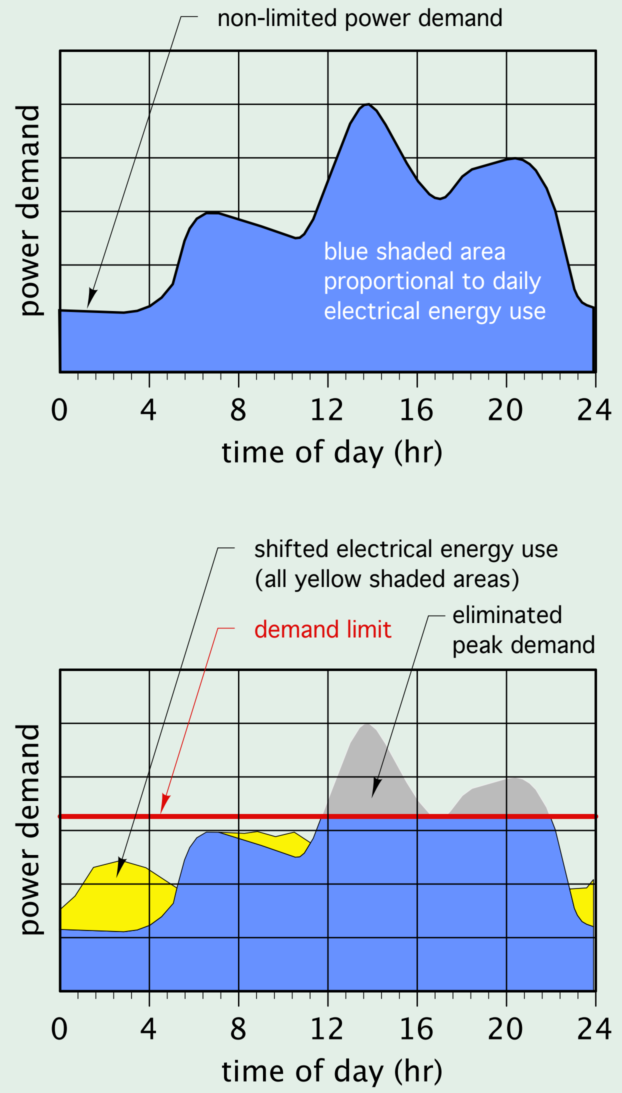
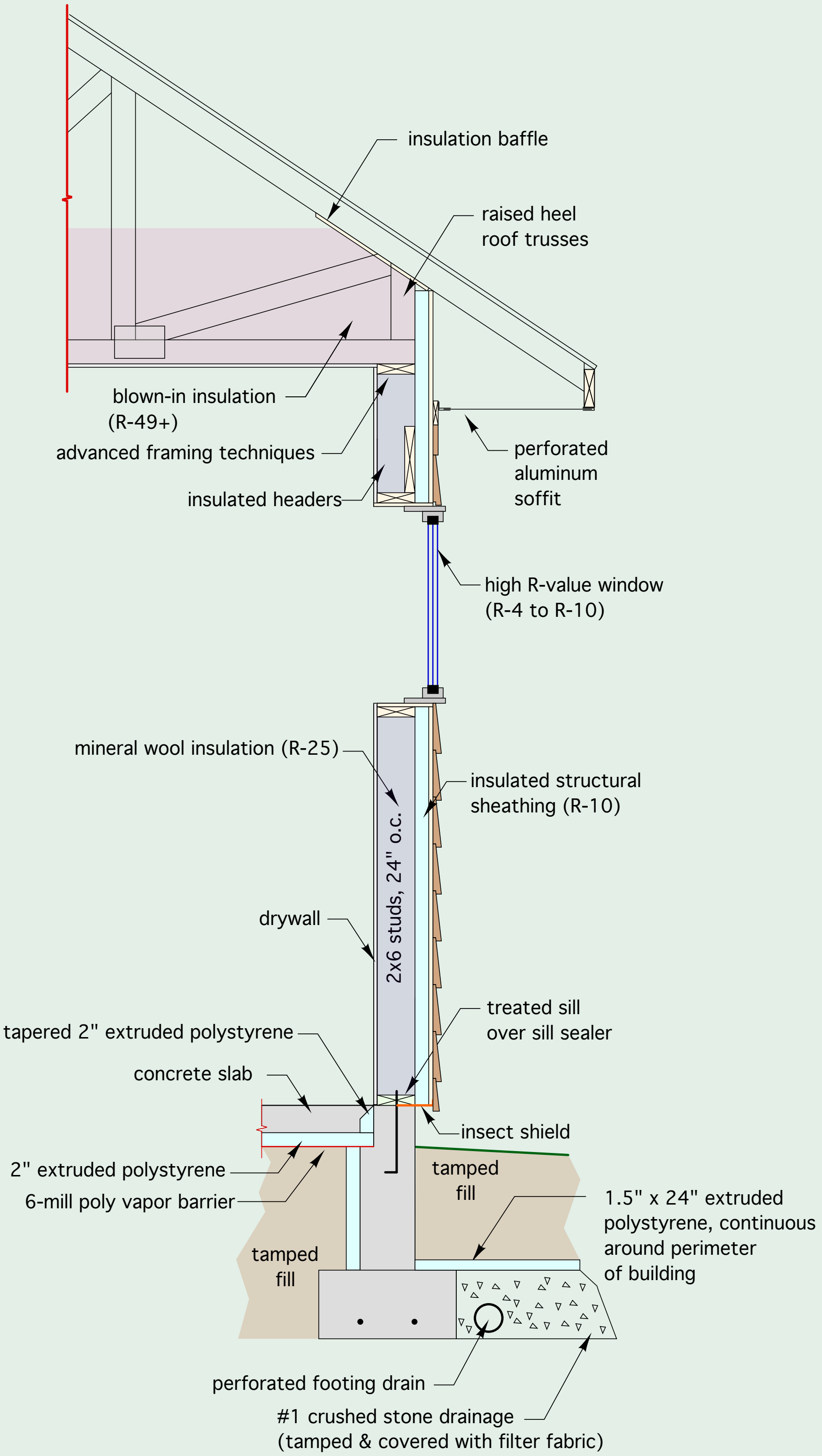


Figure 2-5 shows the concept of "demand limiting" as part of an electrical load management strategy.

The upper graph is a plot of the electrical power demand of an example house versus time of day. Although every house will have a somewhat different profile, it is common to have multiple peak demand periods when occupants prepare for the day in the morning, operate multiple appliances at mid-day, and turn on lights and other devices in the evening. The blue shaded area in the graph would be proportional to the total electrical energy used over the 24-hour period.

Figure 2-6



The lower graph demonstrates the concepts of demand-limiting and load shifting. The red line represents the highest electrical power demand allowed by a controller managed by the electric utility or the home's own energy management system. Notice that there two peak periods, shown in gray, that are above this allowed demand. The energy represented by these peaks has been shifted to other, lower-demand times, and shown as the yellow shaded areas. The yellow areas could represent the energy used by appliances such as washing machines, water heaters or dishwashers, electric vehicle chargers or other devices that are automatically turned on during low-demand periods.

The net result may be that the same total electrical energy was used, but the peak power demand was limited to an extent that eliminated the need for expensive peak power generation by the utility.

HIGH-PERFORMANCE THERMAL ENVELOPES

Contemporary net-zero buildings almost always have high-performance thermal envelopes. High R-value insulation, high-performance windows and extensive air-sealing techniques are used to minimize space heating and cooling loads, and thus reduce the amount of onsite energy generation needed to achieve net-zero status. They also reduce cost and often have a better return on investment relative to using larger solar arrays to meet the demands of less energy-efficient buildings.

Figure 2-6 shows one example of a high-performance thermal envelope for a small wood-framed house with R-30+ walls, R-49+ ceilings and R-4+ windows. The slab-on-grade floor is also well insulated. The sheathing provides a layer of continuous insulation at the exterior to reduce conduction heat loss through the framing. In many cases, advanced

Figure 2-7

Figure 2-8

Courtesy of VanEE

construction techniques, such as 24-inch on-center framing and raised heel roof trusses, are used to further reduce conduction heat loss, speed construction and reduce material requirements.

Residential building and energy codes continue to mandate lower heating and cooling loads. Load reduction is also encouraged through programs such as ENERGY STAR®, Certified Passive House and R-2000 (Canada). Reduced heating and cooling loads in commercial structures are encouraged through programs such as LEED (Leadership in Energy and Environmental Design).

Residential design heating loads in the range of 10 to 15 Btu/hr per square foot of floor area are becoming common in new construction or deep energy retrofits where the eventual intent is net-zero energy operation.

Many low-energy or net-zero buildings also make use of passive solar heating where possible. They are typically oriented with their long axis within 25 degrees of true south, and have a higher percentage of windows placed on their southern side. That orientation also allows for high electrical energy output from roof-mounted solar photovoltaic arrays.

INDOOR AIR QUALITY

The techniques used to reduce space heating and cooling loads in low-energy and net-zero homes, especially those associated with air sealing, greatly reduce the rate of air leakage relative to buildings constructed to older standards. This creates the potential for poor indoor air quality. The typical remedy for this is to include mechanical ventilation systems that can maintain a healthy exchange of outdoor air with indoor air.

ASHRAE Standard 62.2-2016 calls for a residential ventilation rate that would allow a minimum of 0.35 air changes per hour in the home, but not less than 15 cubic feet per minute (CFM) of outdoor air per occupant.

To conserve the thermal energy associated with ventilation, many low-energy and net-zero homes are equipped with heat recovery ventilation systems. The main component in such a system is called a heat recovery ventilator (HRV), or in some cases, an energy recovery ventilator (ERV). Figure 2-8 shows an example of an HRV.

The HRV contains two blowers. One creates an incoming stream of outside air. The other creates an outgoing stream of air from the building. The two air streams pass through a heat exchange “core” within the unit. In winter, the warm outgoing air stream transfers heat to the incoming cold air stream. In summer, the outgoing (cooler) air absorbs heat from the incoming air. The two air streams never mix, but up to 70 percent of the heat (or “cool”) in the outgoing air stream can be recaptured to minimize the effect on the building’s heating and cooling load.

An ERV is similar to an HRV. The difference is that the core in an ERV can also exchange *moisture* between the two air streams. In winter, some of the moisture in the outgoing (higher absolute humidity) air stream is transferred to the incoming (low absolute humidity) air stream. In summer, some of the moisture in the incoming (higher absolute humidity) air stream is transferred to the (lower absolute humidity) outgoing stream. This moisture exchange helps maintain a comfortable (and healthy) indoor relative humidity in winter. It also reduces the latent cooling load in summer.

Both HRVs and ERVs require a ducting system to distribute the pre-conditioned air within the building. In some cases, the ducting system is specifically designed for ventilation only. In other systems, the HRV or ERV can be interfaced with an existing or new forced-air distribution system.

Figure 2-9

Source: Ecoinnovations

This is well-suited to situations where a single chilled water air handler, supplied from an air-to-water or water-to-water heat pump, and connected to a forced-air distribution system, is used for cooling. More details on this approach are provided in upcoming sections.

DOMESTIC HOT WATER CONSERVATION

Another way that building energy use can be lowered is through reduced use of domestic hot water. For a typical family of 4, the energy needed for domestic water heating can be 25 to 30 percent of the total thermal energy used in an energy-efficient house. For projects aspiring to net-zero status, it is common to use low-flow shower heads, washing machines that operate with minimal if any hot water, and drain heat recovery devices, such as shown in figure 2-9.

EMBODIED ENERGY CONSIDERATIONS

Those who focus on the environmental benefits of net-zero buildings often place increased emphasis on “embodied energy” and “embodied carbon.” The concept of embodied energy revolves around the total life-cycle energy associated with the components in the building, including acquisition of raw materials, processing those materials, transportation, installation, maintenance and disposal. The rationale is to avoid materials and construction methods that, although they may save a given amount of energy during their useful life, ultimately require an even greater amount of energy to produce, install, maintain and for disposal.

Embodied carbon is a similar concept. The rationale being to select building materials and methods so that the net effect does not add to the carbon content in the earth’s atmosphere. Some building designers currently use carbon accounting software to minimize the amount of carbon used in the overall life-cycle of various building components.

GLOBAL WARMING CONSIDERATIONS:

Building design as well as mechanical system selection is also being influenced by global warming considerations. The choice of refrigerants used in devices such as heat pumps will increasingly be impacted by these considerations. Existing hydrofluorocarbon (HFC) refrigerants, such as R410a, will eventually be replaced by refrigerants with lower global warming potential. These include carbon dioxide (CO_2), propane (R-290) and difluoromethane (R-32).

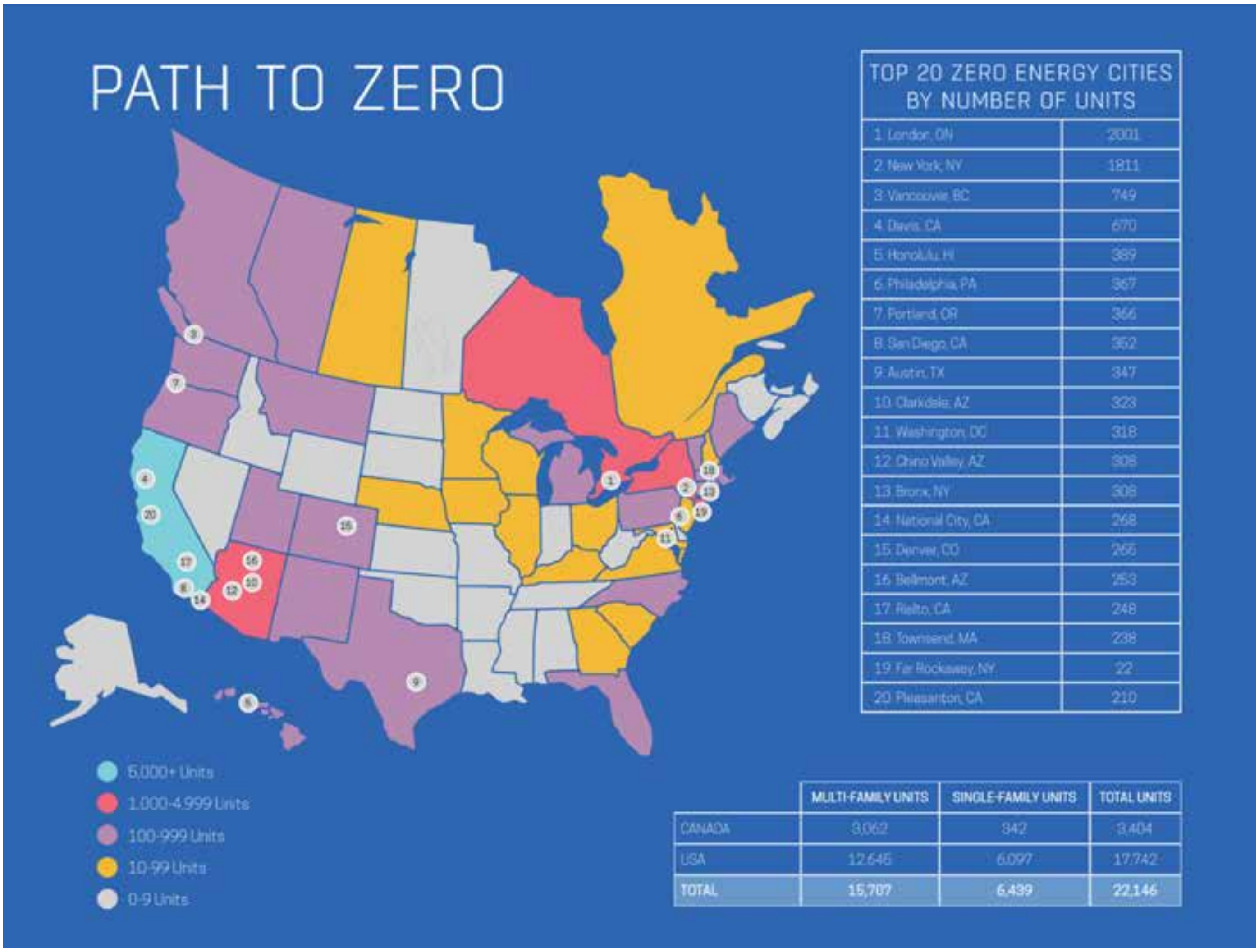
THE MARKET FOR NET-ZERO

Demand for net-zero energy buildings is growing rapidly in North America and globally. It is currently one of the fastest growth segments of the construction industry. The compound annual growth rate for net-zero energy buildings in North America is projected to average 15.6 percent from 2019 through 2024. By 2025, the projected value of the global net-zero building market is over 79 billion U.S. dollars.

North America leads the world in terms of the number of net-zero projects currently constructed. The North American market, combined with the European Union, represents over 95 percent of the global market for net-zero buildings. Figure 2-10 shows the range of market activity in North America.

The primary drivers for this market growth are government regulations that seek to reduce global warming based on carbon emissions from fossil fuels. Carbon emissions associated with building heating and

Figure 2-10



TOP 20 ZERO ENERGY CITIES BY NUMBER OF UNITS	
1. London, ON	2001
2. New York, NY	1811
3. Vancouver, BC	749
4. Davis, CA	670
5. Honolulu, HI	389
6. Philadelphia, PA	367
7. Portland, OR	366
8. San Diego, CA	352
9. Austin, TX	347
10. Clarkdale, AZ	323
11. Washington, DC	318
12. Chino Valley, AZ	308
13. Bronx, NY	308
14. National City, CA	268
15. Denver, CO	266
16. Bellmont, AZ	253
17. Rialto, CA	248
18. Townsend, MA	238
19. Far Rockaway, NY	22
20. Pleasanton, CA	210

	MULTI-FAMILY UNITS	SINGLE-FAMILY UNITS	TOTAL UNITS
CANADA	3,062	342	3,404
USA	12,645	6,097	17,742
TOTAL	15,707	6,439	22,146

Source: www.teamzero.com

cooling are estimated to be between 40 and 50 percent of the total global emissions, and thus carbon reduction programs are keenly focused in this area.

CREATIVE HYDRONIC SYSTEM DESIGN

The rapidly expanding market for net-zero buildings presents a unique opportunity for designers to create hydronic systems that are symbiotic to the previously described characteristics of low-energy and net-zero buildings. Those systems need to be simple, repeatable, reliable, efficient, and perhaps most important, they need to provide excellent human thermal comfort. The sections that follow will show how these objectives can be achieved.

3. ADVANTAGES OF HYDRONIC SYSTEMS IN LOW-ENERGY & NET-ZERO BUILDINGS

There are many ways to provide space heating, cooling and domestic water heating in all-electric net-zero buildings. They range from separate systems for each load, to integrated approaches that leverage energy recovery and energy management to minimize consumption and coordinate the needs of building occupants with the real-time status of the utility grid.

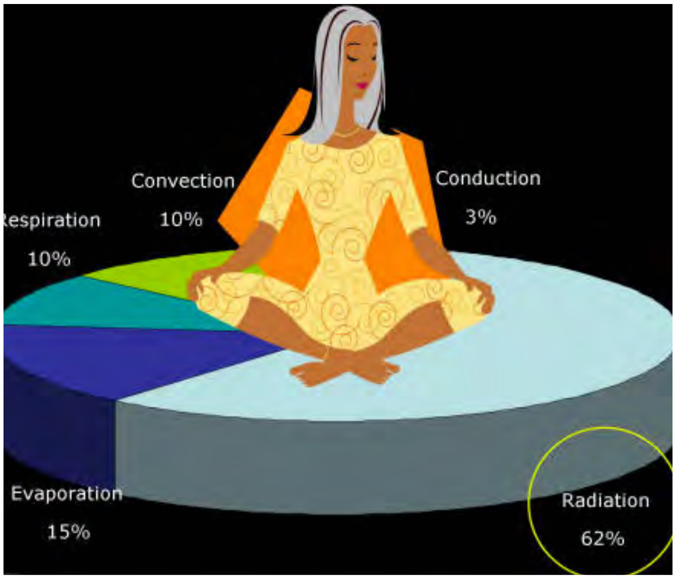
This section describes the advantages and benefits of using hydronic-based systems in low-energy and net-zero buildings. It also discusses some of the hydronic heating and cooling hardware that's appropriate for these applications. Later sections will show specific details and example systems.

SUPERIOR THERMAL COMFORT

Although some energy enthusiasts are willing to live in buildings that minimize energy use at the expense of widely varying comfort, this is not true for most North American consumers. History has shown that approaches to space heating and cooling that require sacrifices in comfort to achieve high energy-efficiency targets or absolute minimum energy use, usually fail to gain significant market share. The lesson learned: _Comfort_, has been and remains one of the most important underlying factors in establishing and *maintaining* a market for building energy systems.

Human thermal comfort is determined by the interaction of processes the body uses to dissipate metabolic heat production, as well as the environmental conditions within the occupied space. These include air temperature, air temperature stratification, interior surface temperatures, relative humidity and air movement. Comfort is established when the conditions surrounding the body allow metabolic heat production to be dissipated at the same rate it is generated. Some degree of discomfort is experienced when these two rates of heat transfer are not balanced.

Figure 3-1



Courtesy of healthyheating.com

A healthy adult engaged in light activity generates heat at a rate of about 400 Btu/hr. Figure 3-1 shows the heat transfer processes by which a human adult dissipates this metabolic heat production.

Notice that a high percentage of the body's heat dissipation comes from thermal radiation to surrounding surfaces. This has profound implications regarding comfort. It can make a person located near a large, cool surface, such as a window on a cold winter day, quite uncomfortable, even if the room's air temperature is 70°F. The opposite is also true: the gentle warmth emitted by a heated surface, such as a warm floor or ceiling, or a panel radiator, can provide excellent comfort, even when the surrounding air temperature is in the mid-60ºF range.

Designers can assess how different building characteristics influence human thermal comfort using software called the CBE Thermal Comfort Tool. It's freely accessible at **https://comfort.cbe.berkeley.edu/**

Several types of hydronic distribution systems simultaneously influence air temperature, temperature stratification and surface temperatures of rooms in ways that enhance human physiological comfort. This distinguishes them from alternatives such as electric furnaces, ductless mini split heat pumps, or central heat pumps that connect to forced-air distribution systems. These air-based delivery systems have less influence on interior surface temperatures and can create undesirable drafts or air temperature stratification. As such, they are not as well-matched to human comfort needs.

ACOUSTICAL COMFORT

Most people want their home to be a quiet refuge from the pace and *noise* of modern life. They don't want to hear sounds emanating from their heating and cooling systems. Properly designed and installed hydronic systems

Figure 3-2

using radiant panels or panel radiators can operate with virtually *no detectable sound within occupied spaces*. The sound produced by the source equipment, such as the compressor in a heat pump, is either outside the building or it can be acoustically isolated within a mechanical room.

Although some ducted forced-air systems can also operate at very low sound levels, the levels associated with wall-mounted fan-coils, such as used in ductless heat pumps, is clearly detectable by occupants with normal hearing. That sound, although not intense, is still undesirable. It can interfere with conversation, listening to music or watching television, especially for occupants with partial hearing loss.

REDUCED AIR VELOCITY

Most hydronic-based systems also create minimal air velocity within conditioned spaces. This reduces the possibility of drafts, which compromise comfort. Lower air velocity also reduces the dispersant of airborne pollutants such as viruses, dust, pollen, smoke, volatile organic compounds and cooking odors.

This characteristic doesn't eliminate the need for proper ventilation, or filtration of ventilation air, such as provided by a heat recovery ventilator, but it does enhance the effectiveness of that ventilation.

EASY ZONING

Hydronic heating & cooling systems can be easily zoned to allow different spaces within a building to accommodate individual comfort preferences and activity levels. Well-planned zoning can also help eliminate overheating or underheating due to variations in internal heat gain from sunlight, appliances, lighting and occupants. This ability is especially beneficial in low-energy and net-zero buildings, which, due to their high-performance thermal envelopes, are more prone to variations in air temperature due to internal heat gains.

ELECTRIC HEATING & COOLING SOURCE EQUIPMENT

There are several electrically operated devices that can provide heating and cooling when combined with a hydronic distribution system in a low-energy or net-zero building.

ELECTRIC BOILERS

One of the simplest hydronic heat sources is an electric boiler, an example of which is shown in figure 3-3.

Electric boilers contain one or more resistance heating elements that directly heat water passing through the boiler. For residential and light commercial systems, these boilers are available with rated heating outputs from 5 kW (17,065 Btu/hr) to 40 kW (136,500 Btu/hr).

Figure 3-3

Courtesy of Thermolec

Electric boilers suitable for use in homes or small commercial buildings are typically supplied by one or more single-phase 240 VAC circuits. *When an electric boiler is being considered, it is essential to verify that the building's electric service has sufficient capacity to operate it, in addition to the other loads. A 200-amp electric service is generally considered a minimum requirement.*

All electric boilers provide one kilowatt•hour (3,413 Btu) of heat per kilowatt•hour of electrical input. That performance can also be represented as a coefficient of performance (COP) of 1.0 when comparing them to heat pumps.

Because they are electric resistance heaters, these boilers require 2 to 4 times as much electrical energy input as a heat pump (assuming heat pumps with seasonal average COPs of 2.0 to 4.0). Their operating cost relative to a heat pump will be proportional to the heat pump's seasonal average COP (i.e., an electric boiler's operating cost would be 3 times higher relative to that of a heat pump with a seasonal average COP of 3.0). This higher operating cost may be justified for a small, highly energy-efficient home, especially where electric rates are low or time-of-use rates are available. The relatively low installation cost of an electric boiler relative to an equivalent heat pump also helps justify their potential use in low-energy and net-zero buildings.

Advantages of electric boilers include:

- Very small and easy to mount
- No combustion or venting requirement
- Some have internal controls that regulate outlet temperature based on outdoor reset
- Much less expensive than heat pumps of equivalent heating capacity
- Can operate at elevated water temperatures up to 200ºF if necessary
- Minimal servicing requirements

Disadvantages include:

- Cannot provide cooling
- Higher operating cost relative to heat pumps of equivalent capacity
- Typically require minimum 200-amp electric service entrance
- High power draw may be beyond what a typical emergency generator can supply

GEOTHERMAL WATER-TO-WATER HEAT PUMPS

To date, most of the North American systems that combine heat pumps with hydronic distribution have used water-to-water heat pumps supplied by geothermal heat sources (e.g., earth loops or water wells).

In heating mode operation, a water-to-water heat pump absorbs heat from a low-temperature geothermal source, increases the temperature of that heat, and passes it to a separate higher-temperature water stream that delivers it using a hydronic distribution system.

In cooling mode, a water-to-water heat pump absorbs heat from a stream of water that passes through one or more air handlers, fan-coils or other cooling terminal unit(s) within the building. The temperature of that absorbed heat is increased, and it is passed to another water (or antifreeze solution) stream that dissipates it outside the building — typically to an earth loop.

Figure 3-4

Figure 3-4 shows an example of a water-to-water heat pump having a nominal heat output of 48,000 Btu/hr.

Two of the four larger pipes connected to this heat pump go to an earth loop. The other two connect to the hydronic distribution system. The two smaller pipes near the bottom of the heat pump connect a desuperheater heat exchanger within the heat pump to a domestic hot water storage tank. All of these pipes will be insulated and vapor-sealed when the installation is completed.

Most currently available water-to-water heat pumps can produce water at temperatures up to approximately 125ºF for space heating. They can also produce chilled water for cooling.

