BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

Flow Environmental Systems ANSWR CO_2 Heat Pump Feasibility Study and Applications Testing

August 2024

Flow Environmental Systems ANSWR CO_2 Heat Pump Feasibility Study and Applications Testing

Prepared for
Matt Booth, Project Principal Investigator
Washington State University Energy Program on behalf of Bonneville Power Administration

Prepared by:
Tim O'Neill, PE, Ecotope Inc.
Scott Spielman, PE, Ecotope Inc.
Jonathan Heller, PE, Ecotope Inc.

The following report was funded by the Bonneville Power Administration (BPA) to assess emerging technology topics that have the potential to increase energy efficiency. BPA is committed to identify, assess, and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

Table of Contents

Table of Figures

Acronyms

CO2 – Carbon Dioxide
COP – Coefficient of Performance
FES – Flow Environmental Systems
FCU – Fan Coil Unit
GWP – Global Warming Potential
HFC – HydroFluroCarbon
PAG - Polyalkylene Glycol
UL – Underwriters Laboratories

Executive Summary

Buildings account for 38% of total energy end use in the United States.[1] Of this total, the largest portion, approximately 41%, goes towards space heating and cooling, while domestic water heating makes up another 5%.[2] In pursuit of electrification, energy efficiency, and decarbonization efforts, building owners are turning to heat pump technologies to replace natural gas and electric resistance heating solutions while providing cooling capacity to their tenants. The ANSWR CO_2 heat pump, manufactured by Flow Environmental Systems (FES), is available as a fully packaged, energy efficient, cost effective and resilient option for meeting building heating and cooling requirements while simultaneously satisfying domestic hot water heating needs with a single piece of equipment. This report provides a Feasibility Analysis for the ANSWR product and concludes that the product is ready for Applications Testing. This report also includes the results of Applications Testing conducted by Ecotope in preparation for a demonstration installation.

The ANSWR product can help Bonneville Power Administration meet the energy efficiency goals outlined in its resource plan[3] through energy efficiency, resilience, load shift capability, and cost effectiveness.

Codes and Certifications: FES designed the ANSWR to meet applicable mechanical and plumbing code requirements. FES is currently in the process of obtaining UL certification through testing at their Flow Innovation Center in Rogers, Minnesota, in cooperation with Intertek.

Performance: ANSWR can produce hot water up to 180°F at an ambient temperature of -15°F and chilled water at 0°F (with glycol) at 120°F ambient air temperature. In addition to providing simultaneous heating and chilled water for hydronic space heating, ANSWR can provide domestic hot water. FES has not yet completed full performance maps for the ANSWR product, though they plan to have this information available in late 2024.

Market Delivery: The ANSWR comes in two delivery methods. The first is a split-system that consists of two parts: the heat pump and a remotely located gas cooler; field-installed refrigerant piping is required for this delivery method. The second is a fully packaged unit that requires only water and power connections. Delivery as a fully packaged system reduces overall costs and improves system reliability and performance. The packaged delivery model also eliminates the need for field-installed refrigerant piping which minimizes the risk of refrigerant leakage.

Building systems that use ANSWR as their primary heating and cooling plant require custom engineering for each facility. The engineering effort includes sizing of equipment, equipment selection, and specification of associated accessories such as pumps, valves, buffer tanks, etc. However, FES will provide detailed design guidance to ensure correct application of each unit.

Constructability: The unit can be used in retrofit applications to replace an existing boiler, chiller, and hot water plant with a single piece of equipment by simply tying it into existing electrical, mechanical, and plumbing distribution systems as applicable. For new construction projects, using this single unit for all three services can simplify system design and speed equipment installation.

Maintenance: Maintenance requirements are comparable to other air-to-water heat pumps or air-cooled chillers. Annual maintenance includes checking refrigerant and oil charge, cleaning the gas cooler assembly, reviewing compressor operation for noise/vibration, reviewing faults, and flushing strainers.

Background

Market Landscape

In pursuit of electrification, energy efficiency, and decarbonization efforts, building owners are turning to heat pump technologies to replace natural gas and electric resistance heating solutions. They are also looking for cooling solutions as tenants require the temperature in their spaces to be comfortable year-round.

Air-to-water heat pumps have gained popularity in the Pacific Northwest over the past decade for their ability to provide energy efficient heating and cooling with a single piece of equipment. However, current heat pumps available on the market have performance limitations. First, depending on the refrigerant used, they operate in ambient conditions limited to approximately 0°F and their capacity decreases significantly at ambient temperatures below 23°F; these limitations typically require designers to include a backup heating source on the hydronic system such as gas-fired or electric resistance boilers. Second, their heating supply water temperature is limited to approximately 130°F since they use conventional HFC refrigerants such as R410a. This limitation requires associated air handling equipment to have heating coils sized for the lower temperature heating water, which increases equipment costs due to larger size and increased flow requirements.

Building owners looking to electrify existing gas-fired heating water plants that serve high-temperature (~180°F) heating water systems have limited options. Current heat pump technologies cannot meet these high supply temperatures and electric resistance boilers are much more expensive to operate as compared to natural gas options (typically at least three times as expensive, depending on local electricity and natural gas billing rates). A heat pump that provides 180°F is a potential "plug-and-play" option for electric or gas boiler replacement projects.

In addition to overall energy savings, if designed with adequate thermal storage (in the form of storage tanks), the ANSWR unit can allow for load shifting. Thermal storage can be provided via large buffer tanks allowing heat pump equipment to be turned on or off to implement grid demands. Variables such as supply water temperature and tank storage size can be designed to facilitate a specific required load shift duration.

FES intends to address the following markets with their ANSWR product:

- Hydronic heating applications that require greater than 120°F heating water supply.
- Retrofits of legacy systems that use high temperature (>160°F) heating water supply.
- Projects with space constraints that require small form factor equipment.
- Commercial applications with simultaneous heating/cooling/domestic hot water loads (e.g., hospitals, labs, campuses).
- Light industrial applications (e.g., pharmaceutical processing).

Purpose

This Feasibility Study examines the FES ANSWR CO_2 air-to-water heat pump's ability to efficiently meet space conditioning (heating and cooling) and domestic hot water heating needs in the Pacific Northwest. This report is the first step in the Technology Innovation Model (TIM), which is designed to take a technology through a series of stage gates representing different areas of inquiry to ensure that the product can be safely and cost-effectively applied in a manner that ensures performance and savings in the marketplace.

Key stage gates for the TIM include:

1. Feasibility Study
2. Applications Testing
3. Demonstration Project
4. Measurement and Verification (M&V)
5. Design Guidelines

Based on the results of this feasibility study, the ANSWR product is ready for Applications Testing.

FES performed Applications Testing on a prototype ANSWR product at its Flow Innovation Center facility in Rogers, Minnesota on April 17, 2024. The prototype was a 60-ton unit with a heating water and chilled water heat exchanger installed. The test unit did not include the domestic hot water heat exchanger and so domestic hot water testing was excluded. Applications Test results are included in **Appendix A.** FES will need to complete additional Applications Testing focused on domestic hot water applications.

Equipment Operation

ANSWR uses a transcritical CO_2 refrigeration cycle which allows simultaneous heating and cooling with no reversing valve. The ANSWR CO_2 refrigerant circuit includes a gas cooler; the gas cooler acts like a condenser in a typical refrigerant circuit, except instead of

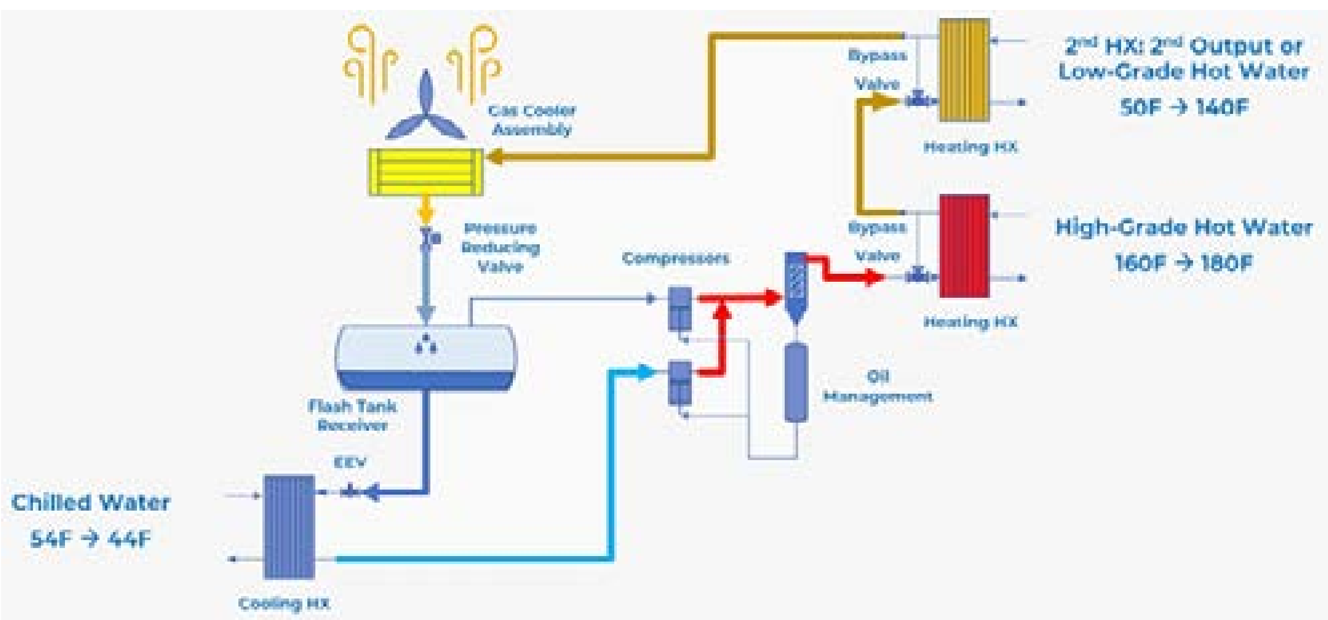

Figure 1. ANSWR refrigerant flow diagram (Image courtesy of Flow Environmental Systems. Diagram is schematic with not all components shown.)

condensing the refrigerant to provide heat, it cools the supercritical CO_2 refrigerant gas. **Figure 1** shows internal components of the ANSWR product in the form of a refrigerant flow diagram.

