# Without Strip Heat: In-Situ Monitoring of a Multi-Stage Air Source Heat Pump in the Pacific Northwest

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## ABSTRACT

The electric resistance elements installed with residential electric air-source heat pumps and the lack of efficient control poses a problem for the air-source heat pump's value as an energy saver in Northern U.S. climates. This paper presents monitoring results of a heat pump with staged capacity capable of providing the seasonal heating needs of houses located in heating dominated climates without use of electric resistance elements

A multi-capacity air source heat pump, installed as the central forced-air heating system at five residences in the Pacific Northwest, was monitored during the heating season. Results include energy use and "real world" efficiency by season and by outdoor temperature. The results of this study show the multi-capacity air-source heat pump is capable of meeting the heating needs of homes without the use of resistance elements even in cold climates. The value of a heat pump installed without electric resistance heat is presented for various Northwest climates. Occupant comfort issues are also discussed.

## Background

Equipping a residential split-system air-conditioner with a reversing valve is a simple way to provide efficient electric heating in moderate winter conditions. Air-source heat pumps are commonly designed and sized for air-conditioning mode with heating as a secondary consideration. This method of design works well for the majority of the U.S. market, which has warm summers and moderate winters. However, for colder areas of the country, the necessary installation of electric resistance supplemental heat and common lack of efficient controls negatively affects the value of the heat pump as an energy saver.

Installation of efficient air source heat pumps is a very popular conservation measure for electric utilities in the Pacific Northwest. A major uncertainty in determining energy savings for air source heat pumps is the frequency of supplemental heat use, or more specifically, resistance heat use during the heating season. Whenever resistance elements are operated, the coefficient of performance of the heating system is reduced. The following are some of the reasons supplemental heat activates during a heating cycle of a heat pump:

- The heat pump cannot meet the load of the house. Air-source heat pumps are typically sized such that, at about a 30°F outdoor temperature, the rated heat output of the heat pump equals the heat loss of the house. At any outdoor temperature below this "balance point" temperature, there is a need for supplemental heat to maintain indoor temperature. There are a number of strategies used to control the supplemental heat below the balance point. Often, the mix of resistance element supplied heat, the most common form of supplemental heat, and heat pump-supplied heat is not ideal; the heat pump is run less, in favor of resistance element runtime.

- The occupant increases the indoor temperature setting. Depending on the heat pump controls, an increase in the heating setpoint can cause resistance heat to initiate.
- The defrost cycles. Resistance heating elements are commonly energized during defrost cycles to reduce the chances of cold air blowing out of the supply registers.
- Heat pumps are sometimes controlled in such a manner that the resistance elements are energized any time the compressor is on.
- Recovery from a deep setback using a programmable thermostat.

In an effort to increase efficiency and energy savings, electric utility efficiency programs mandate installation specifications intended to decrease the amount of resistance heat use. This involves specifying outdoor thermostats, intelligent recovery thermostats, proper system sizing, defrost controls, installed supplemental heater capacity limits, and supplemental heater staging. The specifications do not differ from what HVAC schools would consider “acceptable installation practice,” but they do differ from the “common installation practice” in the Pacific Northwest. Utility conservation programs have met moderate resistance in their efforts to change installers’ common installation practices.

Manufacturers are gradually bringing the concept of heat pumps designed for the heating season to market with one or more available technologies. These systems are designed and installed with enough heating capacity to meet the load of the house at all outdoor temperatures without employing auxiliary heat. If they operate as advertised, these new systems could provide a fix to utilities’ costly struggle to ensure resistance heat elements are controlled efficiently.

Installation of a heating optimized heat pump with little or no resistance elements would give better assurance that the system operates efficiently over the entire heating season than a system installed with the standard resistance elements. In addition, in areas of the country where electric heating makes up a significant portion of the load, lack of resistance heat could help alleviate constraints on generation or transmission and distribution capacity on cold winter days.

However, it is not a generally popular idea to install an air-source heat pump without electric resistance elements. The primary concern is a compressor failure, which would leave the house with no “emergency” heat source. Another concern is providing a comfortable supply air temperature. In order for the concept of elimination of installation of supplemental and emergency heat to be accepted by the general public, there must be proof the house’s heating needs and homeowner’s comfort needs can be reliably met by the heat pump.

## Cold Climate Heat Pump Operation

The heat pump system monitored in this study is called the Cold Climate Heat Pump (CCHP) manufactured by Nyle Special Products. During heating, the CCHP has four distinct modes of operation, depending on outdoor air temperature, as shown in Table 1.