For more information on water-to-water heat pumps, and how they can be applied in geothermal applications, see idronics #9.

Advantages of geothermal water-to-water heat pumps include:

- Can provide heated water up to 125ºF and chilled water for cooling
- No visible outdoor equipment or sound
- Slightly higher seasonal COP compared to air-source heat pumps in cold climates
- Can be ordered with desuperheater for domestic water heating
- Longer expected service life (20-25 years) relative to air-source heat pumps due to their interior location
- No defrost cycle is required (as needed for all air-source heat pumps)
- No venting or combustion air is required

Disadvantages include:

- Significantly higher installation cost compared to air-source heat pumps
- Installation is often highly disruptive of existing landscape
- Not compatible with all installation sites due to lot size, ground water regulations, presence of rock ledge, etc.
- Antifreeze solution generally required in earth loops

AIR-TO-WATER HEAT PUMPS

Low-energy and net-zero buildings equipped with hydronic heating and cooling distribution systems can also be supplied by heat pumps that absorb heat from outside air, even when the temperature of that air is below 0ºF. This low-temperature heat is combined with electrical energy to produce a stream of heated water at temperatures up to about 130ºF. Like water-to-water heat pumps, most air-to-water heat pumps contain refrigerant reversing valves, allowing them to also provide chilled water for cooling.

Air-to-water heat pumps eliminate the need for geothermal earth loops. This allows for installation at almost any site, and at significantly lower cost compared to that of geothermal heat pump systems of equivalent capacity.

There are two primary configurations for air-to-water heat pumps:
- Monobloc
- Split system

Figure 3-5 shows an example of a monobloc air-to-water heat pump.

The refrigeration system in a monobloc air-to-water heat pump is completely contained within the outdoor cabinet. It is charged with refrigerant, sealed and leak-tested before leaving the factory. Installers do not need to add to or adjust any part of this refrigeration system. They only need to run supply and return piping and electrical power to the heat pump. This allows the potential for the heat pump to be installed by a contractor who doesn't have the experience or servicing tools to deal with refrigeration systems.

Figure 3-5


Courtesy of SpacePak

Because they are located outside in cold climates, nearly all monobloc air-to-water heat pumps operate with a mixture of water and antifreeze, such as a 30% solution of non-toxic propylene glycol. This protects the heat pump from potential freeze damage during a prolonged power outage in sub-freezing weather.

Monobloc air-to-water heat pumps also contain significantly less (approximately half) the refrigerant volume per ton of heating capacity compared to ductless heat pumps, especially when the latter are installed with the maximum allowable refrigerant line set lengths between the outdoor unit and multiple indoor units.

Figure 3-6 shows an example of a split-system air-to-water heat pump. The outdoor unit connects with the indoor unit using two copper refrigerant lines, the same as used with most central air-conditioning systems. There is no water in the outdoor unit, which eliminates the need for antifreeze in the system. The indoor unit contains the refrigerant-to-water heat exchanger, which serves as the condenser in heating mode and the evaporator in cooling mode.

Split-system air-to-water heat pumps have comparable performance to monobloc units. In heating mode, both operate over a range of heating capacity and COPs depending on the outdoor air temperature and the leaving water temperature at which they are operating. Both are available with variable-speed, "inverter-driven" compressors that allow them to vary heating and cooling capacity from some maximum rated output down to about 30 percent of that output. This is helpful in situations where a single-zone, chilled-water cooling distribution unit needs to operate at a relatively small capacity compared to the heat pump's full heating capacity.

Figure 3-6a


Courtesy of SpacePak

Figure 3-6b

Advantages of air-to-water heat pumps include:
- Can provide heating water up to 130ºF and chilled water for cooling
- Can be installed at nearly all sites

- Not disruptive to landscaping
- Low ambient units can operate at sub-0ºF air temperatures
- Significantly lower installed cost relative to equivalent geothermal heat pumps

Disadvantages include:

- Shorter expected service life (15-20 years) due to outside installation
- Slightly higher operating cost relative to geothermal water-to-water heat pumps
- Automatic defrost cycles are required
- Monobloc systems require antifreeze in outdoor piping
- Limited availability of units with desuperheater for domestic water heating
- Highly zoned systems will require a buffer tank

For more information on air-to-water heat pumps, see idronics #27.

DISTRIBUTION EFFICIENCY

Professionals who design low-energy and net-zero buildings apply scrutiny when selecting the “source equipment” that supplies space heating, cooling and domestic hot water. They often limit selections to state-of-the-art devices with the highest available thermal efficiencies.

While this approach is certainly relevant and logical, it is also incomplete. The energy used by the source equipment, be it a boiler, heat pump or chiller, is only part of the total energy used by the system. Regardless of how heating energy or cooling effect is generated, additional energy is needed to *distribute* that thermal energy within a building. Treating this “distribution energy” as insignificant or inconsequential is a serious oversight in the design process, especially when the objective is to create buildings that minimize energy use.

The energy required to distribute heat produced by any heat source, or the cooling effect generated by any cooling source, should always be considered when designing a heating or cooling system for a low-energy or net-zero building. Systems that use a significant amount of energy to move heat from where it is produced to where it is needed in the building are undesirable, even if the thermal energy is produced at high efficiency by the source equipment.

Distribution energy is an even more important consideration for cooling systems. *Every watt of electrical energy used to move cooling effect through a building is a watt added to the building’s sensible cooling load.* For example, a constant-torque ECM blower motor used in a nominal 3-ton forced-air heat pump adds about 2,935 Btu/hr (0.24 tons) to the building’s sensible cooling load. An ECM circulator delivering an equivalent cooling effect using chilled water, and operating at an input power of 35 watts, only adds 120 Btu/hr to the sensible cooling load.

Designers should also consider that air-to-air heat pumps typically require higher air flow rates per unit of heat delivery compared to fossil-fuel furnaces, and thus their distribution power requirement is higher, assuming the same blower motor technology in each device.

One way to assess this aspect of system design is through an index called “distribution efficiency,” which is defined as follows:

$$n_d = \frac{Q_{delivered}}{w_e}$$

Figure 3-7

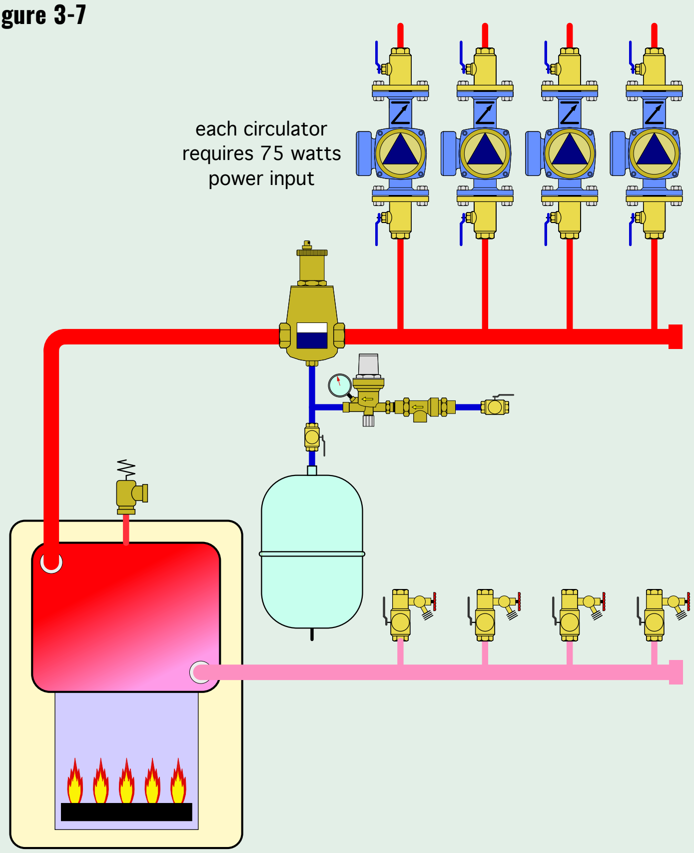
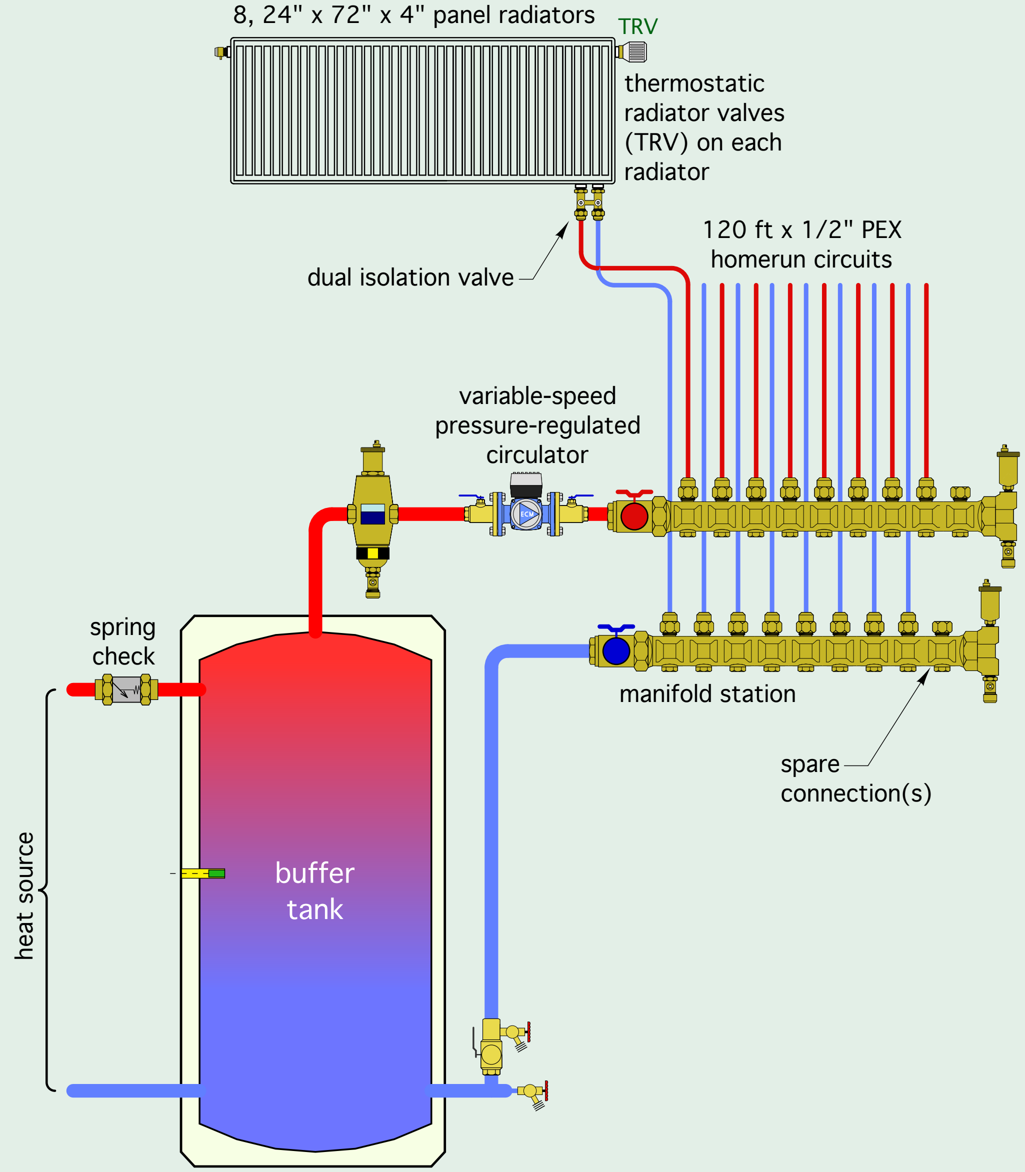


Figure 3-8



Where:
n_d = distribution efficiency (Btu/hr/watt)
$Q_{delivered}$ = rate of heat delivery under design load conditions (Btu/hr)
w_e = electrical power required by the distribution system under design load conditions (watts)

The higher the distribution efficiency, the lower the operating cost of the distribution system per unit of heat delivered.

For example, consider a "traditional" hydronic heating system that uses four small circulators, each operating on 75 watts input power, and collectively delivering 100,000 Btu/hr to the building. A schematic of this system is shown in figure 3-7.

Assuming that all circulators are operating under design load conditions, the distribution efficiency would be:

$$n_d = \frac{Q_{delivered}}{w_e} = \frac{100{,}000\frac{Btu}{hr}}{4 \times 75 watt} = 333.3\frac{Btu/hr}{watt}$$

The number 333.3 Btu/hr/watt can be interpreted as follows: for each watt of electrical power supplied to the distribution system, it delivers 333.3 Btu/hr to where it's needed in the building.

However, this number has little relevance without something to compare it to. To provide such a comparison, consider a forced-air delivery system associated with a furnace that requires 550 watts while delivering 80,000 Btu/hr to the building. The distribution efficiency of that system is:

$$n_d = \frac{Q_{delivered}}{w_e} = \frac{80{,}000\frac{Btu}{hr}}{550watt} = 145.5\frac{Btu/hr}{watt}$$

In this specific comparison, the forced-air system has less than half the distribution efficiency of the hydronic system. This implies that the forced-air system requires over twice the electrical power input of the hydronic system to deliver the same amount of heat to the load.

The concept of distribution efficiency can be used to compare hydronic versus forced-air heating systems, as well as competing hydronic system designs.

Consider, for example, the contemporary “homerun” hydronic distribution system as shown in figure 3-8.

This system, which would be well-suited for use in low-energy or net-zero homes, uses a high-efficiency variable-speed pressure-regulated circulator to create flow between the buffer tank and 8 individually regulated panel radiators. Under design load conditions, the water leaving the buffer tank is maintained at 120ºF, which is well within the operating range of an air-to-water or water-to-water heat pump.

Each panel radiator is assumed to be piped with 1/2-inch PEX tubing, 60 feet out and 60 feet back from a manifold station. A non-electric thermostatic radiator valve regulates the flow of warm water through each panel radiator based on its setting and the current room temperature.

A hydraulic analysis of this system, under the stated conditions, shows that it could deliver 30,800 Btu/hr to a building, with a circulator power input of only 8.6 watts. Thus, it would have a distribution efficiency of:

$$\text{distribution efficiency} = \frac{30{,}800\frac{Btu}{hr}}{8.6watt} = 3581\frac{Btu/hr}{watt}$$

Comparing this to the previously discussed forced air distribution system, which had a distribution efficiency of 145 Btu/hr/watt, shows that this modern hydronic system can deliver heat to the building using only (145/3581) = 4% of the electrical input energy needed by the forced-air system, per unit of heat delivered. *This demonstrates the overwhelming advantage of using water, rather than air, in combination with state-of-the-art hydronic hardware, to deliver heat in a low-energy or net-zero building.*

Assuming that the high-efficiency circulator operated at approximately 75 percent of design input wattage for 3,000 hours per year, in a location where electricity costs $0.12/kWhr, the seasonal operating cost of the distribution system would only be about $2.32. This compares to a seasonal estimated operating cost of $148 for the previously described forced-air system operating under the same assumed conditions.

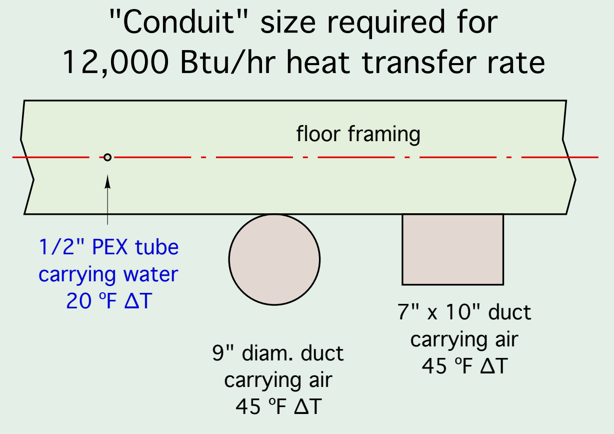
MINIMALLY INVASIVE INSTALLATION

A given volume of water can absorb almost 3,500 times more heat than the same volume of air, assuming both materials undergo the same temperature rise. This allows a given rate of heating or cooling to be conveyed using small diameter hydronic tubing relative to the size of a duct conveying that same rate of heat transport using air.

For example, consider a heat transfer rate of 12,000 Btu/hr. This would be adequate to heat an area of 1,200 square feet in a low-energy or net-zero house having a design load of 10 Btu/hr/ft^2 of floor area. If water is used to convey this heat transfer, and the hydronic distribution system operated at a typical design load temperature drop of 20ºF, the required flow rate is only 1.2 gallons per minute (gpm). This flow rate could be handled by a nominal 1/2-inch PEX tube. That tube could be easily routed along or through framing members with virtually no impact on the structure.

If air is used to provide this same 12,000 Btu/hr heat transport rate, while undergoing a temperature change from 65ºF to 110ºF through the heat source, the required flow rate would be 247 cubic feet per minute (CFM). Assuming a typical duct sizing air velocity of 600 feet per minute (FPM), a 9-inch diameter round duct, or a 7-inch high by 10-inch wide rectangular duct would be needed. Figure 3-9 shows a scaled comparison of these different delivery “conduits.”

Figure 3-9



A 1/2-inch PEX tube could be easily routed through floor framing using 3/4- or 7/8-inch diameter holes. If these holes were drilled near the center of the floor joists, they would have no significant impact on the structure. However, due to their size, the equivalent ducts shown would have to be supported under the floor framing, potentially compromising the use of the space below.

Beyond the heat conveyance consideration is the issue of heat loss and possible insulation requirements. A 9-inch diameter duct has about 14 times more surface area compared to a 1/2-inch PEX tube. The 7-inch by 10-inch rectangular duct shown in figure 3-9 has about 17 times more surface area. Assuming the same insulation requirement, the round duct would require about 14 times more insulation material, and the rectangular duct about 17 times more material, per unit of length. If the ducting and hydronic tubing operated at the same temperature, the heat loss (or heat gain in cooling mode) would be substantially higher for the ducting.

REFRIGERANT CONSIDERATIONS:

Nearly all monobloc-style air-to-water heat pumps and geothermal water-to-water heat pumps used in hydronic heating and cooling systems come with a factory-charged, sealed and leak-tested refrigeration system. With proper handling and installation, the chances of a refrigerant leak occurring during or after installation are very small.

A small 2-ton rated monobloc heat pump contains about 5 pounds of refrigerant. A 5-ton rated unit would contain about 7 pounds.

These relatively small refrigerant volumes should be compared to those of multi-head ductless heat pumps and commercial VRF systems.

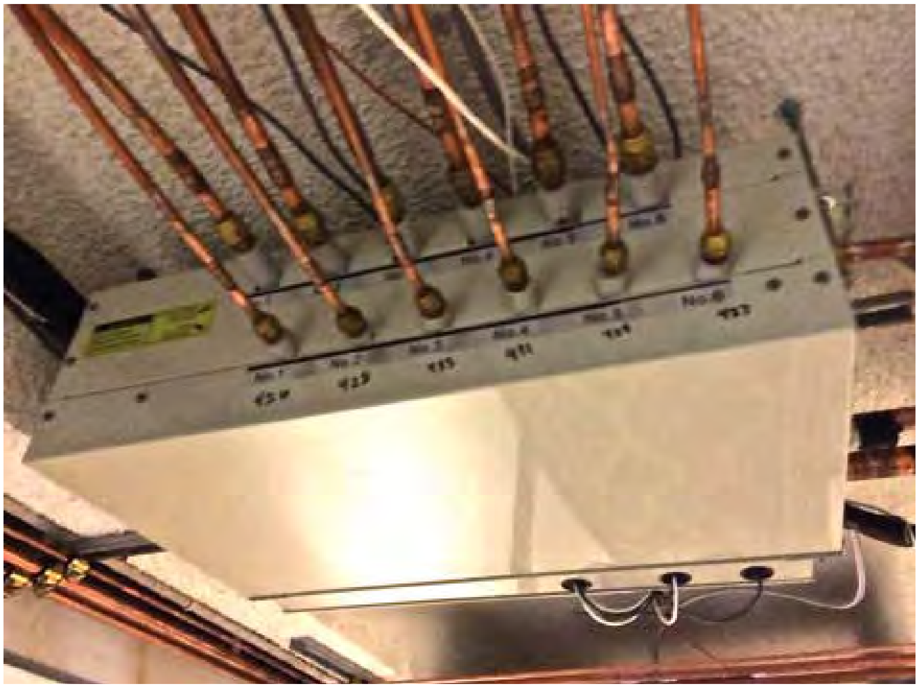
Figure 3-10

One nominal 3-ton ductless heat pump system, when applied with maximum allowable refrigerant piping lengths, requires approximately twice the refrigerant volume per ton of rated capacity compared to that required by a typical factory-sealed air-to-water or water-to-water heat pump. One 8-ton rated VRF system contains over 25 pounds of refrigerant, more than twice the volume of refrigerant per ton of capacity compared to a typical factory-sealed air-to-water or water-to-water heat pump.

Large VRF systems in commercial buildings can contain hundreds of pounds of refrigerant. A leak in such a system is a serious safety issue, as well as an environmental hazard. Although the currently popular refrigerant R-410a is not toxic and non-flammable, it will displace air if allowed to accumulate within a confined space. Given sufficient concentration and the inability to vacate a space quickly, this could lead to asphyxiation.

One OSHA material safety data sheet (MSDS) for R-410a states the following: *"In Case of Spill or Leak Use Halogen leak detector or other suitable means to locate leaks or check atmosphere. Keep upwind. Evacuate enclosed spaces and disperse gas with floor-level forced-air ventilation. Exhaust vapors outdoors.*

Figure 3-11



Do not smoke or operate internal combustion engines. Remove flames and heating elements."

ASHRAE Standards 15 and 34 set specific limits on how much refrigerant a system can contain based on the volume of the smallest interior space into which that refrigerant could potentially leak. Under ASHRAE Standard 34, which applies to systems containing more the 6.6 pounds of refrigerant, there can be no more than 26 pounds of refrigerant in the system per 1,000 cubic feet of the smallest occupied space into which refrigerant could potentially leak. For institutional buildings, where occupants might not be able to evacuate without assistance, the limit is 13 pounds of refrigerant per 1,000 cubic feet of smallest occupied space.

Ductless heat pumps and VRF systems also contain many site-fabricated joints in refrigeration piping. Most of these joints are inside the building. Figure 3-11 shows both brazed and compression joints in refrigeration tubing that's a small portion of a VRF system installed at a multi-story hotel.

Although field-installed refrigerant piping is leak-tested during the installation, the number of connections and the conditions under which they are made inevitably increase the possibility of leaks over time.

Another consideration is the ongoing evolution of refrigerants based on their global warming potential. Prior to the 1990s, the most common refrigerant used in North American heat pumps and central air-conditioning systems was R-22, which, among other compounds, contained chlorine. Rising concern over the effects of chlorine on atmospheric ozone eventually led to a phaseout of R-22. Beginning in January 2020, the production or import of R-22 was no longer allowed in the U.S.

Today, most residential and light commercial heat pumps and air-conditioning systems used in North America operate on R-410a refrigerant. However, due to its global warming potential relative to newly developed alternative refrigerants, R-410a is also scheduled to be eliminated from new equipment beginning in January 2023. There will likely be a multi-year phaseout plan for R-410a similar to that used for R-22. New refrigerants such as R-32, which has a lower global warming potential (roughly 1/3 that of R-410a), are already being used in some new heat pumps systems in Europe and Asia. Eventually, propane (R-290), which has good refrigerant properties and low global warming potential, may be accepted for use as refrigerant in some heat pump applications where all the refrigerant remains in outdoor equipment. However, it remains questionable whether a flammable refrigerant, such as propane and to a lesser degree (R-32), would be allowed in systems with large refrigerant volumes and extensive interior refrigerant piping. This situation has the potential to severely limit the future service of current-generation VRF systems.

Beyond specific refrigerant chemistries are potential compatibility issues related to lubricating oils, and the size/pressure rating of the refrigerant piping used. The latter consideration is especially relevant to large VRF systems, which can contain thousands of feet of copper tubing selected and sized for specific current-generation refrigerants and their associated lubricants.

These considerations should be contrasted with those relevant to the air-to-water or water-to-water heat pumps used with hydronic distribution systems. Monobloc air-to-water heat pumps contain all refrigerant outside the building. As such, they are more adaptable to potential use with flammable refrigerants. The relatively small refrigerant volumes present in these heat pumps in comparison to those present in VRF systems makes the consequences of a leak much less costly, and less of a safety issue.

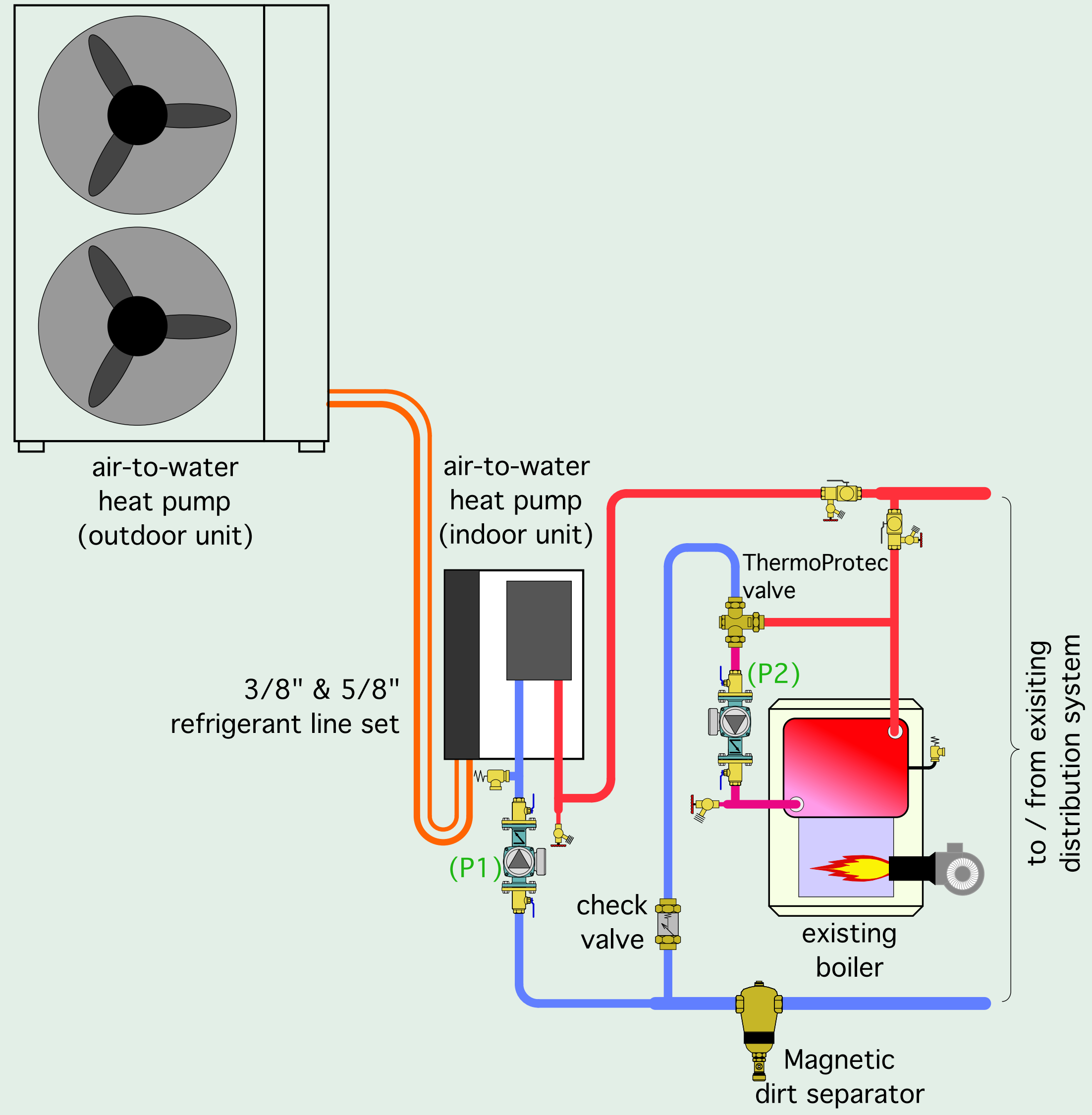
Buildings equipped with hydronic heating and cooling distribution systems are also minimally dependent on evolving refrigerant regulations — provided the source equipment using these refrigerants can meet the capacity and supply water temperatures required by the hydronic distribution system.

