Preventing Refrigerant Leaks in Heat Pump Systems

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Heat pumps are viewed as the primary path to the electrification required to reduce and eliminate fossil fuels and associated carbon emissions in building energy systems. However, most heat pumps used in the U.S. today contain R-410A, which is itself a relatively potent greenhouse gas. Preventing refrigerant leaks is therefore a priority. This article examines the issue and suggests best practices to prevent refrigerant leaks.

Replacing fossil-fuel burning furnaces and boilers with electric heat pumps is an important tool for reducing carbon emissions. Inverter-driven, variable-speed, air-source heat pumps (ASHPs), in particular, are an efficient, affordable and scalable technology (*Figure 1*). Cold-climate models, which can operate at temperatures below 0°F (–17.8°C), have been used successfully throughout the Northern U.S. and Canada.

Most ASHPs are direct-exchange split systems. "Split" refers to separate indoor and outdoor units, which are connected by site-installed refrigerant piping. "Direct exchange" means that heat is carried between indoor and outdoor units by refrigerant rather than a secondary fluid, such as antifreeze. In winter, refrigerant absorbs heat from cold outdoor air and releases it indoors; in summer, the cycle is reversed. Modern heat pumps can deliver roughly three units of heat energy for each unit of electrical energy consumed, on average, over a heating season, depending on location. As a result, installing heat pumps reduces CO_2 emissions, even in fossil-fuel-dominated electric grids. As grids incorporate more renewable energy, CO_2 emissions from heat pumps will continue to drop.[1]

However, R-410A, used in most residential heat pumps in North America, has a 100-year global warming impact 2,088 times that of CO_2, e.g., a global warming potential or GWP of 2,088.[2] If refrigerants remain within a heat pump system, no harm is done. It is only when they escape to the atmosphere, through leaks or during decommissioning, that damage occurs.

Unfortunately, refrigerant leaks are common. A 2014 British study* found that 10% of residential heat pumps leaked, and that 3.8% of total refrigerant charge was lost to the atmosphere annually.[3] The study reported that

*The authors concluded that net climate impacts of heat pumps are highly beneficial, even when refrigerant leaks are taken into account.

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92% of losses could be attributed to catastrophic leaks, in which systems lost 50% or more of their initial charge.

The climate impacts of these losses are significant. Atmospheric concentrations of refrigerants, including both HFCs and older, ozone-depleting compounds phased out under the 1987 Montreal Protocol, are continuing to increase. The impacts are so large that the nonprofit Project Drawdown ranks refrigerant management among the most impactful solutions for climate change.[4]

HFCs will eventually be replaced by compounds with lower GWP; some promising alternatives, including CO_2, R-32 and R-466a, are currently in limited use. In addition, air-to-water and ground-source systems may gain market share versus direct-exchange ASHPs. In these systems, water or an antifreeze solution is used to transfer heat in and out of the building, and the entire refrigerant circuit is contained within a single, factory-made unit. Compared to a direct-exchange heat pump, these systems contain less total refrigerant, and all refrigerant connections are made under factory conditions.

While new refrigerants and technologies may reduce future climate impacts, direct-exchange, HFC-based heat pumps dominate the present market, and reducing losses from these systems is a critical short-term goal. Beyond climate change, there are other reasons to be concerned about refrigerant leaks. Systems that are low on refrigerant will run less efficiently and may be unable to maintain comfort. Low charge may lead to premature failure of system components, particularly compressors.

Left unaddressed, these problems will reduce customer satisfaction and impede adoption of heat pumps. Anecdotally, we know one progressive developer who found that 30% of the heat pumps in his new multifamily building leaked refrigerant. The issue was so bad, he reported, that he was considering electric baseboard heat instead of heat pumps for future projects.

Our objectives in this article are to provide technicians, engineers and energy-efficiency programs with best practices for reducing refrigerant leaks from ASHPs. We draw on our experience as an installer and an HVAC engineer, along with manufacturer's instructions and applicable standards and regulations. We note areas in which existing guidelines are vague, inconsistent or impractical, and recommend standardizing both testing methods and "pass/fail" criteria.

