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ENGINEERS NEWSLETTER

Volume 54-2 //June 2025

Heat Pump Considerations for Low Ambient Operation

Use of air-to-water heat pumps (AWHP) for heating is increasing as one means to reduce the carbon emissions of a building (decarbonization). But applying this type of equipment in a cold climate can present some interesting engineering hurdles.

This *Engineers Newsletter* will discuss application considerations when applying AWHPs in cold climates, limitations of the equipment, defrost methods, and how to mitigate the impact of defrost on occupant comfort.

What is a cold climate?

ASHRAE defines climate zones based on annual cooling and heating degree-days and precipitation data. This EN will focus on ambient conditions defined by climate zones 5 and above (Figure 1).

As with any piece of equipment, AWHPs have their limitations. Understanding these limitations is critical to ensure a successful project.

Figure 1. ASHRAE© Standard 169-2021 United States climate zone map

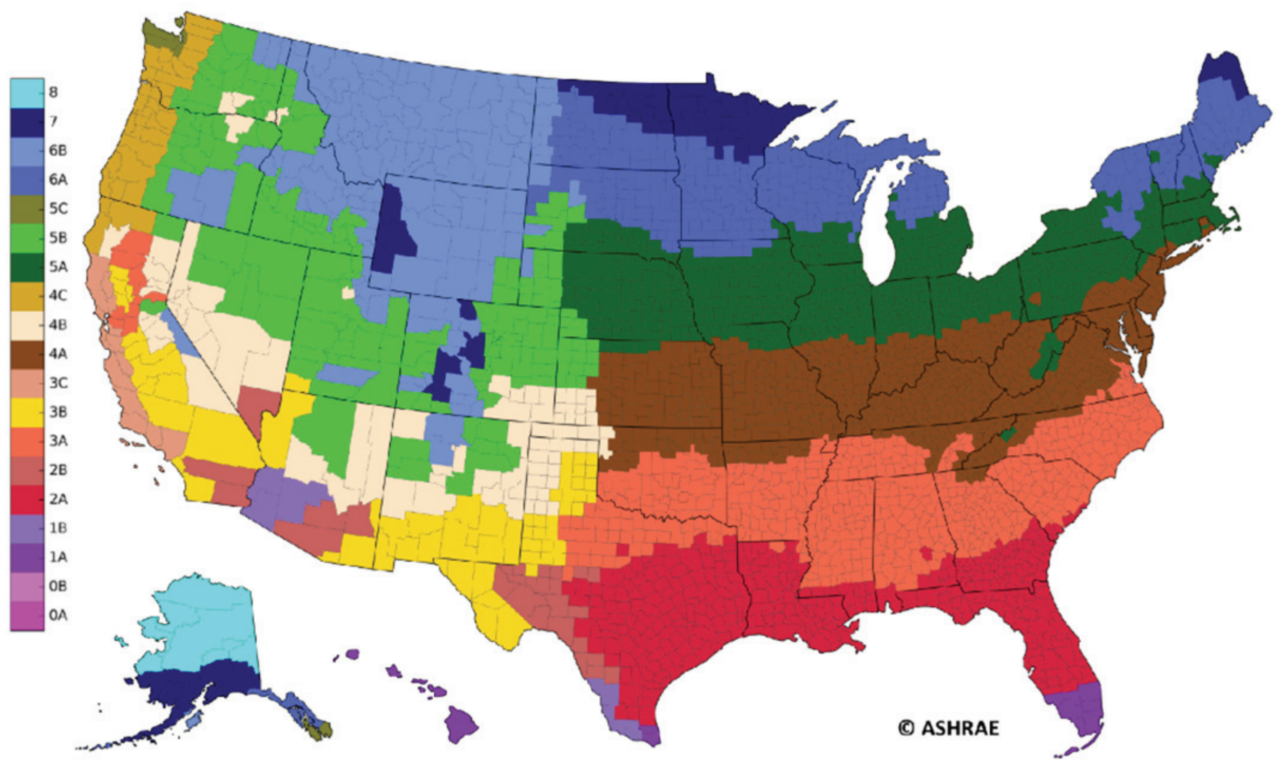


Figure A-2 Climate zones for United States counties.

Key Terms

Figure 2 illustrates the relationship between the following terms in a typical AWHP operating map:

Low Ambient Limit is an equipment operational rating that sets the unit's minimum ambient temperature for operation. Heat pumps will not produce hot water below this temperature.