PIPING FLEXIBILITY

There are several piping configurations that have been used for hydronic heating and cooling systems over many decades. These configurations are highly scalable. In smaller systems, the piping is typically sized so that flow velocities don't exceed 4 feet per second. The orientation of the piping in a closed hydronic system is largely irrelevant — provided that provisions are made to vent air from high points in the system. Piping can be vertical, horizontal, sloped and routed over or under obstructions. Different piping materials, such as copper, steel, PEX and polypropylene, can be combined in the same system when there are advantages in doing so.

In contrast, the piping requirements for VRF system are much more restrictive. Very specific details are required to prevent oil, which is circulated through the system with refrigerant, from being trapped and thus unable to flow back to the compressor. Insufficient oil return has resulted in compressor failures, which can cost thousands of dollars

Figure 3-12



to isolate, replace and recommission. Most VRF systems are also limited to copper tubing.

VERSATILITY OF HYDRONIC SYSTEMS

Although it's likely that heat pumps will steadily gain market share against fossil-fuel boilers in the years ahead, it's unlikely that the fossil-fuel boiler market will suddenly disappear. Existing fossil-fuel boilers will, in most cases, remain in operation until they can no longer be serviced, or until the cost of the fuel they require becomes significantly more expensive on a $/MMBtu basis compared to heat supplied through other means.

This can be beneficial, especially as a step in transitioning existing buildings from fossil fuel to an all-electric status. An existing boiler can serve as an auxiliary heat source as well as a peak load heat source, in combination with an electrically powered heat pump that serves as the primary heat source. In such a system, the objective is to provide heat from the heat pump whenever possible, but also recognize that some heat pumps may not have the heating capacity or be able to produce suitably high water temperatures to meet the building's heating load on extremely cold days. Making use of an existing boiler can also reduce the cost of the installation relative to removing an otherwise functional boiler and replacing it with a heat pump sized to cover the building's design heat load.

Figure 3-12 shows a relatively simple way to incorporate an existing boiler along with a new air-to-water heat pump.

The partial system shown in figure 3-12 has a split-system air-to-water heat pump piped in parallel with the existing boiler. Each heat source has its own circulator. There is also a check valve associated with each heat source to prevent flow reversal when that heat source is off and the other one is operating.

The controls for the system may be internal to the heat pump, or possibly external to either heat source, depending on the specific equipment used. The objective of the controls, during heating mode operation, is to use heat from the heat pump whenever possible, but invoke operation of the boiler when necessary to ensure that the load is being met. The boiler would typically be called to operate if the heat pump is unable to maintain some pre-set temperature on the supply side of the distribution system.

During cooling mode, the boiler would remain off. The heat pump would be operated as necessary to provide a suitable chilled-water supply temperature to the remainder of the system.

One way to maximize the seasonal COP of a heat pump supplying a hydronic distribution system is to regulate the supply water temperature based on outdoor reset control. This control strategy, which is built into the internal controls of some modern heat pumps, only allows the water temperature produced by the heat pump to be high enough to meet the current heating load. During mild weather, the water temperature supplied by the heat pump would be automatically lowered to maximize the heat pump's coefficient of performance (COP). As the load increases, the water temperature supplied by the heat pump would increase, up to a maximum of 125ºF to 130ºF. If higher supply water temperatures are needed, the heat pump would be turned off and the boiler would supply the load.

Depending on its heating capacity relative to the building's design load and the climate, an air-to-water heat pump or geothermal water-to-water heat pump may be able to supply 75 percent or more of the building's seasonal space heating energy, *even when connected to a legacy hydronic distribution system using "high-temperature" heat emitters, such as fin-tube baseboard.*

This percentage of total seasonal space heating energy can be increased by either reducing the building's heating load, or by adding heat emitters to the system. Both of these techniques lower the required water temperature of the distribution system. In some cases, an air-to-water heat pump can provide upwards of 95 percent of the seasonal space heating energy.

See idronics #25 for more information and details on lowering water temperature in existing hydronic distribution systems.

The boiler shown in figure 3-12 is assumed to be an existing "conventional" boiler (e.g., one not intended to operate with sustained flue gas condensation). When outdoor reset control is added to the system, there will be times when the water temperature is significantly lower than temperatures associated with the original installation. A Caleffi ThermoProtect mixing valve should be installed to protect the existing boiler for operating with sustained flue gas condensation.

The existing boiler can also serve as a low-power-demand backup heat source during a power outage. Most residential-sized gas-fired or oil-fired boilers can operate with an electrical power demand in the range of 100 to 400 watts. By comparison, a residential-sized heat pump may have a power demand in the range of 2,000 to 6,000 watts. The relatively low power demand of the exiting boiler could be supplied by a small emergency generator. It might also allow the boiler to operate from the home's electrical energy storage system — if so equipped. This concept demonstrates a degree of resiliency that might not be possible with an electric boiler due to its much higher electrical power demand.

If the building is eventually converted to all-electric as part of a net-zero strategy, the existing boiler could be replaced by an electric boiler with minimal piping modifications. However, this should only be done after an evaluation of the building's electrical service entrance to ensure adequate capacity. It might also entail an upgrade to the building's emergency generator if that generator is expected to power the electric boiler.

THERMAL STORAGE POTENTIAL

Water is one of the best materials available for storing thermal energy. This characteristic allows hydronic systems to include thermal energy storage where it provides a benefit. One possibility that's applicable in areas where utilities offer time-of-use electrical rates is operating a heat pump or an electric boiler during "off-peak" times when the cost of electricity is significantly reduced, and store some of the thermal energy produced during this period in an insulated tank for use during "on-peak" periods. Another possibility is to store heat produced by an electric boiler or heat pump during "off-peak" times in a large, solid, thermal mass such as a thick concrete slab with embedded hydronic tubing. Both of these techniques have been used in limited applications to date. They hold potential for increased adaptation as influencing factors such as real-

Figure 3-13

time electrical pricing become more common. Air-based heat pump systems have virtually no ability to leverage these opportunities without significantly and detrimentally affecting comfort. Thermal storage can also be coordinated with chilled-water cooling systems.

EASY EXPANDABILITY

There are several ways that hydronic heating and cooling systems can be designed for easy future expansion. This is especially true for homerun distribution systems supplying panel radiators or fan-coil units. A manifold station, such as that shown in figure 3-13, can be installed with one or more extra connections to allow heat emitters to be easily added.

Another possibility is to pipe systems during initial installation so that a second air-to-water heat pump could be added in the future to significantly increase heating or cooling capacity. By comparison, most central air-to-air heat pumps and ductless heat pump systems used in residential and light commercial applications do not allow for expansion beyond the configuration in which they were originally purchased. For example, a ductless system that was ordered in a 4-zone configuration could be initially used with 3 zones, but it could not be expanded to 5 zones. Any addition or modification to the building that required a 5th zone would require either a new condenser unit with 5 zones, or a separate single-zone system. Furthermore, multi-zone ductless heat pump systems are restrictive in terms of manufacturer-approved combinations of specific outdoor and indoor units.

ALL LOADS FROM A SINGLE HEAT PUMP

Another unique possibility offered by hydronic systems is the ability to provide domestic water heating in addition to space heating and cooling, all from the same heat pump. In a modern low-energy home, domestic water heating often represents 25 to 30% of the total thermal energy used and is therefore a major consideration if attempting to reach net-zero status. Domestic water heating is typically not provided by central air-to-air heat pumps or ductless heat pump systems.

Traditional approaches to domestic water heating in all-electric homes include electric resistance heating elements in a tank or within a tankless “on-demand” heater. Both of these approaches have been successfully used in thousands of buildings, some of which were likely achieving net-zero status.

A more recently introduced option — the heat pump water heater — is attracting the attention of some designers involved with net-zero buildings. These water heaters use a simple vapor/compression refrigeration cycle to gather heat from surrounding air and transfer it to domestic water in an insulated tank. Figure 3-14 shows a typical heat pump water heater installation and representative schematic of its refrigeration system.

Heat pump water heaters are well-suited to situations where “surplus” heat is available inside, or in some cases, outside a building. When properly applied, they can provide domestic hot water using roughly 1/3 the electrical energy required by electric resistance water heaters.

However, the term “surplus heat” must be scrutinized. Fundamentally, it implies that the low-temperature heat absorbed by the heat pump water heater is present due to circumstances other than being created by the building’s heating system. Examples of such circumstances include low grade heat in outdoor air, excess solar heat gains inside a building, low grade heat in an unconditioned basement or garage, or heat generated by equipment or processes in a commercial building. These sources of heat are a *byproduct* of how the building is configured or used, rather than heat intentionally produced by the building’s heating system. This is an important distinction because the “net” efficiency (measured as net COP) of a heat pump water heater that absorbs heat created by the building’s heating system is significantly lower than that of one that absorbs “surplus” heat.

Figure 3-15 shows the concept of “cascading” heat pumps (e.g., where the heat pump water heater absorbs heat placed in its vicinity it by another heat pump).

Figure 3-14a

Figure 3-14b

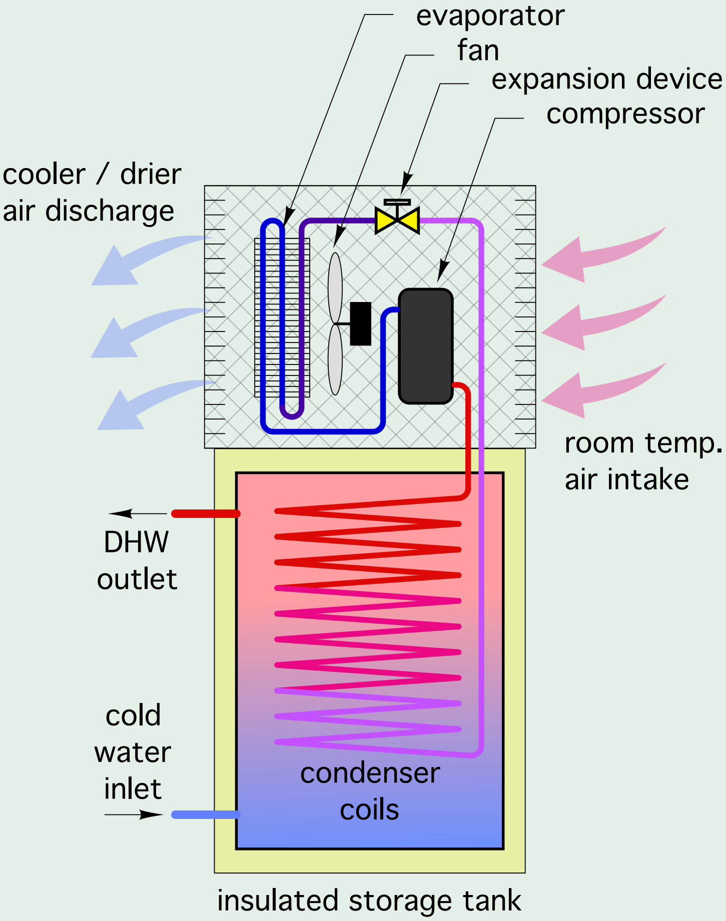
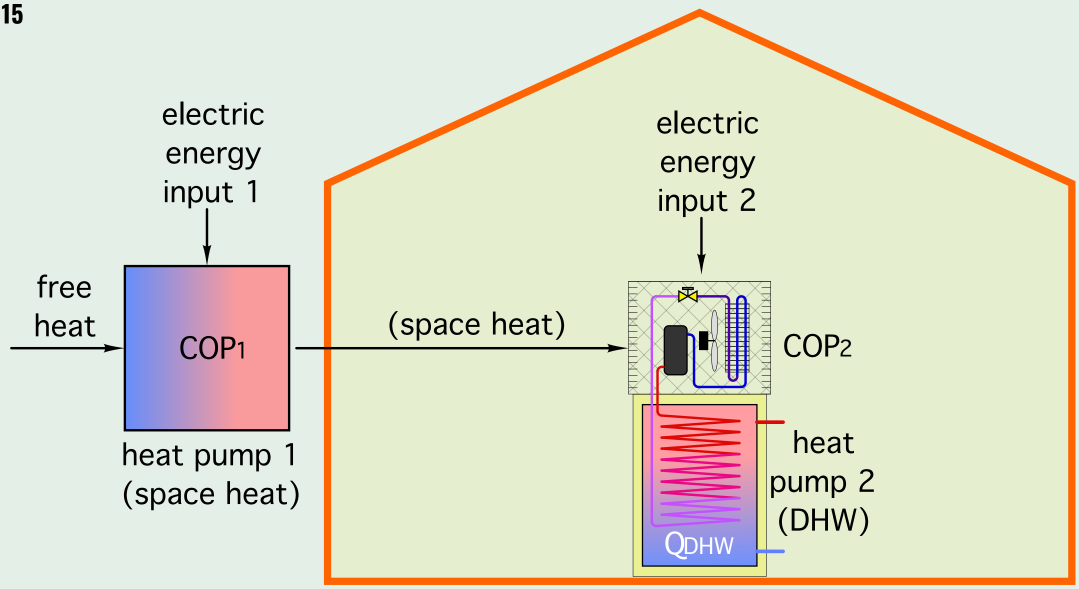


Figure 3-15



Heat pump 1 is absorbing free heat from outside the building, combining it with heat derived from electricity, and sending that heat inside the building. Heat pump 2 is a heat pump water heater. The water heater absorbs heat that was placed inside the building from heat pump 1, combines it with more energy sourced from electricity, and sends combined energy into domestic water within the tank.

The net COP of this cascading heat pump system can be determined as follows:

$$COP_{net} = \frac{\left(\frac{COP_1}{COP_1-1}\right)\left(\frac{COP_2}{COP_2-1}\right)}{\left[\left(\frac{COP_1}{COP_1-1}\right)\left(\frac{COP_2}{COP_2-1}\right)-1\right]}$$

Where:
COP_{net} = the overall COP of the two cascaded heat pumps
COP_1 = the COP off the space heating heat pump (must be > 1.0)
COP_2 = the COP of the heat pump water heater (must be > 1.0)
Note: To use this formula, both COP_1 and COP_2 must be > 1.0

For example, if a heat pump provides space heating to a building while operating at a COP of 4.0, and a heat pump water heater within that building *only absorbed heat produced by the space heating heat pump* while operating at a COP of 3.0, the net COP, defined as the heat added to the domestic water divided by the total electrical input to enable that heat placement, would be:

$$COP_{net} = \frac{\left(\frac{COP_1}{COP_1-1}\right)\left(\frac{COP_2}{COP_2-1}\right)}{\left[\left(\frac{COP_1}{COP_1-1}\right)\left(\frac{COP_2}{COP_2-1}\right)-1\right]} = \frac{\left(\frac{4}{4-1}\right)\left(\frac{3}{3-1}\right)}{\left[\left(\frac{4}{4-1}\right)\left(\frac{3}{3-1}\right)-1\right]} = \frac{2}{2-1} = 2.0$$

A net COP of 2.0 means that for every two units of heat delivered to the domestic water, one came from a "free" source, and the other came as electric heating. Although this net COP is still double the COP of any form of electric resistance heating (e.g., COP = 1.0), it is far lower than the rated COP of the heat pump water heater operating under the assumed condition of absorbing "free" surplus heat.

In most buildings, there will be times when the heat absorbed by the heat pump water heater is indeed surplus heat, and thus the long term net COP will likely be higher than the above calculation asserts. Still, the concept of "cascading heat pumps" demonstrates that placing a heat pump water heater within the heated thermal envelope of a low-energy or net-zero building, where the majority of the heat it absorbs is present due to operation of a space heating heat pump, doesn't yield the savings often cited for heat pump water heaters.

When a single air-to-water or geothermal water-to-water heat pump provides space heating, cooling, and domestic water heating, the heat it absorbs during the domestic water heating mode is always coming from a "free" source (e.g., outside air or heat in the earth). This avoids the derating effect just described for a cascading heat pump installation. An air-to-water heat pump that supplies a year-round domestic water heating load can typically achieve annual average COPs in the range of 2.5 to 3.0, depending on climate and the temperature to which the domestic water needs to be heated.

Some air-to-water and geothermal water-to-water heat pumps also can be ordered with a desuperheater heat exchanger for domestic water heating. During cooling mode operation, the heat gathered by the desuperheater from the hot refrigerant discharged from the heat pump's compressor is heat that would otherwise be dissipated outside the building (e.g., to outside air or into the earth). This scavenged heat is truly "free."

When an air-to-water heat pump is operating in cooling mode, and the thermostatic control in the domestic water storage tank calls for heating, the heat pump will temporarily switch to heating mode, quickly bring the tank temperature up to its setpoint, and then switch back to cooling. Later sections will show other system configurations that use heat pumps to supply domestic hot water as well as space heating and cooling.

RESILIENCY

Many professionals who plan buildings or HVAC systems are being asked to incorporate "resiliency" into their designs. This term implies an ability for buildings, or systems within buildings, to withstand unexpected events such as extended power outages, the effects of climate change or interruption of normal supply chains. The objective is to create buildings and systems that are reliable, long-lasting, adaptable and easy to repair when necessary.

Although it would be flippant to simply state that any hydronic heating or cooling system is highly "resilient," these systems do have characteristics that fit the objectives of resiliency.

One characteristic is that there are many potential sources for much of the hardware used in hydronic heating and cooling systems. For example, the eventual failure of a specific make and model of circulator within a hydronic system, or even the inability to obtain a new circulator of the same make and model, doesn't render the system inoperable for long. Several other makes and models of circulators are readily available for replacing the failed circulator. Most of the potential replacements would have the same flange-to-flange dimension as the original circulator, and could be installed within a few minutes by any competent heating technician using basic tools. This same concept holds true for many other components in a hydronic system, such as pipe, fittings, valves, expansion tanks, heat emitters, manifolds, air/dirt separators and basic temperature controllers, etc.

This adaptability may not be possible for alternatives such as ductless heat pumps or commercial VRF systems. Many of these systems have proprietary controls or other components that must be replaced with exactly the same component obtained from the original manufacturer or their authorized agent at whatever pricing they choose to set. Special tools, software and training are often required to fully service these systems. The eventual discontinuation of proprietary components, or long delays in obtaining them due to supply chain disruption, could render the entire system inoperable for extended periods, or even unrepairable.

Consider the following (real) scenario: A crack forms in a small plastic condensate collection pan inside a high-wall fan-coil that's part of a ductless heat pump (or VRF) system. This causes condensate to leak from the unit. Some makes and models of these fan-coil units do not allow that simple and inexpensive pan to be removed in the field and replaced as a separate component. The entire wall mounted fan-coil unit must be replaced. Doing so requires the system to be turned off. The refrigerant must be reclaimed and eventually reinstalled using specialized equipment. It also requires the refrigerant piping and wiring to be disconnected and reconnected. The overall process could take several hours and cost multiple hundreds of dollars. The fan-coil with the cracked condensate pan will likely be discarded, even though the majority of the components within it are in working order. This true story demonstrates *vulnerability* rather than resiliency.

Another reason that hydronic systems offer resiliency is that water will always be available as the working fluid. It is not subject to evolving global warming directives, refrigerant phaseouts, manufacturing limitations or material handling and transportation regulations. Any water lost from the system due to maintenance or component replacement is easily and inexpensively replaced. The heat source or cooling source within a hydronic system may change over time, but the physical properties that enable water to efficiently convey heat or cooling effect will not change.

Finally, most of the components used in a properly designed, installed and maintained hydronic distribution system will last for many decades. They will outlast the system's initial heat source or cooling source, and perhaps even its second or third heat source or cooling source. Simply stated: Properly executed hydronic systems are long-term investments rather than "throw away" technology. Contrast this with the typical service life of many modern appliances, such as refrigerators, washing machines and microwaves, some of which will not even last ten years under normal service. Portions of those discarded appliances will inevitably end up in landfills.

Professionals who plan low-energy and net-zero buildings, or place emphasis on decarbonization, environmentally conscious design, and resiliency, should carefully consider these benefits associated with hydronic heating and cooling systems.

4. KEY DESIGN CONCEPTS

Some of those who design or build low-energy and net-zero buildings have preconceived notions about hydronic systems. Their opinion is that such systems are overly complicated and unnecessary in these contemporary buildings.

In hindsight, the North American hydronics industry is largely responsible for cultivating these opinions by showcasing unique and elaborate installation photos. Figure 4-1 is an example.

This system uses a nominal 5-ton split-system air-to-water heat pump as its source equipment. Several of the ten circulators visible in the photo have high-efficiency ECM motors. The craftsmanship evident by the piping and electrical work is outstanding. This system certainly combines the concepts of heat pumps and modern hydronic system design, and likely delivers the goals for which it was custom designed.

Still, this system required hundreds of components to be properly selected, purchased, organized into a coherent design, and at least in part — field assembled. As such, this image can be overwhelming to architects, general contractors or owners looking for a simple, affordable and serviceable solution to heating and cooling a home with low space heating and cooling loads. The perceived complexity, cost or reliability of such a system often dissuades these building professionals or the eventual building owners from using hydronic-based systems.

The hardware-intensive approach to hydronic heating and cooling survives as a niche in the market, but mostly for custom-built new homes with generous construction budgets. This niche approach is unlikely to be adapted as a "go-to" solution by professionals designing low-energy and net-zero homes, especially when several alternatives compete for the mechanical system portion of the construction budget.

Figure 4-1

Courtesy of SpacePak

To achieve higher market acceptance, hydronic systems for low-energy and net-zero buildings need to be "tailored" to consumer expectations, load characteristics, desired environmental ramifications and available utility options. The following guidelines are appropriate.

Hydronic systems for low-energy and net-zero buildings should:

- Meet owner expectations for installed cost, reliability, serviceability, aesthetics, embodied carbon and recyclability.
- Provide superior thermal comfort in both heating and cooling modes.
- Provide an option for domestic water heating in addition to space heating and cooling.
- Recognize the unique load and thermal response characteristics of low-energy and net-zero buildings.
- Harmonize with the construction techniques and materials used in low-energy and net-zero buildings.
- Use simple, repeatable and scalable concepts.
- Enhance heat pump performance wherever possible.
- Minimizes electrical power demand (e.g., high distribution efficiency).
- Considers new delivery modes for electricity (e.g., real time pricing, onsite battery storage, load shifting and demand-limiting possibilities).
- Allows continuity of operation under unexpected conditions (resiliency).
- Consider use of existing boilers in retrofit projects.

This section will show and describe methods and hardware that address these design concepts.

HEAT EMITTER OPTIONS

There are dozens of devices and site-constructed assemblies that can serve as hydronic heat emitters. They range from concrete slabs with embedded tubing, to fan-assisted panel radiators, to extended surface-area fin-tube baseboards. These devices cover a wide range of thermal mass and supply water temperature requirements. They also cover a wide range of installation cost and complexity.

There may not be a "perfect" heat emitter selection that meets all of the previously stated system design objectives. For example, a heat emitter option that meets all of the technical requirements may not meet the owner's expectation for cost or aesthetics. Thus, heat emitter selection is often a compromise based on the "weight" the owner and system designer assigns to each of these design objectives.

In the context of low-energy and net-zero buildings, two technical characteristics should be given strong consideration:

- The thermal mass of the heat emitter(s).
- The supply water temperature required by the heat emitter(s) under design load conditions.

The thermal mass of different hydronic heat emitters can greatly influence the comfort achieved and maintained in a low-energy or net-zero building.

Figure 4-2 shows a sampling of thermal masses for several hydronic heat emitters. The numbers in the chart are based on the “amount” of heat emitter needed to release 1,000 Btu/hr into a room at 70ºF, while operating at an average water temperature of 110ºF. Note that the thermal mass for a heated 4-inch concrete slab is over 100 times that of a modern fan-assisted panel radiator.

Heat emitters with high thermal mass take much longer to adjust to changing load conditions compared to heat emitters with low thermal mass. This has both desirable and undesirable implications. For example, a high thermal mass heated slab can often maintain reasonable comfort within a well-insulated building for several hours during a power outage, or during a pre-scheduled time when high cost electricity rates apply, and thus an electrically powered heat source might be intentionally turned off . During these times, the slab slowly releases stored heat without simultaneously receiving heat input. This is a very desirable characteristic _under these circumstances._

However, the same heated slab installed in a building with large amounts of solar heat gain or other “unpredictable” internal heat gains can create wide variations in interior temperature due to its inability to quickly stop emitting heat.