Installation

Refrigerant connections for small inverter-driven ASHPs are typically made using flare joints. The flaring process begins with cutting tubing, leaving a few inches of slack in case a flare is defective and must be remade. Use a good quality cutter, work gradually to avoid deforming the tubing and inspect to make sure that the cut is square. Debur to remove the thin lip of copper inside the tubing, but be careful not to gouge or otherwise damage the tubing wall.

Some line sets come shipped from the factory pre-flared, but these flares are often damaged in transport; we recommend making new ones.

Flaring itself involves site-forging the end of the copper tubing into a female cone, which fits over a brass male cone to form a mechanical seal. To seal tightly, the flare must be of the correct dimensions. The flare angle, specified in the installation instructions, is 45°; the size of the cone varies with tubing diameter. The flaring tool grips the tubing and rotates a steel cone around the inside surface until it is fully expanded.

FIGURE 1 Air-source heat pumps.

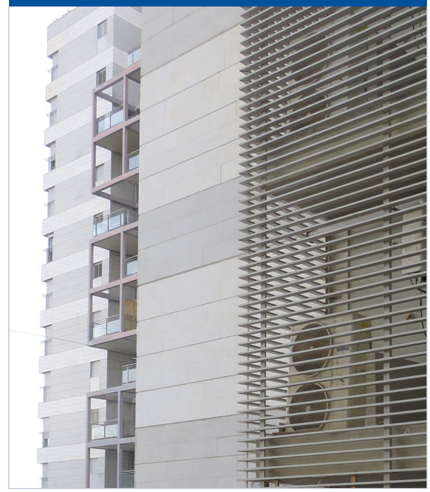


FIGURE 2 Tightening a flare nut with a torque wrench.

Good-quality manual flaring tools have the following features:

- A gauge or stop that ensures that tubing is positioned at the correct depth;

- An "eccentric" cone that rolls around the interior of the tubing, forming it into shape; and
- A clutch that disengages the cone when the flare is complete.

Battery-powered flaring tools share these features, but spin the cone much faster, annealing the copper and making it less brittle.

Prior to assembly, check that the flare is symmetrical and that contact surfaces are clean, shiny, and free of scratches. Apply a thin coat of refrigeration oil or an approved assembly lubricant to the contact surface to improve the seal, as well as to the back of the flare nut to keep it from binding. Align the cones and hand-tighten the flare nut.

Once the flare is assembled, tighten it to spec using a torque wrench (*Figure 2*). If the assembly is too loose, the surfaces will not form a good seal; if it is too tight, the flare will crack or split. Torque specs are found in manufacturers' instructions and range from around 13 ft·lb_f (17.6 N·m) for ¼ in. (6.4 mm) tubing to around 56 ft·lb_f (75.9 N·m) for 5/8 in. (15.9 mm) tubing. Torque wrenches, available in digital and analog models, prevent the installer from over-torquing smaller flares and under-torquing larger ones.

Always use flare nuts supplied with the equipment. Manufacturers' torque specs are for OEM flare nuts, which tend to be longer (with more threads) and of better quality than aftermarket ones. If subsequent testing reveals a leak at any flare connection, do not attempt to tighten it further; cut off the defective flare and start again.

While inverter-driven ASHPs usually use flare connections, other approaches are gaining traction. Brazing, used widely in other areas of HVAC&R, involves soldering joints with a phosphorus/silver/copper alloy. Done correctly, brazing provides a reliable, leak-free joint. Disadvantages include the work of toting extra equipment (brazing tanks and torches), the need to flow nitrogen through the tubing while brazing to prevent formation of copper oxide scale, and safety concerns around open flames. Because of its durability, brazing is a good choice for difficult-to-access connections—for example, those enclosed in walls or high off the ground. Crimped and push-fit refrigerant fittings are also becoming widely available. We are exploring these technologies to determine whether they meet our criteria for reliability and cost-effectiveness.

Other decisions made during design and installation can prevent refrigerant loss. Use continuous line sets wherever possible to reduce potential leakage sites. Allow for pipe expansion, and properly support and protect line sets both inside and outside the structure. Avoid enclosing line sets in wall cavities, where they cannot be inspected and where they may be inadvertently punctured.

Also, take steps to protect refrigerant lines and coils from corrosive chemicals. Salt-spray damage (in coastal settings and from road salt) can be mitigated by physical barriers, periodic rinsing of the outdoor equipment with fresh water, and protective coatings. Corrosion from dog urine can be avoided by fencing or elevating the outdoor unit.