The primary compressor is a twin cylinder reciprocating piston compressor. It has the capability to operate one or two pistons at a time, providing two distinct capacities. When operated in dual piston mode, the primary compressor’s capacity and efficiency curves are similar to those of a single stage compressor found in a standard air-source heat pump. In heating mode, single cylinder operation is never employed.

**Table 1. CCHP Modes of Operation**

| Mode | D | C | B | A |
|---|---|---|---|---|
| **Outdoor Temperature** | **Below 10°F** | **10°F to 20°F** | **20°F to 34°F** | **Above 34°F** |
| **Stage 1 Heating** | Primary & Booster Compressors, Economizer. | Primary & Booster Compressors. | Primary Compressor. | Primary Compressor. |
| **Stage 2 Heating** | Add Supplemental Heat. | Add Economizer. | Add Booster Compressor. | Add Supplemental Heat. |

The booster compressor is a high displacement reciprocating piston compressor. It operates in series with the primary compressor. The booster compressor's primary function is to efficiently increase the intake pressure of the primary compressor, thereby increasing capacity at low outdoor temperatures.

The economizer is a plate type heat exchanger used to recover otherwise wasted heat from the liquid line.

Table 2 compares the CCHP manufacturer's claimed coefficient of performance at various outdoor air temperatures (in stage 1 heating) with the coefficient of performance (COP) of a standard air-source heat pump. The table represents COP of the heat pump cycle only; it does not assume supplemental heating. Standard air source heat pumps are usually not operated at very low ambient temperatures, so manufacturers do not typically publish the efficiencies. This is primarily due to the significant reduction in heating capacity during low temperature conditions.

**Table 2. Manufacturer Claimed COP**

| Outdoor Air Temp. | -20ºF | -10ºF | 0ºF | 10ºF | 20ºF | 30ºF | 40ºF | 50ºF |
|---|---|---|---|---|---|---|---|---|
| **CCHP** | 1.9 | 2.0 | 2.2 | 2.2 | 2.5 | 2.8 | 3.1 | 3.3 |
| **Std. ASHP** | na | na | 2.0 | 2.3 | 2.5 | 2.8 | 3.1 | 3.6 |

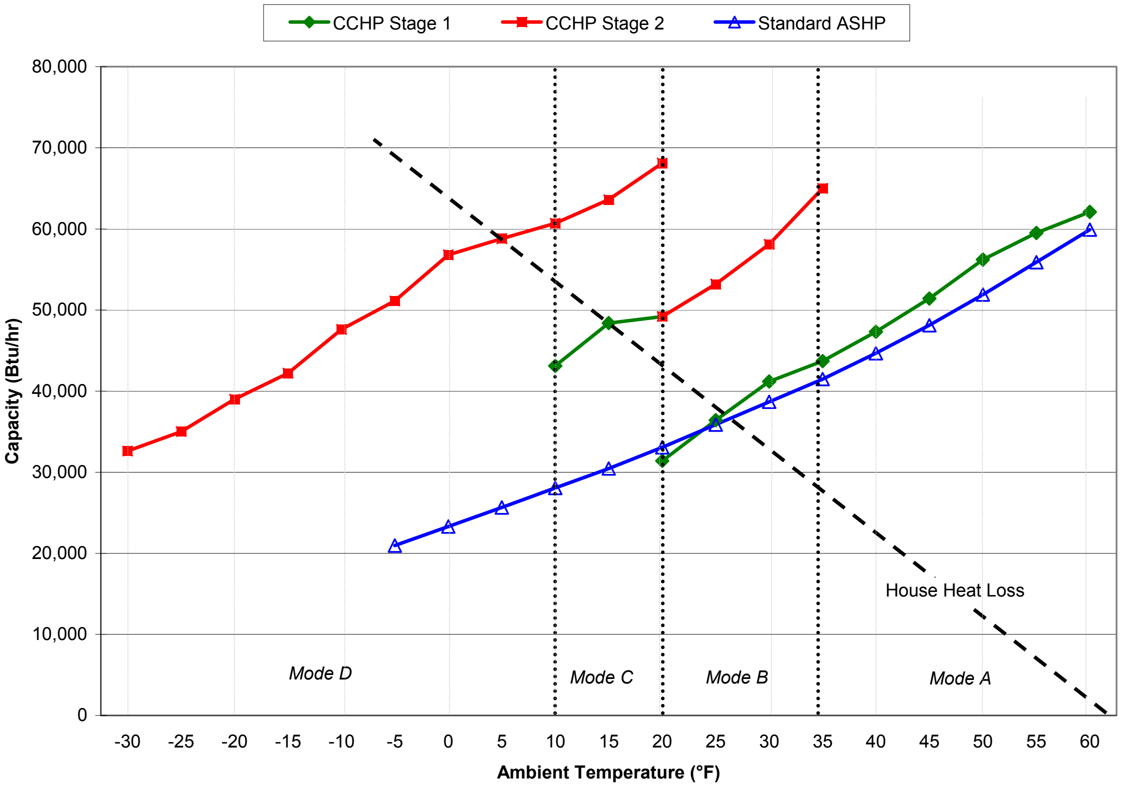
Figure 1 compares the capacity of the CCHP to that of a standard air-source heat pump with the same nominal capacity. Notice how the standard air-source heat pump's capacity falls as outdoor temperature drops. The CCHP, on the other hand, has diminishing capacity within its distinct modes of operation, but capacity is increased as temperature falls across a new mode of operation.