Most currently constructed low-energy and net-zero buildings have high-performance thermal envelopes, and thus low rates of heat loss. These buildings are often designed and sited to take advantage of solar heat gains. _Given these characteristics, along with the goal of maintaining stable comfort, it is typically best to use low_

Figure 4-2

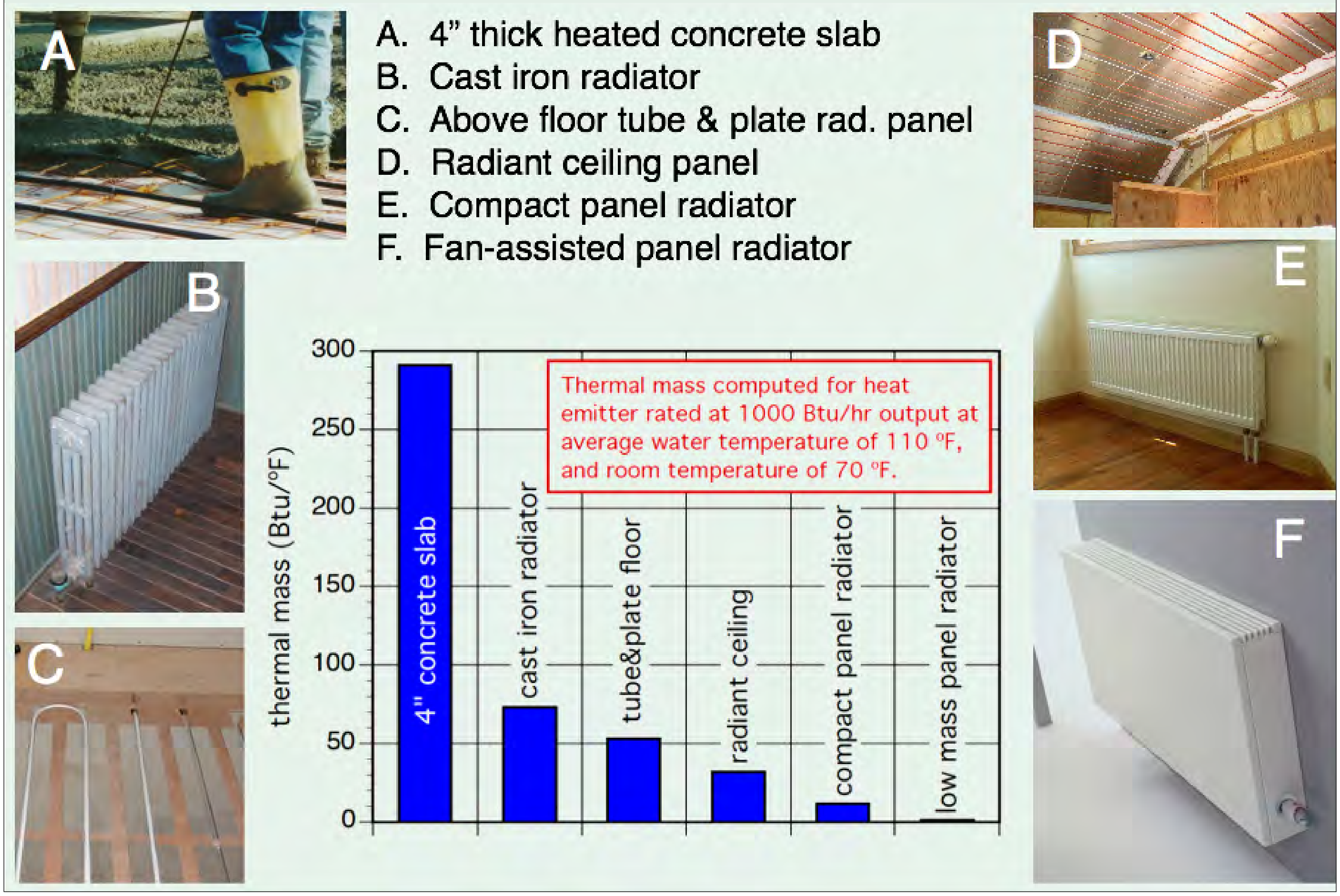
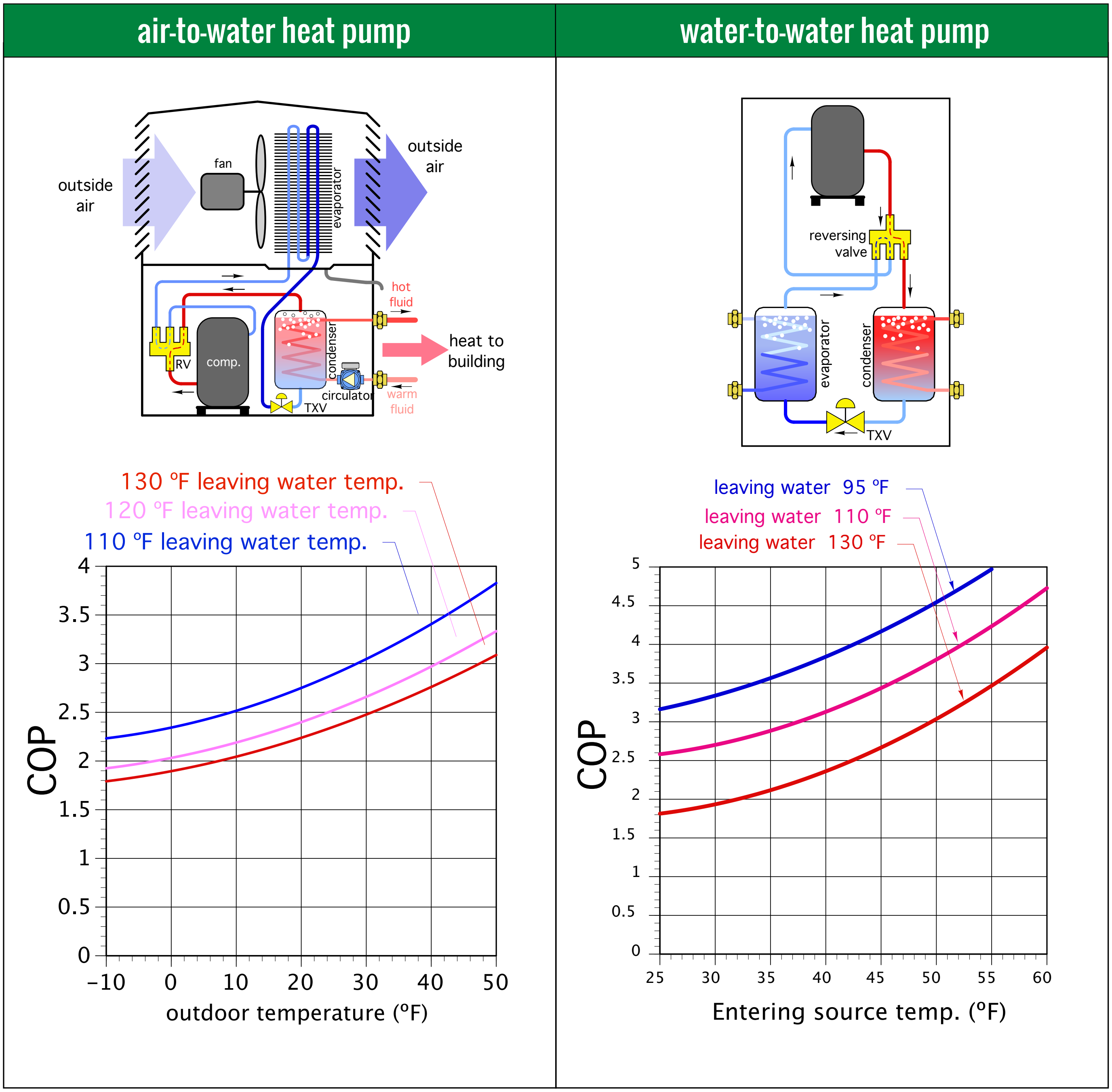


Figure 4-3

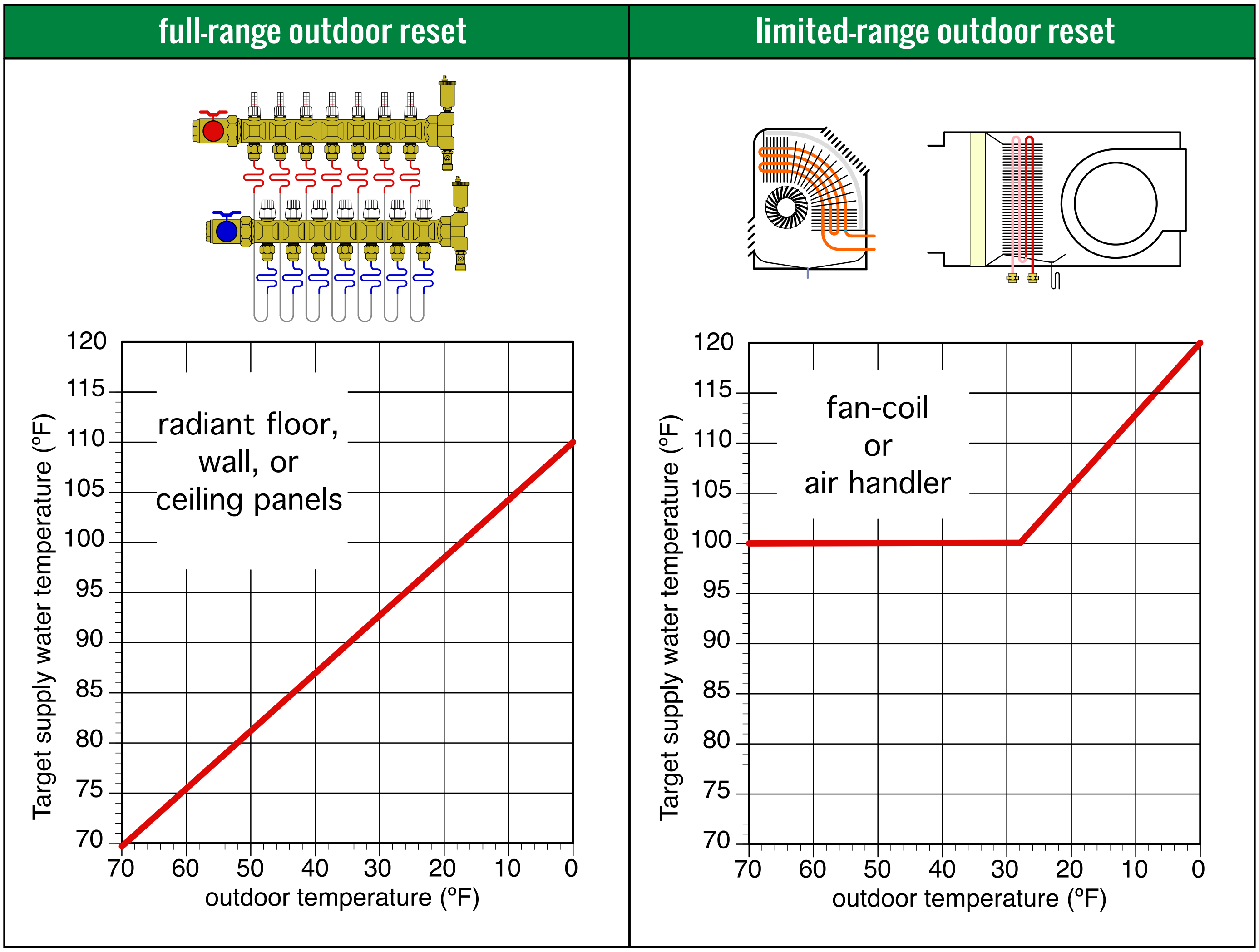


thermal mass heat emitters in these buildings. Preferred options include panel radiators, fan-coils and radiant ceiling panels. These emitters can quickly deliver heat when needed, and just as importantly, they can quickly stop delivering heat when overheating is imminent.

Another important consideration is the supply water temperature required by the heat emitter under design load conditions. *When heat pumps are used as the system's heat source, the lower the supply water temperature can be, while still maintaining interior comfort, the more efficient the heat pump (measured as the heat pump's coefficient of performance COP).*

Figure 4-3 shows representative COP characteristics for a low-ambient air-to-water heat pump and a geothermal water-to-water heat pump.

Figure 4-4



full-range outdoor reset

limited-range outdoor reset

Notice that the COP of both heat pumps is strongly dependent on the water temperature leaving the condenser (as represented by the three curves on each graph). The lower this temperature, the higher the heat pump's COP.

Heat emitters that can meet design heating loads using supply water temperature no higher than 120ºF are generally well-suited for use with heat pumps.

Under partial load conditions the water temperature leaving the heat pump can be reduced based on outdoor reset control. This maximizes the heat pump's COP while ensuring that comfort is maintained in the building.

When panel radiators or radiant ceiling panels are used, it's possible to use "full-range" outdoor reset control. When fan-coils are used, supply water temperature should generally not be reduced below 100ºF, regardless of the load. This helps prevent low-temperature air currents that, while able to maintain the space's setpoint temperature, could create uncomfortable drafts. Air streams from fan-coils or air handlers capable of operating at low water temperatures should be carefully designed to mix with room air in areas away from where occupants would likely be seated. Ceiling diffusers with a wide spread and short throw, or high-wall diffusers with a long throw and minimal spread will help in this regard.

Both "full-range" and "limited-range" outdoor reset are shown in figure 4-4.

For a given rate of heat output and room air temperature, the average water temperature at which any hydronic heat emitter needs to operate depends on its surface area. The larger the surface area, the lower the average water temperature.

This relationship can be represented by Formula 4-1.

Formula 4-1:

$$q = c\left[f_c\right]A(T_w - T_R)^n$$

Where:
q = heat output of the emitter (Btu/hr)
c = a constant based on the construction or geometry of the emitter (determined by testing)
f_c = flow rate correction factor (determined by testing)
A = surface area of the emitter (ft^2)
Tw = average water temperature inside the emitter (ºF)
T_R = room air temperature (ºF)
n = an exponent based on the type of heat emitter

The ASHRAE (HVAC Systems & Equipment) Handbook suggests the following values for the exponent n in Formula 4-1:

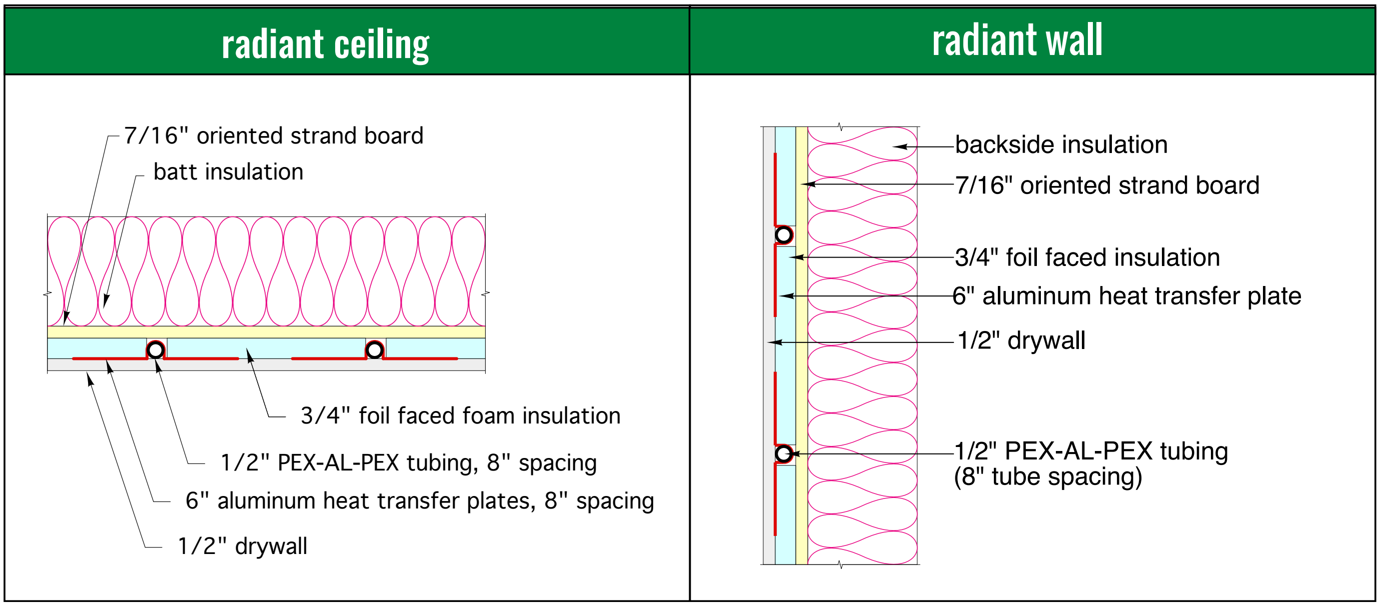
for radiators n = 1.3
for fin-tube baseboard n = 1.4
for ceiling heating or floor cooling n = 1.0
for ceiling cooling and floor heating n = 1.1

This relationship between surface area and required water temperature allows a site-built radiant panel in a low-load building to operate at very low average water temperatures. For example, the average surface temperature of a heated floor supplying an upward output of 10 Btu/hr/ft^2 only needs to be about 5ºF above the air temperature in that space. Assuming 12-inch tube spacing, 70ºF interior air temperature, and a bare or stained concrete slab-on-grade floor, the average water temperature in the embedded tubing circuits only needs to be about 81ºF. The supply water temperature to the panel would likely be in the range of 86 to 91ºF. While this allows a heat pump to operate at very high COPs, it can also lead to disappointment by owners who expect a heated floor to feel warm. A surface temperature of 75ºF is slightly below normal skin temperature. A floor surface at this temperature would feel “neutral” at best to a bare foot.

Figure 4-5

The take-away from this scenario is to be sure that prospective owners of a low-energy or net-zero house who elect to use floor heating are aware of the fact that the floors will not feel noticeably warm, even though the space is being maintained at normal interior temperature. If this is understood and acceptable, floor heating remains an option. If this dissuades the owners based on expectations of noticeably warm floors, other heat emitters options are a better choice.

Figure 4-6



LOW THERMAL MASS RADIANT PANELS

One radiant panel construction that can be used on ceilings as well as walls is shown in figure 4-6.

In this construction, the 1/2-inch PEX-AL-PEX tubing is spaced 8 inches apart. The aluminum heat spreader plates are 5 or 6 inches wide. The 3/4-inch foil-faced polyisocyanurate foam insulation strips are bonded to the 7/16-inch OSB substrate using contact cement. One rear half of each heat transfer plate is also bonded to the foam strips using contact cement. After the tubing circuits are pressed into the plates and pressured tested, the assembly is covered with 1/2-inch drywall. 2.5-inch-long drywall screws are installed halfway between adjacent tubes and spaced 12 inches apart in the direction parallel with the tubes.

Figure 4-7 shows an example of a radiant ceiling panel using this construction. All components other than the 1/2-inch drywall finish are in place.

Figure 4-8 shows an infrared thermograph of the same panel construction turned 90º to create a radiant wall.

The colors in the thermograph image represent surface temperatures on the finish wall surface (e.g., the painted surface of the drywall). A scale showing the range of temperature captured is seen on the right side of the image. The red areas show the effectiveness of the aluminum heat transfer plates in spreading heat emanating from the tubing across the surface of the panel.

Radiant wall panels should be planned so that the space in front of them will not be blocked by furniture or other objects in the room. They can be installed from floor level up to approximately 8 feet high. Radiant walls can also be used in areas such as swimming pool enclosures or walk-in showers. In these applications, the drywall would be replaced by water-resistant backer board and ceramic tile.

Figure 4-7

The rate of heat emission to the room from the radiant ceiling or radiant wall assemblies shown in figures 4-6 and 4-8 can be estimated using Formula 4-2.

Formula 4-2:

$$q = a \times (T_{wa} - T_{room})$$

where:

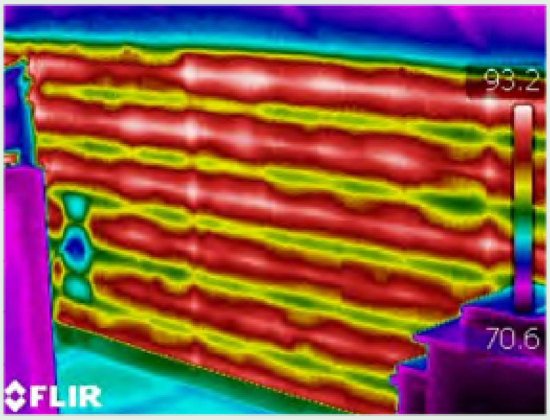
q = heat output of ceiling panel (Btu/hr/ft^2)

a = 0.71 for ceiling applications, or 0.80 for wall applications

T_{wa} = average water temperature in panel (ºF)

T_{room} = room air temperature (ºF)

Figure 4-8



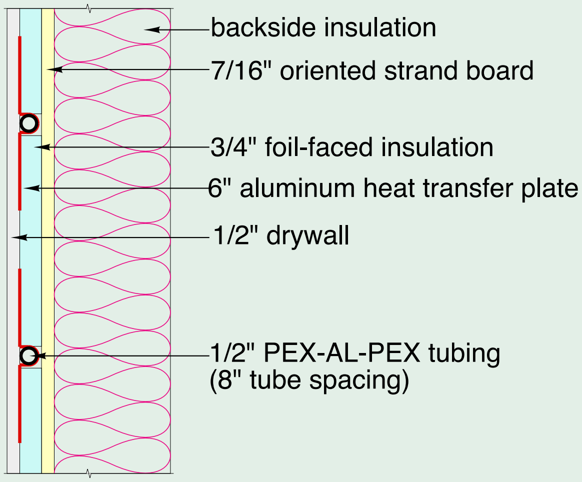
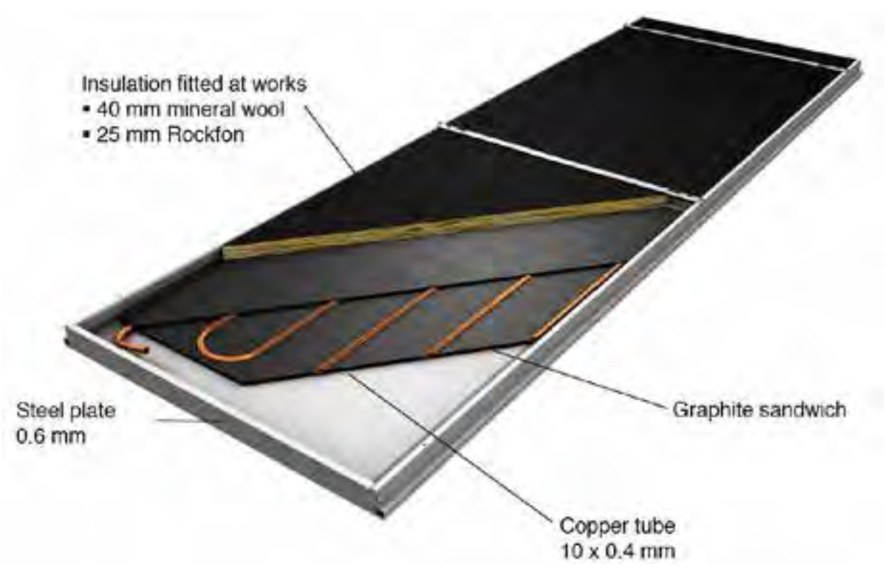


Figure 4-9



Courtesy of Zehnder Rittling

The radiant panel construction shown in figure 4-6 has relatively low thermal mass, and thus can quickly respond to internal heat gains.

Heated ceilings have the advantage of not being covered or blocked by carpeting or furniture, and thus, are likely to retain good performance over the life of the building. They are also ideal surfaces for radiant cooling using chilled water supplied from a heat pump. However, when radiant cooling is used, it is critical to maintain the chilled-water temperature supplied to the distribution system above the dewpoint of the interior air.

idronics #27 provides information on other radiant floor constructions, such as slab-on-grade and underfloor tube & plate systems, which may be suitable for some low-energy and net-zero building applications.

Radiant ceilings can also be used for heating *and cooling* in commercial net-zero buildings. These applications typically use a modular system of prefabricated hydronic panels supported by a T-bar suspended-ceiling system. Figure 4-9 shows the construction of one such modular panel.

These panels are available in nominal widths of 24 inches, and nominal lengths ranging from 24 to 120 inches. Each panel consists of a painted steel frame pan into which is fitted a copper tube circuit, graphite heat diffusion layers and top-side insulation. The graphite layers provide lateral heat conduction between the tubing and panel areas between the tubing. Although these panels are relatively light, they still require support from light gauge chain or steel cables connected to structural elements such as bar joints or concrete slabs.

Figure 4-10 shows an example of how these panels can be quickly connected to supply and return piping using corrugated stainless steel tubing (CSST) hose sets.

When used for cooling, radiant panel systems must be designed and operated so that condensation cannot form on the panel or connected piping. This requirement is typically managed by automatic mixing of chilled water from the source equipment (e.g., heat pump or chiller) with water returning from the panels such that the supply water temperature is slightly above the current dewpoint temperature in the conditioned space.

More information on radiant cooling is available in idronics #13.

Figure 4-10

[insert Figure 4-10] Courtesy of Zehnder Rittling.

PANEL RADIATORS

Generously sized panel radiators are an excellent heat emitter option for low-energy and net-zero buildings supplied by hydronic heat pumps. These steel panels are available in a wide range of sizes from several manufacturers. They have relatively low thermal mass per unit of heat output, and thus respond quickly to internal heat gains or temperature changes. They are also relatively light and easy to install.

One type of panel radiator, often called a "compact" panel, is supplied with an integral valve, which is mounted at the upper right corner of the panel. Figure 4-11 shows an example of this type of panel radiator.

Figure 4-11

All flow through this type of radiator must first pass through its integral valve. The radiator's heat output can be regulated by varying the flow rate through it. This could be done manually, but like many manually adjusted processes, would require repeated adjustment to keep the radiator's heat output matched to the room's heating load.

Figure 4-12

A much-preferred approach is to attach a thermostatic operator to the radiator's valve, as shown in figure 4-12.

This non-electric thermostatic operator continuously senses room temperature and automatically adjusts flow through the radiator to maintain the space very close to a desired comfort level.

When the radiators in a hydronic distribution system are equipped with these operators, each one can automatically and independently adjust its heat output to maintain the desired comfort level in the space where it's located. _This ability is especially beneficial in low-energy and net-zero buildings where each room may be subject to different and variable internal heat gains._ Thermostatic operators are relatively inexpensive, require no wires or batteries, and are easily installed on the radiator's integral valve.

Other types of panel radiators are supplied without integral valves. However, the same zoning and control concepts can be used by installing a thermostatic radiator valve on the inlet connector to each radiator, as shown in figure 4-13.

Figure 4-13

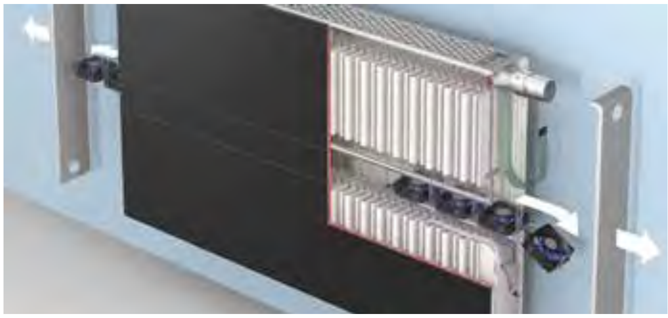
When panel radiators are to be supplied by an air-to-water heat pump or geothermal water-to-water heat pump, they should be sized to provide the design heating load of their associated space at relatively low water temperatures. _A suggested guideline is to size each radiator for design load output of its associated space when supplied with water no hotter than 120ºF._ This is within the operating range of both air-to-water and geothermal water-to-water heat pumps. Under partial load conditions, the water temperature can be further reduced using outdoor reset control. Doing so will increase the seasonal average COP of the heat pump.

The heat output of any panel radiator depends on its total surface area, the average water temperature at which it operates, and the room air temperature where the radiator is installed. Many manufacturers list the output of their panel radiators at relatively high average water temperature (180ºF is typical), along with an assumed room air temperature of 68ºF. This average water temperature is much higher than can be attained using current-generation air-to-water or water-to-water heat pumps. However, it is possible to "derate" the listed output of panel radiators based on lower average water temperatures, different temperature drops between supply and return flows, and when necessary, different room air temperatures. Appendix B summarizes the EN442 method for adjusting panel radiator outputs over a wide range of conditions.

FAN-ASSISTED PANEL RADIATORS

One of the newest low-temperature heat emitters is a *fan-assisted* panel radiator. These units use an array of small, low-power fans installed between the front and back surfaces of the panel. The fans automatically change speed based on room temperature relative to setpoint. They significantly increase convective heat output at low supply water temperatures. Each fan only requires about 1.5 watts of electrical power at full speed, and thus, electrical energy consumption is negligible, especially when compared to the electrical energy savings associated with operating the heat pump at lower water temperatures and higher COPs.

Figure 4-14



Courtesy of the Purmo Group

Fan-assisted panel radiators can operate at water temperatures as low as 95ºF. They have integral controls that can be set for a "boost" mode (e.g., full-speed fan operation) when the system is recovering from a setback temperature. These radiators are ideal for use with hydronic heat pumps.

