SMTI Stone Mountain Technologies, Inc.

Pre-Commercial Scale-Up of a Gas-Fired Absorption Heat Pump
DE-EE0008219

Final Report
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LEGAL DISCLAIMER

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Executive Summary

The objective of the project was preparation for manufacturing and commercialization of an 80 kBTU/hr gas-fired absorption heat pump (GAHP), using natural refrigerants with a heating COP of 1.45 at 47°F. Current gas furnaces are fundamentally limited to COPs < 1.0. SMTI's GAHP technology goes well beyond this to significantly reduce the primary energy requirements for space and water heating for an estimated primary energy savings technical potential for 2030 of 1504 TBtu. Current heating appliances using any fuel with COP > 1.0 are limited in cold climate applications for capacity and/or efficiency, or have prohibitive costs. Optionally installed as a "combi" system that includes domestic water heating, a highly cost-effective method will be also offered to address an additional and important residential energy load beyond space heating.

The project team (SMTI, Trane and GTI) was able to advance the design of the GAHP and system to a pre-commercial status by addressing the goals outlined in the statement of work.

(1) The GAHP underwent significant design for manufacturing (DFM) advancements in an effort to reduce cost to projected targets and improve manufacturability and reliability of component and system design while minimizing impact on GAHP performance. The design of the sealed system was simplified significantly. Performance testing of two sets for prototypes showed that this DFM work did not negatively impact system performance.

(2) Compliance was demonstrated with 95% of the ANSI Z21.40.1 standard with the remaining items open due to test facility requirements beyond those currently available to SMTI. Combustion safety testing of the unit was completed and the unit passed initially with the exception of the blocked vent test that required the addition of a second air proving switch. All heat exchangers except for one passed the 3x operating pressure test (3x 450 psig or 1350 psig). Shell material thickness of the failing heat exchanger was increased one gauge size to provide compliance.

(3) A detailed manufacturing plan and facility layout for the GAHP were completed. This included the development of automated manufacturing techniques for the heat exchangers and solution pump that make up the core of the sealed system. Production cost estimates were within 10% of target at a volume of 50,000 units per year and CapEx requirements were within prior target estimates.

(4) A reliability test plan was developed collaboratively between SMTI and Trane. An ALT test of a full system from the 2018 prototype build was initiated and the unit has accumulated over 5000 hours of operation. Reliability testing was initiated on the solution pump with four pumps being installed on a specially constructed ALT stand. Planning was completed for reliability testing of desorber and other heat exchangers of the sealed system.

(5) A field demonstration was completed in Wisconsin with a combination space and water heat and space heat only installation. This was the first effort with Trane based GAHP and System

controls. The demonstration highlighted the potential of the GAHP system but also many of the potential pitfalls if the GAHP and indoor system are not controlled properly.

(6) A detailed Techno-economic analysis was completed that highlighted the potential energy, cost and CO2 emissions savings potential of the GAHP in comparison with more conventional gas and advance electric heat pump technologies. The study showed that the GAHP system offers a 36-50%, 21-39% and 23 to 61% natural gas, operating cost and carbon emissions savings, respectively, depending on the technology it is compared with. In all cases, carbon emissions are lower using a GAHP than an advanced electric heat pump. The study also highlighted that the payback for investing in a GAHP is highly sensitive to the price of natural gas.

(7) A market research study was completed that showed that there is significant opportunity in the market for a reasonably priced GAHP technology. The price-demand curve suggests, based on current market and regulatory conditions, GAHP potential sales into furnace replacement situations ranges from 140,000 to 219,000 units per year depending on the total installed cost.

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1.0 Introduction

Thermally driven heat pumps (TDHP) have the potential to serve as drop in replacements for furnaces and boilers while offering a next step in heating Coefficient of Performance (COP). In cool and cold climates, thermally driven heat pumps offer more reliable and comfortable heat at lower carbon emissions compared to cold-climate electric heat pumps. Unfortunately, a low cost thermally driven heat pump option is not yet commercially available.

With the support of the natural gas and propane industry, US Department of Energy (DOE) and commercialization partners, SMTI has progressed its gas absorption heat pump (GAHP) design from proof-of-concept to prototype field demonstrations with heating capacities ranging from 10 to 140 kBTU/hr (3 to 40 kW). This development has focused on a single-effect ammonia-water absorption cycle that is reliable and easy to control, uses standard materials, mass-producible heat exchanger designs, and a novel direct-acting solution pump.

Under DOE grant EE0003985[1], SMTI developed a residential heat pump water heater prototype (3 kW) with a target UEF of 1.2-1.3. Follow-on support allowed for design refinements and the installation of thirteen successful field test installations[2,3]. The most recent of which was completed in late-2019 in the Los Angeles area under a CEC grant with the Gas Technology Institute (GTI).

Under DOE grant EE0006116[4], SMTI developed a larger model (80 kBTU/hr, 23 kW) for residential space heating. Follow-on support has resulted in design refinements and initial field test demonstrations[5,6] on a 2,200 sqft home (providing space and water heating) and small warehouse. A ‘Beta’ prototype was tested by the Gas Technology Institute (GTI) and achieved an AFUE[7] of 139%. Another ‘Beta’ prototype was installed on a 2700 sqft home in North-west Wisconsin in early 2018. Two 23 kW field test units were installed on restaurants providing water heating with simultaneous space cooling in early 2019.

Under a CRADA with ORNL and an OEM partner, SMTI developed a 140 kBTU/hr (40 kW) model for light commercial heating[8,9]. A 40 kW prototype has been undergoing field testing at a commercial laundry facility since early 2018.

The following effort focused on advancing the maturity of SMTI’s 80 kBTU/hr residential space/water heating GAHP from the current engineering prototype stage (TRL-7) to pre-production readiness by addressing remaining manufacturing, balance of system/control design and installation, cost, reliability, and field application questions. Although the focus was the 80 kBTU/hr model, all of the work proposed can be transitioned to all product sizes and models.

2.0 Scope of Work & Project Tasks

The project sought to advance the maturity of SMTI's 80 kBTU/hr residential space and water heating GAHP from the engineering prototype stage (TRL-7) to pre-production readiness by addressing manufacturing, balance of system design and installation, cost, reliability, and field application questions. As part of this project, the project team has:

(1) Matured the design package for a commercially ready product
(2) Demonstrated compliance with relevant ANSI standards
(3) Completed manufacturing and assembly process specifications
(4) Completed total production cost estimates and capital equipment requirements
(5) Initiated component and system level reliability assessments
(6) Completed a small field demonstration including measured performance, installation requirements and expected costs, and customer/key stakeholder feedback.
(7) Completed a Techno-economic analysis for representative applications and climate zones, including justification for utility incentive programs.
(8) Completed a market intelligence report

Scope of Work: A multi-faceted project was completed that included: (a) design for manufacturing tasks for both the sealed system and balance of system, (b) development and trial of key manufacturing processes and techniques, (c) evaluation of component and system level reliability, (d) exploration of make/buy decisions including impact on cost and required capital. Additionally, (e) installation and monitoring of a small number of field test units was completed to demonstrate energy savings and collect customer/installer feedback, and (f) a focused market research task was completed to explore potential barriers and improve market introduction plans.