Maximum Lift Limit is the highest hot-water supply (HWS) temperature the unit can produce at the minimum ambient temperature. It is based on the compressor and refrigeration cycle. When the outdoor air temperature is low, the maximum HWS temperature may be limited.

Maximum Operating Temperature is the hottest HWS temperature the unit can supply. This is based on refrigerant pressure and component capability.

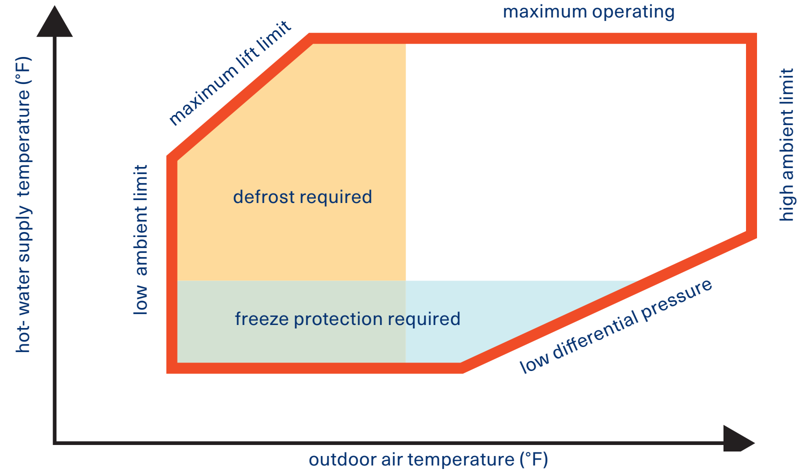
High Ambient Limit is an equipment operational rating that sets the unit's maximum ambient temperature for operation.

Low Differential Pressure happens when equipment operates below the minimum pressure differential specified by the equipment manufacturer. This can lead to compressor operational issues, such as oil management.

Defrost Required is when the saturated refrigerant temperature in the outdoor heat exchanger is below freezing temperature, causing humidity to collect/freeze on the heat exchanger.

Freeze Protection is required if the fluid temperature is near the freezing temperature. This is often accomplished by adding either ethylene glycol or propylene glycol to the fluid. Note that this causes the properties of the fluid to change, including in air-handling or terminal unit coils, unless there is an intermediate heat exchanger between the AWHP and building fluid distribution. Heat trace is another option to consider.

Figure 2. Typical air-to-water heat pump operating map



Application Considerations

The three most important metrics to understand if AWHPs are considered for a system design are:

- *Maximum operating temperature* (maximum HWS temperature)
- *Low ambient limit* (coldest operating temperature)
- *Maximum lift limit* (difference between ambient and permissible HWS temperature).

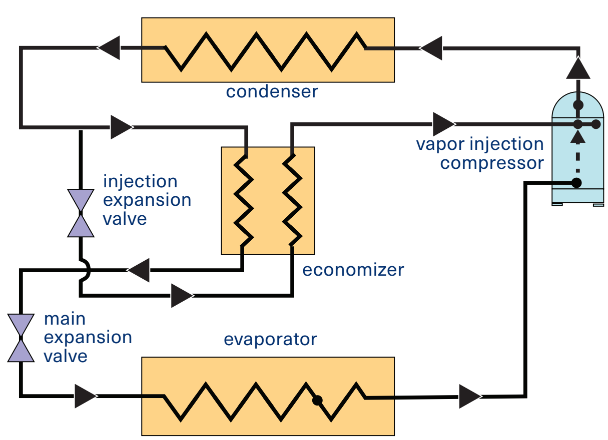
These metrics differ depending on the manufacturer and design of the AWHP. Typically, the maximum HWS temperature is not achievable at the low ambient limit (minimum ambient operating temperature). This is when the **maximum lift limit** becomes important.

Some AWHP units may be capable of 90°F of lift, while others may be capable of more, potentially over 130°F of lift.

How is more lift achieved?

Many standard scroll compressors can achieve 90° to 100°F of lift. Some scroll compressors are configured with a form of injection technology. *Vapor* injection often increases the amount of lift and is commonly deployed in AWHPs. This technology includes an additional heat exchanger and additional piping in the refrigeration circuit (Figure 3).