The example "House Heat Loss" line crosses the standard air-source heat pump's capacity line at a temperature of about 27°F. This would be the heating balance point if the standard ASHP were installed in the example house. At outdoor temperatures above 27°F, the heat pump would theoretically be able to supply enough heat to the house to meet the house's heating requirements. At temperatures lower than 27°F, the heat pump does not have enough capacity to meet the heating requirements of the house, so some form of supplemental heat would be required. This supplemental heat source is commonly an electric resistance furnace, which is an integral part of the heat pump's indoor air handler.

In this example, the balance point temperature for the CCHP is about 5°F. Although the house heat loss line crosses the CCHP capacity lines at temperatures above 5°F, they cross the stage 1 capacity line. At these temperatures, the CCHP is able to employ stage 2 to meet the heating requirements of the house. It is only at this balance point of 5°F in which the CCHP no longer has enough heating capacity to meet the needs of the house. Similar to the ASHP, the

CCHP system requires supplemental heat from another source in order to meet the heating requirements of the house below the balance point. As with standard air-source heat pumps, the CCHP commonly employs an electric resistance furnace as a supplemental heat source. However, in this example, if the home's winter design temperature was 5°F or higher, the CCHP could theoretically meet the needs of the house without supplemental heat.

**Figure 1. Capacity and Balance Point**



Or, if a heating design temperature of 0°F is assumed, theoretically only 6,000 Btu/hr supplemental heat capacity is required for the CCHP. Under the same conditions, the standard air-source heat pump needs 40,000 Btu/hr supplemental heat capacity.

## Monitoring Setup

This study monitored five CCHP units manufactured in 2004 and installed in 2004 and 2005. The in-field monitoring project began in November 2005. Monitoring equipment was in place over the 2004-2005 winter at four residences heated with newly installed CCHPs. Equipment was installed at two additional sites in the fall of 2005.

### House Descriptions

Three CCHP units were available for monitoring for the winter of 2004-2005. These units were installed on houses located in three fairly different climates. The locations include:

Chiloquin, Oregon, located in the moderately cold wintered high desert of South Central Oregon; and Burley and Paul, Idaho, a significantly colder area than Chiloquin. In the fall of 2005, monitoring equipment was added at two more sites for monitoring of the winter of 2005-2006. These new sites are near the towns of Rigby and Ashton in Eastern Idaho. Rigby and Ashton have fairly similar climates; they are much colder than the first four sites. Figure 2 shows the time each 5-degree temperature bin as a percentage of the total time monitored.