Figure 2 includes a pressure-enthalpy diagram that provides a simplified example of the ANSWR refrigerant cycle; below is a discussion of the points labeled on the diagram:

1. Flash gas from the liquid/vapor separator (flash tank) enters the inlet of the high temperature compressor.

2. Hot high-pressure gas is available to enter either of the two hot water heat exchangers: a high-grade hot water heat exchanger that produces 160°F - 180°F water or a low-grade hot water heat exchanger that can produce between 50°F and 140°F. System designers can use these two heat exchangers to best suit the

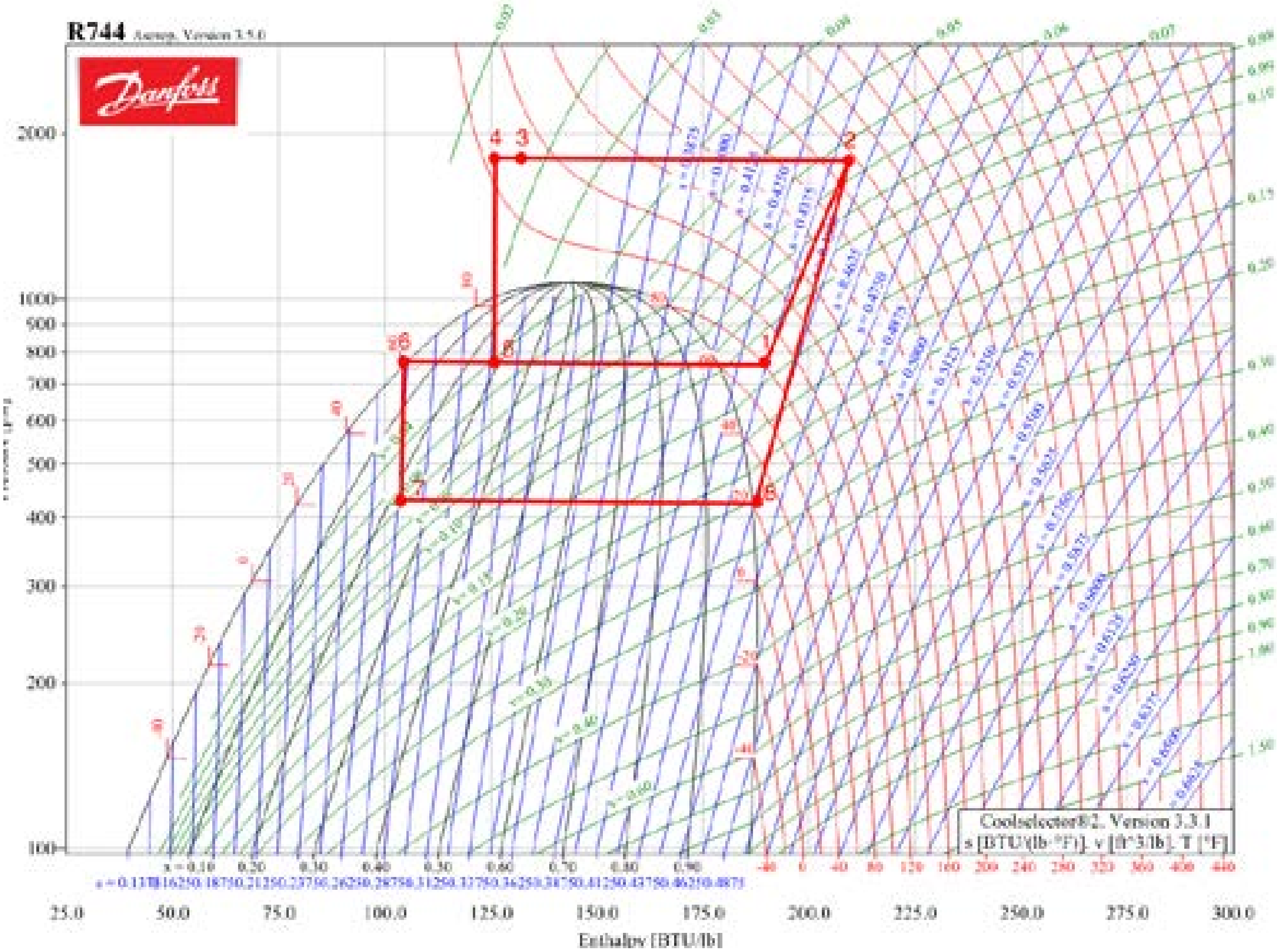

Figure 2. R-744 (CO_2) Pressure-Enthalpy diagram showing example ANSWR cycle

The ANSWR refrigerant circuit acts as a variable-flow system. Variable-speed compressors maintain discharge pressures while bypass valves at each heat exchanger and various pressure reducing valves modulate to control compressor suction pressure. This level of control allows ANSWR to operate with unbalanced heating and cooling loads. The unit can shift between "boiler" and "chiller" operation on the fly and can also react to significant (up to 10-to-1) step-changes in either heating or cooling loads). Additionally, unlike conventional heat pumps, the ANSWR product needs no reversing valve and can service heating, cooling, and domestic water heating loads simultaneously.

desired application.

3. Warm gas enters the gas cooler to reject additional heat as necessary.
4. Low temperature gas enters an expansion valve where it expands to becomes a liquid/vapor mixture.
5. The liquid/vapor mixture enters the flash tank. From this point low temperature gas goes to the high temperature compressor inlet (point 1) while liquid (identified as point 6) is sent to another expansion valve.
6. Liquid is sent through an expansion valve where it becomes a low temperature liquid/vapor mixture.
7. Low temperature liquid/vapor mixture is sent through either a chilled water heat exchanger, an evaporator coil (if no chilled water is needed), or a combination of both, after which it enters the medium temperature compressor (at point 8). The chilled water heat exchanger can produce water between 38°F and 75°F, or down to 0°F with the use of glycol.

Refrigerant

Currently available air-to-water heat pump technologies use conventional HFC refrigerants such as R410a. R410a has a global warming potential (GWP) of 2088 (as compared to the index of CO_2 which has a GWP of 1).

Refrigerant policy in the United States is moving the industry away from traditional refrigerants. Self-contained HVAC systems using R-410a will no longer be manufactured or imported after January 1, 2025, and other, high-GWP refrigerants are scheduled to be phased out as well.

The ANSWR uses CO_2 refrigerant (R-744), which works well in low and high ambient air temperatures (down to -15°F and up to 120°F[a]) making it a viable option in most locations throughout the United States. The use of CO_2 refrigerant also future-proofs the systems against refrigerant phase-outs.

A disadvantage of using CO_2 as a refrigerant is that it has a limitation on entering water temperature; the efficiency drops significantly when inlet water temperature is above 90°F. However, according to FES, the ANSWR product can maintain a Coefficient of Performance (COP) of at least 1.3 with entering water temperatures up to 160°F by using an additional heat exchanger located downstream of the gas cooler for heat reclaim. At lower entering water temperatures, COP values greater than 3.0 are expected.

Current Installations

There are no current installations using the ANSWR product. One unit has been built and is undergoing testing at the Flow Innovation Center facility in Rogers, Minnesota. The next stage of the TIM, Applications Testing, can be performed at this facility.

Codes and Certifications

This section identifies the required codes and certifications associated with a product installation in the Pacific Northwest and California.

a The ambient operating range can be expanded beyond these limits with addition of specialized components and control strategies.

Codes

FEDERAL LAW

- The Safe Drinking Water Act (SDWA Section 1417

ENERGY CODE

- International Energy Conservation Code (IECC) (Includes Idaho and Montana)
- Washington State Energy Code (WSEC)
- Seattle Energy Code (SEC)
- Oregon Energy Efficiency Specialty Code (OEESC)
- Title 24 (in California)

MECHANICAL CODE

- International Mechanical Code (IMC)

PLUMBING CODE

- Uniform Plumbing Code (UPC)
- International Plumbing Code (IPC)

ELECTRICAL CODE

- National Fire Protection Agency (NFPA) 70 – National Electrical Code (NEC)

System Component Assessment

System Component Assessment identifies the equipment needed for a complete system deployment.

The ANSWR is a packaged air-to-water heat pump that includes a refrigerant circuit with a high-grade hot water heat exchanger, a low-grade hot water heat exchanger, a gas cooler with fan, pressure reducing valve, flash tank receiver, chilled water heat exchanger, evaporator, and high- and medium-temperature compressors. For a complete heating and cooling system, accessories such