Figure 3. Vapor injection scroll compressor



The additional injection port reduces mechanical stress at a given operating point, allowing the compressor to operate at higher lift conditions (Figure 4) before exceeding mechanical limits. Table 1 provides a comparison of capabilities between standard and vapor injection scroll compressors.

Importance of hot-water supply (HWS) temperature selection

As shown in Table 1, the maximum HWS temperature for most AWHPs is 140°F but there are ambient temperature limitations for reaching this. Therefore, it is imperative to design heating systems for lower HWS temperatures (less than 130°F in most cases) so the heat pump can provide the desired HWS temperature across the expected ambient temperature range.

Some systems may require a higher HWS temperature for heating or other processes. When the HWS temperature is higher than an AWHP can directly deliver, a cascaded system could be considered. A cascaded system consists of one or more AWHPs used as a source of heat for one or more heat-recovery chillers (Figure 5).

Figure 4. Standard versus vapor injection operating map

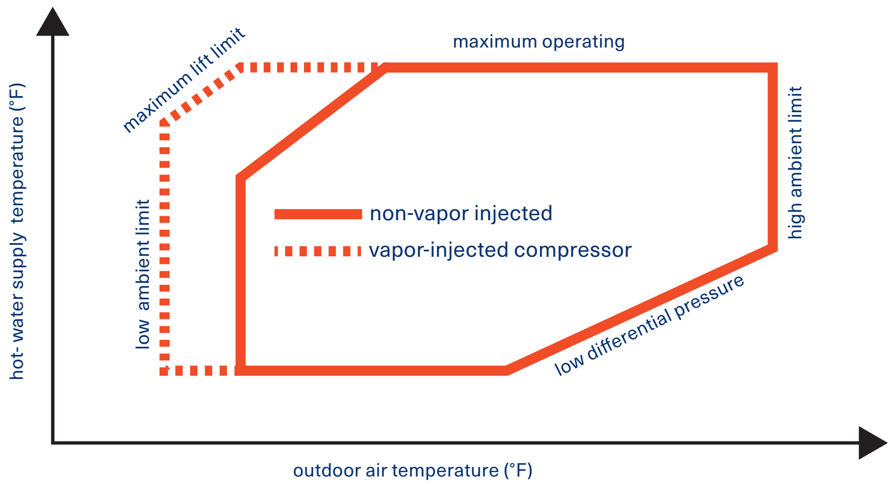
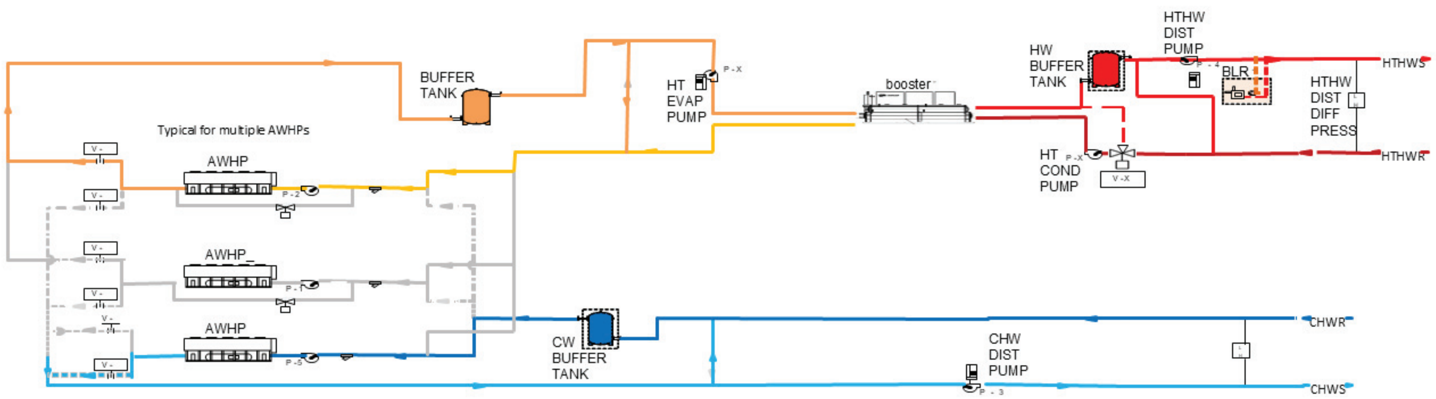


Table 1. Compressor operating capabilities (°F)

Standard scroll compressor capabilities		
	supply range	**ambient operating range**
chilled water	30° to 65°	0° to 115° ambient
hot water	60° to 140°	0° to 95° ambient
hot-water temperature with ambient temperature at 0°		
Vapor injection scroll compressor capabilities		
	supply range	**ambient operating range**
chilled water	30° to 65°	0° to 115° ambient
hot water	60° to 140°	-18° to 95° ambient
hot-water temperature with ambient temperature at -18°		

Please refer to *Trane Engineers Newsletter* ADM-APN084-EN “Heating with Lower-Temperature Hot Water” for more information on coils and distribution devices utilizing lower temperature hot water.