These tasks addressed many of the remaining technical risks regarding long-term reliability, verification of manufacturing cost estimates and identification of cost concerns, identify installation and balance of system design criteria necessary to achieve energy savings and installed cost goals, and identify market barriers and strategies prior to product market introduction.

Task 1.0 Develop and Deliver Intellectual Property Management Plan (IPMP): At the start of the project, SMTI, the commercialization partner and the research partner established and formalized an IPMP.

Task 2 Design for Manufacturing: For the engineering prototypes produced previously, SMTI had designed and assembled the entire end-use product, which can be broken into two major sub-assemblies: (1) the sealed system, or all of the absorption cycle heat exchangers (and solution pump) which contain the working fluids under pressure and (2) the balance-of-system, or all other components required for an end-use product controls, combustion system, fans, motors, hydronic loop, insulation, and cabinetry). SMTI had predominately focused on the sealed system, as the balance of system has always been intended to be provided by an OEM/commercialization partner.

During Task 2, SMTI modified the sealed system design to reflect the use of production tooling and automated fabrication/assembly techniques. This was an iterative process between design (form, function, reliability and safety) and manufacturing engineering (process, equipment, tooling, cost and material availability) functions. In parallel, the commercialization partner completed design and specification of the balance of system components/controls, combining desired end-use product features and current product design/manufacturing capabilities. SMTI and commercialization partner worked cooperatively on heat pump control algorithm development. This task required significant SMTI participation, as the balance of system design has significant impact on the function and reliability of the end-use product. Additionally, SMTI worked with the commercialization partner to design an optimal air-handler and (optional) indirect storage tank for the GAHP, based on prior testing and development work performed by SMTI.

Task 3 Demonstration – Stage 1: Four (4) GAHP prototypes were fabricated, assembled and tested, based on the design completed in Task 2. Since production equipment and tooling was not available, the prototypes were fabricated “as close as possible” to the Task 2 design. All four prototypes were initially tested by SMTI to verify performance consistency with prior engineering prototypes.

One unit was delivered to the commercialization partner for performance testing in their laboratory. At the end of Task 3, confirmation that the design for manufacturing task did not impact performance or function was completed, baseline field performance was documented, and feedback from key stakeholders (contractors and home owners) obtained.

Task 4: Codes and Standards Analysis: The research partner reviewed and analyzed codes and standards relevant to the GAHP system. This included ANSI Z21.40.1, IIAR-2, other relevant standards and buildings codes, and an analysis of condensate management requirements. Recommendations for future codes and standards development or improvements were generated.

Task 5: Market Assessment & Analysis: The commercialization partner’s ultimate decision to internally commit the capital investment for manufacturing a GAHP furnace will, in large part, be determined by the strength of the business case and expected market penetration. Besides the basic technical question, “Will it work?” it is imperative to also ask and answer, “Who will buy it and why?” SMTI and the commercialization partner engaged a professional market research firm with deep experience in the HVAC industry. Using a combination of secondary and primary research methods, and in close coordination with the commercialization partner, SMTI developed data to support regionally-specific sales projections, as well as market entry strategies designed to maximize market acceptance. While the home-owner makes the final purchase decision, installation contractors play a critical role in the vast majority of gas furnace sales transactions. Thus, their acceptance and support of the product is important for market uptake. Using best-practices for gathering both qualitative and quantitative data, this task formulated and tested important market response hypotheses for consumers and contractors regarding product features, economics, and sales channels, and identify and test market barrier mitigation strategies to enhance GAHP acceptance.

Task 6: Manufacturing Process & Demonstration: Manufacturing processes, equipment and tooling required for the sealed system were developed and specified. For assemblies where specialized automated assembly processes are required (such as the absorber, condenser and desorber), bench-scale proof-of-concept assembly equipment and tooling were designed and fabricated in order to demonstrate functionality and cost (process time and labor). Vendor quotes for certain components or sub-assemblies were solicited in order to complete make/buy decisions. In parallel, the commercialization partner completed end-use product assembly process development, identification of required equipment and tooling, and development of a prototype integrated control board.

Task 7: Demonstration: Two units, along with prototype hydronic air-handers provided by the commercialization partner, were installed as field test units, at residence locations in Northwest Wisconsin. The research partner provided M&V services. The Commercialization partner also completed lab testing of a prototype unit.

Task 8: Manufacturing Process & Demonstration – Stage 2: All manufacturing processes, equipment and tooling required for the sealed system were developed and specified. For assemblies where specialized automated assembly processes are required (such as the absorber, condenser and desorber), bench-scale proof-of-concept assembly equipment and tooling were designed and fabricated in order to demonstrate functionality and cost (process time and labor). Vendor quotes for certain components or sub-assemblies were solicited in order to complete make/buy decisions. In parallel, the commercialization partner completed end-use product assembly process development, identification of required equipment and tooling, and development of a prototype integrated control board. At the end of Task 8, manufacturing processes were determined, equipment and tooling requirements identified (including capital cost estimate), and an estimate of the final heat pump manufacturing cost at volume developed.

Task 9: Reliability Assessment: Prototypes were subjected to testing required by ANSI Z21.40.1 Gas-Fired Air-Conditioning and Heat Pump Appliances, after which any deviations were identified and corrective actions taken. One unit assembled in Task 3 was installed on accelerated reliability test stands at SMTI, where it was operated 7-days a week, 24-hrs a day (allowing for programed start/stop cycles). Critical individual components were subjected to initial component-level accelerated reliability testing. Two new GAHP prototypes, reflecting the culminated development activities of this project, were built and tested. At the end of Task 9, an initial reliability assessment and action plan was completed.

Task 10: Techno Economic Analysis: The Research partner completed a techno-economic analysis for representative applications and climate zones, including justification for utility incentive programs. Using EnergyPlus and GAHP performance data provided by the commercialization partner and SMTI, the research partner modeled three representative homes located in nine cities, assuming three types of heating equipment: (1) standard 80% non-condensing furnace, (2) 92% condensing furnace, (3) GAHP, (4) 7.7 HSPF electric heat pump (EHP) and (5) 10 HSPF cold climate EHP. For each case, the total seasonal heating energy use (natural gas and electric) and utility cost (using local rates) were calculated. Consumer simple pay-back, IRR and total product life cost for each case were developed, using projected retail price and installation cost estimates developed by the commercialization partner and SMTI. The research partner conducted the analysis and reporting in terms necessary for gas utilities to develop preliminary rebate programs.