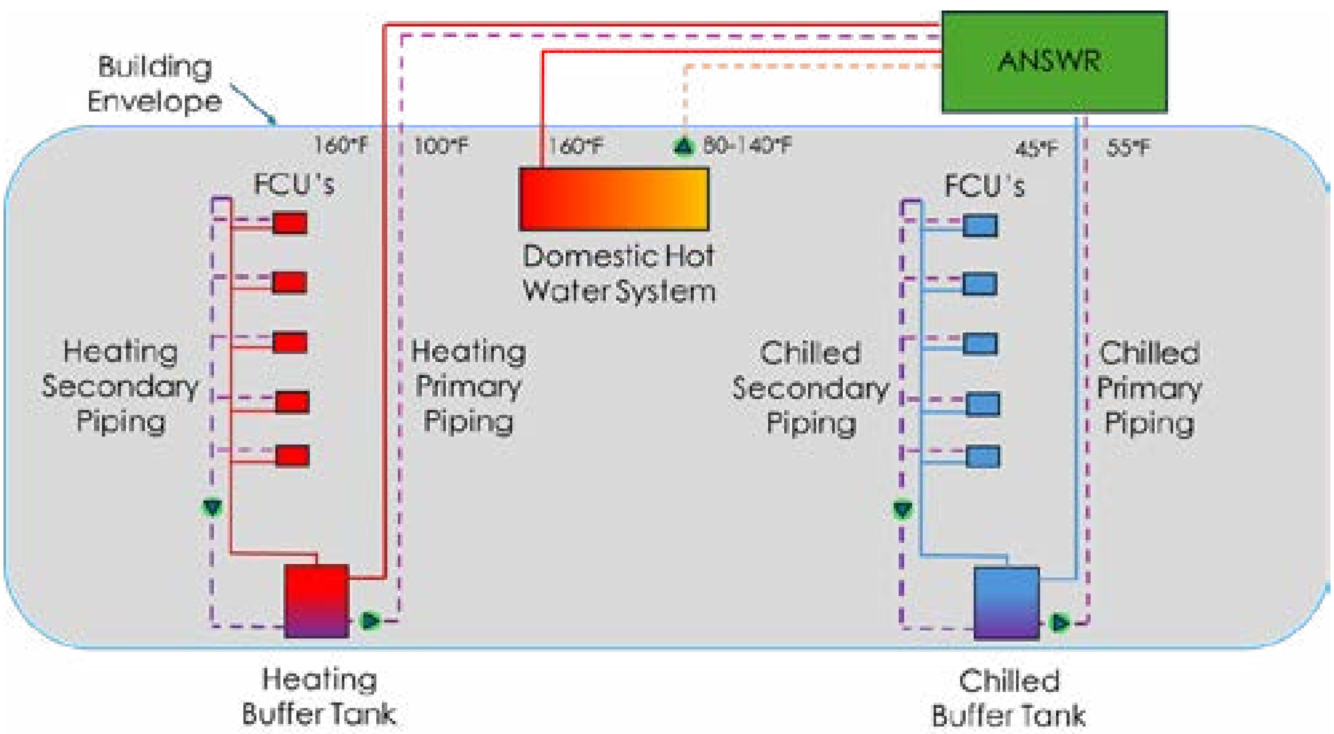

Figure 3. ANSWR shown in a heating/cooling/domestic hot water application

as primary and secondary pumps, buffer tanks, etc., are also required. **Figure 3** shows a simple diagram of ANSWR installed in a configuration to provide hydronic heating and cooling (to Fan Coil Units – FCU's) as well as domestic hot water. When used to provide domestic hot water, additional equipment (e.g., thermal storage tanks, pumps, and temperature maintenance equipment) is also required. (This ancillary domestic hot water equipment has been omitted from Figure 3 for clarity.)

Currently, FES does not plan to provide all components required for a full building heating and cooling system. Designers will be required to specify ancillary equipment for their specific application. FES plans to provide detailed engineering guidance to designers to help size and specify ancillary equipment to ensure the success of each installation.

Architecture

The main system components to consider with respect to the building architecture are the central air to water heat pump and any necessary buffer / thermal storage tanks. Installation location of the central heat pump unit impacts the site's architectural design and acoustics. The most typical practice is to install the heat pump unit on a rooftop or at grade adjacent to the building. When installed in a visible location, the architect may want to provide a screen wall to obscure it from view. As with the locating of any equipment, architects will need to coordinate with the mechanical or plumbing engineer to identify an appropriate location.

The buffer / thermal storage tanks, which can total more than 1,000 gallons of capacity, can require a significant amount of space, so attention should be paid both to allowances for adequate floor space and ceiling-height. These tanks can typically be installed in a dedicated mechanical space or garage (though freeze protection concerns should be addressed if located in an unconditioned space). If installed indoors, the tank size should be limited to allow for movement through doorways. Alternatively, multiple smaller tanks installed in parallel can be used in lieu of a single large tank.

Like any equipment locating, architects will need to coordinate with the mechanical engineer to identify an appropriate location.

Space Requirements

Unit dimensions vary by model and are provided by FES in their equipment literature. For applications where the split-system delivery option is selected (where the heat pump is installed inside the building envelope while the gas cooler is installed outside), the heat pump section size comes standard at 126" long by 84" wide by 92" high. The gas cooler dimensions vary by model and are provided by FES in their design literature (though the gas cooler width and height dimensions match those of the heat pump). For special applications, gas coolers can be provided in various configurations to fit available laydown space (see section on *Mechanical-Configuration*).

Units should be installed with ~42" walk-around clearance to facilitate maintenance. In addition to maintenance clearances, unit placement should be designed in a way that allows for future removal and replacement at its end of life.

Because of the potential size of major system accessories, such as pumps, expansion tanks, and buffer tanks, it is important to identify equipment too large to fit through standard doors early so architects and designers can plan appropriately for equipment installation and replacement.

Acoustics

Published data on ANSWR shows a maximum sound pressure level of 69 dBA which is less than many conventional air-cooled chillers and is comparable to the background noise level in a typical office setting.

Like other heat pumps, the unit should be installed away from bedroom or office windows and outdoor amenity spaces. An acoustic screen wall can reduce sound transmission and obscure equipment. Allowable sound power levels at property lines vary by jurisdiction. FES aims to have the lowest possible sound power level to increase flexibility when locating the unit.

Climate

As with any heat pump product, it is important to consider weather, such as wind and snow. Designers should avoid placing units so that the air intake faces into the prevailing wind. The preferred orientation for air intake is perpendicular to prevailing winds. When installed outdoors in locations that receive snow, units should be elevated above the snow line.

The ANSWR is suitable for cold-weather applications with its ability to operate at design capacity down to 0°F. The unit can safely operate down to -15°F with only a slight decrease in capacity (designers should review required derate at low temperatures with the manufacturer). During extreme weather conditions, the unit will continue to operate down to an ambient temperature of -40°F, though output capacity will be adversely affected. FES is developing a modified ANSWR product for specific use in extreme cold-climate applications. Designers interested in using ANSWR in that type of environment should contact the manufacturer for specific guidance.

The unit can also operate at full design capacity at ambient temperatures up to 116°F. Beyond this temperature, capacity begins to decrease, and designers should review required derates at high temperatures with the manufacturer. FES offers an adiabatic gas cooler option for use in hot climates. The adiabatic cooling system saturates the incoming ambient air with moisture using atomizing nozzles. This system causes the ambient dry bulb temperature to approach the ambient wet bulb temperature which increases efficiency. This option, which requires a piped water supply, provides an increase in unit cooling capacity in hot temperatures. However, in hot, humid climates, where the wet bulb temperature can be close to the dry bulb temperature, adiabatic cooling will not provide much, if any, additional cooling capacity. Additionally, adiabatic cooling uses potable water. When the unit is installed for a demonstration, the water use should be monitored as water is an important natural resource that must be conserved, especially in drought prone areas of the West Coast.

Engineering

Engineering is broken into structural, mechanical, electrical, and plumbing performance.

Structural

The ANSWR comes in two delivery methods. The first is a split-system that consists of two parts: the heat pump and a remotely located gas cooler. The second is a fully packaged unit.

The main weight considerations for system installation are associated with the air-to-water heat pump, the gas cooler (if located remotely) and the system buffer tanks. For systems that incorporate thermal storage tanks for load shift capability, the weight of those tanks should also be considered.

Depending on system capacity, air-to-water heat pump weight loads can vary from nearly 1,000 pounds up to several thousand pounds. Care should be taken to include the weight added when the system is filled with water/glycol. The installed unit may require vibration isolation depending on the installation location and facility vibration requirements. Like other major mechanical components, the unit must be securely mounted to prevent it from falling in seismic or wind events.

The ANSWR weights vary by model. For the 60-ton unit, the heat pump and gas cooler assemblies weigh approximately 6,000 pounds and 3,000 pounds, respectively. Refer to FES equipment cut sheets for the exact weight by model.

The weights of the buffer tank(s) also vary with system configuration. For a 1,000-gallon tank, weight (when filled) can easily be more than 12,000 pounds.

Structural engineers should be notified early in the design process regarding proposed locations for the heat pump and decoupling tank(s) so they can plan accordingly.

The ANSWR unit includes motorized components for which vibration isolation should be considered. The heat pump section includes reciprocating compressors while the gas cooler uses axial fans. The compressors are not provided with local vibration isolation, primarily since the high-pressure stainless steel tubing connections require rigidity to maintain integrity. Depending on the installation location and facility vibration tolerances, vibration controls for the skid assembly should be evaluated. Like other major mechanical components, the unit must be secured to structure to prevent it from falling in seismic events.

Figure 4. Multiple heat pumps in a parallel configuration (Image courtesy of Flow Environmental Systems.)

Mechanical

CONFIGURATION

ANSWR heat pump systems can be scaled to meet capacity needs and are designed to be installed for parallel installation. See **Figure 4**.

Gas coolers can be ordered in various configurations to meet site requirements. The typical configuration is a V-bank with horizontally mounted fans. If space constraints require alternate configurations, FES also offers low-profile horizontal units or vertical units that can fit into narrow areas. See **Figure 5.**

Figure 5. Gas cooler configuration options (Image courtesy of Flow Environmental Systems.)

The transcritical CO_2 refrigerant cycle used in the ANSWR allows for simultaneous production of heating water, chilled water, and domestic hot water.

PIPING

The unit can be delivered either as a packaged, one-piece unit, or as a split-system with a heat pump and remote gas cooler, to suit the required application. In cases where the remote gas cooler is selected, field-installed refrigerant piping is required between the heat pump and gas cooler. FES requires this piping to be rated for 1885 psi (130-bar) and recommends either K65 tubing or stainless-steel tubing with orbital butt welding.

Depending on the desired application, a single ANSWR unit can be used to supply high-temperature heating water (up to 160-180°F), medium-temperature heating water (100-140°F), domestic hot water (120-160°F), and chilled water (38-75°F). Designers should select materials for field-installed hydronic and domestic hot water piping based on the appropriate application.

Due to the ability of the ANSWR to vary refrigerant flow in the system by modulating compressor speed as well as refrigerant flow to each heat exchanger using bypass valves, the unit is tolerant to sudden changes in system water flow. However, FES recommends installing system hydronic piping in a primary-secondary configuration with dedicated primary pumps to maintain the required flow through the heat pump. Recommended methods for speed control of the pumps are either to maintain differential pressure across the heat pump or maintain a constant flow using field-installed flow meters.

The manufacturer plans to include requirements such as minimum system volume and minimum flow rates in their design guidelines.

INSULATION

For split-system applications, field-installed refrigerant piping should be insulated per manufacturer's guidance. This insulated piping should be protected from weather and personnel traffic as appropriate.