Figure 5. Example cascade AWHP system: Helical rotary screw high temp heat pump boosted from ASHPs



For more details about cascade systems, please download Trane application guide SYS-APG003-EN “Air-to-Water Heat Pump System with Cascade Option: Part of the Comprehensive Heat Pump Chiller System.”

Defrost Methods

During cold ambient temperatures, frost formation on the outdoor heat exchanger (the evaporator in the heating mode) reduces heat transfer and efficiency, requiring an energy-intensive defrost process.

- Frost typically begins forming when the outdoor relative humidity (RH) is above 60 percent and the outdoor (ambient) dry-bulb temperature is below 42°F.
- Frost forms in stages: first, water droplets begin to condense out of the ambient air on the surface of the heat exchanger; second, these condensate droplets begin to freeze (frost); third, frost crystals begin to appear on the heat exchanger; and fourth, multiple layers of frost (with varying densities) begin to build up. (See Figure 6.)

Effective defrosting is vital to maintain AWHP performance, with robust and simple controls being crucial. While time-based defrost control strategies are straightforward, they do not adapt to changing conditions. So consider advanced methods for optimal defrost initiation and control.

Following are a three common methods for defrosting an AWHP heat exchanger:

Electric Heat. Heat trace, or an electric resistance element, can be mounted to the heat exchanger to thaw the built-up frost. The primary benefit is a quicker thaw (defrost) time. Drawbacks include:

- not producing hot water during defrost (assuming the compressors are off),
- energy used by the electric element,
- added parts and complexity, and
- potential reliability of the element.

Hot Gas Bypass (HGBP) & Refrigerant Injection. The second most common method of defrost is to use a hot gas bypass circuit, which directs hot refrigerant vapor from the compressor discharge to melt the frost on the outdoor heat exchanger. The defrost cycle lasts a little longer than a reverse cycle, however, delivery of hot water is less impacted.

Active defrost reduction (slowing down frost accumulation) could be used instead of, or in addition to, full defrost. This involves injecting heat into the evaporator in smaller amounts to limit (slow) the build-up of frost. The method is similar to HGBP and could use vapor or liquid injection. Vapor injection is more common since it allows for a more efficient and higher capacity heat pump compared to liquid injection.

Reverse Cycle (active defrost). The most common method of defrost in AWHPs is the reverse cycle method (Figure 7). As the name suggests, this involves reversing the refrigeration cycle from heating mode to cooling mode, thus changing the roles of the heat exchangers. The outdoor heat exchanger changes from an evaporator to a condenser, thus rejecting heat to melt any accumulated frost. Because the AWHP is now extracting heat from the load-side heat exchanger, it cools the working fluid, so evaluating this effect on the overall system should be considered carefully. Additional heat pumps, increased loop volume, or auxiliary boilers are commonly used in systems that employ AWHPs to help mitigate this effect during defrost. These can result in relatively short duration in defrost mode, increased efficiency (higher COP) during heating and defrost cycles, and relative simplicity in system design and control.