3.0 Task 2: Design for Manufacturing

3.1 Sealed System Design

Significant redesign of the sealed system assembly was performed, including the integration of components, elimination of parts and number of welds, reduction in the number of tube sizes and tube wall thickness variations, and relocation of components to improve compactness and serviceability. The width of the sealed system was reduced from 38 to 34 inches. This reduction not only reduces cost, but was identified as an important feature so that the heat pump will fit through a 36” wide gate during installation. Significant attention was given to the smaller details of the system. This included plumbing between components, service considerations, interface points between the sealed system and auxiliary systems (hydronic, gas and electric), reduction of welds and simplification of routing, and the defrost valve.

<u>Heat Exchangers:</u> Each heat exchanger was assessed individually to evaluate manufacturability. Individual components were revised to reflect volume production using tooling (compared to starting point using components that could be produced without tooling), and heat exchanger assembly using automated techniques. One assembly was eliminated altogether by incorporating its function into another assembly. The layout of the heat exchangers was evaluated with a focus on reducing connecting tube lengths, bends and welds, as well as ease of replacement and service if ever required.

<u>Evaporator</u>: The evaporator coil that exchanges heat with the outdoor air is the largest and one of the most expensive components of the system. The prototypes fabricated during this project used a higher fin density than previous units, allowing for a slight reduction in overall component size. Air flow testing with the higher fin density coil was performed to evaluate the coil-fan-motor assembly. It was determined that fan-motor assembly in use was able to meet air flow requirements with the higher pressure drop of the smaller coil containing more fins per inch.

Modeling of a continuous finned tube evaporator showed potential to significantly reduce component size and weight. The team explored options to produce a prototype evaporator using carbon steel tubes (required for use with ammonia-water), an option that is not commercially available at this time. SMTI investigated the availability of a prototype finning system with a small manufacturer who had previously made this finned tubing. Unfortunately, the company no longer had the equipment available and would have to build a whole new system from scratch. A sample aluminum continuous finned tube coil, provided by the commercialization partner, was retro-fitted into an older GAHP prototype. The goal of this test was to evaluate effectiveness of the continuous fin in this application, even though the aluminum tube material was not been proven for long term use. Although the small tube diameter presented inlet and outlet header challenges, overall acceptable performance of the coil was demonstrated. However, detailed performance testing was limited by the headers and limitation of the old GAHP prototype which had been out of service for more than a year.

Service valves: The sealed systems previously used industrial type service valves (only option available due to use of ammonia refrigerant). These valves work reasonably well but are bulky, high cost and have known long-term reliability problems. Two paths were pursued in parallel to identify a lower cost option.

1. SMTI worked with a service valve manufacturer whose products are more typical of that used in the HVAC and refrigeration industry. The service valve manufacturer provided a final design with a weldable valve body and removable core/valve. Production and prototype quotes for these valves were received.
2. SMTI investigated a lower cost service valve option using an off-the-shelf part originally designed for a different application. This assembly is lower cost than the above mentioned valves and could be assembled by SMTI. SMTI completed testing with this prototype valve with positive results. SMTI also developed a service valve tool to open and close the valve when connected to a refrigerant service hose. This design progressed to the point that these valves were included on the pre-commercial units built in the fall of 2019.

At present, SMTI is continuing to pursue the low cost service valve that would be assembled in-house by SMTI. Further work to prove out this design and its reliability is ongoing.

Defrost valve: The defrost valve is used to flow hot ammonia vapor directly to the evaporator coil and melt frost/ice build-up that occurs during operation in a temperature and humidity band around an outdoor temperature of 32°F. Snow or freezing rain accumulation on the coil is another instance where defrost would be required and has been observed in a prior field demonstration. SMTI currently uses an off-the-shelf valve for implementing a defrost cycle. The cost of this valve is relatively high and two paths were pursued in parallel to identify a lower cost option. SMTI investigated internally designed options and evaluated other low cost off-the-shelf options.

SMTI investigated two internally designed and three “off-the-shelf” options for the defrost valve. Variations to the internal design concepts being pursued were implemented and bench tested. Performance was found to be similar or better than the off-the-shelf valves, but reliability/repeatability was questionable.

Samples of the lower cost “off-the-shelf” options were delivered and bench tested. These valves were shown to have performance similar or better than prior valves, and were installed and tested in prototype units. Based on testing to date, three “off-the-shelf” options are viable options. Production cost will likely be the decided factor on the defrost valve selected for production.

Solution Pump: A design for manufacturing effort was completed on the solution pump. Design changes were made to reduce part count, cost and assembly time. The solution pump contains a large number of parts, many of which can be consolidated with advanced manufacturing techniques not available for typical prototyping (casting, spray coatings, over-molding and others).

The solution pump was simplified with the reduction and combination of parts to complete the same functions with reduced cost and increased effectiveness. A specific example of this is the main body of the pump which is designed to be a single cast part and was previously assembled from 7 individual parts. By pursuing a single cast part, the overall cost was reduced as well as the reliability of the pump by reducing the number of leak paths.

Assembly methods of the redesigned solution pump were evaluated. The elimination and integration of parts simplified the overall design but has required additional thought specific to prototype and production level assembly. The solution pumps used for the prototypes were an intermediate design that allowed for the evaluation of many of the production level design and assembly concepts.

Off-the-shelf inlet and outlet check valves for the solution pump were investigated in addition to internal design improvements. A low cost off-the-shelf outlet check valve is in use in SMTI’s smaller pumps and a larger version of the valve was tested and initially proved to be less reliable. A more robust design was then provided by the vendor and bench tested in a solution pump before installation in an 80K prototype. This upgraded valve showed promise but failures were later encountered on accelerated life test units and several units in the field. This resulted in further design work by the check valve manufacturer to design an even more robust valve. It also required the manufacturer to learn more about the specific pumping application.

An off-the-shelf inlet check valve was initially pursued but did not end up being a good fit after additional conversations and data review with the supplier. SMTI did learn about the modular design of these cartridge style valves from this evaluation and a cartridge style valve designed that meets SMTI’s requirements was developed for in-house production.

3.2 Balance of System Design

An evaluation of the balance of system parts was performed by the commercialization partner with support from SMTI. This balance of system design focused mostly on the high cost parts where the commercialization partner has purchasing leverage.