The split-system delivery method may be the preferred configuration for use in cold climates...

SIMULTANEOUS HEATING AND COOLING

The CO_2 refrigerant cycle used in the ANSWR allows for simultaneous production of heating water, chilled water, and domestic hot water. This ability to produce both heating and chilled water simultaneously allows several possible applications such as heat recovery from centralized building exhaust air by circulating chilled water through air-to-water heat exchangers located in the exhaust air stream.

CAPACITY

Heat pumps come in four capacities: 30, 60, 90, and 120-tons. For applications where more than 120 tons is required, multiple heat pumps (up to 10 units) can be installed in parallel.

Designers should size heat pump capacity based on building design, climate, domestic hot water loads, and need for redundancy. One benefit of the ANSWR is that unit output capacity is maintained throughout most of its ambient temperature operating range. However, derate should be considered in applications at extreme high/low ambient temperatures or when excessive defrost could be required (e.g., in cold marine climates). The adiabatic gas cooler is also an option for installation in extreme hot-weather conditions.

SUPPLEMENTAL HEATING

Due to ANSWR's ability to operate at near full capacity at ambient temperatures down to -15°F, supplemental heating is only necessary in the coldest of climates. In extreme cold climate applications, electric or gas-fired boilers can be installed to supplement ANSWR heating capacity during extreme cold weather conditions. While the heat pump can continue to operate at ambient temperatures down to -40°F, supplemental heating should be sized to account for the equipment derate at lower ambient temperatures.

REDUNDANCY

For critical applications where redundancy is necessary, additional heat pumps can be installed in parallel to offer N+1 backup capability (e.g., installation of three 60-ton units to meet a 120-ton design load would yield N+1 redundancy).

FREEZE PROTECTION

The split-system delivery method may be the preferred configuration for use in cold climates since no water penetrates the building envelope and therefore no freeze protection is required on either the hydronic or domestic hot water lines.

In cold climates, freeze protection may be necessary for packaged one-piece units where the assembly is installed outdoors, and hydronic and domestic hot water piping penetrates the building envelope. Glycol can be used as the working fluid for hydronic piping; FES plans to provide information on glycol derate in their design guidance. For domestic hot water, heat trace can be installed on the piping outside the building; alternatively, a short glycol loop could be installed along with a water-to-water heat exchanger so that domestic water does not flow outside the building envelope. Glycol protects the system in case of a power outage where heat trace does not unless heat trace is put on a backup power system.

DEFROST

As with any heat pump, evaporator coils can contain refrigerant at a temperature below the freezing point of water so frost can build up on the outer surface of the coils. The ANSWR employs an advanced design that can reject additional heat from the gas cooling process into the air before it reaches the evaporator coil. This strategy minimizes the need for defrost because heating the air before the evaporator increases its dry bulb temperature

without adding moisture, which reduces relative humidity of evaporator air.
Under extreme ambient conditions, when defrost may be necessary, the ANSWR is capable of mechanical defrost and accomplishes it via hot gas bypass. According to FES, the maximum expected derate due to defrost is 10% of capacity.

For retrofit applications where a chiller is used, no new power feed is typically required; power distribution to the existing chiller can be repurposed to serve the ANSWR equipment.

CO_2 REFRIGERANT AND INLET WATER TEMPERATURE

The ANSWR unit is a CO_2 based heat pump and relies on the transcritical refrigeration cycle. To maximize the efficiency of the system, as much heat as possible should be extracted from the refrigerant between the compressor discharge and the gas cooler. To this end, an entering water temperature of approximately 90°F or less is typically desirable to achieve the highest Coefficient of Performance (COP). However, by recovering waste heat rejected by the gas cooler via an evaporator coil installed in the airstream immediately downstream of the gas cooler, the ANSWR can maintain COP's of at least 1.3 with entering water temperatures of up to 160°F.

WATER QUALITY

Water quality must be maintained within certain ranges to protect the refrigerant-to-water heat exchangers. FES plans to provide information on acceptable ranges in their design guidelines. It is believed that most municipal water supplies in the United States will meet the water quality requirements.

LONGEVITY

All components of the ANSWR are rated for industrial use. FES expects the product to have a minimum 20- to 30-year life span.

CONTROLS

The ANSWR will be provided with on-board CO_2-specific CAREL controllers that execute all equipment-level operations. CAREL is the world's largest supplier of CO_2 refrigerant control systems. These controllers are BACnet ready to facilitate communications with a centralized building control system.

The unit accepts various external commands including enable/disable, temperature control setpoints, and power limits. Status feedback is available for multiple temperature and pressure sensors, valves, compressors, and fans.

Electrical

Initially, the ANSWR will be available for 460 Volt, 3-phase applications. In the future, FES may offer packages for specific applications at other voltages. A field-installed step-up transformer can be employed in buildings that only include a 208 Volt service as is common in multifamily buildings.
Information on electrical requirements, including minimum circuit ampacity, maximum overcurrent protection, and short circuit current rating, is available from FES. For packaged units, the ANSWR requires a single-point power connection. For split-system applications, separate power connections are required for the heat pump and the gas cooler.

For retrofit applications where a chiller is used, no new power feed is typically required;

power distribution to the existing chiller can be repurposed to serve the ANSWR equipment.

The unit must be hardwired, and the circuit feeding the device must comply with the National Electrical Code (NEC). Article 440 of the NEC applies to all devices that include hermetic refrigerant compressors; this section is applicable to ANSWR.

Plumbing

DOMESTIC WATER HEATING

In addition to providing heated and chilled water for space conditioning, ANSWR can simultaneously provide heating for domestic hot water.

When considering methods of heating domestic water, attention should be given to maximizing heat extraction from the refrigerant. Ecotope recommends that the low-grade heat exchanger be used in a single-pass return to primary configuration to heat domestic water (see **Figure 6**). This configuration is simple, eliminates the need for an electric-resistance swing tank, and allows the heat pump to provide all domestic water heating. It also allows cold (~45° to 60°F) city water to enter the heat exchanger; this feature maximizes heat extraction from the refrigerant which increases system efficiency.

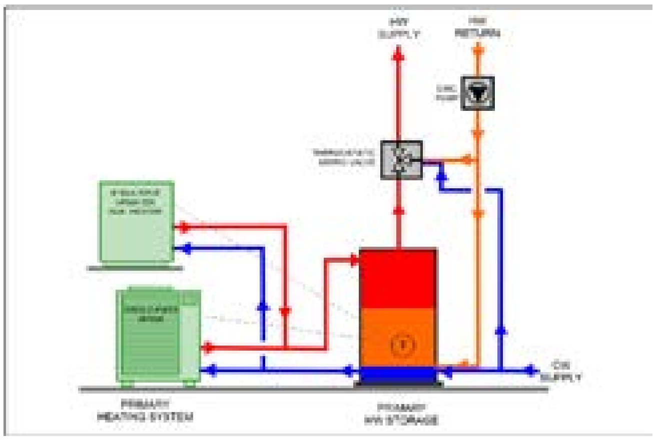

Figure 6. Single-pass Return to Primary

A double-walled heat exchanger is a standard feature in the ANSWR product to eliminate the need for a secondary heat exchanger to process potable water. Also, routing of potable water outside the building envelope should be avoided due to freeze protection concerns; the split system ANSWR configuration should be used when heating domestic hot water in cold climates. Further study is recommended to compare system configurations for using heat produced by ANSWR to provide domestic hot water; see section Further Research.

CAPACITY

Building owners want a product that is affordable to install, performs consistently, requires little maintenance, meets green building targets, and reduces energy costs. Due to the variable refrigerant flow nature of the ANSWR product, domestic water heating does not need to be decoupled from space conditioning loads; ANSWR can produce domestic hot water either with no space conditioning loads or with full simultaneous space conditioning loads. When sizing unit capacity, designers should consider how peak domestic water heating loads interact with peak space conditioning loads.

CONDENSATE

In either configuration (split-system or packaged), condensation may form on the coils of the gas cooler in certain conditions. This condensation is collected and routed away from the unit. In cold-weather applications, this condensate drain line requires insulation and heat trace to prevent freezing.

Owners

Building owners want a product that is affordable to install, performs consistently, requires little maintenance, meets green building targets, and reduces energy costs. When designed, installed, and maintained correctly, ANSWR should provide long-term quality performance. The ability to satisfy heating, cooling, and domestic water heating loads via a single central plant unit will allow for reduced installation costs, increased energy efficiency (and potentially lower utility costs), consistent operation, and simplified maintenance. The ability to store energy in thermal storage tanks can allow the system to shift electricity usage to periods with lower energy costs. This load shifting maximizes value for customers and can reduce the simple payback period for system installation.

End Users

The needs of end users are centered around occupant comfort and consistent delivery of hot water. The ability of a system to meet these needs relies on proper design and installation.

FES will publish literature to provide design best-practice guidelines for engineers to ensure proper application. FES will also support startup and commissioning of each installation. Depending on the nature of the application, designers should consider system redundancy requirements to allow continued operation during both planned and unplanned downtime.

Cost and Constructability Assessment

The Cost and Construction Assessment confirms challenges associated with acquiring and installing the product.

Cost

System costs are dependent upon the specific site and application, though they are expected to be competitive with comparable alternative systems that include centralized sources of heating water (e.g., boiler), chilled water (e.g., chiller), and domestic hot water.

Availability

Air-to-water heat pumps that can achieve high supply water temperatures (around 180°F) are a top retrofit candidate for replacing electric resistance or gas-fired central heating water systems.

The ANSWR product will be manufactured in South Africa, though it is intended for the North American market. To minimize supply chain constraints, every component is sourced from at least two unique vendors. FES is taking orders for the ANSWR product. The expected lead time is approximately 40 weeks.

Construction Schedule

The expected lead time of 40 weeks should not adversely affect schedules for new construction projects. The ability of the unit to service heating, cooling, and domestic hot water heating via a single piece of equipment can simplify system design and speed equipment installation.

Retrofit projects should consider ordering the product as soon as possible once equipment capacity sizing is finalized to avoid project delays.