**Figure 2. Percentage of Time in Each Temperature Bin**

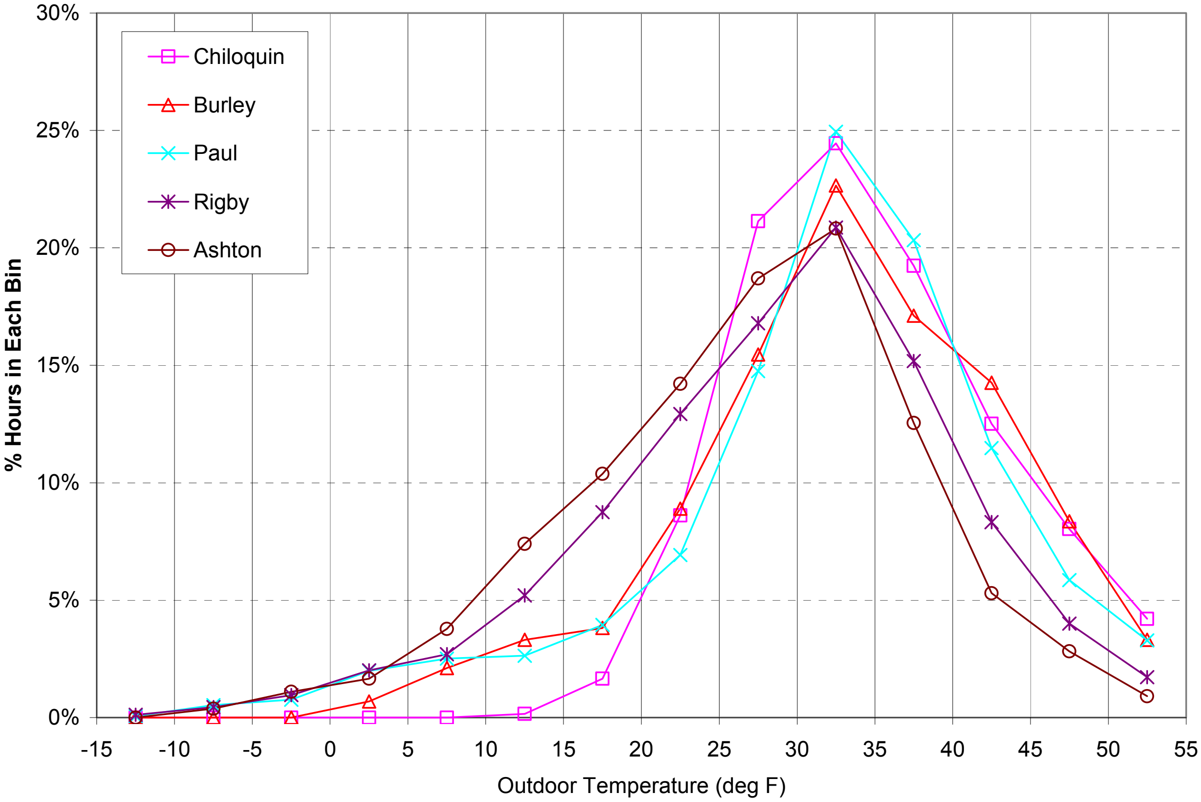


**Table 3. House Characteristics**

| | Chiloquin, OR | Paul, ID | Burley, ID | Rigby, ID | Ashton, ID |
|---|---|---|---|---|---|
| **Monitoring Installation Date** | 11/15/2004 | 2/15/2005 | 2/16/2005 | 12/1/2005 | 11/30/2005 |
| **Avg. Heating Degree Days** | 6300 | 6877 | 6704 | 7995 | 8777 |
| **Winter Design Temperature** | 4 °F | -5 °F | -5 °F | -12 °F | -12 °F |
| **CCHP Nominal Size** | 4 ton | 2.5 ton | 3.5 ton | 3.5 ton | 3.5 ton |
| **Indoor Airflow** | 1652 CFM | 1101 CFM | 1108 CFM | 1425 CFM | 1400 CFM |
| **Strip Heat Toggle Control** | yes | yes | no | yes | no |

Table 3 summarizes the characteristics of each house and associated CCHP. Four homeowners opted for installation of a manual toggle switch to control the resistance elements. When in the "off" position, the toggle switch interrupts any and all calls for resistance elements. This includes resistance heat call during the defrost cycle as well as during a normal heat cycle.

All homeowners agreed to refrain from using fireplaces, woodstoves, or unit heaters. The Chiloquin heat pump was the only unit to receive third-party refrigerant charge verification.

## Monitoring Equipment

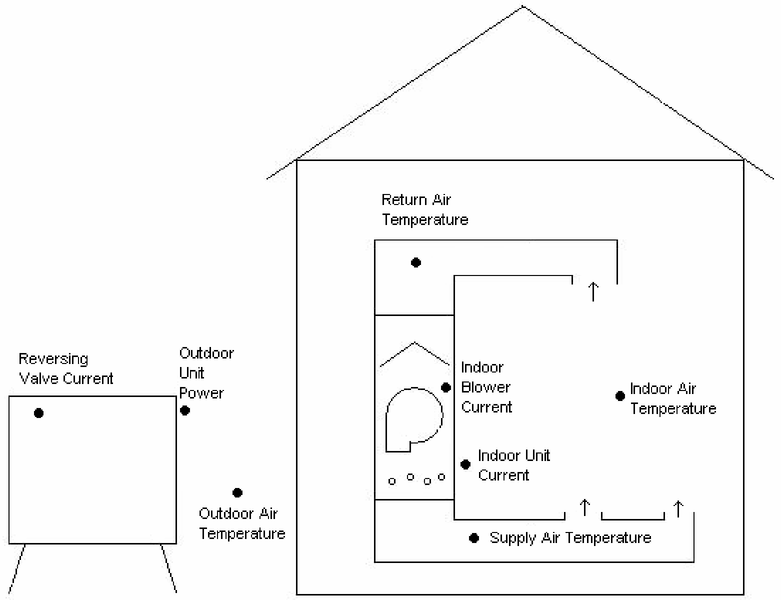
Two Micro Data Loggers and associated sensors, made by Architectural Energy, were installed at each house along with a telephone modem. Temperature and current measurements are a 1-minute average of samples taken every 3 seconds. The power measurement is an accumulation of pulses representing 0.0025 kWh. The total energy use is recorded every minute and converted to average kW for that minute.