A detailed review of motor options and solution pump drive configurations (current prototypes utilize a belt drive) was completed. This included sourcing of sample PSC and ECM motors to bench test in belt and direct drive configurations. The standard ECM was found to stall at the higher pressure head tests. This was expected based on prior ECM testing performed by SMTI. Consensus was to use a high efficiency PSC motor and leave the solution pump as belt driven based on the work completed. ECM options are still being pursued but a reliable solution has not yet been identified. Balancing motor cost and efficiency, and drive system reliability were the major focus.

The commercialization partner has two standard outdoor fan motor assembly sizes. For production, one of these two will be integrated in final system to take advantage of high volume pricing. Testing of the two sizes was completed and showed that the standard single speed motors included in these assemblies did not have sufficient power to overcome the pressure drop of the coil (this was not surprising). The commercialization partner supplied an ECM fan motor equivalent in size to what SMTI used on prior prototypes but from one of their high volume suppliers. Testing with this motor was positive and showed that the motor had more than enough power to provide the required air flow rates for the system at high efficiency.

Controls:

SMTI developed a control requirement specification for the GAHP and the auxiliary systems that it could be connected to (air handler, hot water storage tank, hydronic pump and valves) and Trane identified an available printed circuit board (PCB) that would meet the control requirements of the GAHP. Prior GAHP prototypes used PLC based controls which are bulky and not representative of a commercial project. The move to a PCB is a major step and requirement for a commercial system. Both size and cost are major factors for this.

Using the control specification provide by SMTI, the commercialization partner developed software for control of the GAHP and the indoor system that could readily interface with their production equipment (Thermostat, AHU blower, etc.). First boards with software were produced and implemented on the prototypes tested as part of this project. Initial testing with the GAHP boards and software were positive and improvements were made throughout the project. However, the commercialization partner produced GAHP and system controls have still not reached the performance and reliability level of that previously achieved with SMTI's PLC controls.

A combustion system supplier worked with the project team to develop and supply modulating combustion control boards for the prototype and commercial units. In production, these boards will have to be CSA certified which is why they will be built separate from the main GAHP control board.

Detailed wiring diagrams for the prototypes were developed and will be used as the boards and design are moved further to a commercial product.

Combustion System:

Beckett Thermal Systems, Inc. (combustion system supplier) developed the combustion system and controls for the pre-commercial system. This development included:

- Design of a cast manifold to connect the desorber, burner and premix blower-mixer-gas valve assembly. This single cast part will replace an assembly that was previously made out of 7 parts (tubing and laser cut parts) that were welded together. The manifold also includes the sealing interface surface and ports for the igniter and flame sense rod.

- Switch from a hot surface ignition and to spark ignition. Based on discussion with the combustion system supplier it should improve reliability, specifically during cold ambient starts.
- Design of a lower cost fuel-air mixing venturi.

3.2.1 Cold Ambient Modulating Gas Valve Assessment

Using a modified climate chamber, GTI evaluated off-the-shelf combinations of components from three major suppliers: Honeywell, ebm-papst, and SIT. These gas valves were rated for a minimum -15°C/5°F (Honeywell) and 0°C/32°F (SIT, ebm-papst). An overall summary of results are as follows:

- **Modulation of 4:1 at 0°F:** By calibrating combustion at a nominal 47°F condition, all combinations were able to modulate firing rate at 0°F, however some equipment exhibited flame stability and/or excessive CO emissions at the 25% firing rate and, in some cases, the 50% condition. It is worth noting that not all combinations of gas valves, venturis, and blowers were rated to cover the intended modulation range (13,750-55,000 Btu/hr or 4 to 16 kW), namely the venturies for the SIT and Honeywell have lower rated limits of 17,000 Btu/hr or 5 kW. Improvements were made to the test rig controls for back-pressure, which in turn improved the ability of test samples to meet the criteria. Of all combinations evaluated to date, the SIT system was best able to retain good combustion stability over the modulation range.
- **Full-Fire Cold Start at -20°F:** Using the same calibration from operation at 47°F, all product combinations evaluated were fired from a cold start in a -20°F environment. The combination of components from SIT, Honeywell, and ebm-papst (the NRV77 product, specifically) were able to ignite and sustain combustion from a -20°F cold start, however some had poor combustion (high CO emissions, moderate noise). The SIT product was able to fully modulate at this condition as well.

From these preliminary results, GTI confirmed that:

1) Off-the-shelf combinations of components (blower, gas valve, venturi mixer, controls) are, for the Gas Absorption Heat Pump's (GAHP) target operation, able to support 4:1 modulation at 0°F and sustain ignition from a -20°F cold start. This is despite the components' operation below their rated ambient temperature.
2) Auxiliary heating within the GAHP enclosure for cold starts at -20°F will not be necessary.
3) For components evaluated, using pneumatic control or a zero governor valve to maintain fuel/air mixing ratios, modifications may be necessary to meet the milestone goal while maintaining acceptable CO emissions and operational noise, depending on the product selected.

A detailed report covering the testing and evaluation to date is included as Appendix A.

Indoor System:

The commercialization partner designed an intermediate air handler for the field demonstration using their existing electric heat pump air handler platform. Sizing of the hydronic coil was completed using performance targets provided by SMTI. A production level product sized to be a drop in replacement for a furnace was later designed and prototypes built.

The DHW storage tank sourced for the field tests was an of the shelf design but it has a high cost because it is constructed from stainless steel. SMTI evaluated a lower cost "production" indirect storage tank and reached out to prospective vendors. This lower cost option will be a glass lined carbon steel tank with an indirect coil sized similarly to those used in the field demonstration.

4.0 Task 3 & 7: Demonstration

4.1 Assembly and SMTI Lab Testing of 4 Prototype GAHPs

The design of an intermediate prototype that used as much content as possible from the DFM work (Task 2) was completed during the summer of 2018. This design was used as the blueprint for fabrication of the four GAHP prototypes in the fall of 2018. Fabrication of the prototypes took place over the course of several months.

Assembly of the first prototype was completed towards the end of September 2018. Figure 1 presents several images of the first prototype. The outer dimensions of the system are 34" x 47" x 46" (W x L x H). Both width and weight were reduced between these and prior prototypes. This unit was installed in one of SMTI's test rooms and underwent laboratory testing beginning on October 1. The focus of testing was split between improving system controls and performing steady state performance tests. The control software was written with documentation and support from SMTI but testing on a real unit helped to identify mis-alignment with the documents and code as well as other issues and bugs. Testing was be completed through early November. At this time, the unit was shipped to Lacrosse, Wisconsin to be installed as a field test unit.