Figure 6. Visual of defrost operation

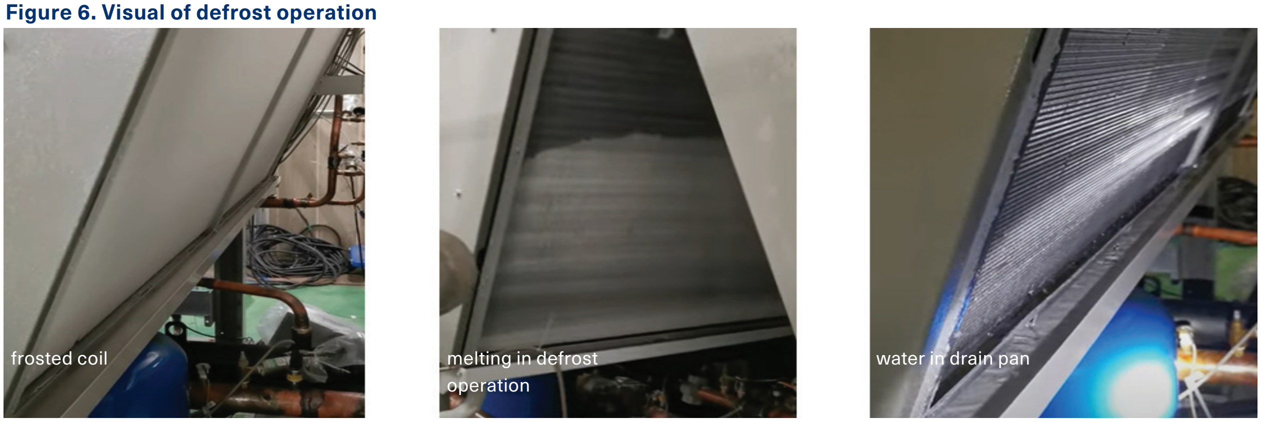
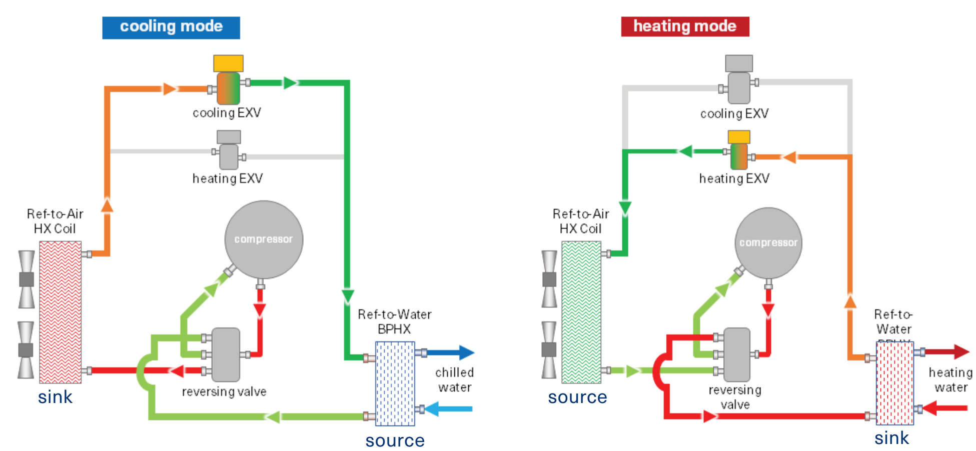


Figure 7. Example refrigeration system in cooling (defrost) and heating mode



Defrost Detection

The criteria used to determine the need for defrost operation is typically programmed into the unit controller, which triggers the start and completion of defrost mode. There are several ways to detect frost, either for entering or exiting defrost mode: based on time, based on refrigeration cycle conditions, or based (directly or indirectly) on coil pressure drop.

Time Based. As the name implies, when to enter and exit defrost mode is based on a timed setting. A timer may be set to operate the unit in defrost mode for a certain amount of time every hour, every day, or some other time interval. While this method is simple, it does not measure any operating conditions, so the unit may go into defrost mode when not needed, or may operate for a long time with a frosted coil, which degrades efficiency and could lead to equipment damage. However, a minimum and a maximum time in defrost mode are commonly used in conjunction with the following two methods.

Refrigerant Cycle Based. This method of defrost detection monitors real-time operating temperatures and pressures in the refrigeration circuit to determine when to enter and exit defrost mode. For example, the source heat exchanger's approach temperature (difference between the ambient temperature and the compressor saturated suction temperature) could be monitored, entering defrost mode when this approach exceeds a set threshold. And the compressor discharge temperature could be monitored, exiting defrost mode when this exceeds a set threshold. The benefit of this method is that defrost mode is only used when needed, and is exited as soon as possible. A drawback is that all heating for that circuit is unavailable during defrost mode.

Coil Pressure Drop Based. There are two strategies for this method: direct or indirect measurement. The *direct* method involves a measurement of frost accumulation through a variety of sensor types. The *indirect* method may measure the airside pressure drop across the outdoor heat exchanger or refrigerant conditions. Because this method measures a variable related to frost build up, indirect measurement can be very effective and efficient.