Air-to-water heat pumps that can achieve high supply water temperatures (around 180°F) are a top retrofit candidate for replacing electric resistance or gas-fired central heating water systems.

Retrofit Feasibility

If replacing a gas boiler, the project engineer must determine if sufficient electrical capacity is available or if an electrical upgrade is needed to power the air-to-water heat pump. For buildings that either have existing electric boilers or are served by an air-cooled chiller, electrical capacity needed for an air-to-water heat pump may already be in place.

The ANSWR can serve space heating, space cooling, and domestic hot water loads simultaneously. This versatility allows the unit to be used in retrofit applications to replace the existing boiler, chiller, and hot water production with a single piece of equipment.

The ANSWR product comes in both a split-system and packaged option. Though the gas cooler must be installed outdoors, the heat pump section of the split-system can be installed in a boiler room (or similar space) resulting in minimal heating/chilled water distribution system configuration changes. If a packaged option is selected, heating/chilled water piping must be routed through the building envelope to the unit.

Maintenance Assessment

Maintenance assessment is broken into two sections: customer service and maintenance. Customer service assesses the ability of the manufacturer to aid Northwest customers. Maintenance addresses upkeep requirements performed by the owner to ensure product longevity.

Customer Service

FES sells products through a network of manufacturer's representatives across the US. Current representative territories include the West coast, Northeast, upper Midwest, and central plains. Representatives are currently trained at the Flow Innovation Center in Rogers, MN; Flow is currently working on another product training and demonstration site located in California to help expedite training. Representative training includes applications/design, startup and commissioning, and maintenance and troubleshooting.

Every ANSWR unit installation will receive startup and commissioning service, provided either by FES or by a manufacturer-authorized vendor. Warranty registration requires ANSWR unit startup to be performed by a manufacturer-authorized individual.

FES provides a minimum three-year parts warranty on all units. The warranty can be extended to five years if a client selects the optional factory-authorized preventative maintenance agreement.

Maintenance

ANSWR is designed to facilitate maintenance and service. Controls and service are accessed on the same side of the unit. Serviceable parts such as filter driers have built-in isolation valves to allow removal and service. Each relief valve includes a service valve installed immediately upstream to facilitate service. The receiver has sight glasses and a pressure gauge at charging ports. Compressor oil is Polyalkylene Glycol (PAG) for higher temperature operation. No threaded fasteners are used; all piping joints are welded to minimize potential for system leaks.

Maintenance requirements for the ANSWR are comparable to other air-to-water heat pumps or air-cooled chillers. Annual maintenance includes checking refrigerant and oil charge, cleaning the gas cooler, reviewing compressor operation for noise/vibration, reviewing faults, and flushing strainers. FES plans to outline maintenance requirements in the owner's manual; these instructions should be followed to ensure equipment longevity.

Field refrigerant charging of split-system installations and overall system recharging should be accomplished using only CO_2 with a purity equal to or greater than Bone Dry (99.8%) purity in accordance with FES's maintenance literature. The use of Bone-Dry grade or higher prevents contaminants from degrading system performance. For example, higher levels of moisture may react with CO_2 to form carboxylic acid which can degrade component integrity.

Conclusions, Recommendations, and Future Research

The ANSWR air-to-water heat pump is the first CO_2 heat pump capable of meeting heating, cooling, and domestic hot water needs. Its ability to produce 180°F water makes it a viable retrofit option for existing buildings with a high-temperature hydronic distribution system. For existing buildings that have either electric boilers or chillers ANSWR can potentially tie into existing electric circuits eliminating the need to upsize the power distribution system. For new construction projects, heating water, chilled water, and domestic hot water service can be provided by a single piece of equipment, reducing first costs as well as ongoing maintenance costs.

ANSWR provides solutions for building owners and benefits to the electric grid. However, the complexity of the refrigerant circuit and controls of the ANSWR make it more suitable, at least at first, for large commercial and light industrial processes where maintenance staff are prepared to work with complex machinery. Based on the results of this feasibility study, the ANSWR product is ready for Applications Testing.

This research into the feasibility of ANSWR has raised opportunities for further research. One such topic is the comparison of configurations and needed ancillary equipment for producing domestic hot water (e.g., single-pass or return-to-primary). Further Applications Testing of the product in various domestic water heating configurations should be performed prior to installation in a demonstration project.

Appendix A: Applications Testing – Procedures and Results

Executive Summary

Ecotope and Flow Environmental Systems (FES) conducted applications testing of the ANSWR product on April 17, 2024, at the Flow Innovation Center located in Rogers, Minnesota. The purpose of this testing was 1) to verify unit operation under normal heating, cooling, and simultaneous heating/cooling operation, and 2) to verify alarms and associated responses to specific abnormal conditions. The intent was to verify these functions prior to installation of a demonstration project.

High-level take-aways from the testing include:

1. The ANSWR product operates effectively and reliably while producing either heating wateror chilled water. The highest efficiencies can be realized when producing heating and chilled water simultaneously.
2. Internal controls of the ANSWR appear robust. Control loops respond quickly to changes in system parameters.
3. Unit operation appears reliable and suitable for various commercial and industrial applications, including those that may be mission critical. Unit responses to abnormal conditions are resilient. The unit requires little to no human interaction to return to normal operation once the abnormal conditions (such as loss of water flow or loss of power) are restored.
4. There is not currently an alarm for a blocked airflow condition at the gas cooler. Flow Environmental Systems will evaluate using specific refrigerant pressure data and gas cooler fan speed data to initiate such an alarm for production units.

Though the production model from FES will allow simultaneous production of heating water, chilled water, and domestic hot water, the prototype tested during this applications testing was not provided with a domestic hot water heat exchanger; therefore, no domestic hot water testing was performed. Ecotope recommends that FES perform applications testing in Single-Pass Return to Primary Configuration, using a double walled, low grade heat exchanger. Ancillary equipment (including storage tanks, temperature maintenance system components, and associated controls) should be included in this testing to help inform design engineers of the appropriate means to employ ANSWR to produce domestic hot water.

The ANSWR product is ready for a demonstration project with the caveat that FES should conduct specific domestic hot water testing prior to a field demonstration that includes that application.

Part 1 - Purpose

This document outlines a test setup and procedure to test controls, alarms, and response to certain abnormal conditions for the FES "ANSWR" air-to-water heat pump prior to field installation.

Applications testing is designed to demonstrate compatibility and functionality of all system components before installation in the field so that further adjustments to the system design can be made without impacting building occupants. Applications testing is the second step in the Technology Innovation Model (TIM) designed to test controls, alarms, and 3rd party equipment for a complete system prior to field installation.

Applications testing should be an ongoing process designed to improve the quality and affordability of the product over time while maintaining functionality. The intent is to provide feedback to the manufacturer for optimization of the product and system design and application recommendations.

The test procedures included in this document present a starting point and focus on alarms and the ANSWR's response to abnormal conditions. The test procedures included in this document constitute the minimum testing required to move onto the third step in the TIM, a demonstration project.

Part 2 – Test Setup

TEST EQUIPMENT

Tests included in this document were performed at the Flow Innovation Center located in Rogers, Minnesota. This facility has a prototype 60-ton ANSWR product installed in a test configuration. The prototype consists of a split-system product that includes a heating water heat exchanger and a chilled water heat exchanger. The prototype unit did not include a domestic hot water heat exchanger that is planned for the production units; domestic hot water testing should be performed at a later date and prior to installation at a demonstration site.

The test setup consisted of:

1. Four 3300-gallon water storage tanks.
2. Primary heating water circulation pump with variable frequency drive.
3. Primary chilled water circulation pump with variable frequency drive.
4. Associated valves to allow control of inlet water temperatures to both the heating water and chilled water heat exchangers.

A schematic of the test setup is shown in **Figure 7**. Photographs of the test setup are included in **Figures 8** and **9**.