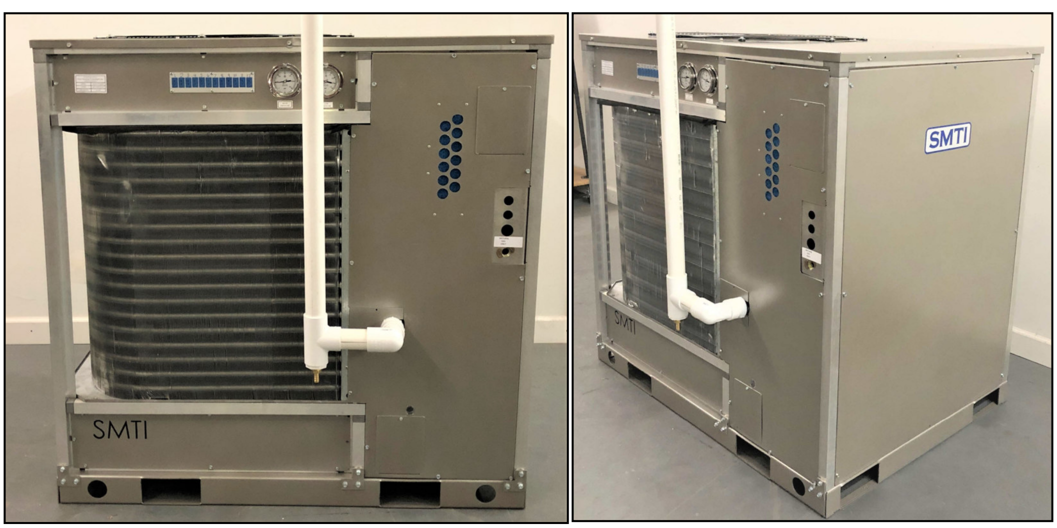

Figure 1: Images of of the first prototype unit (Beta 6)

Assembly of the second sealed system was completed in October 2018. Testing was completed by mid-November. The unit was then shipped to Wisconsin to be installed as the second field test unit. Assembly of the third and fourth sealed systems were completed shortly after completion of the second unit. The third unit was tested through late December and delivered to the commercialization partners engineering test facility. The fourth unit remained at SMTI for more extensive testing and evaluation.

Figure 2 presents data for the 4 prototypes at an ambient of 47°F and several return water temperatures including the design of 100°F. The plot shows that there is some variation in the COP_gas values recorded for the prototypes and that all achieved COP_gas values above the 1.40 Milestone and Go-No Go target. There is some scatter in the data and this is expected due to variation in system settings like target superheat, impact of prototypes being hand built and expected error with the test facility. Maintaining a high level of performance with the degree of DFM modifications implemented was a big step in moving towards a production ready system.

A detailed performance review of the components that make up the heat pump was performed using the test data collected. The evaluation of temperatures at the inlet and outlet of each component showed that the Absorber was underperforming compared to the prior set of GAHP 80K prototypes fabricated by SMTI. The lower than expected performance of the Absorber impacted the performance of other components in the system, most notably the Rectifier and therefore the ammonia purity entering the condenser.

The absorber component experienced no fundamental change in functional design between these prototypes and the prior sets fabricated by SMTI, but experienced a slight reduction in performance. This was noted by evaluating the temperature difference between the ammonia-water solution exiting and the hydronic line entering the component. This temperature difference from prior units was between 7-10°F at design and was 13-15°F for the four prototypes tested. SMTI engaged the supplier used to fabricate this component to understand if there was a difference in materials used, assembly process, or some other cause for the reduction in component performance. Note that all of our heat exchangers at this point are “hand built and assembled”, without tooling, so part-to-part and lot-to-lot variation is expected.

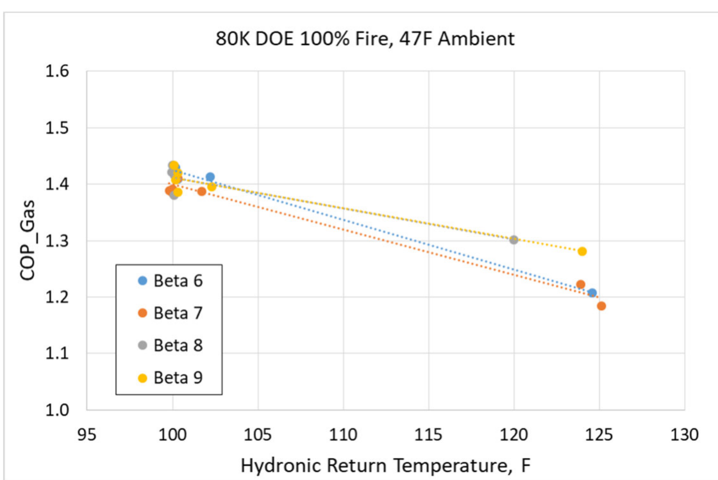

Figure 2: Steady state performance of the GAHP prototypes at the design ambient and firing rate

Overall, the difference between the measured COP of these four units (nominal 1.40-1.43) and our previous "best" performance (1.45) was the slightly higher strong solution temperature exiting the absorber, which slightly reduces our strong solution concentration and vapor purity exiting the rectifier (the reason (confidential) for the low Absorber performance was discovered later in the project).

The RHX and SHX underwent orientation changes that did not impact component performance. The evaporator was reduced in size but had its fin density increased. This change was critical to getting the width of the component below 36 inches. This change did not appear to impact component or system performance. The Desorber and Condenser designs were relatively unchanged and their performance was maintained with these prototypes.

4.2 Lab testing of GAHP Prototype by Commercialization Partner

Figure 3 shows one of the GAHP prototypes installed in the commercialization partner's environmental chambers. The unit was used to verify SMTI performance data, and prove out GAHP and system controls. This unit extensively during the 2019 portion of the 2018-2019 heating season to evaluate GAHP and System controls. Having the unit onsite provided a platform to complete controls development work and build confidence in changes before deploying to the units in the field. It also provided the ability to recreate and troubleshoot control scenarios observed with the field test units.

Steady state testing was completed over the course of several months in-between controls trouble shooting and development. A COP_gas value of 1.41 was recorded at 47F/100F/100% fire and verified SMTI recorded performance at the design condition. A COP_gas value of 1.45 was recorded at a 47F/95F/25% fire operating condition that corresponds to an AFUE test point.