Refrigerant loss can also occur in cold climates when built-up ice crushes outdoor coils. This can be avoided by providing good drainage below the unit and ensuring that a base-pan heater is installed. In snowy areas, moisture load on outdoor units can be reduced by avoiding driplines or installing snow-shields or awnings.

Another source of refrigerant loss is intentional inhalation ("huffing") of refrigerants, mainly by teenagers. Some jurisdictions have adopted provisions in the International Mechanical Code and International Residential Code that require locking caps on charging ports.

Testing

Installed refrigerant piping must be tested for leaks prior to charging the system. The standing pressure test involves filling the system with nitrogen. Once the system is pressurized, isolated and allowed to stabilize, it must hold steady for a specified period. Pressurization should be done gradually so that catastrophic leaks are caught with minimal waste. The target pressure, specified by the manufacturer, is typically 500 psig to 550 psig (3447 kPa to 3792 kPa).

The standing pressure test alone will reveal large leaks, but its sensitivity is limited by gauge precision and the duration of the test. Analog pressure gauges can be read to about the nearest psi; digital gauges typically have a resolution of 0.1 psi (689 Pa). Under perfectly stable outdoor air temperature conditions, any measurable drop in pressure over the test period would represent a leak that would lead to significant refrigerant loss over the 15- to 20-year life of the system.

Changes in outdoor air temperatures can significantly alter nitrogen pressures; for a system initially pressurized to 500 psig (3447 kPa), pressure will increase or decrease by about 1 psi (6.9 kPa) for each 1°F (0.6°C) of outdoor air temperature change. In fluctuating temperature conditions, this relationship can be used to calculate a temperature correction. Before and after temperatures should be measured in a shady location.

If the outdoor air temperature increases, an increase in pressure could still indicate a leak. For example, if outdoor air temperature increases by 6°F (3.3°C), we would expect an increase in pressure of 6 psi (41 kPa). A smaller increase, for example 3 psi (21 kPa), indicates a likely leak. If any deviation from expected pressures is found, a leak should be suspected, investigated and repaired.

Some manufacturers recommend that the standing pressure test last a minimum of 24 hours. It is our position that daily temperature fluctuations undermine the value of 24-hour tests. In addition, a 24-hour test may add an extra visit to what might otherwise be a one-day installation.

For both of these reasons, we have moved toward a shorter standing pressure test, about one hour in duration, combined with rigorous bubble testing. We apply an approved leak-testing solution (not household dish detergent) to all flares and other site-made connections (*Figure 3*). After about 10 minutes, we check each fitting for bubble formation, using a flashlight and inspection mirror when necessary.

Once the system has been successfully pressure-tested, it must be evacuated. The purpose of evacuation is to remove air and moisture from the system, but a high-resolution digital micron gauge also allows evacuation to be used as a secondary leak check. Once the system is pulled down to a deep vacuum below 200 microns, it is isolated from the vacuum pump, and changes in vacuum readings are observed. If the system remains below the decay target for the specified period, the system passes (our decay target is 500 microns or less after 10 minutes of isolation).

If the system fails, it may be because air is entering through a leak or because excess moisture remains in the system. In a leaking system, the vacuum will continue to decay in a near-linear fashion, while, in a wet system, the micron reading will rise quickly, then level off (*Figure 4*).

Bluetooth-enabled micron gauges, paired with mobile apps, can extrapolate the rate of vacuum decay, often determining in less than a minute whether a system will pass. These apps can also provide a time-stamped record of the test result.

While standing pressure and bubble tests check for leaks under a large, positive pressure differential (~500 psi [~3447 kPa]), vacuum decay tests check for leaks under a much smaller Δ*P*; the difference between atmospheric pressure and deep vacuum is only about 14.7 psi (101.4 kPa). In an eye-opening video on his YouTube channel, Zack Psioda shows an evaporator coil with a known pinhole leak passing both a typical standing pressure test (done with a precise digital gauge) and a vacuum decay test similar to that described above.[5] While some small leaks will escape detection, the combination of standing pressure test, bubble test, and vacuum decay test, together with a final check after charging (see below), will catch all large leaks and many smaller ones.