Defrost Delay. Some unit controllers may have advanced capabilities to delay the time at which the unit will enter defrost. The building automation system (BAS) can send a signal to the unit that delays the point when the unit enters defrost. The time allowed for delay may range from 15-30 minutes depending on the unit control system. The intent is to minimize the quantity of units in defrost at the same time. Similarly, the unit controller may be capable of sending a signal to the BAS alerting it when the unit is in defrost so the defrost status can be monitored.

Operation of Reverse Cycle Defrost

Air-to-water heat pumps use a refrigerant-to-air heat exchanger (coil) as the evaporator when in heating mode. When the refrigerant temperature inside the coil is below 32°F, frost can build up on its outer surface. This frost layer degrades heat transfer and coil performance. A reverse cycle defrost mode temporarily reverses the refrigeration cycle, heating up the refrigerant-to-air coil and melting the accumulated frost.

When the AWHP is in defrost mode, the hot-water loop is temporarily cooled instead of heated. When defrost is complete, the heat pump operates at an elevated capacity until the hot-water loop temperature returns to the desired setpoint. This operation is called *defrost recovery*. This recovery time depends on how much heat was removed from the hot-water loop during defrost mode and the amount of excess heating capacity available from the AWHP.

Figure 8 illustrates cumulative BTUs of heating over time, the heating load (BTU/hr) is represented by the sloped, dashed line.

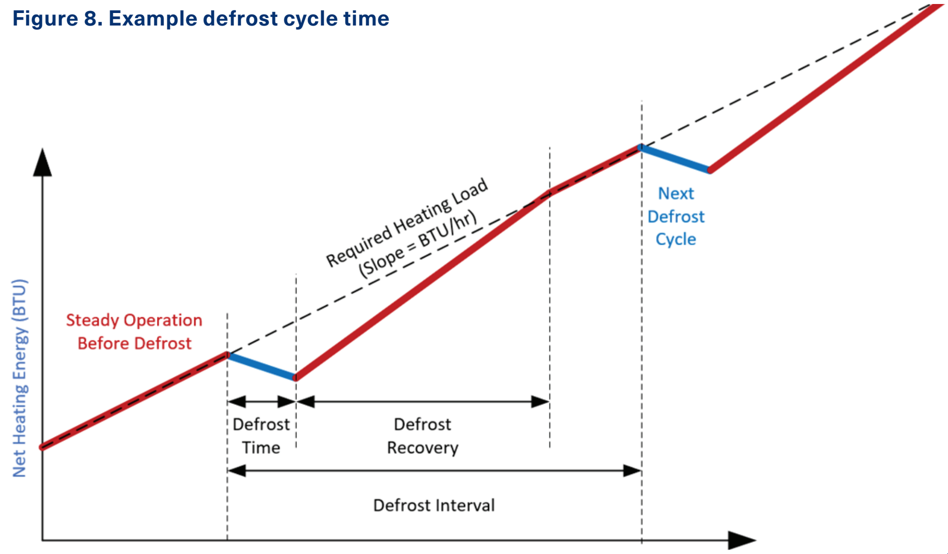
Before entering defrost mode for the first time, the heat pump capacity is modulated to match the heating load (left-hand side of Figure 8). When the unit enters defrost mode, the refrigeration cycle is reversed and the AWHP temporarily cools the hot-water loop (depicted by the blue line with a negative slope) while rejecting heat from the outdoor coil to melt the frost. A typical Defrost Time is about 5 minutes.

After exiting defrost mode, the hot-water loop has a deficit of BTUs and the heat pump must operate with extra capacity to catch back up (the slope of the red line, which depicts heat pump capacity, is steeper than the dashed black line, which depicts the building heating load). This Defrost Recovery time depends on how much extra capacity is available and how much of a BTU deficit was accumulated during the Defrost Time. When sizing heat pumps, the "defrost derating" is what ensures that the heat pump has the extra capacity needed to recover from defrost. (See "Derate" sidebar, p.6.)

At the end of Defrost Recovery, the hot-water loop temperature is fully recovered back to setpoint, so the heating capacity of the AWHP modulates to match the building heating load. Eventually, frost accumulates on the outdoor heat exchanger again, and the process repeats. The time between defrost cycles is referred to as the Defrost Interval.