4.3 Field Demonstration

A field test plan was developed using previous field test monitoring and validation resources. Two homes were selected in the Lacrosse, Wisconsin area for the purpose of the field test (Table 1 and Figures 4 and 5). Baseline monitoring equipment for the field demonstration was installed

Figure 3: GAHP installed in 'outdoor' test room (left), AHU installed in 'indoor' test room (right)

in March 2018. The un-seasonably cold weather that carried into April provided good data pertaining to the baseline heating systems within both homes. Appendix B provides a detailed baseline field demonstration M&V report. Overall the report shows that both homes were a good fit for evaluating performance of the GAHP systems in residential cold climate applications. Site A and B were selected to be combi and heating only installations, respectively, based on the space and water heating loads observed during the baseline monitoring period.

Installation and Commissioning: The project team collaborated on the development of a set of installation documents to be provided to the HVAC contractor to prepare them for the installation of the two units in December 2018. These documents included sub-assembly diagrams, wiring diagrams, plumbing diagrams and a breakdown of responsibilities for all parties participating in the installation.

Table 1: Site Details

Site	Home Details	Occupants	Existing HVAC	Existing DHW Equipment
Site A	Two-story, 1973 build, 2,451 sf	2 Adults	Gas Furnace, Dual stage, 100 kBtu/h input, 96.7% AFUE	Standard Gas Storage, 40 kBtu/h, 40 gal.
Site B	Two-story, 1978 build, 1700 sf, full basement	2 Adults	Gas Furnace, Single stage, 80 kBtu/h input, 78% AFUE	Standard Electric Resistance, 80 gal

Figure 4: Photos of Site A

Figure 5: Photos of Site B

Installation of the two field test units was completed the week of December 10, 2018. Figures 6 and 7 show the units installed on the two homes in La Crosse, WI. Personnel from the project team were on site for the commissioning of the units.

2018-2019 Heating Season: Operation of the GAHPs, with Trane based controls continued through mid-January before starting to encounter intermittent issues. Figures 8 and 9 present plots developed by GTI that show the delivered energy, DHW gallons drawn, number of cycles and average ambient. The plots show a high rate of on/off cycling (No. of Cycles) that reduces with time as controls are improved to limit short-cycling of the GAHPs. Both units experienced indoor and outdoor controls based issues that started in January and continued for several months (these are the first prototypes using a control algorithm not developed by SMTI, and there was a steep learning curve). These issues resulted in the intermittent operation presented on the plots and included the following:

- GAHP Control Board
  - EEV Control Logic
    - Glide not controlled properly in all conditions
    - EEV Valve too far open or closed, causing intermittent issues

Figure 6: GAHP Prototype installed on Site 1 (Combi)

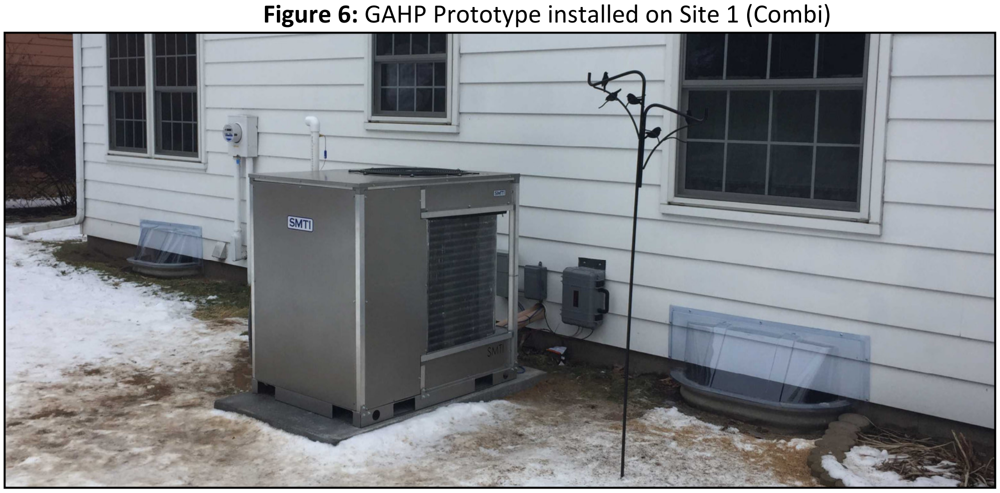

Figure 7: GAHP Prototype installed on Site 2 (Space heating only)

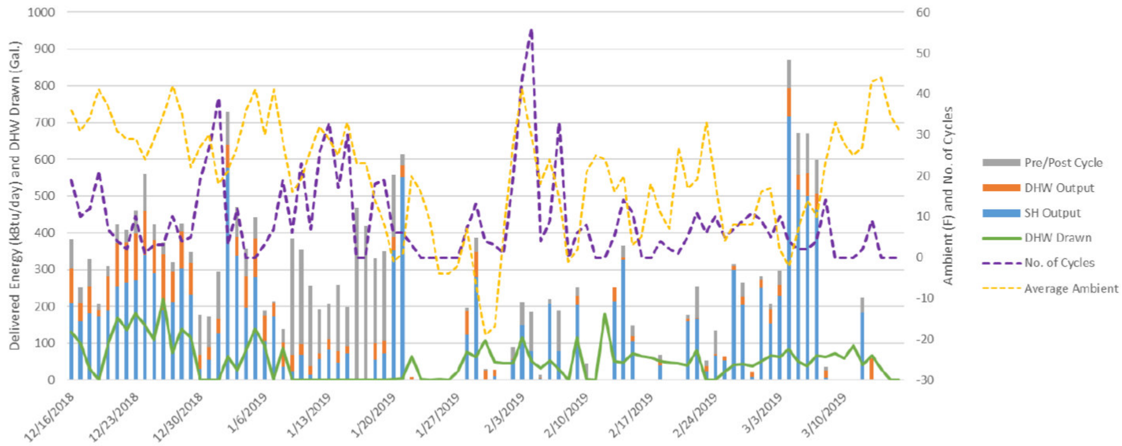

Figure 8: Site 1 summary data for the 2018-2019 heating season (Courtesy of GTI)