FIGURE 3 Applying a leak-testing solution to newly made flares.

Once the system has been charged with refrigerant, use a bubble solution or electronic leak detector to make a final leak check on the service valves and charging ports; these cannot be checked earlier in the installation process.

Service and Decommissioning

Standard practice in traditional HVAC is to hook up refrigerant pressure gauges (either individual short-stem gauges or a manifold gauge set with hoses). For systems with fixed-speed compressors, gauges provide critical information on operation of the system. Paired with measurements of air and refrigerant temperatures, pressure readings allow technicians to adjust charge, adding or removing refrigerant as needed. In cooling mode, systems are charged to achieve the recommended level of superheat (°F [°C] that the vapor line is above low-side saturation temperature) or subcool

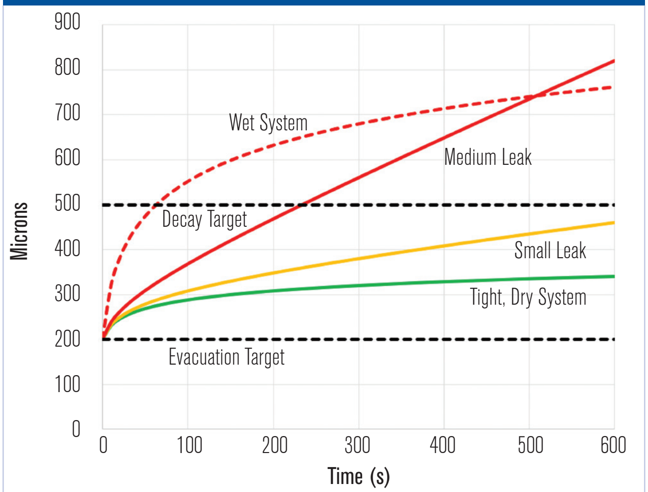
(°F [°C] that the liquid line is below high-side saturation temperature).

On modern inverter-driven heat pumps, like other critical-charge systems, refrigerant adjustments cannot be made based on field measurements of temperature and pressure. Because the compressor, controlled by microprocessors with feedback from sensors throughout the system, operates across a range of frequencies, there is no fixed relationship between charge and superheat/subcool. Systems come charged from the factory for line sets up to a certain length; for each foot beyond that length, a calculated quantity of refrigerant must be added at start-up. Once a system has been put in operation, the only way to confirm that it has the correct charge is to remove and weigh the refrigerant.†

Each time gauges are attached to a heat pump, a small but unknown amount of refrigerant is lost. Refrigerant escapes whenever a gauge or hose is connected to a valve, and additional refrigerant is stranded in the hoses and manifold after they are disconnected. Although the amounts are small (and are considered allowable *de minimis* releases under EPA regulations), they eventually add up, so that, after a series of careful but unnecessary gauge attachments, ounces of refrigerant could be lost. Because connecting gauges to inverter-driven heat pumps provides little useful information and eventually hurts performance, we recommend avoiding hooking gauges to these systems.

Noninvasive tests are a better choice for inverter-based systems. The most basic noninvasive test involves running the system at maximum output and measuring ΔT across the heat exchanger at steady state. A more thorough test involves measuring delivered capacity, which requires measuring ΔT (heating), ΔH (cooling) and airflow. A complete procedure for performing this test on ductless systems is described elsewhere.[6] If these tests reveal a ΔT or delivered capacity outside the manufacturer's recommended range, a leak check must be performed, and refrigerant must be recovered and weighed. Leaks can be found before recovery using an electronic leak detector or after recovery using nitrogen and bubble solution. Once the leaks are fixed and the system tested, the correct charge can be weighed back into the system.

FIGURE 4 Potential results of a vacuum decay test. In a system with a medium or large leak (solid red line), the vacuum will decay rapidly in near-linear fashion. In a system that is free of leaks but in which significant moisture remains (dashed red line), the vacuum will decay rapidly at first but will stabilize above the decay target. A tight, dry system (green line) will stabilize below the decay target and remain there for the duration of the test. Some systems with very small leaks (yellow line) may also pass the vacuum decay test.