An important design consideration for a system that includes AWHPs is the hot-water loop volume (or loop time). Ensure that this loop time (volume of fluid in the loop divided by the fluid flow rate) is longer than the Defrost Time to avoid the fluid passing through the heat pump a second time while in defrost mode.

Figure 8. Example defrost cycle time



The impact of cooling the hot-water loop during defrost mode can be reduced with the following methods:

- Install a buffer tank at the outlet of the AWHP that mixes the cooler water produced during defrost mode with hot water in the tank.
- Enable another AWHP to counteract the cooling effect of the AWHP operating in defrost mode.
- For an AWHP with multiple refrigerant circuits, the unit controller could operate one circuit in heating mode while the other operates in defrost mode.
- Enable a backup (or supplemental) heat source to counteract the cooling effect of the AWHP operating in defrost mode.

When frequent defrost operation is required, the interval between defrost cycles (Defrost Interval) must be longer than the Defrost Recovery time. If the Defrost Interval is too short, the heat pump may not recover quickly enough to keep the hot-water loop temperature at setpoint. A “defrost delay time” feature allows the system controller to bring on another source of heat before the heat pump enters defrost mode, and can also prevent multiple units entering defrost mode at the same time (Figure 8).

If using defrost delay and additional AWHPs are available, the system controller could enable another heat pump to counteract the cooling effect of an AWHP operating in defrost mode, depicted by the horizontal (not a negative slope) blue line in Figure 9. And in this case, when defrost is complete the additional heat pump capacity allows the hot-water loop to recover more quickly (shorter Defrost Recovery).

It may seem logical that using a slower defrost cycle (that avoids cooling the hot-water loop) will shorten the recovery time. However, while in defrost mode the hot-water coils in the system continue to absorb heat from the hot-water loop. Figure 10 compares a fast defrost cycle (that cools the hot-water loop) to a slow defrost cycle (that *does not* cool the hot-water loop). The faster defrost actually recovers more quickly, even though the hot-water loop was temporarily cooled.

Figure 9. Defrost enabling additional heat pump

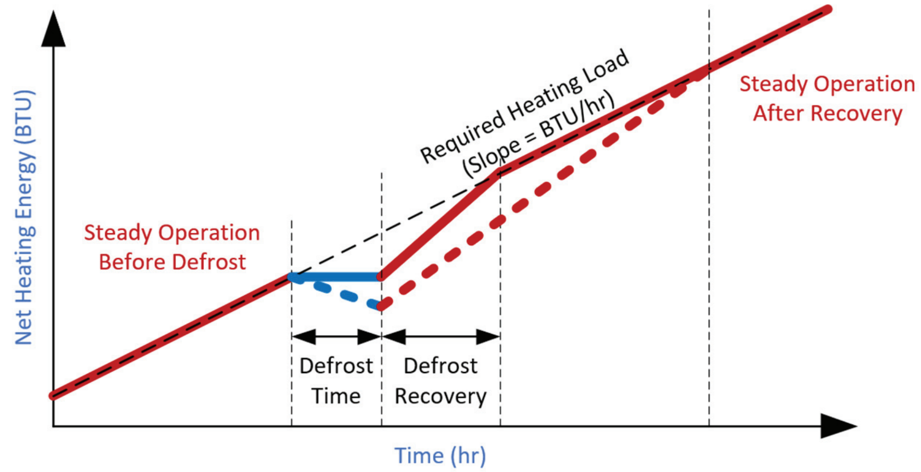
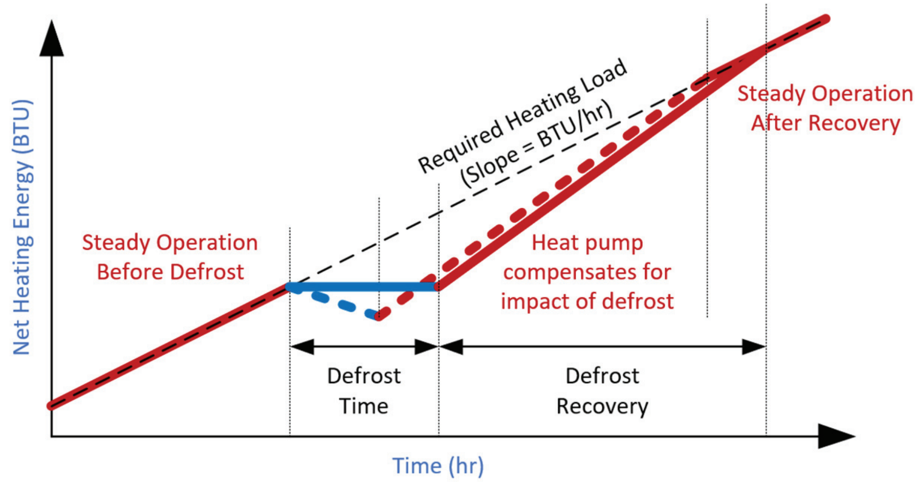