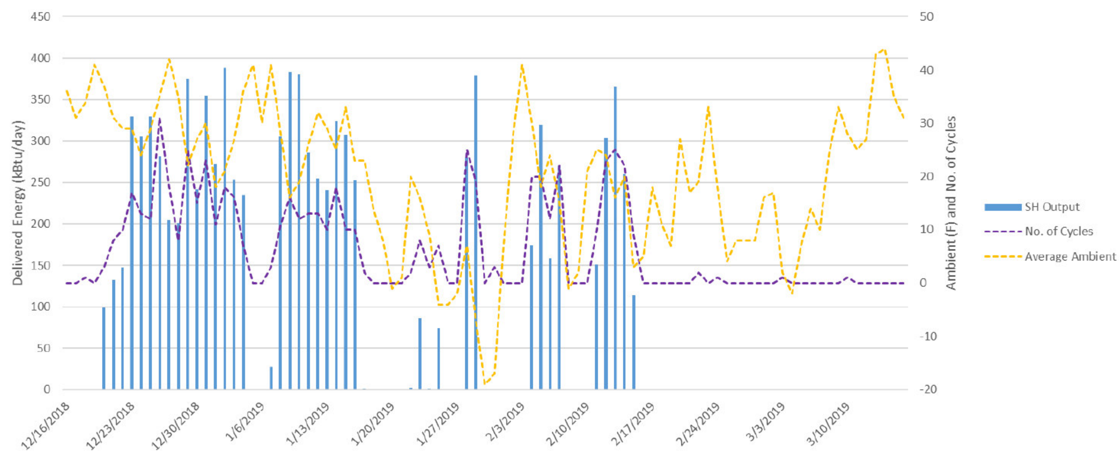

Figure 9: Site 2 summary data for the 2018-2019 heating season (Courtesy of GTI)

- Combustion Control Board (Vendor)
    - Software bug or noise creating a random general Error
    - Vendor installed monitoring system to identify issue (3/20/19)
- Indoor Controls
    - Short cycling of controls based on programming tuned for a furnace
    - End of cycle water heat 'top-off' for combi system not implemented yet
    - End of cycle hydronic circuit energy recovery not implemented yet

Figure 6 also shows that the unit at this site was disabled on February 15, 2019 due a component failure caused by control algorithm mistakes and learning. The damaged unit was replaced with the fourth prototype from the fall 2018 build in mid-April. The space heating season ended in early/mid-May which has resulted in the 'space heating only' site being idle and the combi site operating in water heater only mode.

This field test was a significant learning experience for controls group of the commercialization partner and combustion Vendor. The performance results of the field test were below that of prior SMTI field tests but the test has been an important step for the commercialization partner to better understand GAHP operation. Based on the learning that occurred, the project team agreed to extend the field demonstration through the end of the 2019.

2019-2020 Heating Season: Operation of the two units in La Crosse, WI continued through the 2019 portion of the 2019-2020 heating season as an extension to the originally planned demonstration period. Prior to the heating season, the SMTI and commercialization partner team worked collaboratively to try and ensure that GAHP and system performance were more in line with expectations. Issue identification and resolution continued throughout the heating season.

GTI completed an analysis of the field demonstrations through the end of 2019. Figure 10 is a plot that resulted from this analysis. The plot shows Daily Average COP_gas values for three field demonstration sites in La Crosse, WI as a function of Operating hours/number of cycles on a daily basis. The sites included are one that predates the DOE sites (WI site #1) and the two DOE sites (DOE WI Site #1 & 2). The site that predates the DOE sites uses SMTI GAHP and system controls. The DOE sites use commercialization partner controls. The plot shows that performance of the WI Site #1 and DOE WI Site #2 are similar. DOE WI site # 1 has significantly lower performance in comparison to the other sites. This site is combination space and water heating like WI Site #1. The added complexity of combi operation in addition to poor EEV control (not able to maintain a positive glide across the evaporator which minimizes energy input from the evaporator resulting in COP's less than 1) and indoor thermostat related short cycling issues were major factors in the reduced performance of this unit. At both DOE WI sites, the commercialization partner has not been able to successfully implement a post-cycle system heat recovery algorithm with helps reduce the cycling losses, especially for water heating cycles.

Control of the GAHP and the overall system are a major step outside of the commercialization partner's comfort zone. Improvements were made pertaining to GAHP performance from the

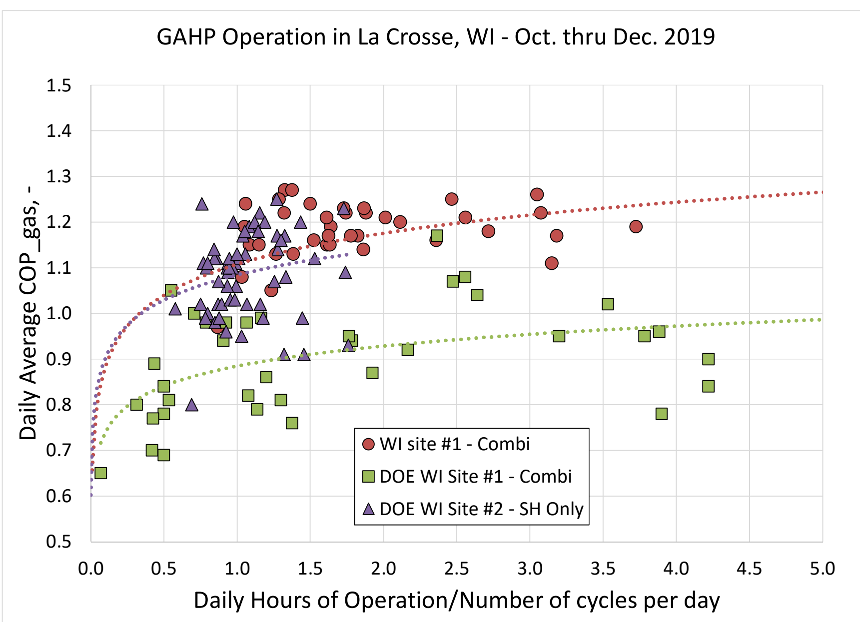

Figure 10: Performance as a function of operating hours divided by cycles per day

2018-2019 to 2019-2020 heating seasons but there is still significant work to be done to ensure proper performance, primarily evaporator glide control with the EEV. SMTI and the commercialization partner continued to collaborate in an effort to further improve the GAHP and system controls with the hope of bringing them in line with SMTI's PLC based controls (used on WI site #1).

The plot also highlights the impact of short cycle times on COP_gas values. For short (< 0.75 hours) heating cycles, the energy and time (~0.2 hours) required to get the heat pump up to peak performance is a large enough fraction that it reduces the average COP_gas values of the heating cycle. This cycling penalty is true of any heating appliance but can be more impactful on GAHP performance if system operation is not designed to limit or even eliminate short cycle times. This has been a challenge pertaining to adapting the commercialization partners existing modulating thermostat controls that have a tendency to short cycle heating equipment.

Stakeholder Feedback: In this unique case, for an early-stage demonstration of a prototype technology, the host sites were also a representatives from the commercialization partner. While this does not provide a pure independent test site, the hosts' attentive and constructive comments shown in Table 2 are nonetheless useful for this product development phase. It should be noted that this survey was completed during the summer of 2019 and captures the perspective following the difficulties encountered during the 2018-2019 heating season that are described in section above.