Indoor airflow was tested at installation using the TrueFlow® Air Handler Flow Meter made by the Energy Conservatory. The manufacturer claims a ± 7 percent accuracy for the device. The airflow numbers reported in Table 3 are volumetric airflows.

The following sensors were located in each house as described below and shown generically in Figure 3:

- Indoor Air Temperature (°F); located near the indoor thermostat
- Outdoor Air Temperature (°F); located on the north side of the building or shaded from direct sun
- Supply Air Temperature (°F); located in supply air plenum within 6 feet of air handler after first corner
- Return Air Temperature (°F); located in return air plenum within 3 feet of air handler
- Indoor Unit Current (Amps) (includes the blower and electric resistance current); 100-amp split core current transformer
- Indoor Blower Current (Amps); 5-amp split core current transformer
- Outdoor Unit Power (kW); WattNode energy meter with 50-amp split core current transformer
- Reversing Valve Current (Amps); 5-amp split core current transformer

**Figure 3. Sensor Locations**



Each electric and temperature measurement was double checked with a handheld electric power meter and a handheld electronic temperature sensor, respectively. All temperature sensors are thermistors. Extra care was taken in locating the supply air temperature sensor to avoid false readings from radiated heat from the electric resistance elements. Despite efforts, the supply air temperature sensor reading is unreliable when resistance elements operate, largely due to uneven air-stream mixing. This theory was confirmed by short-term coefficient of performance tests at Paul and Chiloquin with the system in "emergency mode," which resulted in lower than expected efficiencies (COP less than 1.0). When operated in heat pump mode only, the supply air temperature reading proved to be very reliable.

## Results & Discussion

### CCHP Reliability

Of the five CCHPs monitored, one experienced a major component failure and one experienced abnormal operation.

**Primary compressor failure.** Six months after installation, in April 2005, the primary compressor at Chiloquin failed. After a few failed attempts, a replacement primary compressor was successfully installed in mid-summer 2005. The reason for the compressor failure remains unknown.

**Lack of booster compressor operation.** The CCHP at Burley never used the booster compressor, even at low ambient temperatures. The booster compressor operation is key to the operation of the CCHP. Without it, the CCHP acts very much like a standard air-source heat pump. However, the control logic incorporated into the CCHP does not allow resistance heat to be energized at ambient temperatures between 10ºF and 34ºF, except for during defrost cycles. It is still unknown how the crippled heating system at Burley managed to maintain setpoint.

### Efficiency

The Coefficient of Performance (COP) is defined as the "energy output" divided by the "total energy use." Energy output includes all energy delivered to the supply duct as a change in temperature of the return air-stream. This includes negative energy output during defrost cycles. Total energy use includes all energy use by the compressor motor, outdoor fan motor, crankcase heater, indoor blower motor, and resistance element energy use.

$$\text{COP} = \frac{(\text{Specific Heat}_{\text{air}})*(\text{Density}_{\text{air}})*(\text{Supply Air Temperature} - \text{Return Air Temperature})*(\text{Airflow})}{(\text{Outdoor Unit Power}) + (\text{Indoor Unit Current})*(\text{Indoor Unit Voltage})*(\text{Power Factor})}$$

Presented results include only "useable data" collected. "Useable data" is defined as data collected in the heating season between November and April, below outdoor temperatures of 55°F, without CCHP equipment or monitoring equipment failures. Table 4 presents the average COP, total heating system energy use, resistance element energy use, and the resistance element energy use as a percent of the total heating system energy use. The "number of monitoring days" is the accumulated time represented by useable data.

**Table 4. Monitoring Period Results**

| | Average COP | Heating System Energy Use (kWh) | Resistance Element Energy Use (kWh) | % Resistance Element Energy Use | Number of Monitoring Days |
|---|---|---|---|---|---|
| **Chiloquin** | 1.7 | 3811 | 0 | 0% | 77 |
| **Burley** | 1.5 | 4632 | 860 | 19% | 163 |
| **Paul** | 1.8 | 4135 | 0 | 0% | 159 |
| **Rigby** | 1.5 | 5527 | 4 | 0% | 124 |
| **Ashton** | 1.3 | 4152 | 541 | 13% | 124 |

Table 5 shows the measured coefficient of performance of the heat pumps in each house by outdoor temperature in 5-degree bins. The manufacturer's reported efficiency is included, designated as "Nyle." In general, the in-situ COP is in the 1.1 to 2.1 range, depending on outdoor temperature.