FAN-COILS

Several companies now offer hydronic fan-coils that can be used for heating, and in many cases, for chilled water cooling. The latter function requires the fan-coil to have a condensate drip pan and drain connection. Figure 4-15 shows an example of such a fan-coil.

Figure 4-15

Courtesy of the Purmo Group

This fan-coil combines a large surface-area "coil" made of copper tubing with aluminum fins with a low-power tangential blower located under the coil. The large coil allows for good heat output at relatively low supply water temperatures. The fan coil shown in figure 4-15, sized at 24 inches high and 32-inches wide, can release 6,700 Btu/hr while operating at an average water temperature of 110ºF.

As with the previously discussed heat emitters, a suggested guideline is to size and select fan-coils that can release the design heating load of the space they serve while operating with supply water temperatures no higher than 120ºF.

One significant benefit of fan-coils equipped with drip pans, relative to panel radiators or site-constructed radiant panels, is their *ability to provide both sensible and latent cooling when supplied with chilled water*. The combination of one or more fan-coils with either an air-to-water or geothermal water-to-water heat pump is a relatively simple way of providing cooling to some or all areas of a net-zero building.

The fan-coil(s) could be used for cooling only, or for both heating and cooling. A cooling-only application would require other selections for heat emitters, and thus cost more than using the fan-coil(s) for both heating and cooling. However, the use of panel radiators or radiant panels for heating provides radiant and convective output that's better-matched to human physiological comfort requirements.

It's also important for owners to know that any fan-coil emits some sound while operating. The sound level of modern fan-coils is relatively low. For example, the fan-coil shown in figure 4-15 emits sound measured between 25 and 48 decibels (depending on blower speed), and measured approximately 8 feet away from the unit. For comparison, a modern refrigerator emits about 50 decibels.

The cooling performance of fan-coils is based on the temperature of chilled water supplied to the coil. Lower water temperatures improve both sensible and latent cooling capacity. Designers need to assess the sensible and latent ratings of perspective fan-coils to ensure adequate overall cooling. Heat pump performance (e.g., both cooling capacity and EER) increases as chilled-water temperatures increase. To achieve the best heat pump performance, designers should use the highest chilled-water temperature that can ensure adequate sensible *and latent* cooling. Chilled-water supply temperatures in the range of 50 to 60ºF are possible with some fan-coils and are well within the operating range of air-to-water and water-to-water heat pumps.

AIR HANDLERS

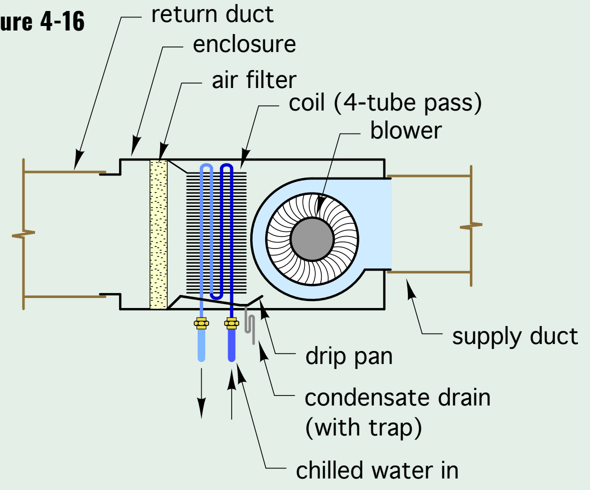
Air handlers are used to transition the delivery of heat or cooling effect from water to air and deliver it to a building through ducting. They are available in a wide range of sizes and capacities, ranging from small units intended for residential application to very large custom-built units for commercial or industrial applications.

The main components inside an air handler are a water-to-air heat exchanger called a "coil," and a blower. Other components include a removable filter and electrical controls. Any air handler intended to provide cooling must also have a condensate collection pan, which leads to a drainage connection. Figure 4-16 shows a representation of a typical horizontal air handler.

Small air handlers are often available with cabinets and internal components that allows them to be configured to connect to either horizontal or vertical ducting. Figure 4-17 shows an example of each.

The horizontal air handler shown in figure 4-17 has a condensate collection pan under its internal coil. The trap assembly and 3/4-inch PVC piping seen near the bottom of the cabinet carries condensate away to a drainage pipe. The piping is pitched to allow for gravity drainage.

Figure 4-16

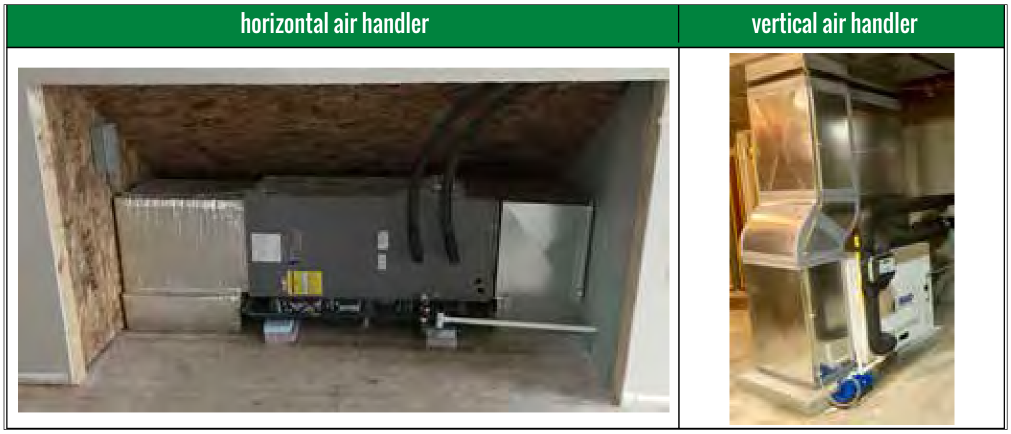


The vertical air handler seen in figure 4-17 is located in a basement that doesn't have a floor drain. Condensate from the internal collection pan is routed to a condensate pump, which pushes it upward and outside the building above grade level.

Notice that the piping carrying chilled water to each of these fan-coils is fully wrapped with an elastomeric foam pipe insulation. This is critical to prevent surface condensation when the air handler is operating in cooling mode. All piping components, such as circulator volutes, valves, etc., should also be wrapped with an insulation that provides both thermal resistance and acts as a vapor barrier.

Additional information on chilled-water cooling using air handlers and piping insulation is available in *idronics* #28.

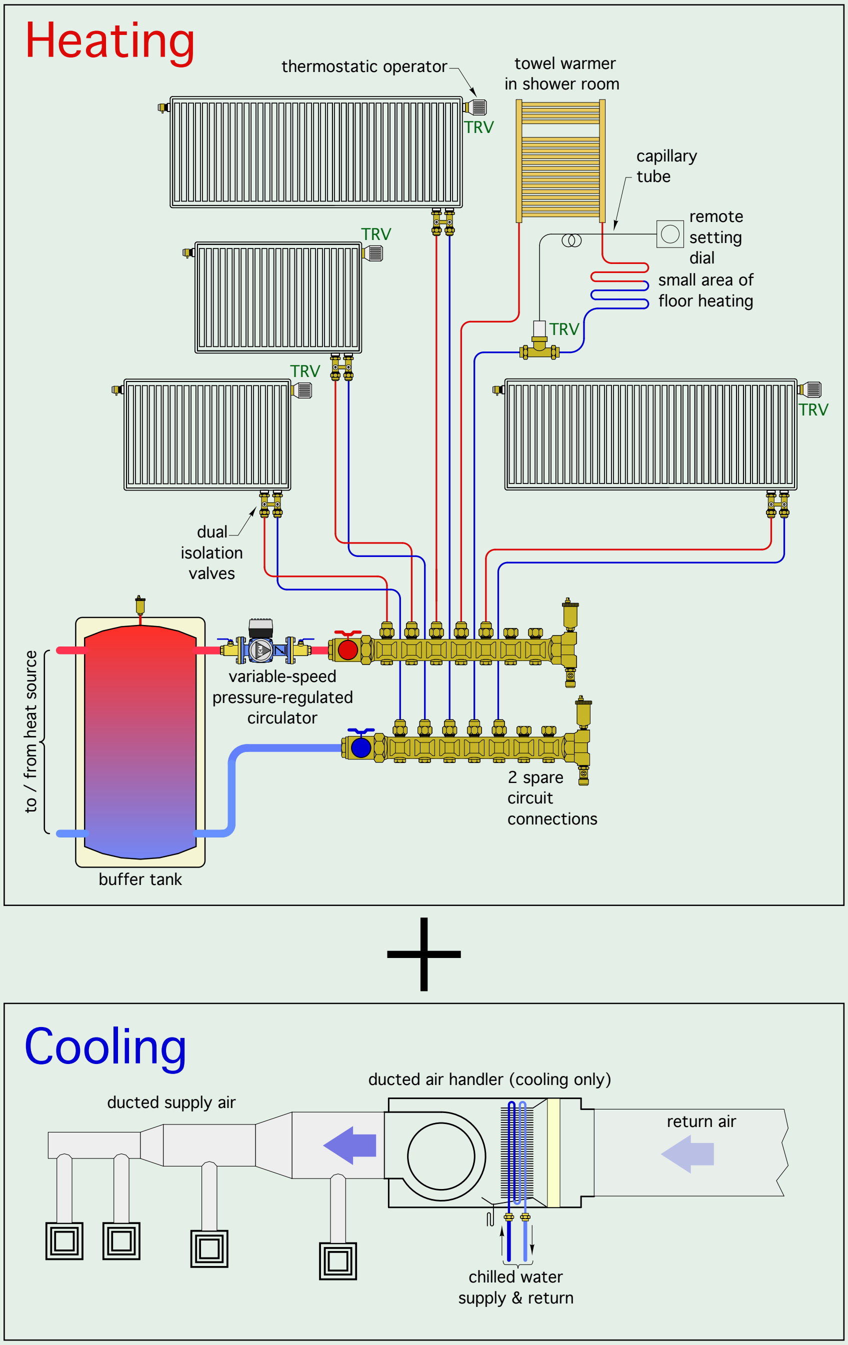
Figure 4-17



horizontal air handler

vertical air handler

Figure 4-18



One system configuration that's appropriate for residential and small commercial low-energy and net-zero buildings has *multiple zones of heating* combined with a *single zone for cooling*. The heating zones could be handled by multiple panel radiators, each equipped with thermostatic operators. Single-zone cooling is provide by a ducted air handler equipped with a chilled-water coil. Figure 4-18 shows two component assemblies based on this approach.

The heating assembly is called a "homerun" distribution system. Each of the 5 heated spaces served by this assembly has a small diameter (i.e., 1/2-inch) PEX tube for supply water and another for return water. All 5 homerun circuits begin and end at a manifold station that's located in a mechanical room or within a recessed framing cavity. Heated water is supplied to the manifold station by a variable-speed pressure-regulated circulator. The high-efficiency motor in this circulator automatically adjusts its speed as the thermostatic operators on the panel radiators open, close or modulate the flow through their associated radiators.

To show versatility, one of the homerun circuits is routed to a towel warmer radiator that's piped in series with a small area of floor heating. This would be appropriate in a bathroom with a tile floor. Flow through this circuit is also controlled by a thermostatic valve that would typically be located in an accessible framing cavity near the room, and connected by a small capillary tube to a wall-mounted adjusting knob that sets the comfort level in the room.

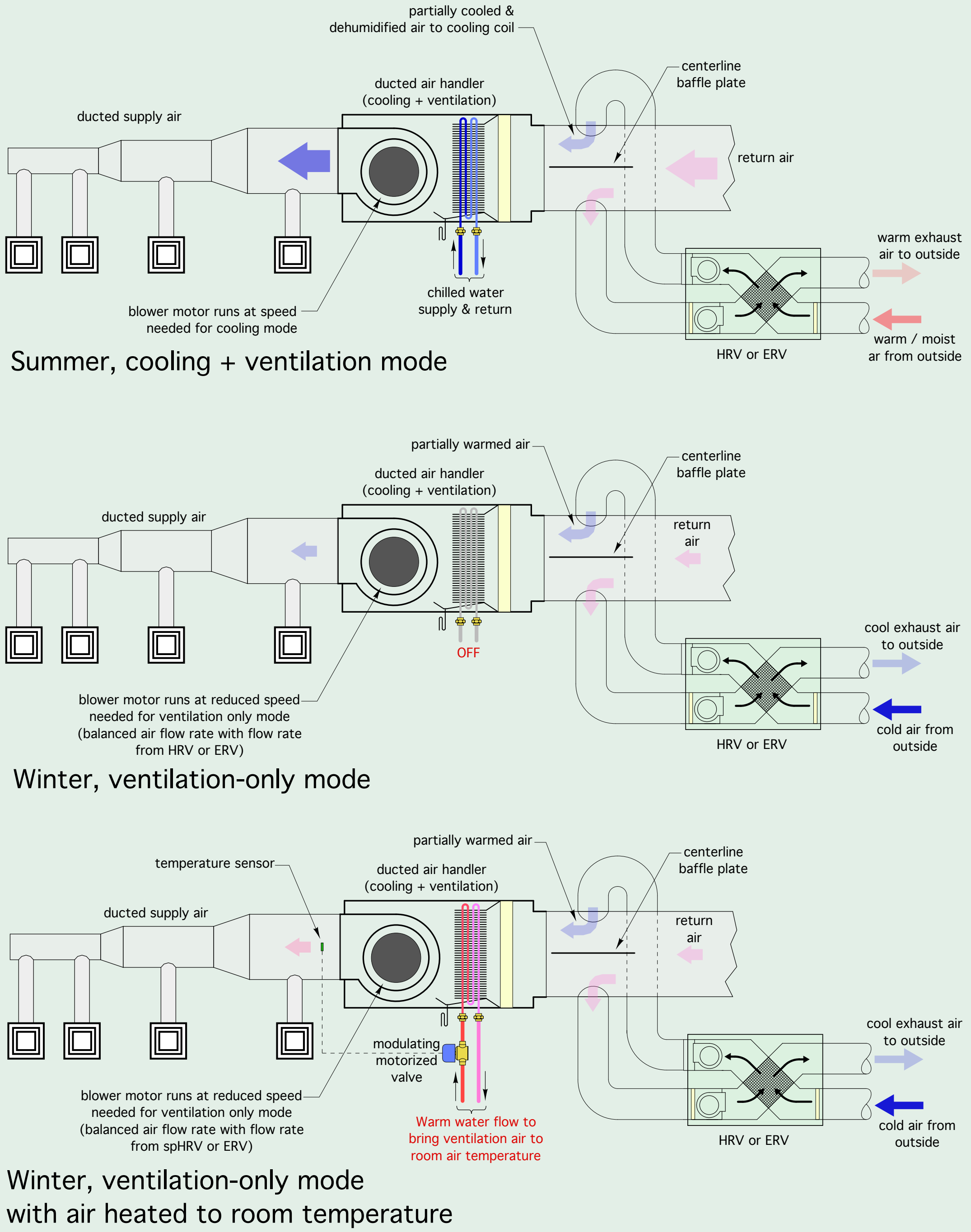
The buffer tank would be heated by the heat source (e.g., typically a heat pump). The thermal mass of this tank allows for very small heat dissipation rates at the heat emitters, when conditions warrant, without short cycling the heat source.

The only electrical component in this heating sub-system is the circulator.

Several examples of homerun distribution systems will be shown in section 5.

The single-zone cooling assembly uses a small air handler (either vertical- or horizontal-mounted) combined with a ducted forced-air distribution system that supplies several ceiling or high-wall diffusers, each with a balancing damper. The chilled-water

Figure 4-19



coil in the air handler cools and dehumidifies the air passing through it. Condensate is collected by the pan under this coil and routed to a suitable drain. A horizontal air handler could be suspended from floor joists or placed on a small platform between trusses and within the building's thermal envelope. A vertical air handler could be located in a small closet, again within the building's thermal envelope.

INCORPORATING HEAT RECOVERY VENTILATION

It is also possible to add a heat recovery ventilator (HRV), or an energy recovery ventilator (ERV) to the forced-air distribution system used for chilled-water cooling, as shown in figure 4-19.

The supply and return ducts that lead back to the HRV or ERV are connected to the return air duct leading into the air handler. Ideally, these ducts are connected opposite from each other with a sheet metal baffle fixed along the centerline of the duct. This placement puts both ducts from the HRV or ERV at the same static pressure point on the return duct. This minimizes any tendency for induced air flow through the HRV or ERV if it is off, and the air handler is on. The centerline baffle prevents a "short circuit" of fresh incoming air back into the exhaust stream leading back to the HRV or ERV.

Operation of the HRV or ERV must be coordinated with the blower in the air handler. For example, in a "ventilation-only" mode, the blower in the air handler would operate at a relatively low speed sufficient to carry the required ventilation air flow rate, but significantly lower than the required flow rate when the air handler is providing cooling. During cooling mode operation, the blower speed would increase to provide an air flow of approximately 400 CFM per ton (12,000 Btu/hr) of cooling capacity. Modern air handlers have high-efficiency ECM motors with multiple-speed tappings that allow these different air flow rates to be achieved.

During winter, it would also be possible to pass a small flow of warm water through the air handler coil to bring the incoming ventilation air stream up to room temperature. The discharge air temperature from the air handler would be measured and used to modulate a motorized valve that regulates the warm water flow rate through the coil. This option would require additional piping design and components to enable warm water flow through the air handler's coil. In cold climates, it may also require the air handler coil to operate with an antifreeze solution.

This approach eliminates the need to install a separate ducting system for the HRV or ERV.

BUFFER TANKS

There are several ways to zone a hydronic heating or cooling distribution system. The ease of doing so allows designers to create residential or light commercial systems that might have, for example, 3 to 8 zones. Even more zones are possible when individually controlled panel radiators are used, or for systems in larger commercial buildings.

Zoning frequently creates situations where the rate of heat delivery to a zone is much lower than the rate of heat generation by the heat source. This is especially true when an "on/off" heat source is providing the heat.

For example, consider an air-to-water heat pump with a single-speed compressor that's producing heat at a rate of 40,000 Btu/hr and imparting that heat to a hydronic distribution system. At the same time, only one of the building's zones is calling for heat, and the rate of heat transfer to that zone is 3,000 Btu/hr. Assume the water in the heat emitter, the heat pump and the piping between them totals to 6 gallons. Also assume that the controller operating the heat pump allows a temperature differential of 15ºF between when the compressor is turned on and when it's turned off. Under these conditions, the on-cycle time of the heat pump will only be 1.2 minutes! Such a short on-cycle time, repeated thousands of times per year, would shorten the life of the components in the heat pump, especially the compressor and the compressor contactor. This situation must be avoided.

The common method of avoiding short-cycling in multi-zone hydronic systems is to incorporate additional water (and its associated thermal mass) into the system using an insulated buffer tank.

Figure 4-20 shows an example of such a tank installed between an air-to-water heat pump and a zoned distribution system for a space heating-only application. The buffer tank is piped in a "3-pipe" configuration. This allows the distribution system to draw the hottest available water, either directly from the heat pump circuit when the heat pump is operating, or from the upper connection on the buffer tank when the heat pump is off. Heated water leaving the heat pump doesn't necessarily pass through the buffer tank before flowing to the panel radiators. Return water enters the lower side connection on the buffer tank. This ensures that the thermal mass of the buffer tank is always "engaged" with the flow returning from the radiators, and flow returning to the heat pump.

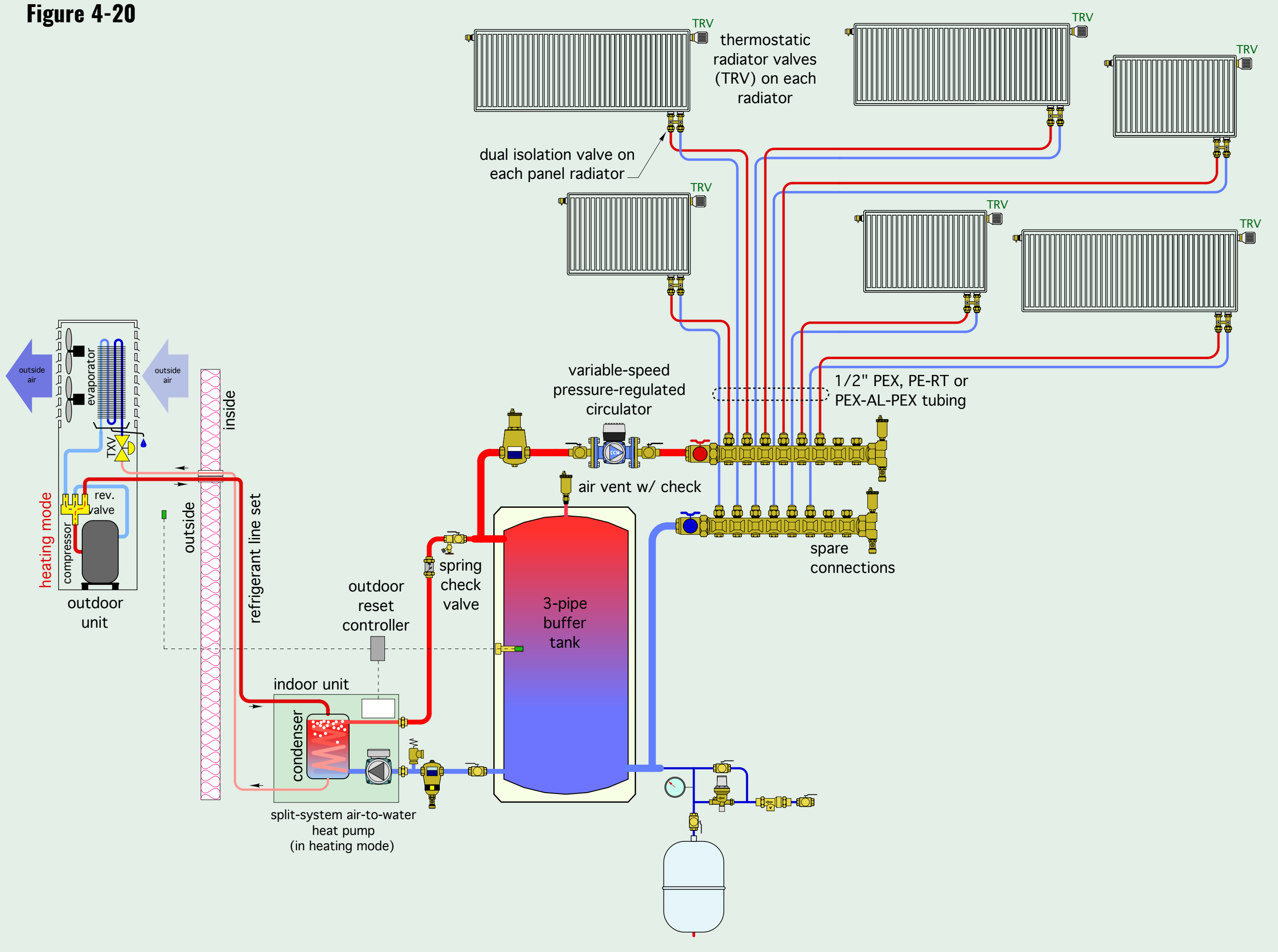
A variable-speed pressure-regulated circulator provides flow to six panel radiators using a homerun distribution system. The latter consists of a manifold station and 6 circuits of 1/2-inch PEX tubing. Each radiator has an integral valve and is equipped with a thermostatic operator, allowing for independent heat output regulation.

Other components in the system include a Dirtmag dirt and magnetic particle separator on the flow inlet to the heat pump, and a Discal air separator on the supply to the manifold station.

A spring-check valve prevents reverse thermosiphoning from the buffer tank through the heat pump when the latter is off.

An outdoor reset controller continuously monitors the water temperature at the mid-height of the buffer tank.

Figure 4-20



This controller turns the heat pump and its associated circulator on and off as necessary to keep the average water temperature in the tank close to the target value calculated by the outdoor reset controller.

The system automatically begins operation when the outdoor temperature drops below some preset value known as the “warm weather shutdown temperature.”

There are no electrical thermostats in this system. All room temperature control is regulated by the thermostatic operators on the panel radiators.

BUFFER TANK SIZING

The size of the buffer tank can be calculated based on the desired on-cycle time of the heat pump, the heat pump’s rated heating capacity, and the change in buffer tank temperature during the on-cycle. Use Formula 4-2.

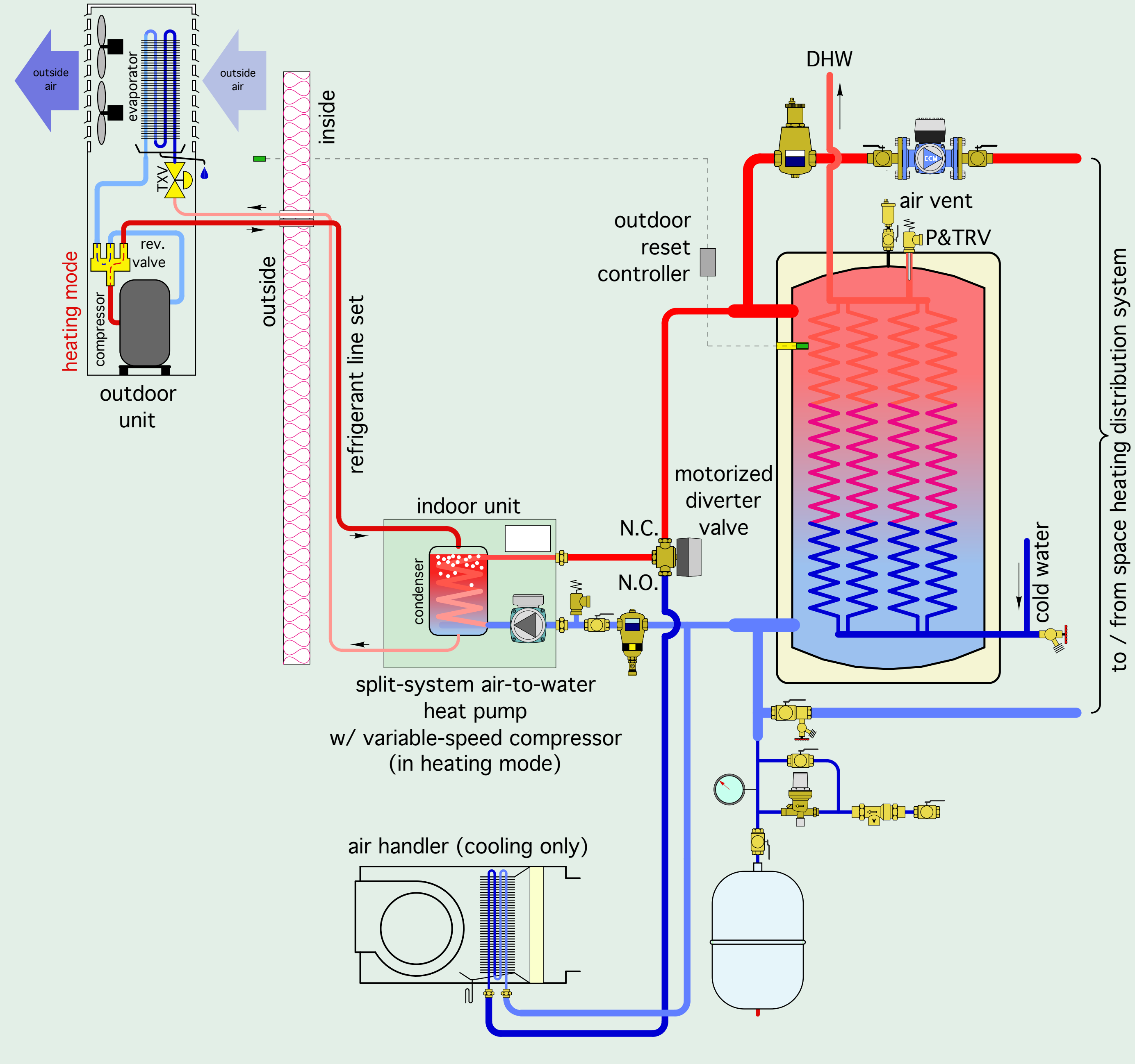
Formula 4-2:

$$V = \frac{\left(q_{hp}\right)t}{500(\Delta T)}$$

Where:
V = minimum volume of buffer tank (gallons)
q_{hp} = rated heat output of heat pump (Btu/hr)
t = length of desired on-cycle (minutes)
ΔT = temperature swing in buffer tank during on-cycle (ºF)

For example, assume the minimum desired on-cycle time is 10 minutes, and the desired temperature change in the buffer tank during that on-cycle is 15ºF. Determine the minimum buffer tank volume assuming the heat pump’s rated output is 36,000 Btu/hr.