Electronic leak detectors, useful for finding known leaks, can also become part of a standard preventive maintenance. Good-quality leak detectors are available, many for under $500. An electronic detector can be used to make a quick pass over accessible line sets, fittings, and heat exchangers, allowing the technician to find and fix small leaks before they lead to complete loss of charge.

Strengthening Leak Prevention Standards

Proper recovery, recycling or disposal of refrigerants during repairs and replacement are also key to reducing climate impacts. Section 608 of the Federal Clean Air Act, written originally to prevent release of ozone-depleting compounds, also regulates non-ozone depleting HFCs. The act prohibits venting (deliberate release of all but *de minimis* amounts of refrigerant) and provides standards for recovery/reclamation equipment. It also requires technicians working with refrigerants to pass a certification test and keep records of refrigerant disposal. While the act spells out large fines for violations,

†Some manufacturers incorporate built-in pressure sensors along with diagnostic tools that allow the technician to read these data without attaching gauges. Multiple thermistors also provide detailed data on the state of refrigerants throughout the system. We suspect that these data, paired with information on compressor speed and graduated opening of electronic expansion valves, will ultimately allow technicians to make charge adjustments without weighing out all the refrigerant in the system. However, to our knowledge, no manufacturers currently offer this functionality.

enforcement in the residential sector is generally weak.[‡]

There is also a lack of consistency concerning refrigerant leakage standards and testing protocols. The Northeast Energy Efficiency Partnerships (NEEP) publishes a generally excellent "Guide to Installing Air-Source Heat Pumps in Cold Climates," referenced as a best-practice document by several state and utility programs.[7] The NEEP guide specifies a standing pressure test but does not give details on duration or bubble testing. It also specifies an evacuation target below 500 microns, but does not require a vacuum decay test.

The Building Performance Institute's (BPI) "Technical Standards for the Air Conditioning & Heat Pump Professional," also used by some state programs, does not discuss the standing pressure test.[8] BPI sets the default evacuation target at 500 microns and the acceptable rise at 300 microns within five minutes.

The Air Conditioning Contractors of America (ACCA) Standard 5, *HVAC Quality Installation Specification,* requires "leak-free circuit: achieved by purging with nitrogen during brazing, conducting a nitrogen pressure test, evacuating (triple) and holding to 500 microns or less."[9] The ACCA standard, which is also an ANSI standard, does not provide a detailed protocol for the pressure test or vacuum decay test. Groups like NEEP, ACCA, ANSI, and BPI can help reduce refrigerant leaks by clarifying, aligning and strengthening their standards.

State and utility programs providing incentives and rebates for heat pumps can also adopt policies to reduce refrigerant leakage:

- Make leak prevention a priority in program manuals and contractor trainings;
- Require time/location-stamped photographs of best practices (torque wrenches, bubble testing, and electronic leak detection) on each jobsite;
- Require time/location-stamped reports of vacuum decay tests generated by mobile apps;
- Develop a quality assurance program that tracks leak occurrence by contractor and provides corrective training as needed; and
- Work with supply houses and/or refrigerant management companies to provide incentives and operational support for recycling or disposal of used refrigerants.

Contracting companies can also take leadership in reducing refrigerant leaks. In doing so, they will benefit the environment, their customers, and their own bottom line. Efforts begin with training staff in both the "why" and the best practices of leak prevention. Managers should work with technicians to build testing into their workflow—for example, assigning a helper to perform bubble testing and begin evacuation while the lead installer completes electrical wiring.

Technicians should be equipped with good-quality tools, including wireless micron gauges and electronic leak detectors. Checklists, digital photographs and app-generated reports can be used to document that jobs are done right. Although a good leak-prevention program requires investment in equipment and training, and sometimes a little extra time on-site, it will pay for itself in better performance and fewer callbacks.

[‡]The act also contains regulations on allowable leak rates, but these apply only to larger systems containing more than 50 lb (23 kg) of ozone-depleting refrigerants.

Conclusion

Refrigerant leaks have a major impact on the environment, specifically on global warming. Best practices in installation and service can measurably reduce leaks. Such best practices require harmonization between standards-setting organizations, manufacturers' requirements, engineering specifications and contractor training. Harmonized best practices will reduce leaks and could even expedite installation by eliminating conflicting requirements between standards, manufacturer requirements and typical design specifications.

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