Figure 10. Comparison of fast versus slow defrost cycles



Derate: Defrost Implications to Sizing

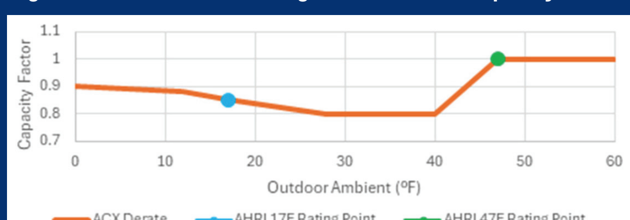
Defrost operation results in a weighted performance derate to the equipment heating capacity. Some designer judgment is required since the frequency of defrost operation depends on actual operating conditions. Figure 11 offers a suggested range for the heating derate capacity factor, based on design outdoor air temperature. This derate capacity factor should be applied to the unit’s required design heating capacity. This helps ensure heat pump selections include the proper impact of defrost.

Accounting for defrost doesn’t always mean upsizing the equipment. If the AWHP is sized for heating design day temperature, every hour below that temperature means the unit will have surplus capacity. If a design day condition only occurs for a few hours on that day, then defrost derate may not be as important if that temperature were to last for a week. Consider accounting for defrost, it may mean upsizing the unit, but in many cases it may not.

If the AWHP is used for heating and cooling, and the unit was sized for cooling, there may already be capacity available for defrost consideration.

The number of units on site is a factor in defrost derate impact. In a system with a single, dual circuited AWHP, when one circuit goes into defrost the unit loses 50 percent of the heating capability. However, in a system with two units, when one circuit goes into defrost, the heat pump system is only down 25 percent.

Figure 11. AWHP unit heating defrost derate capacity factors at outdoor temperatures



$$Scheduled\ Heating\ Capacity = \frac{Building\ Heating\ Block\ Load}{Defrost\ Derate\ Factor}$$

If the design ambient temperature is below the AWHP limit, designers might consider the following:

- Including auxiliary heat in the in the distribution to boost the heat pump fluid temperature during cold ambient conditions or to mitigate the impact of defrost cycles.
- Storage-source heat pump system (download APP-APG022-EN)
- Geothermal system (download SYS-APM009-EN)

Conclusion

The use of air-to-water heat pumps (AWHPs) in cold climates presents unique design challenges that must be carefully considered to enable optimal system performance and effi ciency.

Understanding the key operational limits, such as the Low Ambient Limit, the Maximum Lift Limit, and defrost requirements, is crucial for the successful application of AWHPs in these climates.

Selection of equipment using lower hot-water supply temperatures, the implementation of eff ective defrost strategies, and considering the system impact during defrost cycles are all vital when designing and operating an AWHP system.

By addressing these factors, AWHPs can eff ectively contribute to the decarbonization of the built environment, even in regions with harsh winter conditions. As technology continues to evolve, advancements in compressor design, defrost detection, and control strategies will further enhance the reliability and effi ciency of AWHPs, making them a viable and sustainable heating solution for cold climates.

By Dan Gentry, Applications Engineer, Trane. To subscribe or view previous issues of the Engineers Newsletter visit trane.com/EN. Send comments to ENL@trane.com.

Resources

Purdue University, Martin, C. and P. Oppenheim, J. Bush, H. Stillman "Alternative Defrost Strategies for Residential Heat Pumps." International Refrigeration and Air Conditioning Conference (2019)

Purdue University, Nawaz K., B. Fricke "A Critical Literature Review of Defrost Technologies for Heat." International Refrigeration and Air Conditioning Conference (2021)

Purdue University, Mashhadian, A., T. Ismail, C. Bach "A Review Of The Effects And Mitigation Of Frost With Focus On Air-Source Heat Pump Applications" International Refrigeration and Air Conditioning Conference (2022)

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ADM-APN095-EN
June 2025