Figure 4-21



Just put the given values into Formula 4-2 and calculate.

$$V=\frac{(q_{hp})t}{500(\Delta T)}=\frac{(36{,}000)10}{500(15)}=48 gallons$$

Larger buffer tanks would allow either longer on-cycles, smaller values of ΔT, or some combination of both. Likewise, small buffer tanks would result in shorter on-cycles, assuming the same desired tank temperature swing (ΔT).

BUFFER TANKS & VARIABLE-CAPACITY HEAT PUMPS

Several air-to-water and water-to-water heat pumps are now available with variable-speed ("inverter driven") compressors. These heat pumps can reduce their output down to 30-40 percent of their rated output. If the heating requirement of the smallest zone in the system is approximately the same as the minimum output of the heat pump, one could argue against the need for a buffer tank. However, in systems with several small zones, such as individually controlled panel radiators in each room, a buffer tank should still be used in heating mode operation.

When multiple zones of heating are combined with a single cooling zone, and the system is supplied by a variable-capacity heat pump, it is possible to use a buffer tank in heating mode, but not in cooling mode. This combination allows the buffer tank to be maintained at an elevated temperature year-round to supply preheating, or possibly all the heating required for domestic hot water. Figure 4-21 shows one possible system configuration.

This system uses a "reverse" indirect water heater as a buffer tank. The heat pump maintains the water temperature in the shell of this tank between some upper and lower temperature limits, such as 110 and 130ºF. Domestic cold water passes upward through multiple copper coils inside the tank whenever domestic hot water is drawn from a fixture. That water is either partially heated or fully heated depending on the temperature of the water in the tank shell, the flow rate through the internal coils, and the desired domestic hot-water delivery temperature.

In cases where the domestic water is only partially heated as it passes through the coils, it's possible to include an electric tank-type or on-demand water heater. Figure 4-22 shows piping for the latter.

The water leaving the heat pump in figure 4-21 enters the common port of a motorized diverter valve. This valve is energized when the heat pump operates in heating mode, allowing flow from the common port to the normally closed port, and onward to the buffer tank. When the heat pump is off, the diverter valve is off, and the normally closed port is closed. This prevents reverse thermosiphon flow from the buffer tank through the heat pump. It also prevents flow returning from the space-heating load from flowing through the heat pump when it is off.

The diverter valve should be selected with a flow coefficient (Cv value) approximately equal to the design flow rate through the heat pump. This limits the pressure drop through the valve to approximately 1 psi and reduces circulator power requirements.

Some air-to-water and water-to-water heat pumps are supplied with an internal circulator, and some require an external circulator. Figure 4-23 shows pipe detailing for both cases. The spring-loaded check valve in the external circulator, or as a separate component when an circulator is present inside the heat pump, provides a slight forward opening resistance to prevent flow migration through the chilled-water air handler when the heat pump and circulator are off.

A Dirtmag separator is installed on the pipe leading into the heat pump. This location is also upstream of the heat pump's circulator (whether internal or external). The Dirtmag separator helps prevent dirt or ferrous metal particles from entering either the circulator or the heat pump's heat exchanger, and thus helps maintain peak performance and reliability.

The system configuration shown in figure 4-21, and in subsequent details shown in figures 4-22 and 4-23, uses a variable-capacity ("inverter-driven") heat pump. The internal controls for this type of heat pump typically allow compressor speed to be referenced to a user-set outlet water temperature in both heating and cooling mode.

When the heat pump is used to maintain the buffer tank within some range of temperature suitable for space heating and domestic water heating, it should be turned on and off based on the buffer tank temperature, rather than the outlet temperature from the heat pump. This typically requires an external controller that can open and close a set of electrical contacts based on either a setpoint temperature and associated differential, or on outdoor reset control.

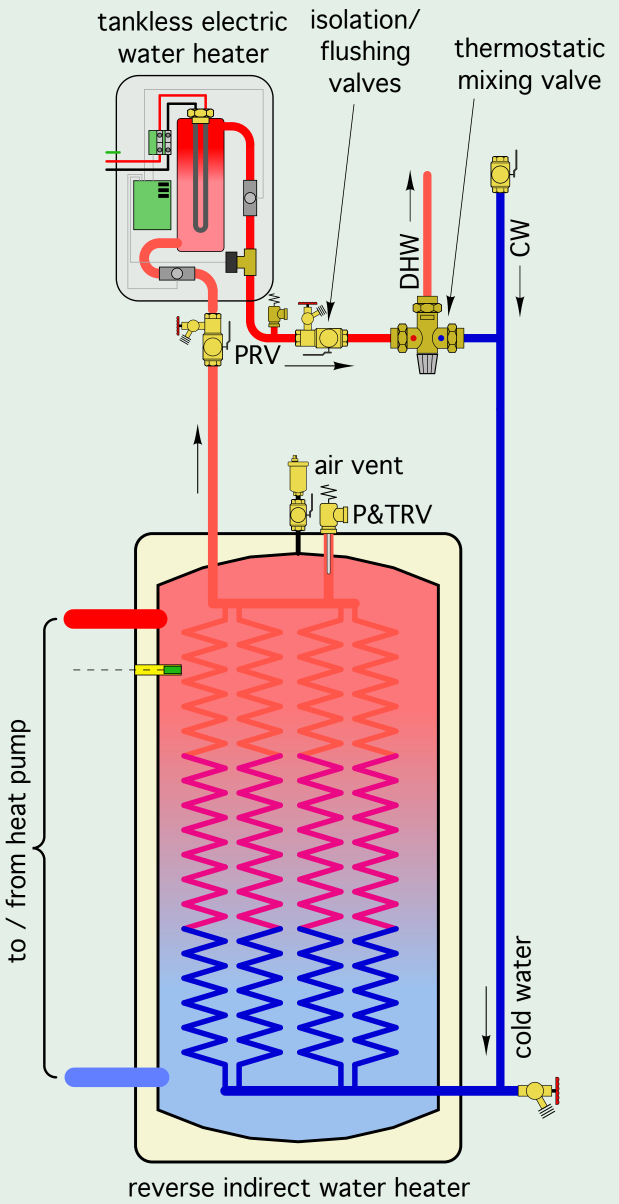
An example of setpoint control would be as follows:
Heat pump = ON when tank sensor temperature drops to 100ºF or lower.
Heat pump = OFF when tank sensor temperature increases to 125ºF or higher.

An example of outdoor reset control, with specific settings, is shown in figure 4-24.

With outdoor reset, the heat pump is turned on when the sensor in the tank drops to the temperature shown on the dashed green line in figure 4-24. The heat pump continues to run until the sensor reaches the temperature on the dashed red line. Outdoor reset controllers can be adjusted to change the slope of these lines, the temperature differential between the "on" and "off" lines, the minimum supply water temperature setting, and in some cases, additional settings. This allows wide flexibility in how the temperature of the buffer tank is regulated.

Reducing the tank temperature as the outdoor temperature increases allows the heat pump to operate at higher COP. This is ideal when the system only provides space heating. However, in systems that supply both space heating and domestic hot water, this control action decreases the temperature to which domestic water can be heated by the heat pump, especial during mild weather. This can

Figure 4-22



be modeled using specific space heating and DHW load information, heat pump performance information, and climate data.

Figure 4-25 shows the simulated seasonal performance of an air-to-water heat pump based on supplying just space heating (blue line), or both space heating and domestic hot water (red line). Any temperature boost needed to ensure a DHW delivery temperature of 120ºF is assumed to be provided by electric resistance heating. Figure 4-24 plots seasonal average COP of the system versus the average temperature at which the buffer tank is maintained by the heat pump (e.g., based on setpoint control, not outdoor reset control). In this graph, the seasonal COP is for the entire system, including energy supplied to supplemental electric heating elements.

The simulations used to produce figure 4-25 were based on a modern low-ambient air-to-water heat pump operating in a (6,700ºF•day) winter climate with a 60-gallon per day domestic water load heated from 50 to 120ºF.

The upper (blue) curve shows significant improvements in seasonal average COP as the average water temperature in the buffer tank is reduced. This demonstrates the previously discussed advantages of using heat emitters that can operate at low water temperatures.

However, when the domestic water-heating load is factored in, the seasonal COPs are lower, especially when the average buffer tank temperature is lower. This happens because of increased use of electric resistance heating to ensure a DHW delivery temperature of 120ºF under all conditions.

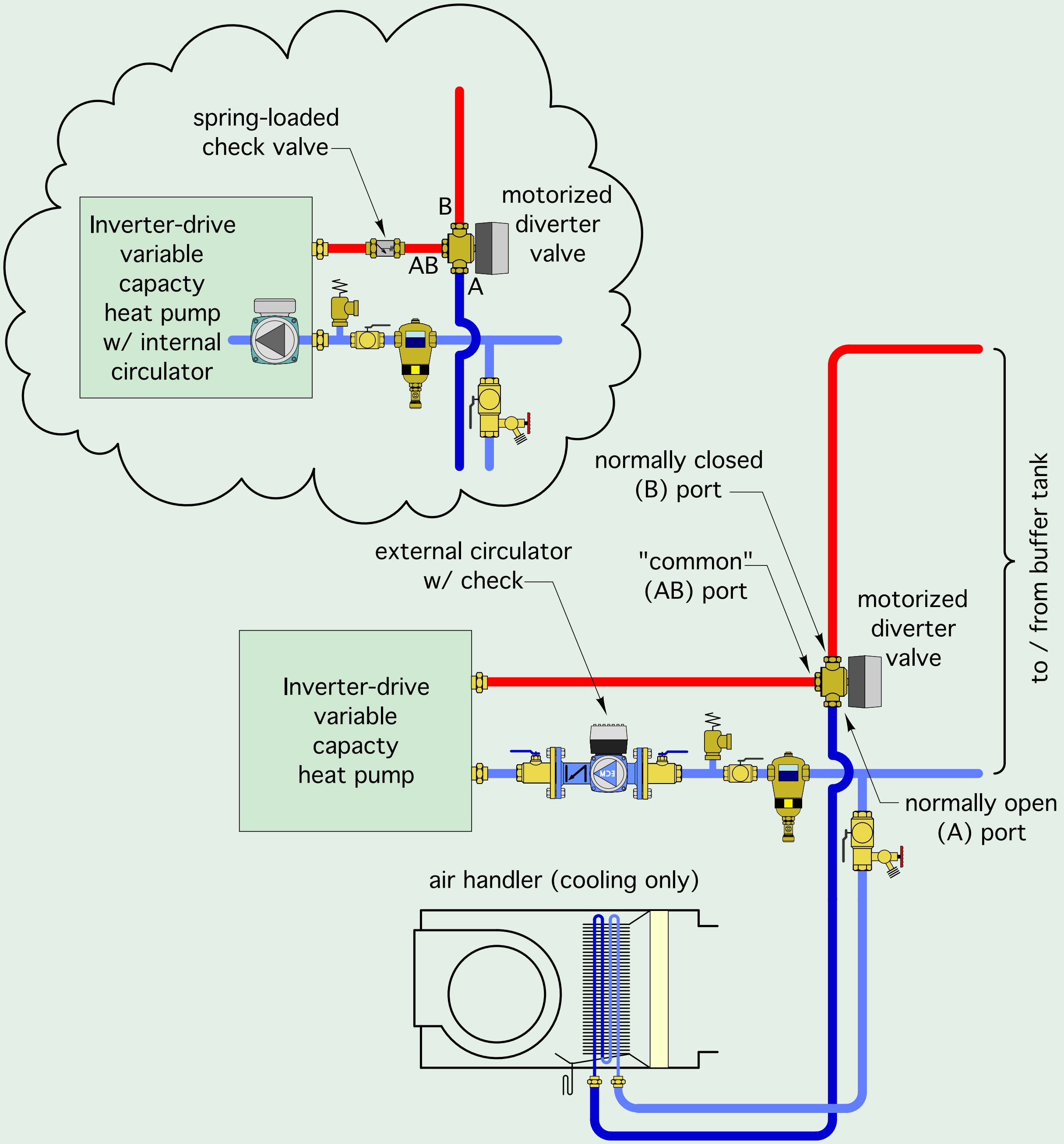
If the heat pump is only used for space heating, and all domestic hot water is provided by electric resistance heating, the simulated seasonal average COP for the system was 2.57.

When the buffer tank temperature is maintained based on outdoor reset control, heat from the buffer is used to preheat domestic water, and all supplemental heat to bring the DHW delivery temperature to 120ºF is provided by electric resistance heating, the system's simulated seasonal COP was 2.82.

COOLING MODE CONTROL

The use of a variable-capacity heat pump, and a system configured as shown in figure 4-21, eliminates the need for the buffer tank to store chilled water during cooling mode operation. When the heat pump is operating in cooling mode, its compressor speed is varied to maintain a set leaving-water temperature (typically in the range of 45 to 55ºF). This allows the heat pump cooling capacity to track the cooling capacity of the chilled-water air handler. However, the air handler should be selected with a cooling capacity that is not lower than the minimum cooling capacity of the heat pump. For example, if the minimum cooling capacity of the heat pump is 22,000

Figure 4-23



Btu/hr when supplying chilled water at 45ºF and receiving return water at 55ºF, the air handler should also be able to absorb 22,000 Btu/hr when operating at the average water temperature of 50ºF (e.g., 45ºF in/55ºF out).

Whenever a heat pump (geothermal or air-to-water) can provide year-round domestic hot water as well as cooling, system controls must set a priority as to which load the heat pump services at times when both loads are simultaneously calling for operation. The most common scenario is to prioritize domestic water heating over cooling. This is based on the likelihood that the "call" for domestic water heating can be satisfied quickly (perhaps 5-10 minutes) during warm weather

Figure 4-24

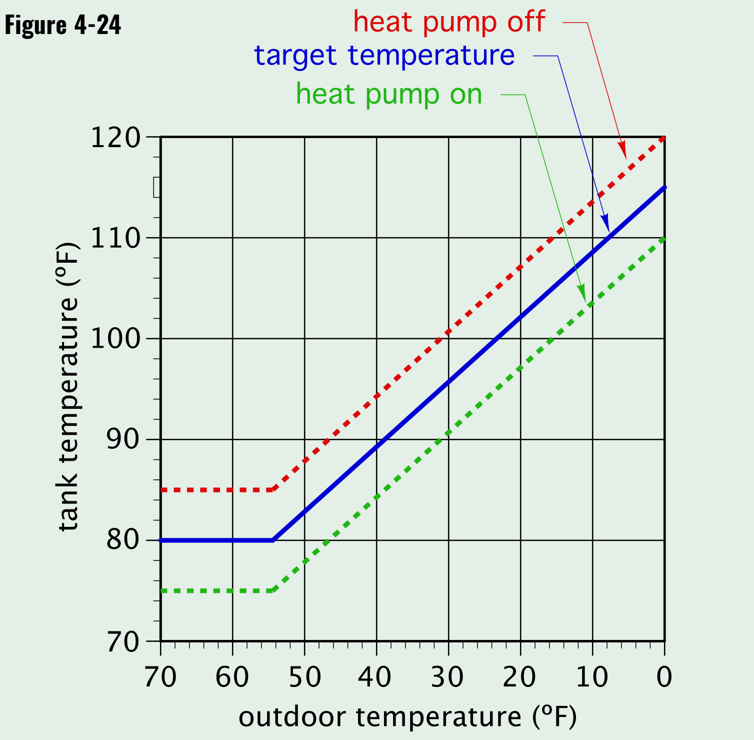
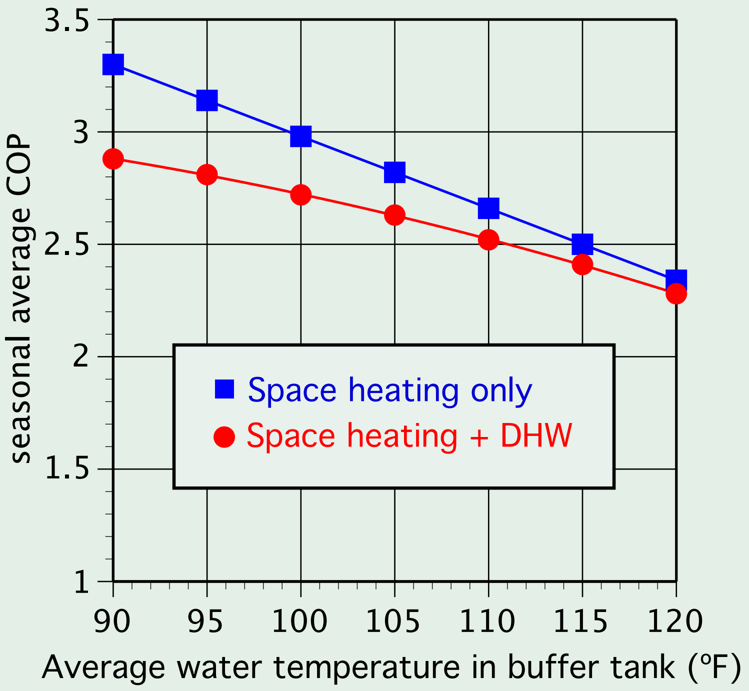


Figure 4-25



when the cooling load is active. Once the tank that provides domestic hot water (e.g., the buffer tank in figure 4-21) has reached a set temperature limit, the heat pump turns off, goes into a typical 3-5 minute time delay to allow for refrigerant pressures to equalize, then resumes cooling mode operation.

Given the loads and thermal mass associated with a typical low-energy or net-zero home, this method of priority control is generally acceptable. If the situation "insists" on simultaneous cooling and domestic water heating (e.g,, without prioritizing either load), a separate chilled-water buffer tank can be used, albeit at significantly higher cost and complexity.

5. EXAMPLE SYSTEMS

Previous sections have described the advantages of using hydronic heating and cooling in low-energy and net-zero buildings. Simple and repeatable concepts have been shown along with a range of appropriate hardware.

This section brings those concepts together to form several complete systems. They range from space heating only, to systems that also provide domestic hot water and cooling.
These systems show a "diversity" of heat sources, such as split-system and monobloc air-to-water heat pumps, geothermal water-to-water heat pumps and electric boilers. Any of the heat pump types represented can be "swapped" for one of the other types, along with any necessary details (such as the use of antifreeze with a monobloc air-to-water heat pump). This "swapping" concept is also true for the loads shown. A given system could use different heat emitters, or different methods of producing domestic hot water, relative to those shown. Any of the heat pump-based systems could include chilled-water cooling. Any of the systems using heat pumps could also include an electric or fossil-fuel boiler as a supplemental and backup heat source This concept of interchangeable sub-assemblies provides enormous flexibility in configuring systems to the exact needs of each project.

SYSTEM #1:

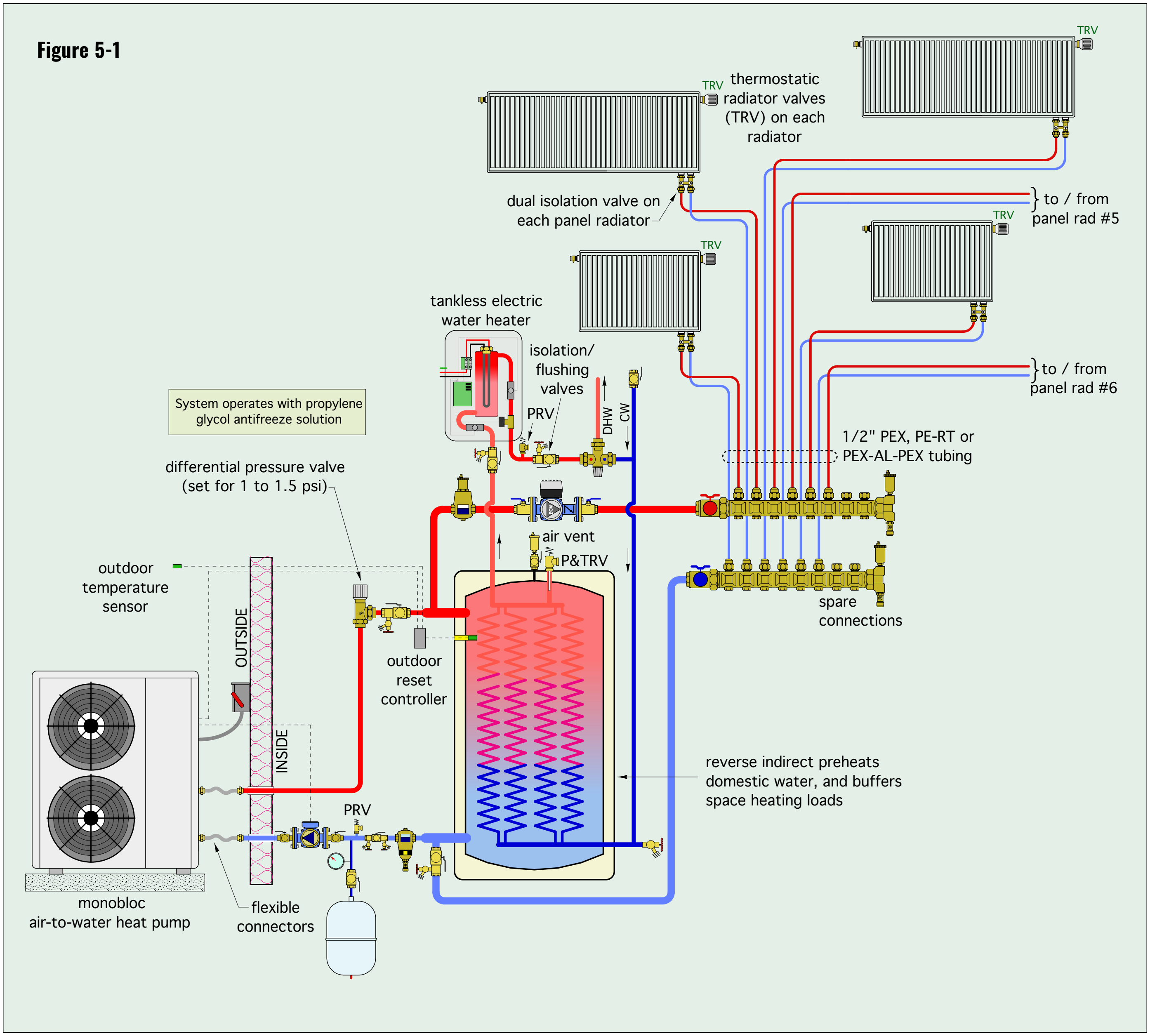
The system shown in figure 5-1 provides space heating and domestic hot water. It uses a monobloc air-to-water heat pump with a single-speed compressor and a reverse indirect water heater. The latter serves as a buffer tank and domestic hot water source.

Space heating is provided by 6 individually controlled panel radiators. Each radiator is sized for the design heating load of its associated space when operating at a supply water temperature of 120ºF, with a 20ºF temperature drop, and thus an average water temperature of 110ºF. During partial load conditions, the water temperature in the buffer tank is reduced based on outdoor reset control. This maximizes the seasonal COP of the heat pump, while also ensuring that the supply water temperature to the radiators is high enough to maintain comfort.

Each radiator is equipped with a thermostatic operator and supplied by a pair of 1/2-inch PEX tubes that begin and end at a manifold station. The latter has two additional sets of connection ports to allow other heat emitters to be easily added in the future.

Flow to all radiators is provided by a variable-speed pressure-regulated circulator that operates continuously during the heating season. The speed of this circulator automatically

Figure 5-1



changes as the thermostatic operators on the radiators open, close or modulate flow. If all radiator valves are closed, the circulator goes into a low-power "sleep" mode, typically drawing less than 10 watts of electrical power. The sleep mode ends as soon as a radiator valve begins to open.

The majority of the domestic water heating takes place whenever hot water demand at a fixture pulls cold water upward through the copper coils inside the buffer tank. Any additional temperature rise needed to bring the domestic water to the desired delivery temperature is provided by an on-demand electric water heater.

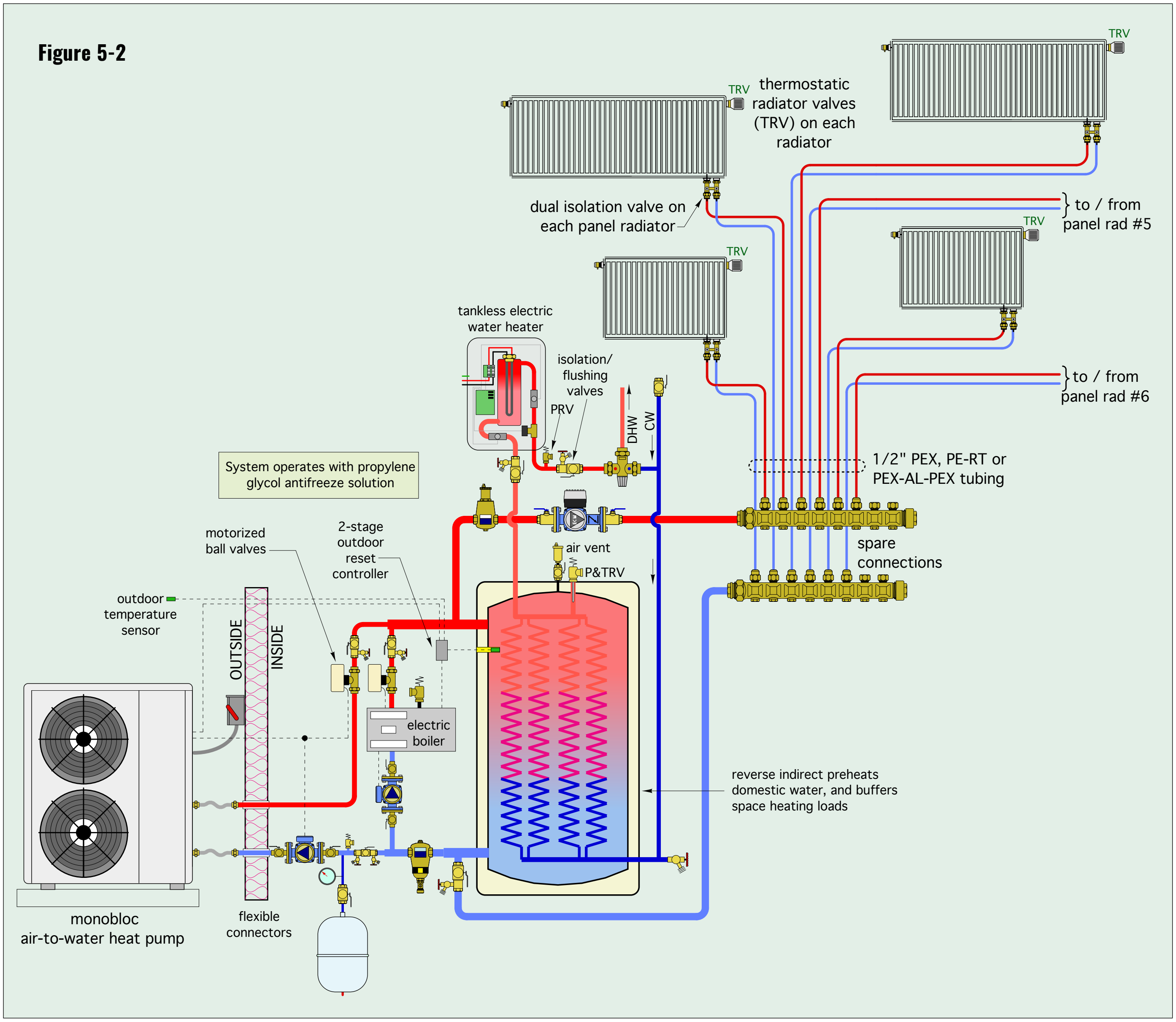
During late spring, summer and early fall, when space heating is not required, it would be possible to increase the temperature setting of the outdoor reset controller to allow the heat pump to fully heat domestic water to 120ºF. The on-demand electric water heater could be turned off during this time.