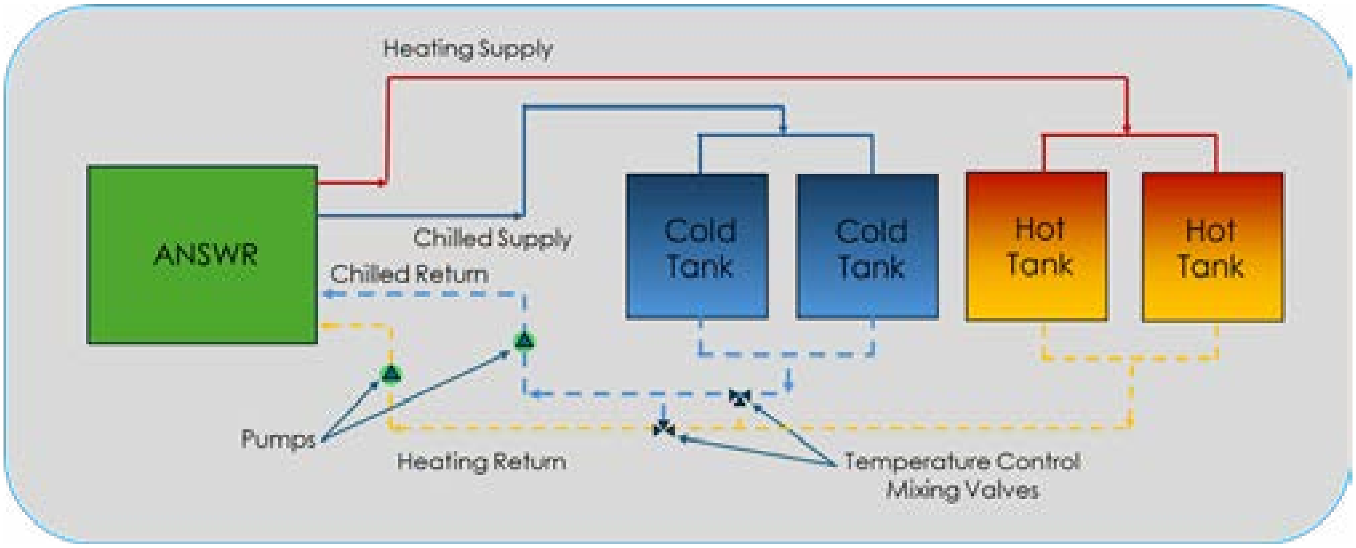

Figure 7. Applications Test Setup

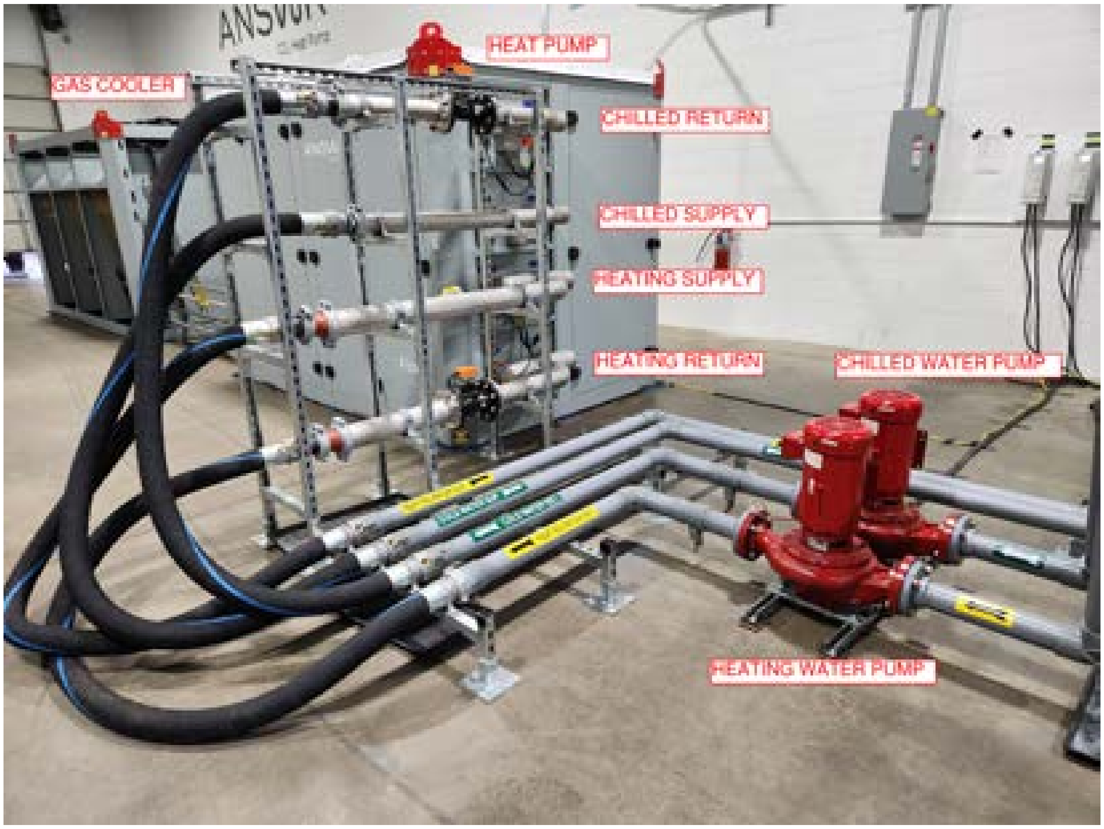

Figure 8. Heat Pump Connections and Pumping Configuration

Figure 9. Storage Tanks and Mixing Valves

DATA INSTRUMENTATION AND ACQUISITION

Data from each test listed in Part 4 – Functional Testing was recorded and submitted to Ecotope in CSV (comma separated variables) format. A separate CSV was submitted for each test. The CSV included a column for time and columns for each of the points listed in the points list. Columns for each point were labeled with the point tag. Data was collected in two-minute intervals.

Flow meters, temperature sensors, power data, operating capacities, and pump speeds were provided by FES either via installed third-party devices or via devices installed internal to the ANSWR unit. The following data points were collected:

1. Ambient room temperature (°F)
2. ANSWR unit command (ON/OFF)
3. ANSWR unit power draw (kW)
4. Primary heating water flow (GPM)
5. Primary chilled water flow (GPM)
6. Heating water enable command (ON/OFF)
7. Heating water operating capacity (% of capacity)
8. Heating water supply temperature setpoint (°F)
9. Heating water supply temperature (°F)
10. Heating water return temperature (°F)
11. Chilled water enable command (ON/OFF)
12. Chilled water operating capacity (% of capacity)
13. Chilled water supply temperature setpoint (°F)
14. Chilled water supply temperature (°F)
15. Chilled water return temperature (°F)

Part 3 – Test Procedures and Results

TEST 1: HEATING-ONLY OPERATION

Procedure:

1. Posture the system in normal operation.
2. Start recording data.
3. Simulate a condition where there is a substantial (~50%) heating water load with no cooling water load for approximately 30 minutes.
4. End recording data.
5. Release overrides.

Results: Prior to the test, the storage tanks were charged with cool water to ensure sufficient load was available to allow the >30 minutes of heating operation. The unit heating water setpoint was set to 185°F to help ensure load was greater than 50% throughout the test duration. The unit capacity ramped up as expected to try to meet the load. Supply water temperature continued to approach setpoint during the test duration as expected. No issues were encountered during the test. The test appeared to prove the unit is able to operate in a heating-only configuration. A graph showing relevant data collected during the test is included in **Figure 10** below:

TEST 2: SIMULTANEOUS HEATING AND COOLING

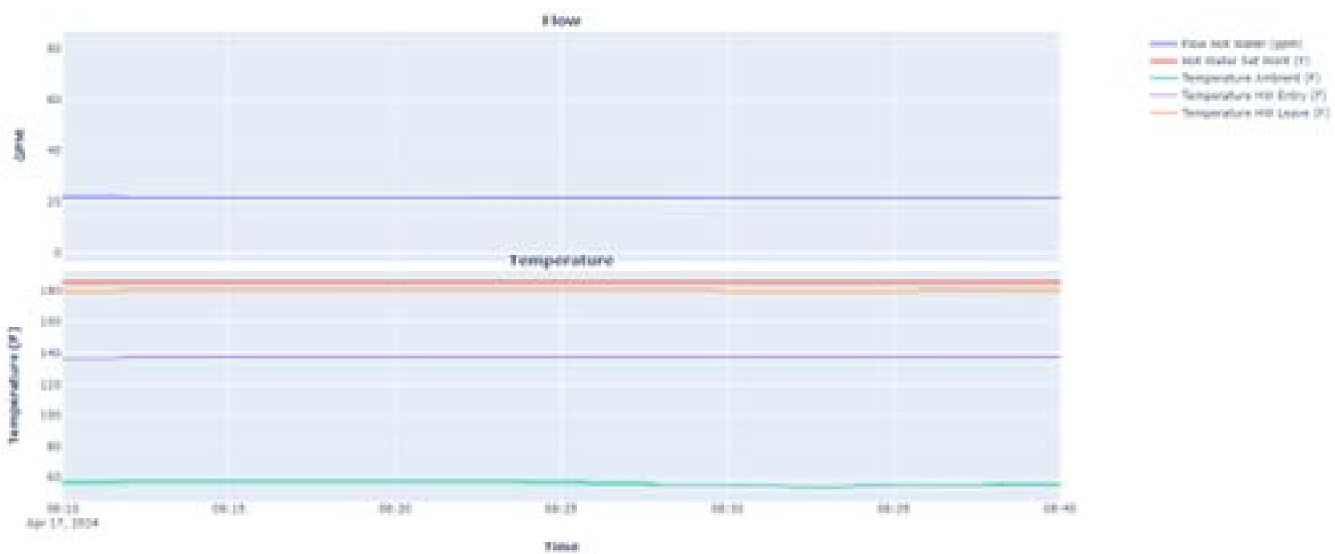

Figure 10. Heating-Only Operation

Procedure:

1. Posture the system in normal operation.
2. Start recording data.
3. Simulate a condition where there is a substantial (~50%) heating water load and a substantial (~50%) cooling water load for approximately 30 minutes.
4. End recording data.
5. Release overrides.

Results: Prior to the test, two storage tanks were charged with warm water while two storage tanks were charged with cool water to ensure sufficient load was available to allow the >30 minutes of simultaneous heating and cooling operation. The unit heating water setpoint was set to 185°F and the chilled water setpoint was set to 38°F to help ensure heating/cooling loads were both greater than 50% throughout the test duration. The unit capacity ramped up as expected to try to meet the loads. Both heating and chilled supply water temperatures continued to approach setpoints during the test duration as expected. No issues were encountered during the test. The test appeared to prove the unit is able to provide simultaneous heating and cooling. A graph showing relevant data collected during the test is included in **Figure 11** below:

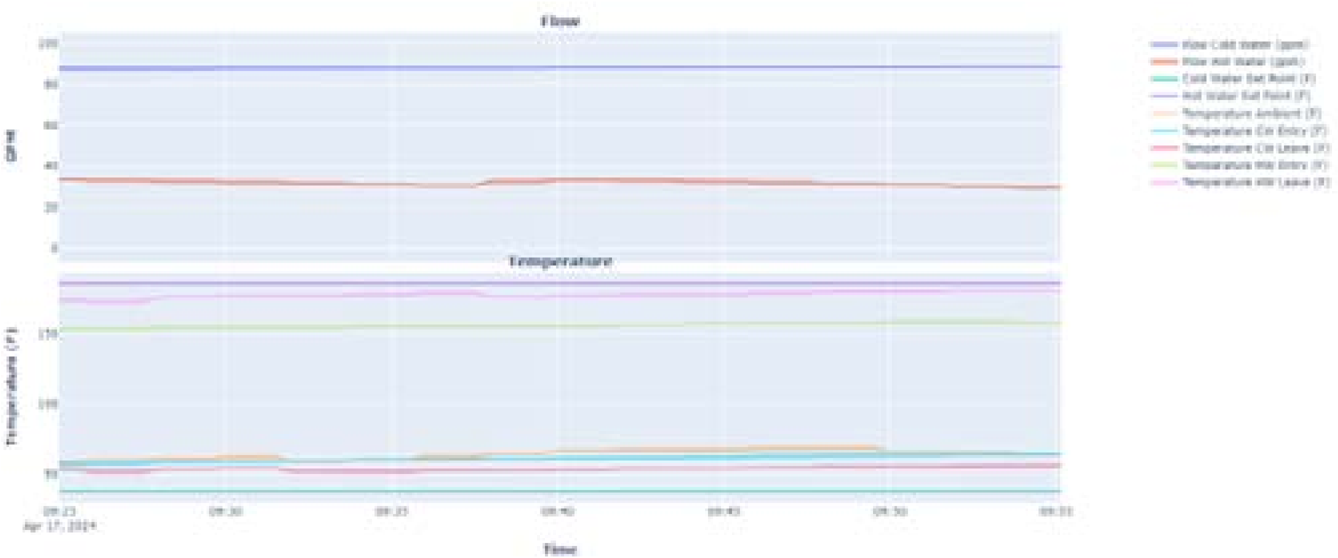

Figure 11. Simultaneous Heating and Cooling Operation

TEST 3: COOLING-ONLY OPERATION

Procedure:

1. Posture the system in normal operation.

2. Start recording data.

3. Simulate a condition where there is a substantial (~50%) cooling water load with no heating water load for approximately 30 minutes.