**Table 5. Measured Coefficient of Performance**

| Outdoor Temperature Bin | -15°F to -10°F | -10°F to -5°F | -5°F to 0°F | 0°F to 5°F | 5°F to 10°F | 10°F to 15°F | 15°F to 20°F | 20°F to 25°F | 25°F to 30°F | 30°F to 35°F | 35°F to 40°F | 40°F to 45°F | 45°F to 50°F | 50°F to 55°F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chiloquin** | - | - | - | - | - | 1.3 | 1.5 | 1.6 | 1.6 | 1.7 | 1.9 | 1.9 | 1.8 | 2.0 |
| **Burley** | - | - | 1.7 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.6 | 1.7 | 1.7 | 1.6 |
| **Paul** | 1.5 | 1.5 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.1 | 1.9 |
| **Rigby** | 1.3 | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 | 1.6 | 1.6 | 1.6 | 1.5 | 1.4 |
| **Ashton** | - | 1.0 | 1.4 | 1.3 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.4 | 1.4 | 2.0 | 1.7 |
| **Average** | **1.4** | **1.2** | **1.5** | **1.3** | **1.3** | **1.4** | **1.4** | **1.5** | **1.6** | **1.6** | **1.7** | **1.7** | **1.8** | **1.7** |

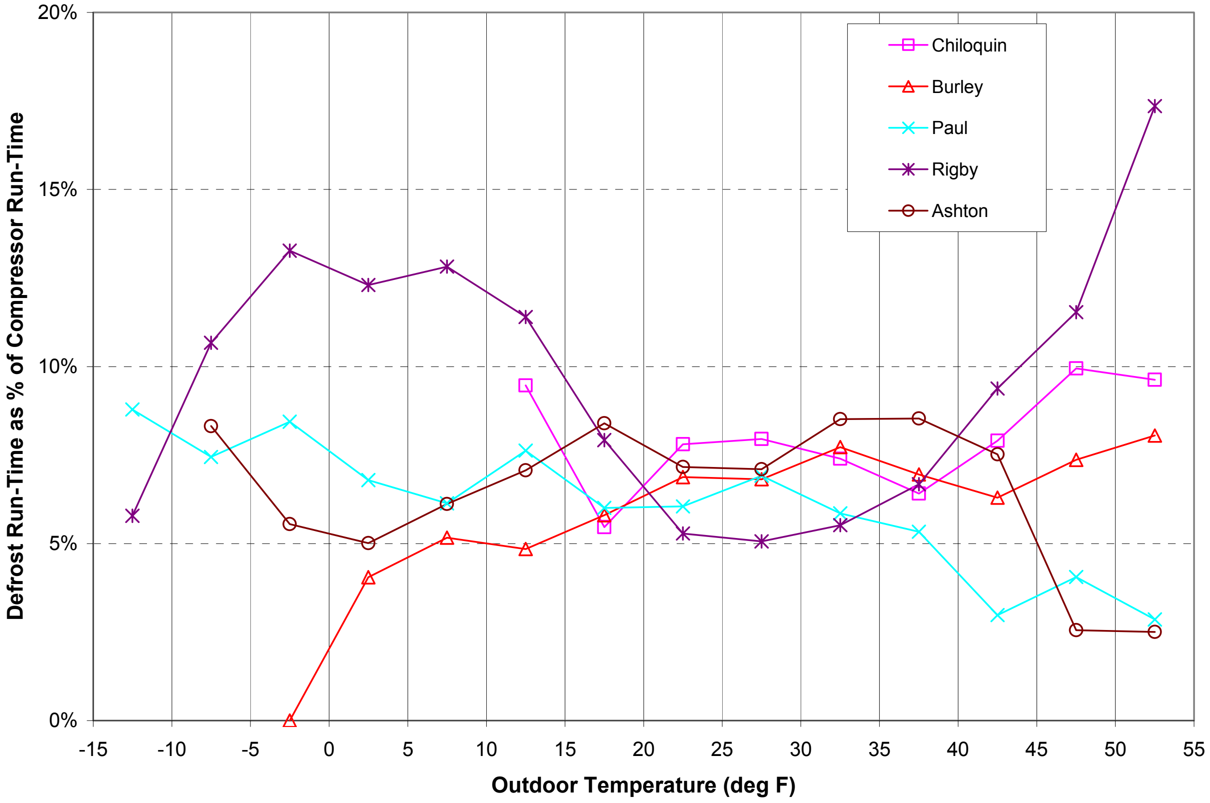
The COP of each unit shown in Table 5 is much lower than the manufacturer's claimed COP in Table 2. The manufacturer tested the unit at an independent testing laboratory under steady state conditions. The in-situ performance of the units in this study is expected to be lower than the lab results because of part-load inefficiencies and defrost operation. However, in similar studies of standard air-source heat pumps, such as Howard Reichmuth's "High Efficiency Heat Pump Monitoring Project," the difference between measured COP and manufacturer's claimed COP was not as drastic as in this study.