To protect the heat pump from freezing, the entire system operates with a 30% solution of non-toxic propylene glycol antifreeze.

SYSTEM #2:

This system adds an electric boiler and associated details to system #1. This boiler can provide supplemental heat input if needed during extremely cold weather. It can also serve as a backup heat source if the heat pump is down for servicing.

Figure 5-2



A 2-stage controller manages operation of both the heat pump and electric boiler. It's objective is to maintain the buffer tank at a target temperature based on outdoor reset control. This controller provides a 10-minute time delay between activating the heat pump and possibly activating the electric boiler. This allows time for the heat pump to stabilize its initial operation and gives the controller time to "decide" if a second stage of heat input is needed.

Motorized ball valves are installed in the piping for each heat source. They open when their associated heat source is on and close at all other times. These valves prevent reverse thermosiphon flow from the buffer tank through the piping of either heat source when that heat source is off. They also prevent reverse flow through one heat source when the other heat source is on. Finally, they prevent flow returning from the manifold station from inadvertently passing through either heat source when it is off.

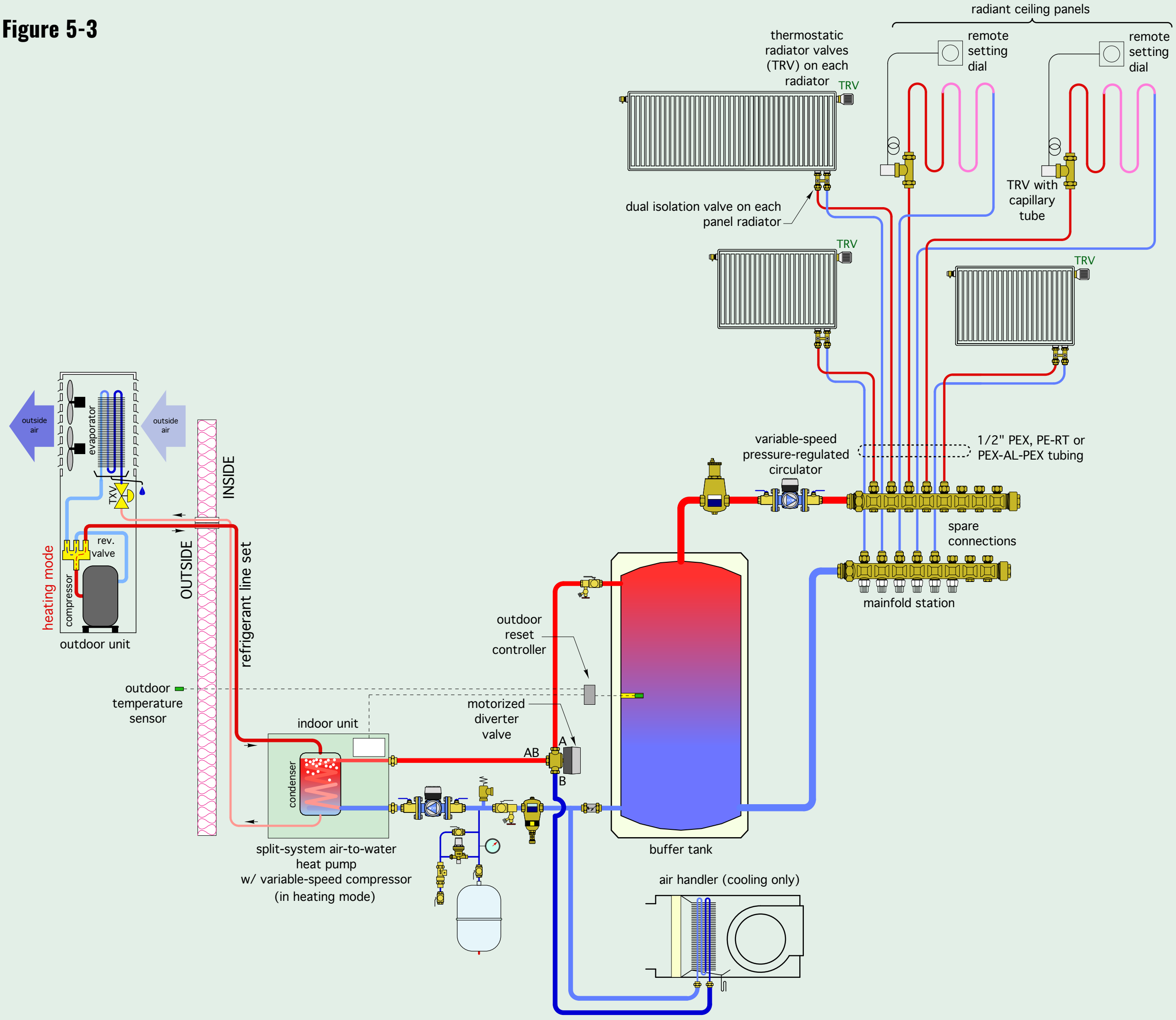
Domestic water is heated the same way it was in system #1.

SYSTEM #3:

This system uses a split-system air-to-water heat pump with an inverter drive compressor to provide space heating and cooling.

Space heating is provided by a combination of panel radiators and low-thermal mass radiant ceiling panels, all operating at the same supply water temperature and connected as a homerun distribution system. A variable-speed pressure-regulated circulator provides flow to this distribution system and automatically adjusts its flow rate

Figure 5-3



and power input as the thermostatic valves on the radiators and radiant ceiling panel circuits open and close.

The 3-way motorized diverting valve opens between the AB and A ports when the heat pump operates in heating mode, and closes between these ports at all other times. This prevents reverse thermosiphoning between the buffer tank and heat pump when it's off.

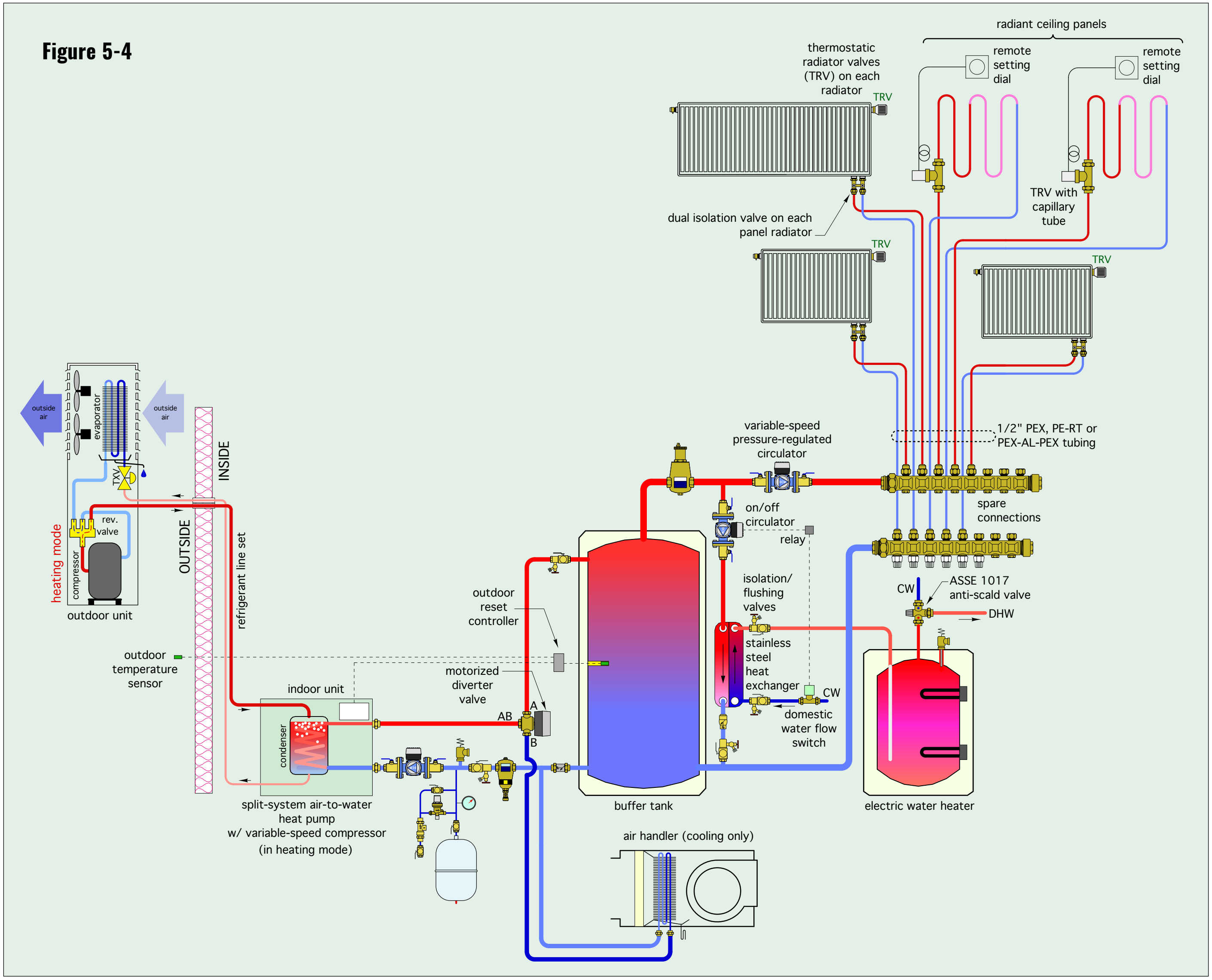
During cooling mode, the motorized valve routes flow between its AB and B ports. The heat pump's compressor speed automatically adjusts to maintain a chilled-water outlet temperature of 50ºF to the air handler.

The system includes a Dirtmag separator to ensure that the heat pump condenser and the circulators supplying the heat pump remain clean of dirt and magnetic particles (e.g., magnetite). The manifold station includes additional connections that allows more heat emitters to be easily added in the future.

SYSTEM #4

This system shows one way to add domestic water heating to system #3. It uses an external stainless steel brazed-plate heat exchanger mounted close to the buffer tank to transfer heat into cold domestic water whenever the demand for domestic hot water reaches 0.7 gpm or higher. This threshold is determined by a flow switch mounted in the cold water pipe leading into the heat exchanger. The temperature of the domestic water leaving this heat exchanger depends on the buffer tank temperature, which itself is regulated by outdoor reset control. In most cases, this temperature will be lower than the desired DHW delivery temperature. This system uses a standard tank-

Figure 5-4



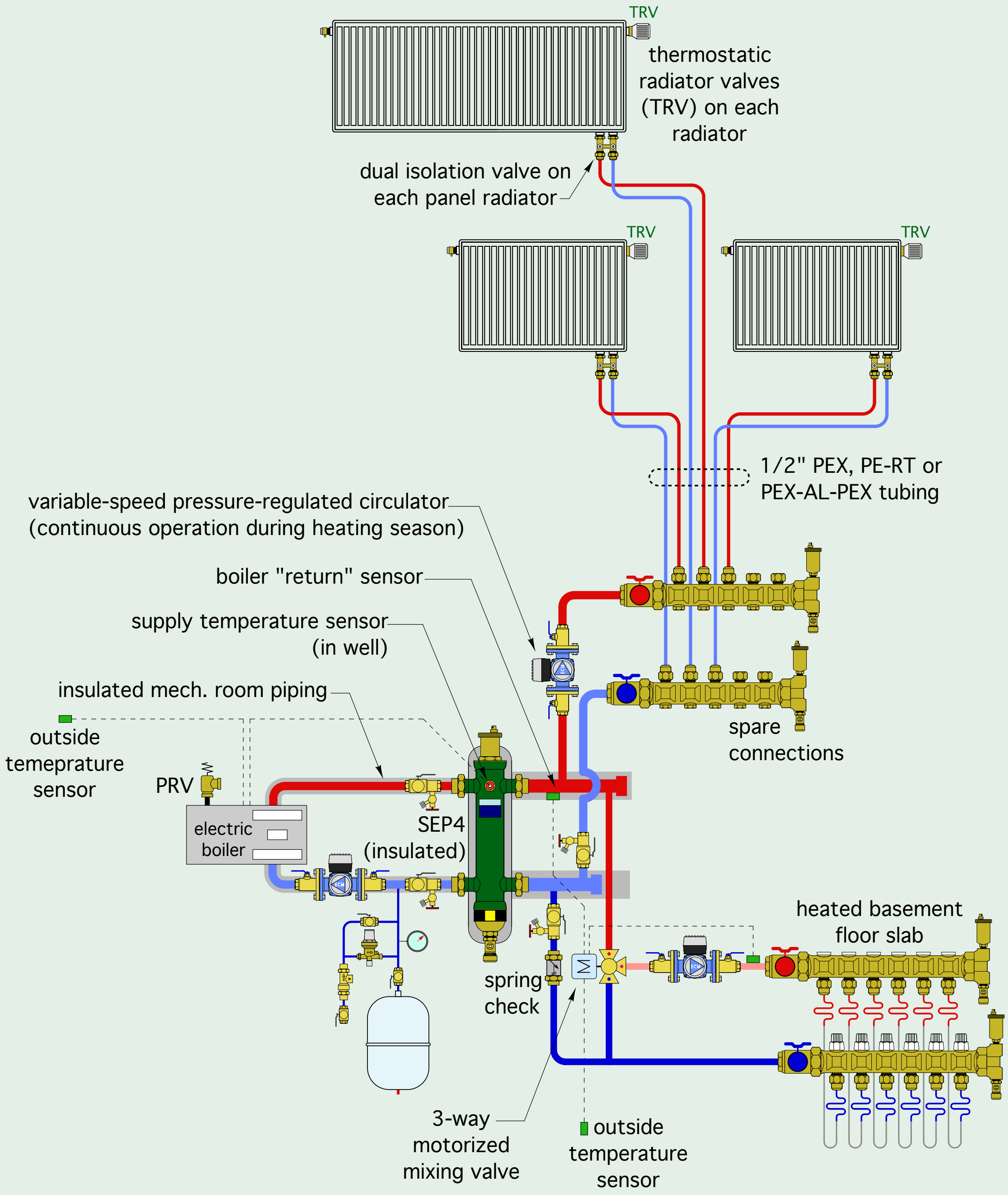
type electric water heater to boost the preheated water to its final delivery temperature. This tank could also provide 100 percent of the DHW load if the heat pump is down for service.

See idronics #29 for more information on sizing heat exchangers for domestic water heating applications.

SYSTEM #5:

A low-energy or net-zero home could also be fully heated by an electric boiler. An ideal application would be a home with a high-performance thermal envelope in a cold climate that doesn't require cooling, and where electrical rates are relatively low. In this scenario, the electric boiler may have a lower life-cycle cost compared to a heat pump.

Figure 5-5



The system shown in figure 5-5 shows one example of how an electric boiler can be configured to supply a heated floor slab in the basement and three panel radiators on the home's main floor.

Although electric boilers can operate at elevated temperatures without a decrease in efficiency, there are advantages associated with sizing the panel radiators for a relatively low water supply temperature, such as 120ºF, under design load conditions. Doing so allows the possibility of using a heat pump as a future heat source without having to add heat emitters or increase the size of existing emitters. It also allows the radiators to have a higher percentage of radiant versus convective heat output, which improves comfort. Heat loss from the distribution piping is also reduced when the system operates at lower water temperatures.

All-electric boilers require a minimum sustained flow rate whenever they operate. In this system, that flow is provided by a dedicated low-power ECM circulator that operates continuously during the heating season.

The SEP4 hydraulic separator and the short/generously sized headers ensure that all three circulators are hydraulically isolated from each other. It also provides air, dirt and magnetic particle separation for the system.

The three panel radiators are supplied by a homerun distribution circuit powered by a variable-speed pressure-regulated circulator. Each panel radiator is equipped with a dual isolation valve and a thermostatic operator. The latter allows each radiator to adjust its heat output to meet the desired comfort level in the space served by that radiator.

The floor-heating circuits in the basement are supplied through a 3-way motorized mixing valve, which reduces the supply water temperature relative to that supplied to the panel radiators.

The boiler piping, SEP4 hydro separator, and surrounding metal piping should be insulated to minimize heat loss to the building's mechanical room.

This system combines a very high thermal mass heat emitter (e.g., the heated basement slab), with other very low thermal mass heat emitters (e.g., the three panel radiators). This combination sets up the possibility that the high mass slab can absorb much of the heat supplied by the boiler, especially if that slab is warming from a cool starting condition. This transient condition can significantly depress the water temperature in the entire system and not allow the panel radiators to properly heat their associated spaces. In effect, the slab's mass will "dominate" where heat from the boiler is going.

To avoid this undesirable temperature depression, the system needs to operate in one of two possible control configurations.

Configuration #1: Provide ALL of the following requirements:

- Operate the boiler and its circulator continuously during the heating season, with the water temperature based on full outdoor reset control. The outdoor reset settings should allow the panel radiators to maintain room comfort on a design load day. Most modern electric boilers have internal controllers that allow for outdoor reset control.

- Operate the panel radiator circulator and the floor-heating circulator continuously during the heating season.

- Configure the mixing valve controller for outdoor reset with settings sufficient to maintain the basement comfort level on a design load day.

- Equip the mixing valve controller with indoor temperature feedback, which eliminates the need for a thermostat in the basement.

- Do not make frequent adjustments (such as nighttime setback) to the desired basement air temperature.

Configuration #2: Provide ALL of the following requirements:

- Operate the boiler and its circulator continuously at a *setpoint temperature* high enough to allow the panel radiators to maintain room comfort on a design day. A suggested not-to-exceed temperature is 120ºF.

- Install the boiler "return" temperature sensor — supplied with the mixing valve controller — on the outlet of the SEP4 hydro separator, and set the minimum boiler return temperature setting on this controller 2ºF lower than the supply water temperature required by the panel radiators on a design day. This allows the controller to partially close the mixing valve's hot port as necessary to prevent a temperature drop that would otherwise limit the output from the panel radiators.

Control configuration #1 reduces piping heat losses, but also counts on "consistent" operation of the basement floor-heating subsystem (e.g., not making frequent changes in the desired room temperature setting for the basement).

Control configuration #2 allows for frequent changes in the desired temperature setting for the basement. It also ensures that the panel radiators will have sufficient supply water temperature to maintain comfort in their associated spaces. However, this configuration will result in higher heat losses from the distribution piping. If used, it is essential to insulate all metal piping and piping components within the mechanical room.

Either control configuration is possible. The choice will likely be based on how the air temperature of the basement will be (or won't be) changed.

SYSTEM #6:

Another possible application for an electric boiler in a low-energy or net-zero house is when the local utility offers time-of-use electrical rates, and the boiler can be combined with thermal storage. The objective is to operate the electric boiler as much as possible during times when low-cost "off-peak" rates apply, and keep the boiler off when possible during times when "on-peak" rates apply.

Time-of-use rate structures vary among utilities. Most provide their lowest rates from late night to early morning. Some utilities also offer off-peak rates on weekends and holidays.

One example of a time-of-use rate structure would be:

- Between 11:30 PM and 7:00 AM weekdays, and between 11:30 PM Friday and 7:00 AM Monday, electricity is priced at $0.05/kWhr.

- Between 7:00 AM and 11:30 PM weekdays, electricity is priced at $0.20/kWhr.

The feasibility of an off-peak thermal storage heating system depends on the utility rate structure, the building load, the thermal mass available for storing heating, and to some extent, the willingness of the occupants to "cooperate" with the system's operating objectives. Buildings with high-performance thermal envelopes can use smaller and less expensive thermal storage systems. Owners willing to reduce room temperatures, if necessary, during the final hours of an on-peak rate period will also help the system minimize operating cost.

Low-energy or net-zero buildings with grid-connected/net-metered solar photovoltaic systems are good candidates for this type of system. The solar electric system is likely to produce most of its output during times when on-peak utility rates apply. This solar-derived electricity would minimize the need for higher priced on-peak electricity from the utility grid, especially in situations where the electric boiler might have to operate during on-peak times.

Figure 5-6a shows a possible system configuration in which an electric boiler supplies heat to a thermal storage tank, and ultimately to a homerun distribution system supplying panel radiators. An alternative high-thermal mass floor-heating distribution system is also shown.

The controls for this system turn on the electric boiler and its circulator at the start of each off-peak period. The boiler and its circulator remain on until the thermal storage tank temperature reaches 180ºF. Space heating can take place during this time, with excess boiler output routed into thermal storage.

In this system, the panel radiators are sized to deliver design load output at a relatively low supply water temperature of 110ºF. Doing so allows for the thermal storage tank to be "discharged" to a relatively low temperature while still supplying adequate heating capacity to the radiators.

The amount of heat stored in the tank is 8.33 Btu/gallon/ºF. Thus, a 119-gallon tank undergoing a temperature discharge from 180 to 110ºF would release 8.33 x 119 x (180-110) = 69,390 Btus. This could represent several hours of heating in a low-energy or net-zero home, especially during partial load conditions.

The 3-way motorized mixing valve blends hot water from the thermal storage tank, or coming directly from the electric boiler, with cooler water returning from the radiators to achieve a target supply water temperature to the radiators. That target temperature is based on outdoor reset control. The latter allows the tank to supply the radiators down to the minimum water temperature that can still maintain comfort in the building. On partial load days, that temperature could be in the range of 80ºF. The lower this temperature can be, the greater the amount of heat the tank can deliver to the load on each discharge cycle.

If the tank cools to the point where the radiators can no longer maintain comfort, as determined by some minimum tank temperature, the electric boiler is enabled to operate regardless of which electrical rate is in effect. Boiler operation during on-peak periods should be minimized to keep overall operating cost low. This situation would typically occur during early evening hours, when the output of a solar electric system is low or zero, and internal loads in the building tend to diminish.

The alternative concrete slab floor-heating system adds substantial thermal mass to the system, extending its ability to maintain comfort in the building for longer periods when on-peak electrical rates are in effect. For example, a 4-inch-thick concrete slab can store 9.8 Btu/square foot/ºF of temperature change. A 6-inch-thick slab can store 14.7 Btu/square foot/ºF of temperature change. Thus, a 1,500-square-foot slab, 4 inches thick, and undergoing an average temperature drop of only 3ºF, can release 44,100 Btus.

A word of caution is appropriate. High-thermal mass distribution systems, although good at storing heat, and thus allowing buildings to "coast" through several hours without heat input from source equipment, are not well-suited to buildings where significant and unanticipated internal heat gains might occur. This type of system should not be used in buildings that are designed for significant solar heat gain, or where a large number of occupants or other heat-generating activities may be present at times.

It is also critically important to insulate all piping and components in areas of the system that are subject to high water temperatures. Be sure that all components used are rated to handle the highest water temperatures that might be present. The system shown in figure 5-6a also uses several spring-loaded check valves to limit heat migration within the system.