4. End recording data.

5. Release overrides.

Results: Prior to the test, the storage tanks were charged with warm water to ensure sufficient load was available to allow the >30 minutes of cooling operation. The unit chilled water setpoint was set to 38°F to help ensure load was greater than 50% throughout the test duration. The unit capacity ramped up as expected to try to meet the load. Supply water temperature continued to approach setpoint during the test duration as expected. No issues were encountered during the test. The test appeared to prove the unit is able to operate in a cooling-only configuration. A graph showing relevant data collected during the test is included in **Figure 12** below:

TEST 4: HEATING WITH 160°F INLET WATER

Figure 12. Cooling-Only Operation

Procedure:

1. Posture the system in normal heating operation.

2. Charge the heating water storage tank with >160°F water.

3. Start recording data.

4. Simulate a condition where ~160°F water is drawn into the heating water return for approximately 30 minutes.

5. End recording data.

6. Release overrides.

Results: Prior to the test, the storage tanks were charged with warm water to ensure warm inlet water conditions could be maintained throughout the test/ The unit heating water setpoint was set to 185°F to help ensure there was load throughout the test. The unit appeared to operate steadily throughout the test. No issues were encountered during the test. The test appeared to prove the unit is able to operate with a high inlet water temperature. A graph showing relevant data collected during the test is included in **Figure 13** below:

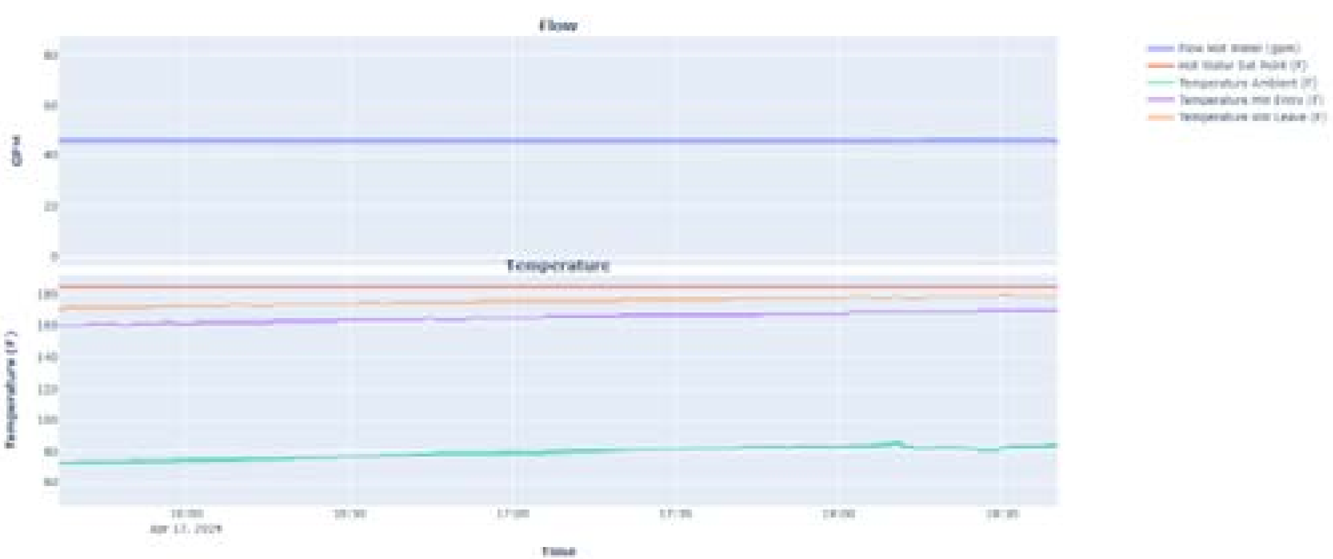

Figure 13. Heating-Only Operation with >160°F Entering Water

TEST 5: DEFROST DURING SIMULTANEOUS HEATING AND COOLING

Procedure:

1. Posture the system in normal operation.

2. Start recording data.

3. Simulate a condition where there is a substantial (~50%) heating water load and a substantial (~50%) cooling water load.

4. Simulate a condition where there are two subsequent calls for defrost of the dry cooler Continue recording data throughout the duration of both defrost calls.

5. End recording data.

6. Release overrides.

Results: Based on discussions with FES, this test was not conducted. The ANSWR product controls the evaporator inlet temperature above freezing such that defrost is not typically needed. In order to test defrost on the prototype unit, regular control of the evaporator inlet temperature would have needed to be overridden; Ecotope determined that overriding normal operation would not yield relevant results. Under normal operation, if defrost is needed, the unit uses hot-gas bypass to initiate the defrost. Ecotope suggests that monitoring of defrost operation be conducted during the first site demonstration.

TEST 6: ALARM – BLOCKED AIRFLOW AT GAS COOLER

Procedure:

1. Posture the system in normal operation.

2. Start recording data.

3. Simulate a condition where there is a significant airflow restriction through the dry cooler: restrict airflow to the unit in increments of 25% until an error is shown. Allow the unit to operate for a minimum of 30 minutes between increasing airflow restriction. Record the error code and the percent restriction which initiated it.

4. Record whether unit continues to operate.

5. Remove airflow restriction and restart unit if applicable. Record if unit requires manual intervention for restart.

6. End recording data.

7. Release overrides.

Results: Per discussions with FES before this test, there currently is not a specific trigger for a gas cooler blocked airflow condition. However, they will evaluate using specific refrigerant pressure data and gas cooler fan speed data to initiate such an alarm for production units.

TEST 7: ALARM – BLOCKED CONDENSATE DRAIN AND DRY COOLER

Procedure:

1. Posture the system in normal operation.
2. Simulate a condition where there is a substantial (~50%) heating water load.
3. Start recording data.
4. Simulate a condition where the condensate drain line at the dry cooler is blocked (e.g., plug condensate drain). Record the error code.
5. Record whether unit continues to operate.
6. Remove condensate drain line restriction and restart unit if applicable. Record if unit requires manual intervention for restart.
7. End recording data.
8. Release overrides.

Results: Based on discussions with FES, this test was not conducted. The prototype used for this applications test did not include a method of detecting a blocked condensate drain. FES currently does not have a plan to include such a detection device as the gas cooler will typically be installed outside the building envelope; in the case of a blocked condensate drain line, the condensate pan will simply overflow.

TEST 8: ALARM – LOSS OF HEATING WATER FLOW WHILE UNDER >50% LOAD

Procedure:

1. Posture the system in normal operation.
2. Simulate a condition where there is a substantial (~50%) heating water load.
3. Start recording data.
4. Simulate a loss of flow condition by deenergizing primary heating water pump (either by

setting speed signal to zero or command pump to off; record method). Record the error code.

5. Record whether unit continues to operate.

6. Restore primary heating water flow and restart unit if applicable. Record if unit requires manual intervention for restart.

7. End recording data.

8. Release overrides.

Results: With the system operating at >50% heating water load, power was shut off to the primary heating water pump by setting the Variable Frequence Drive (VFD) switch to the "OFF" position. The unit registered a loss of flow and the compressors were seen to go to an idle mode, both audibly, and visually via the on-site instantaneous data visualization tool. After a time delay, the compressors shut down though the unit remained energized in an idle state. Primary heating water flow was restored by manually setting the VFD switch to the "HAND" setting (which restored the pump speed to its initial setting). After a timed startup delay sequence, the unit was seen to re-energize, and control was restored to the last known operating state. This test successfully demonstrated automatic equipment restoration after a loss of flow condition. A graph showing relevant data collected during the test is included in **Figure 14** below:

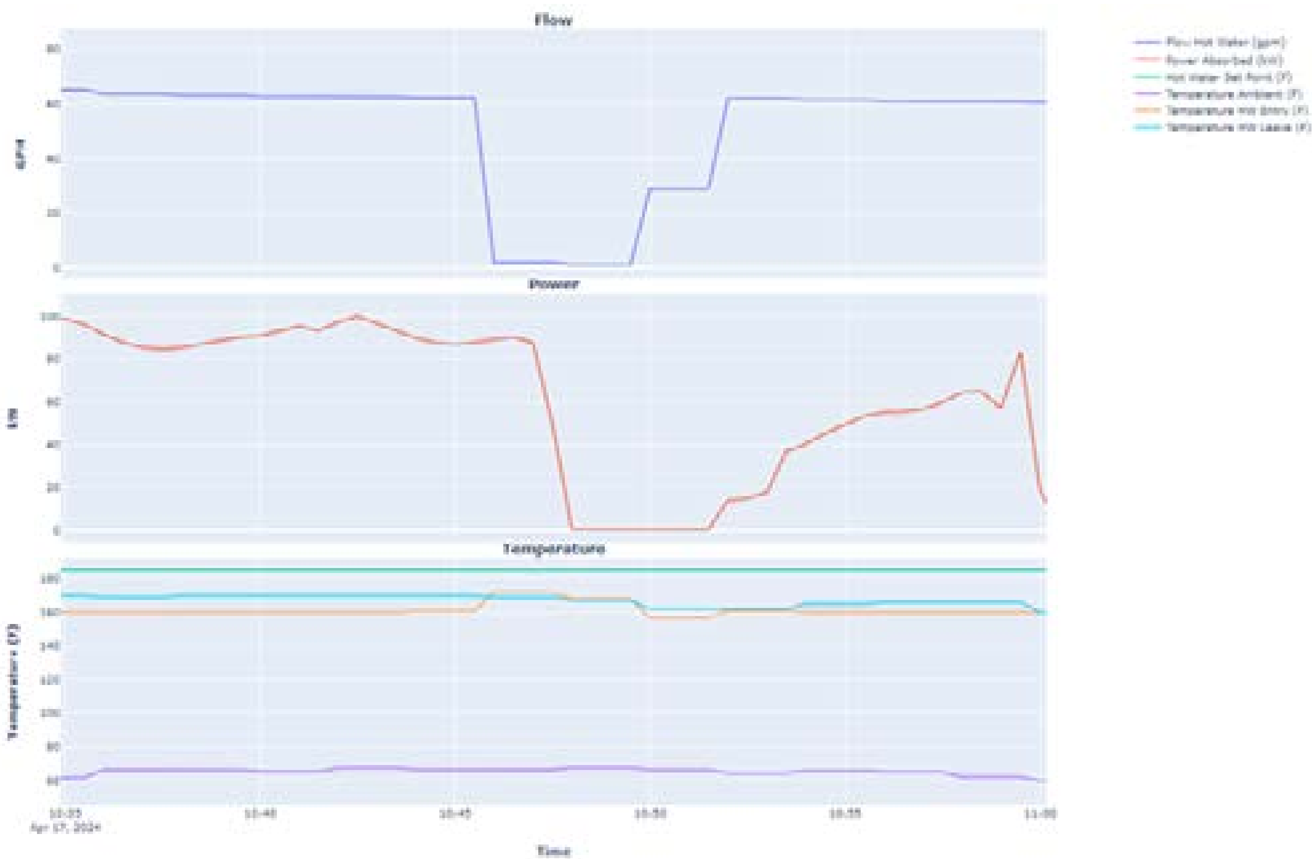

Figure 14. Loss of Flow Condition During Heating Operation

TEST 9: ALARM – LOSS OF CHILLED WATER WHILE UNDER >50% LOAD

Procedure:

1. Posture the system in normal operation.
2. Simulate a condition where there is a substantial (~50%) chilled water load.
3. Start recording data.
4. Simulate a loss of flow condition by deenergizing primary chilled water pump (either by setting speed signal to zero or command pump to off; record method). Record the error code.
5. Record whether unit continues to operate.
6. Restore primary chilled water flow and restart unit if applicable. Record if unit requires manual intervention for restart.
7. End recording data.
8. Release overrides.

Results: With the system operating at >50% chilled water load, power was shut off to the primary chilled water pump by setting the Variable Frequence Drive (VFD) switch to the "OFF" position. The unit registered a loss of flow and the compressors were seen to go to an idle mode, both audibly, and visually via the on-site instantaneous data visualization tool. After a time delay, the compressors shut down though the unit remained energized in an idle state. Primary chilled water flow was restored by manually setting the VFD switch to the "HAND" setting (which restored the pump speed to its initial setting). After a timed startup delay sequence, the unit was seen to re-energize and control was restored to the last known operating state. This test successfully demonstrated automatic equipment restoration after a loss of flow condition. A graph showing relevant data collected during the test is included in **Figure 15** below:

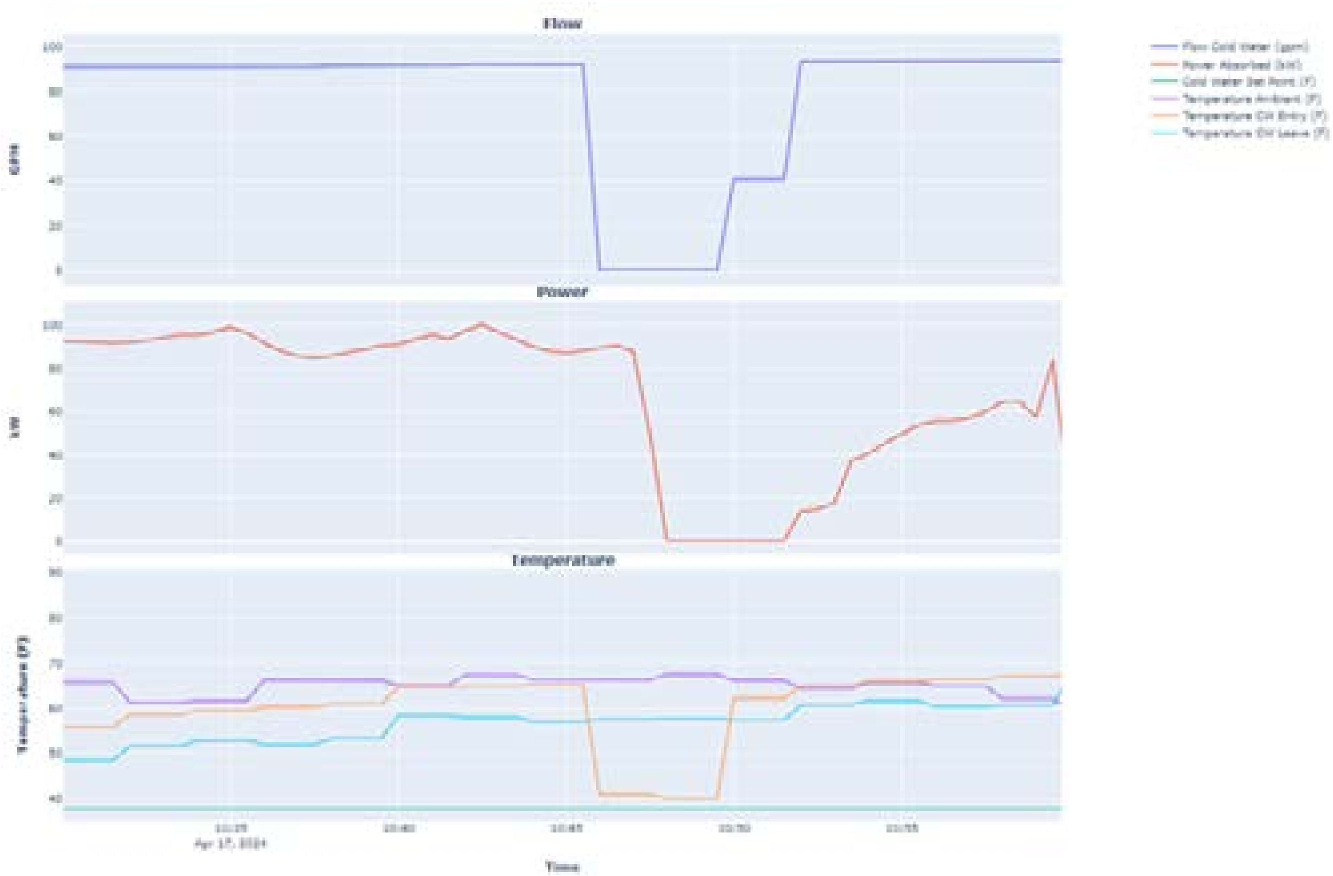

Figure 15. Loss of Flow Condition During Cooling Operation

TEST 10: ALARM – LOSS OF POWER

Procedure:

1. Confirm unit is set to restart after power loss.
2. Posture the system in normal operation.
3. Simulate a condition where there is a substantial (~50%) heating water load and a substantial (~50%) cooling water load.
4. Disconnect power to the unit for one (1) minute. The unit should restart automatically when power is provided. Record any error codes and whether the unit restarts.
5. End recording data.
6. Release overrides.

Results: Unit was de-energized by shutting off the main electrical disconnect while the unit was under load. After approximately one minute, power was restored. After a timed startup delay sequence, the unit was seen to re-energize, and control was restored to the last known operating state. This test successfully demonstrated automatic equipment restoration after a loss of power condition.

It should be noted that the loss of power test was conducted while waiting for the heating water tanks to charge with warm water to facilitate the Heating with 160°F Inlet Water test. When power was initially restored to the unit, the unit returned to the last operating state (full heating) and subsequently shut down on an equipment safety. Upon reset, the unit shut down again on the same safety. Inlet water temperature was approximately 160°F. Upon further review, the heating ramp rate of this prototype had been accelerated prior to testing for other reasons. Upon discussions with FES, the production unit will have its ramp rate slowed to prevent these safeties from activating. Since an inlet temperature of 160°F is an abnormal (unexpected) condition, the decreased ramp rate upon startup, though it should prevent the premature equipment safeties from activating, it should not be necessary as this condition should not be seen during normal operation.

TEST 11: ALARM – LOSS OF SINGLE POWER PHASE

Procedure:

1. Confirm unit is set to restart after power loss.
2. Posture the system in normal operation.
3. Simulate a condition where there is a substantial (~50%) heating water load and a substantial (~50%) cooling water load.
4. Simulate a condition where a single phase of power is lost.
5. Record whether the unit continues to run or shuts down. Record any error codes.
6. Release the phase loss condition and restart unit if applicable. Record if unit requires manual intervention for restart.
7. End recording data.
8. Release overrides.

Results: Due to safety concerns, the test could not be conducted exactly per the procedure. However, the intent of the test was met by shutting down power to the unit, removing a single fuse at the main electrical disconnect, and re-energizing the unit. The product has an on-board phase monitor which disables the unit on the loss of a single power phase. During the test, when power was restored to the unit with a fuse missing on one phase, the phase monitor was seen to activate, and the unit was prevented from starting as expected. Power was again shut down, the fuse was replaced, and power was restored to the unit. After a timed startup delay sequence, the unit was seen to re-energize, and control was restored to the last known operating state. This modified test successfully demonstrated the phase loss protection feature and met the intent of the test procedure.

Works Cited

1 U.S. Energy Information Administration (EIA), Monthly Energy Review (September 2023).

2 U.S. Energy Information Administration (EIA), 2018 Commercial Buildings Energy Consumption Survey (December 2022).

3 Bonneville Power Administration. Energy Efficiency Action Plan 2022-2027. www.bpa.gov/energy-and-services/efficiency/action-plan/. Accessed 13 Feb. 2024.