The drop-off in COP of most systems in the higher outdoor temperature range is likely due to inefficiency from short compressor runtimes.

**Resistance heat use**. The toggle switch installed to prohibit resistance element operation worked very well. Only Burley and Ashton, sites without toggle switch control, experienced any significant use of resistance elements; over 10 percent of the total heating system energy use was from electric resistance elements at both Burley and Ashton. With an exception at Rigby, the remaining four houses kept resistance elements off for the entire monitoring period. It is unclear why Rigby used a very small amount of energy for resistance elements in the 30-35°F temperature bin.

Much of the resistance element energy use at Burley and Ashton happened during defrost. Figure 4 shows the time the compressor spent in defrost as a function of the total compressor run-time. In general, about 7 percent of the compressor run-time was devoted to defrost. The control strategy of the CCHP is such that the resistance elements are not a part of the first or second stage heat call at outdoor temperatures between 10° and 34°F. In this temperature band, resistance elements are energized only during a call for defrost.

## Figure 4: Defrost Run-Time



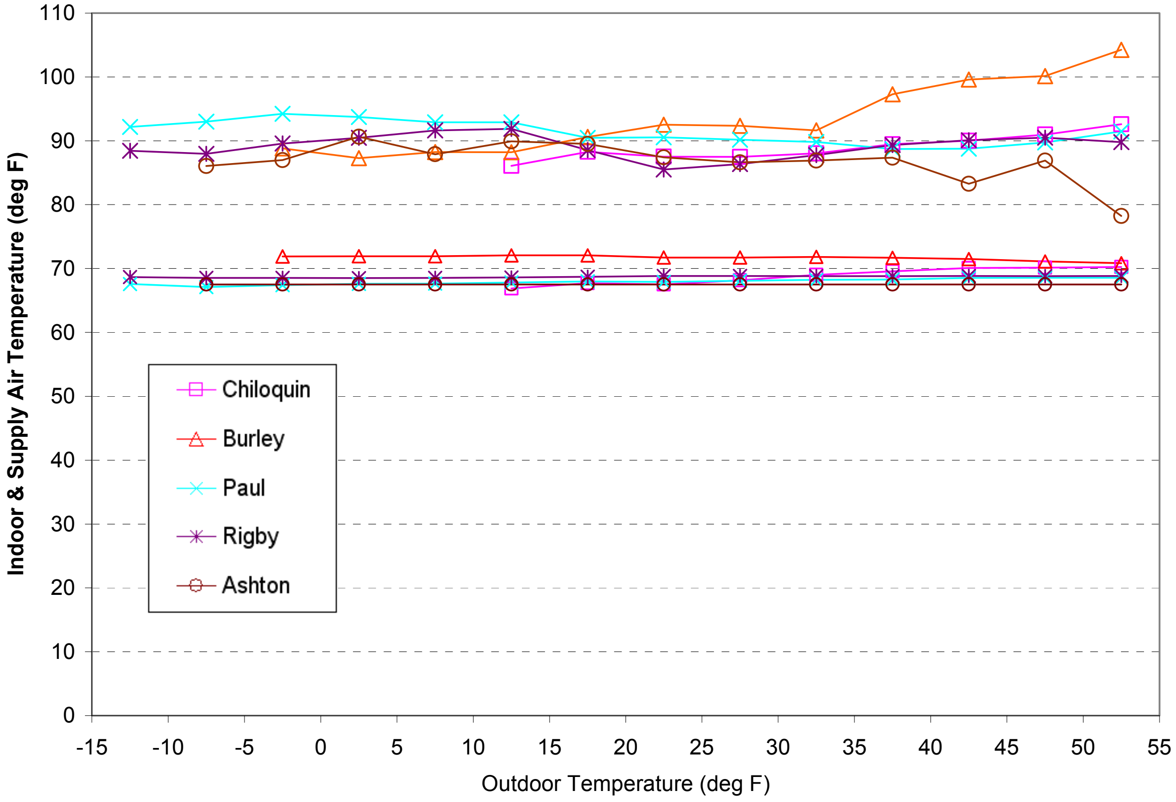
## Comfort

Comfort is a major issue for heat pumps. Heat pumps are notorious for low delivery air temperatures, otherwise known as “cold blow.” The CCHP installed with a toggle switch on the resistance elements relies solely on its added capacity from the booster and economizer as outdoor temperature falls.