Figure 5-6a

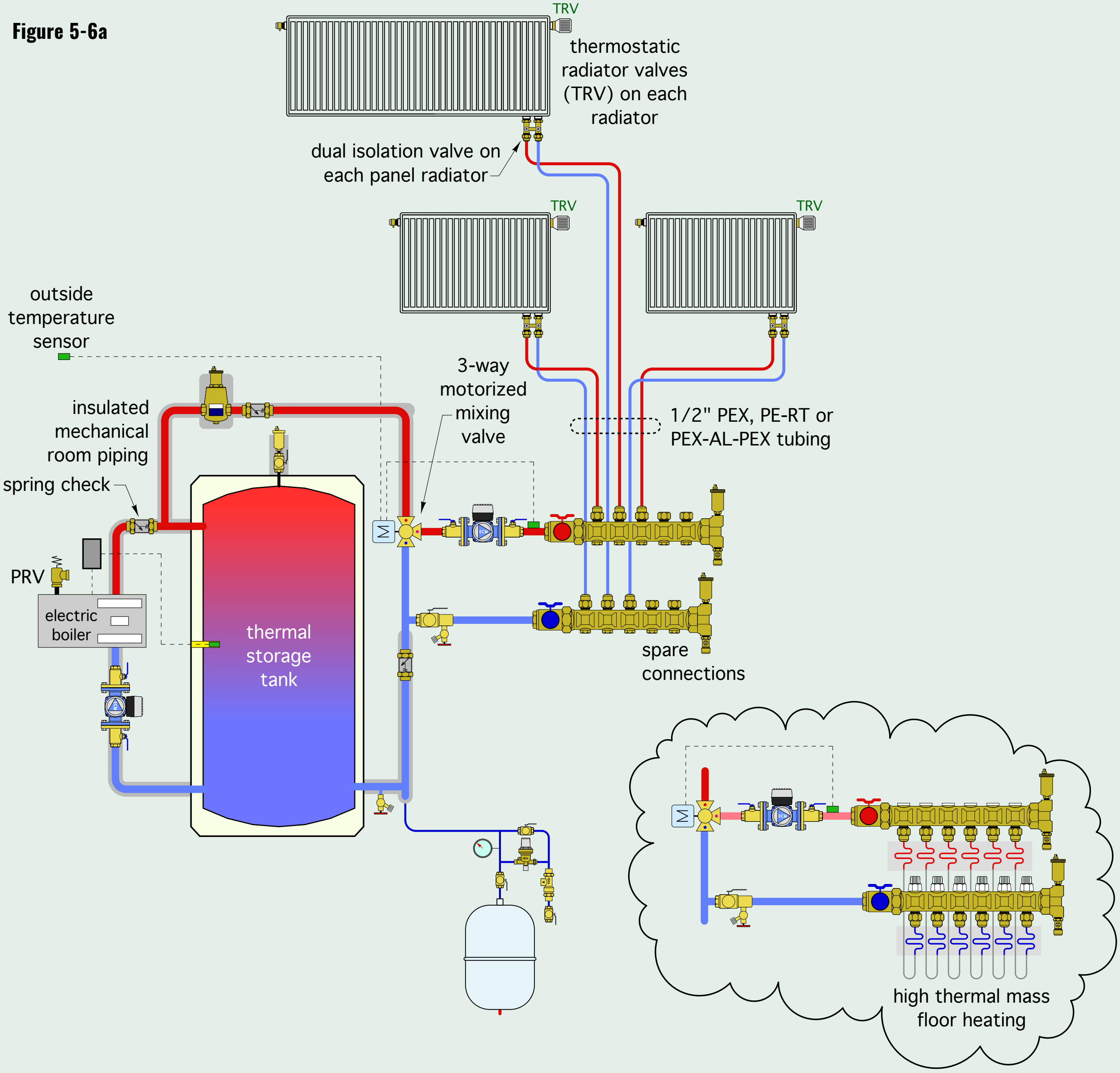
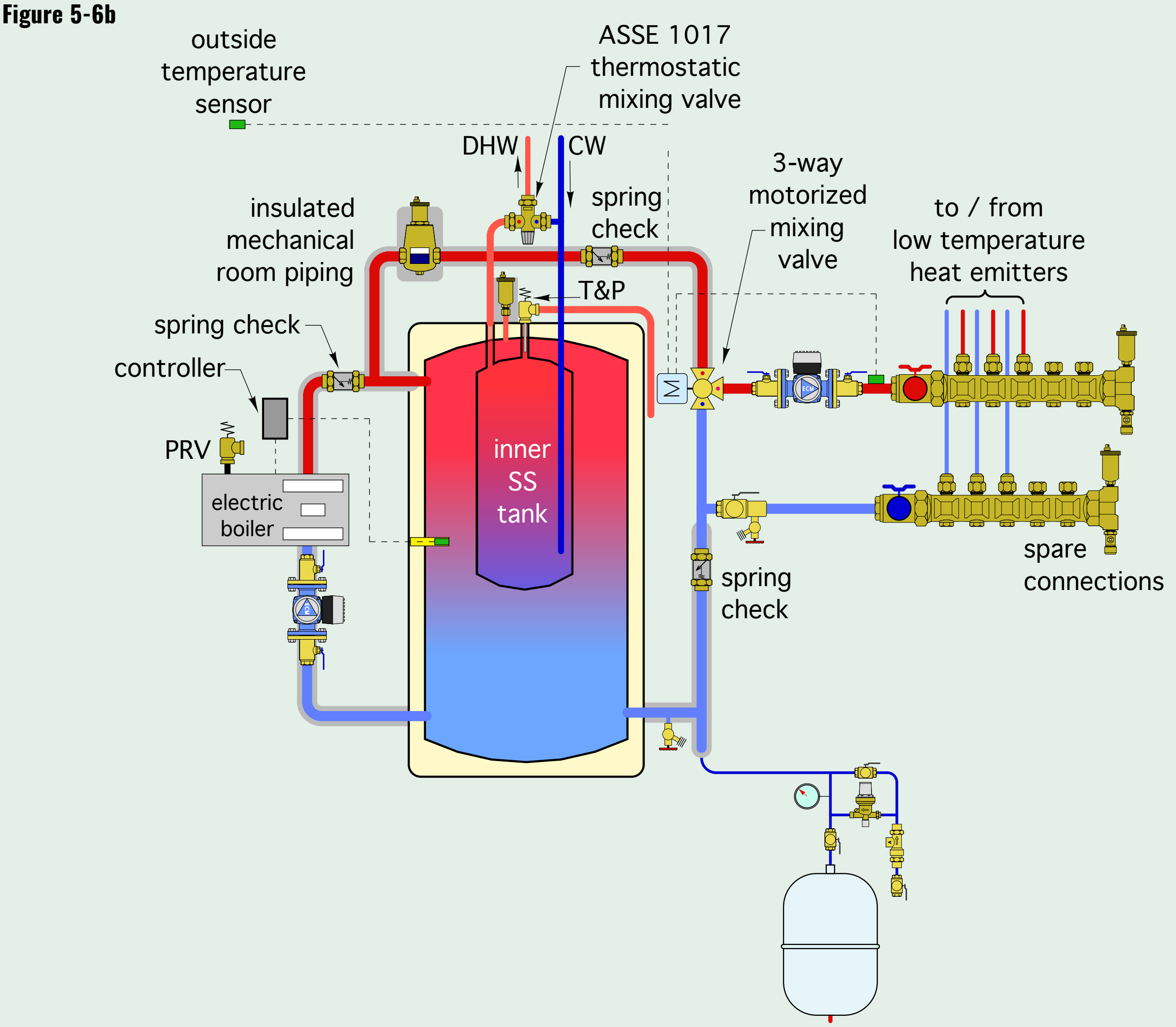


Figure 5-6b



The thermal storage tank, piped as shown in figure 5-6a allows the electric boiler to operate at or above its minimum flow rate, even when only a "trickle" of hot water is passing into the 3-way mixing valve. It also provides hydraulic separation between the boiler circulator and the distribution circulator.

Another variation on the system is shown in figure 5-6b.

This system uses a "tank-in-tank" reverse indirect water heater for thermal storage. Heat added to this tank by the electric boiler can be used for either space heating or for domestic water heating. The latter occurs within the inner stainless steel tank.

If the temperature in the tank shell is maintained at or above 120ºF, the domestic water should be fully heated to a reasonable distribution temperature by the time it leaves the inner tank. If the minimum tank temperature will be lower, some type of auxiliary electric water heater (tankless or tank-type) could be added to boost the domestic water to its final desired temperature.

An ASSE 1017-listed thermostatic mixing valve, installed as shown in figure 5-6b, is critically important to ensure that the domestic water leaving the tank doesn't exceed 120ºF.

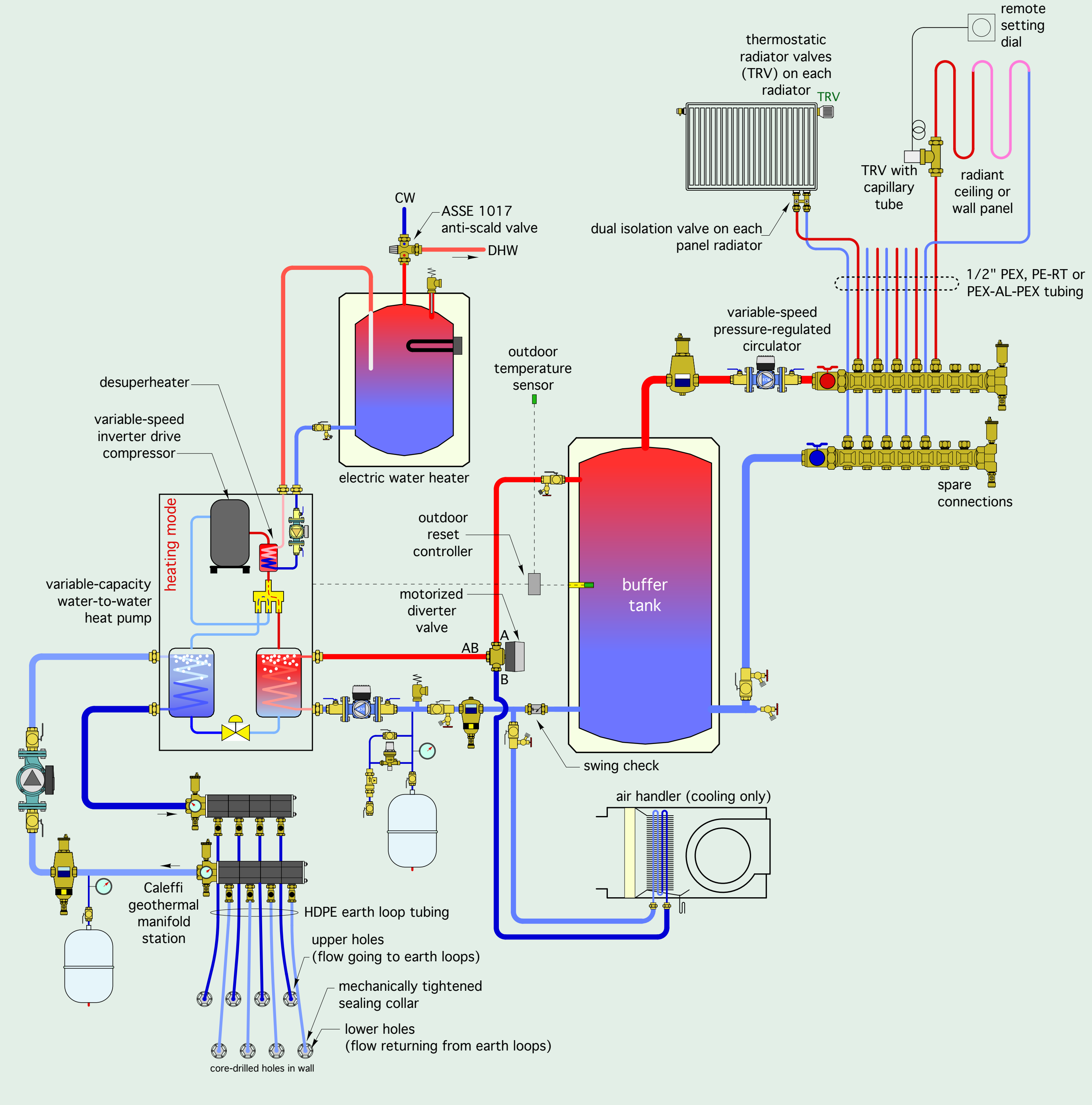
SYSTEM #7:

This system provides multi-zone heating using a combination of low-temperature, low-thermal mass panel radiators and radiant panels. It also provides a single zone of chilled-water cooling, and domestic-water heating. A variable-capacity geothermal-sourced water-to-water heat pump serves as the primary heating and cooling source.

The heat pump is supplied from a closed earth loop system consisting of four buried HDPE earth loop circuits piped in parallel. All the earth loop circuits begin and end at a Caleffi GeoCal manifold station, which allows each circuit to be individually isolated and flushed. Since the manifold station is inside the building, it is possible to install the entire earth loop without having to thermally fuse the HDPE pipe.

The earth loop subsystem includes an expansion tank as well as a Caleffi Discaldirtmag separator, which removes air, dirt and magnetic particles from the earth loop fluid.

Figure 5-7



During heating mode, the heat pump maintains the buffer tank temperature based on outdoor reset control. This keeps the water in the buffer tank just warm enough to ensure that comfort is maintained, while also maximizing the heat pump's COP.

All heat emitters are connected to a single homerun distribution system supplied from the buffer tank. Flow through the heat emitters is controlled by a variable-speed pressure-regulated circulator. All heat emitters are sized to meet the design loads of their associated building spaces using a supply water temperature no higher than 120ºF.

Single-zone cooling is provided by a chilled-water air handler. The inverter-driven heat pump varies its cooling capacity as necessary to maintain a chilled-water outlet temperature of 45ºF.

Domestic water is heated by the heat pump's desuperheater whenever the heat pump's compressor is on. A small stainless steel circulator within the heat pump moves cool domestic water from the lower portion of the tank-type water heater through the desuperheater and back to the tank. Any final temperature boost needed is provided by an electric resistance heating element in the upper portion of the tank.

Additional information on geothermal heat pump systems is available in idronics #9.

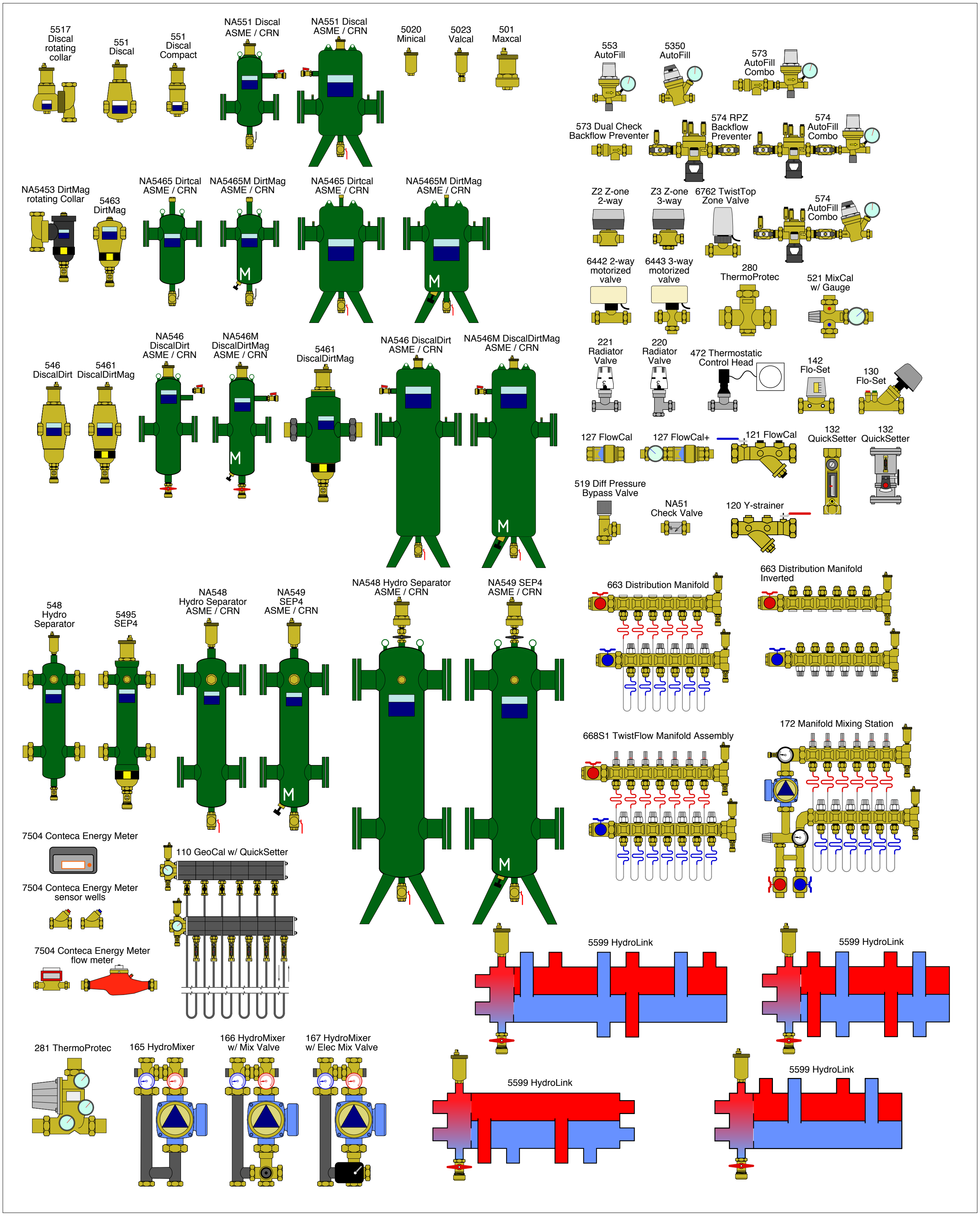
SUMMARY:

Demand for net-zero buildings is rapidly increasing across North America and globally. The majority of buildings designed to operate on a net-zero energy basis use electrically powered heat sources and cooling sources in combination with site-generated electricity from solar photovoltaic systems. Heat pumps of several types are commonly used for heating and cooling. Among these are air-to-water and water-to-water heat pumps, both of which are ideally suited to hydronic system applications.

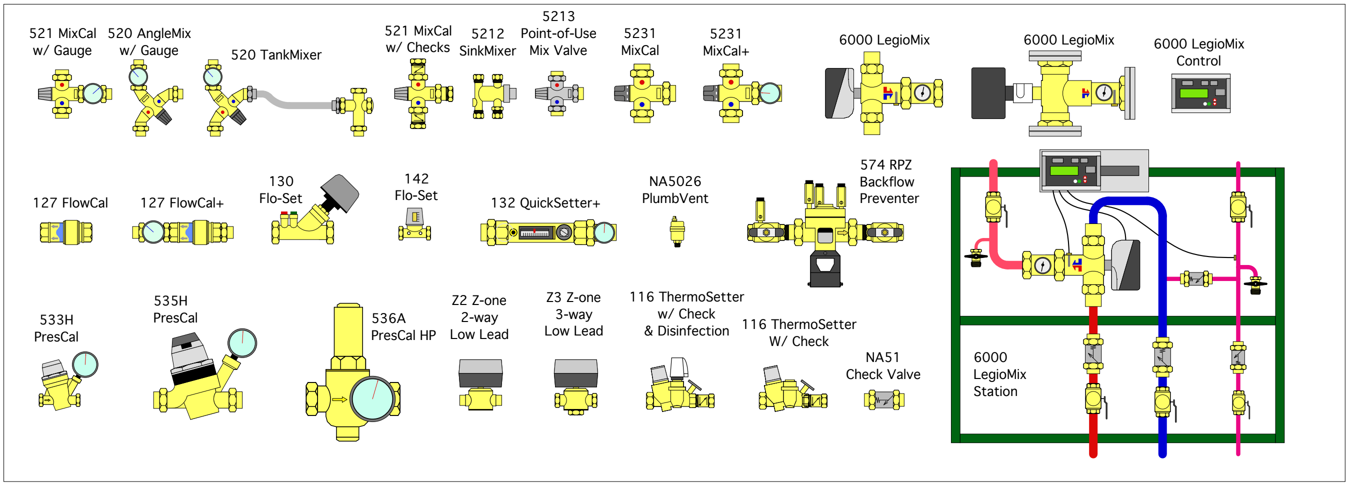
By combining modern heat pump technology with hydronic heating and cooling distribution systems, designers can achieve benefits not possible with forced-air distribution systems. These include superior comfort, radiant as well as convective heat delivery, high distribution efficiency, minimally invasive installation, the ability to heat domestic water, the ability to coordinate with time-of-use electrical rates, adaptability of the distribution system to future heating and cooling sources, and a long service life.

The legislative, cultural and economic incentives that encourage beneficial electrification and decarbonization, and the accompanying demand for low-energy and net-zero buildings, collectively represent one of the biggest opportunities set before the North American hydronics market in decades. The concepts and details presented in this issue serve as building blocks that creative designers can assemble into systems that meet this demand and are precisely tailored to the needs of each building.

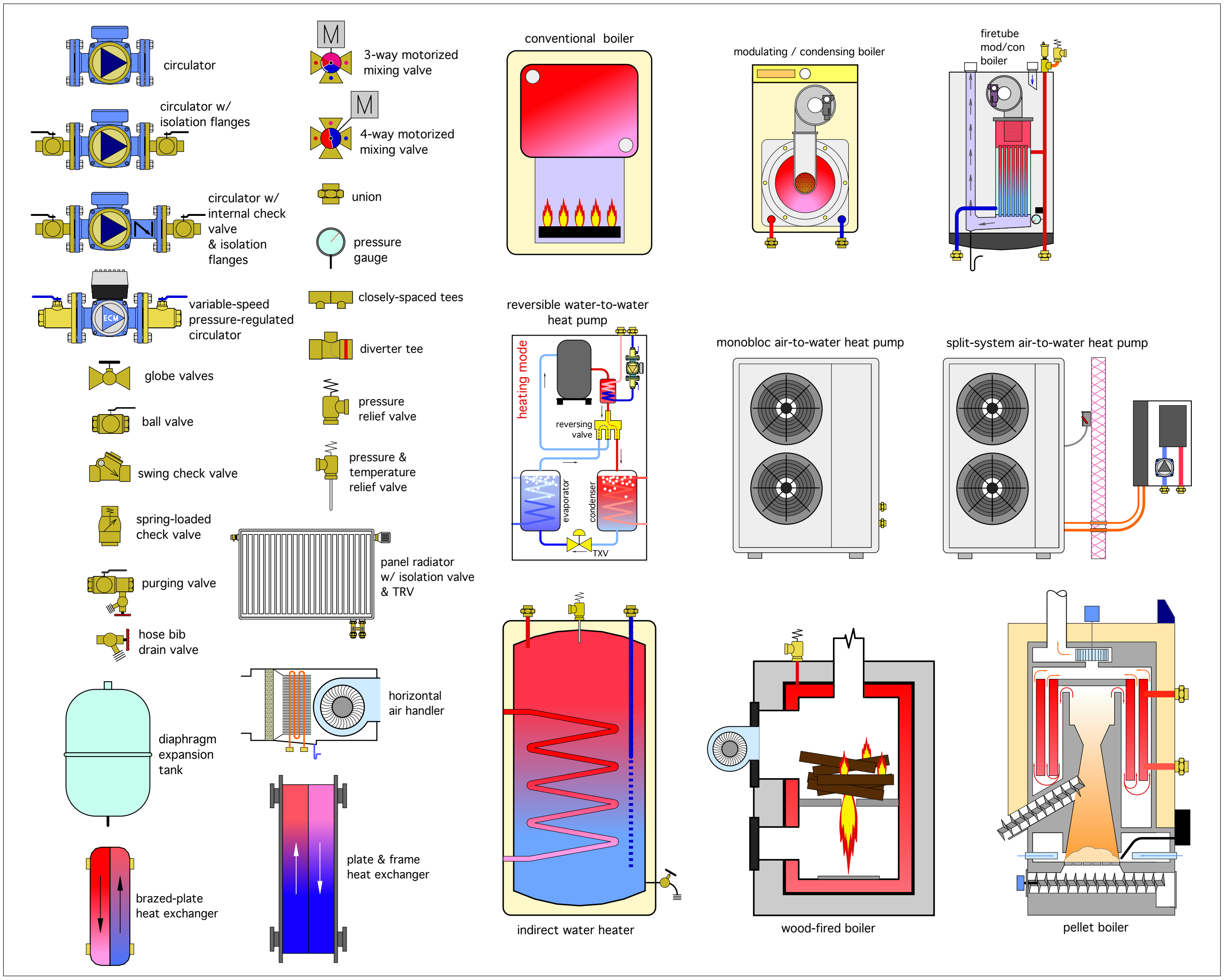
APPENDIX A: CALEFFI HYDRONIC COMPONENTS



APPENDIX B: CALEFFI PLUMBING COMPONENTS



APPENDIX C: GENERIC COMPONENTS



APPENDIX D: ESTIMATING PANEL RADIATOR HEAT OUTPUT AT REDUCED WATER TEMPERATURES

In North America, the published data for heat output from panel radiators is typically based on high water temperatures. The most common being an *average* water temperature of 180ºF, and an assumed room air temperature of 68ºF. This makes the difference between the *average* water temperature in the radiator and the room air temperature 180 - 68 = 112ºF. This temperature difference, or ΔT, is a reference condition that can be used as part of the following procedure, based on European standard EN442, to determine the output of panel radiators at lower water temperatures.

The general relationship between the heat output of a panel radiator and the difference between the average water temperature at which it operates and the surrounding air temperature is given by Formula B1.

Formula B1:

$$Q_e = Q_{112}\left(\frac{\Delta T_d}{112}\right)^{1.3}$$

Where:

Q_e = estimated heat output of the panel radiator (Btu/hr)

ΔT_d = temperature difference determined using either Formula B2 or Formula B3 below (ºF)

Q_{112} = the output of the panel radiator when the difference between the *average* water temperature and room air temperature is 112ºF (Btu/hr) (e.g., average water temperature = 180ºF, and room air temperature = 68ºF)

1.3 = an exponent (not a multiplier) *(use [y^x] key on scientific calculator or your smart phone)*

The value to be used for ΔTd is based on either Formula B2 or B3:

Formula B2:

$$\Delta T_d = \left[\left(\frac{T_{in} + T_{out}}{2}\right) - T_{air}\right]$$

Formula B3:

$$\Delta T_d = \frac{(T_{in} - T_{out})}{\ln\left(\frac{T_{in} - T_{air}}{T_{out} - T_{air}}\right)}$$

Where:

ΔT_d = effective temperature difference (ºF)

T_{in} = inlet water temperature to panel (ºF)

T_{out} = outlet water temperature from panel (ºF)

T_{air} = room air temperature (ºF)

ln = natural logarithm function *(use [ln] key on scientific calculator or your smart phone)*

Another formula, (B4), is used to determine if Formula B2 or Formula B3 should be used to calculate ΔTd.

Formula B4:

$$u = \frac{(T_{out} - T_{air})}{(T_{in} - T_{air})}$$

Where:

T_{out} = outlet fluid temperature from panel (ºF)

T_{in} = inlet fluid temperature to panel (ºF)

T_{air} = room air temperature (ºF)

If the calculated value of u from Formula B4 is less than 0.7, use Formula B3 to calculate ΔT_d.

If the calculated value of u from Formula B4 is greater than or equal to 0.7, use Formula B2 to calculate ΔT_d.

For example, assume water enters the panel radiator at 115ºF, and exits at 92ºF. The air temperature in the room is 65ºF. Determine the correct ΔT_d to use in Formula 1.

Solution: Start by calculating the value of u using Formula B4:

$$u = \frac{(T_{out} - T_{air})}{(T_{in} - T_{air})} = \frac{(92 - 65)}{(115 - 65)} = 0.54$$

Since 0.54 < 0.7 use of Formula B3 to calculate ΔT_d:

$$\Delta T_d = \frac{(T_{in} - T_{out})}{\ln\left(\frac{T_{in} - T_{air}}{T_{out} - T_{air}}\right)} = \frac{(115 - 92)}{\ln\left(\frac{115 - 65}{92 - 65}\right)} = \frac{23}{\ln\left(\frac{50}{27}\right)} = \frac{23}{\ln(1.85185)} = 37.33^\circ F$$

Now that the appropriate value of ΔT_d has been determined, the final step is to plug the numbers into Formula B1:

$$Q_e = Q_{112}\left(\frac{\Delta T_d}{112}\right)^{1.3} = 9500\left(\frac{37.33}{112}\right)^{1.3} = 2277\frac{Btu}{hr}$$

This is about one quarter of the “rated” heat output of the panel when the average water temperature is 180ºF and the assumed room temperature is 68 ºF.

When searching manufacturer’s rating tables for an appropriately sized panel radiator, it’s sometimes necessary to work this procedure “backwards.”

For example, consider a room with a design load of 2,500 Btu/hr. Assume that the panel radiator in this room will be supplied with water at 115ºF and operate with a 25ºF temperature drop. The room temperature will be 70ºF. Use the above procedure “in reverse” to find an appropriately sized radiator based on output at an average water temperature of 180ºF and a room temperature of 68ºF.

Solution: Start with Formula B4:

$$u = \frac{(T_{out} - T_{air})}{(T_{in} - T_{air})} = \frac{(90-70)}{(115-70)} = 0.44$$

Since u < 0.7 use Formula B3 to get ΔT_d:

$$\Delta T_d = \frac{(115-90)}{\ln\left(\frac{115-70}{90-70}\right)} = 30.83^{\circ} F$$

Next, set up Formula 1 with all the known information, including the required heat output at the lower water temperature (e.g., 2,500 Btu/hr):

$$2500 = Q_{112}\left(\frac{30.83}{112}\right)^{1.3}$$

This can be solved for the necessary output at the ΔT_d = 112ºF

$$Q_{112} = \frac{(2500)}{\left(\frac{30.83}{112}\right)^{1.3}} = 13{,}374\frac{Btu}{hr}$$

At this point, the designer can look through a table of radiator ratings based on an average water temperature of 180ºF and a room air temperature of 68ºF to find one or more panel radiators that can output approximately 13,400 Btu/hr.

Based on data from one manufacturer, a radiator with three water plates, a height of 24 inches, and length of 48 inches has an output of 13,664 Btu/hr, which is very close to calculated output at ΔT_d = 112ºF. A radiator with three water plates that is 20 inches high and 64 inches long has a listed output of 15,829 Btu/hr — more than enough.

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