**Defrost.** With the toggle switch set to keep the resistance elements off, resistance elements are not allowed to energize, even during defrost. Depending on the length of defrost operation and proximity of supply registers to occupants, the toggle switch could pose a threat to occupant comfort. When questioned about comfort, the four homeowners with toggle switches either said they did not notice cold air blowing from the supply registers during defrost or that the cold air did not pose a comfort problem.

**CCHP setpoint maintenance.** Figure 5 shows the average supply air temperature during the heating cycle (not defrost) and the average indoor temperature in each 5-degree outdoor temperature bin for each house. Some of the variability in indoor temperature in Figure 5 is due to occupants manually changing thermostat settings. While it is possible some of the fall-off in indoor temperature is due to a lack of heating capacity, some may also be from nighttime temperature setback coinciding with colder nighttime outdoor temperatures. For the most part, the CCHP seems capable of maintaining comfortable setpoint as outdoor temperature drops.

**Figure 5. Average Indoor Temperature and Supply Air Temperature**



**Supply air temperature.** The high supply air temperature shown in Figure 5 for Burley at outdoor temperatures greater than 35°F is primarily because of the resistance element operation. Since supply air temperature readings are not reliable during resistance element operation, the Burley and Ashton data should be ignored. Some units, such as Paul, saw a rise in supply air temperature as outdoor temperature fell. This is as expected for two reasons: the CCHP adds capacity with the booster and economizer at lower outdoor temperatures; and the heat pump runs longer as outdoor temperature falls, causing a higher average supply air temperature. In general, the three systems operating only in heat pump mode (Chiloquin, Paul, and Rigby) saw fairly constant supply air temperatures over varying outdoor air temperatures. Overall, the units monitored in this study maintained fairly constant supply air temperatures between 85°F and 95°F.

## Conclusion

This study was undertaken because of interest in a heat pump with the potential to operate efficiently in cold climates. If they operated as advertised, these new systems could provide a fix to utilities' costly struggle to ensure resistance heat elements are controlled efficiently. In this study, the homeowners with resistance heat controls were aware of their ability to turn the toggle switch to the "on" position if they so desired. Yet all of them found their homes comfortable enough to leave it in the "off" position for an entire winter. There were no extreme measures taken to keep the strip heat off. In fact, the data from this study show the homes maintained reasonable average temperatures, even in cold winter conditions, without the use of strip heat. This is a major accomplishment for an air-source heat pump.

There are many benefits to installing air-source heat pumps without resistance elements. This study shows the CCHP or similar air-source heat pump technologies are capable of providing an "equipment based fix" alternative to the Pacific Northwest utilities' costly "installation based fix" to control resistance elements efficiently. This type of air-source heat pump also has proven its capability to provide solutions for electric utility peak power demand reduction programs.

The fact that the CCHP systems in this study did not perform as efficiently as the high efficiency standard air-source systems in a similar study is not a major concern. Compared to the large manufacturers of the standard systems, this product was produced by small manufacturer in low volume with little experience manufacturing residential heat pumps. With a wide network of installers and refinements in the product and installation practices, it is possible the CCHP or similar product could be installed without resistance elements. With continued effort and experience on the part of the manufacturer, a multi-stage air-source heat pump like the CCHP should be capable of matching the efficiency levels of standard air-source heat pumps.

Although the CCHP has proven the concept of installing heat pumps without resistance heat can work in cold climates, the market is not currently keen on the idea. As an intermediate step, most would agree removing resistance heat from the control strategy as "supplemental heat" is acceptable with today's heat pumps, depending on climate. The CCHP expands the concept to colder climates. The next step would be to improve defrost cycles and duct locations so resistance heat is no longer needed to make defrost cycles comfortable to the homeowners in the heat pump market. Both of these concepts would retain resistance elements as a backup in case of compressor failure, in other words, for "emergency mode." The authors hope there will be a day when heat pumps capable of providing full heating capacity are considered as reliable as air-conditioners or refrigerators. Ultimately, the heat pump market will decide the fate of heat pumps installed without strip heat.

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