During initial installation and early commissioning period, the installation contractor provided preliminary guidance grouped as follows:

- **Reliability:** Generally the contractor felt that the flame sense and hydronic fittings are problematic, they needed to be replaced and serviced often, and generally speaking the combustion system needs to be easier to service with more space for access.
- **Customer Experience:** In the long term, the contractor felt that the CP shouldn't require their own thermostat, but that it should be universally controlled for more market acceptance.
- **Ease of Installation:** The contractor stated that there is a need for a simplified installation kit for outdoor hydronic connections, also there are things crowding the return line that could be moved. Finally, the GAHP should be sized for transport on a dolly, it could be difficult to navigate some backyards.
- **Product:** Where auxiliary heat is needed to prevent condensate freezing, it would be desirable to put an outlet on the GHP for heat trace.

The detailed contractor survey responses are shown in Table 3. The challenge with broad GAHP market acceptance is highlighted in their responses, however, the opportunity is there with customers disproportionately using gas-fired furnaces. The contractor also offers excellent feedback regarding the size of the equipment, issues with access/orientation, and challenges with siting equipment during installation. Also, the desire for integrated A/C is expressed. Note that there are two sets of responses, from the two primary contractor employees for this project.

Table 2: Host Survey Response

Question	Site 1	Site 2
How satisfied were you with the space heating in your home during the demonstration period?	Satisfied	Neither satisfied nor dissatisfied
Were there instances in which space heating did not meet you comfort levels?	Yes	No
Site 1 Detailed response to Question Above: This was generally related to trips or shut-downs due to control issues. Sometimes, due to lack of availability of support personnel or a part replacement, there would be a lag between the GHP heating and electric (backup) heating, causing periods of discomfort. Last but not least, the unit didn't seem to hold up too well under extreme cold temperatures.		
How difficult was it to use the GHP system?	Neither easy nor difficult	Neither easy nor difficult
How satisfied were you with the hot water provided during the demonstration period	Satisfied	N/A
From your experience, please rate the reliability of the space heating during the demonstration period.	Neither reliable nor unreliable	Unreliable
From your experience, please rate the reliability of the water heating during the demonstration period.	Reliable	N/A
From your experience, please rate your home's temperature stability during the demonstration period.	Neither stable nor unstable	Stable
From your experience, please rate your hot water temperature stability during the demonstration period.	Stable	N/A
Has any maintenance been needed during the demonstration period?	Yes -	Yes -
Detailed responses to Question Above: **Site 1 -** A lot of trouble-shooting, whether controls-related or component-related (especially burner), and in the case of the latter, part replacement. **Site 2** - Lots of "maintenance" needed on the GAHP. Control software development and inter-component communication issues caused hardware failures that led to replacement of the first GAHP with a second.		
Please rate your overall satisfaction with the GHP system	Satisfied	Neither satisfied nor dissatisfied
Detailed responses to Question Above: **Site 1 -** I have rated the experience as "satisfied" only because, the operational issues notwithstanding, these can be improved via better supplier quality for the burner and better integration of the controls for the various sub-systems. There is significant potential for this technology to become a robust, mainstream technology for space and water heating. **Site 2 -** 2018-2019 was certainly a challenging season, at least at Site #2. However, expect that continued development over the summer will lead to a productive and comfortable 2019-2020 heating season.		

Table 3: Contractor Survey Response

Question	Response #1	Response #2
What percentage of work is residential vs. commercial?	92% residential	90% residential
What fraction of business is retrofit vs. new construction?	90% retrofit	50% retrofit
What fraction are for emergency vs. non-emergency replacements?	50/50	98% of water heaters are "emergency" (leaking tank), 2% are proactive.
What fraction are for gas vs. electric?	40 gas 60 electric	50%
What fraction for storage type water heaters vs. tankless water heaters?	95% storage	95% storage
What fraction are for natural gas minimum efficiency?	40/60	10% natural draft vent, 90% power vent
What fraction are for natural gas Energy Star?	15%	0%
What fraction are for natural gas condensing?	5%	Only 5% (tankless) are condensing.
What fraction are for electric water heaters vs. heat pumps water heaters?	98/2	Only seen one DHW heated by a heat pump, and he hated it and ripped it out.
What fraction are for systems with water softeners vs. without water softeners?	50/50	70% have water softeners.
What fraction are for forced air vs. hydronic/radiant?	85/15	80% forced air
What fraction are for gas furnaces vs. electric furnaces?	95/5	97% gas, 2.5% fuel oil, 0.5% electric.

What fraction are for less than 83% efficient vs. greater than 90% efficient?	10/90	10% are 83 percent (garage heaters only), 90% high efficiency (all houses)
What fraction are for electric furnaces vs. heat pumps?	20/80	Maybe 2% of new construction will do a ground source heat pump. Nobody puts in electric furnaces in their house. Some spec home contractors will do baseboard electric heat as it's a cheap installation.
What fraction are for single vs. multi-zone thermostats?	80/20	15% are zoned.
What fraction are for "smart" thermostats?	1/99	20% want wi-fi to monitor the house from afar.
What are the challenges with gas/venting/electric upgrades?	Finding an area on the exterior to terminate intake/ exhaust and in older homes, cutting those holes.	Electric upgrades are costly. HVAC installers are usually not licensed to do that work so another party has to get involved. 50% of our furnace replacements involve running PVC pipe for the first time so that's routine work.
What are the challenges with condensate management with/without neutralization?	Insuring the condensate plumbing is pitched correctly as not to create an airlock.	Our experience (before this project) is run condensate to the drain IN the house. Digging a hole in the ground outside is a challenge and will surely meet with a situation where it can't be done. Heat tapes are energy hogs and will kill any cost benefit realized from the high efficiency heat pump.
What are the challenges retrofitting larger/different footprint equipment?	The larger footprint equipment may not fit in the area provided. Smaller footprint, just deciding the best way for the equipment to operate efficiently and effectively.	This is the toughest challenge. Most equipment can be wheeled to the location (oftentimes up or down a hill, across a slope) on a 2-wheel dolly. And lifted into a service van with one or two people. Could the units come in 2 pieces with some field assembly required? Connecting/brazing and then evacuating is normal routine for HVAC installers.
What are the challenges managing noise and other customer nuisance complaints?	Changing fan speeds, finding loose sheet metal or something rubbing.	Sound is one of the few places companies can differentiate their products from the competition. Comfortmaker, Daikin, and Mitsubishi make some incredibly quiet stuff. The HVAC contactor can only do so much to attenuate sounds. Most of that falls with the manufacturer.

What were the challenges during installation of GAHP, indirect tank, and hydronic air coil.	Finding a cost effective location for plumbing distance for the tank. The A/C evaporator would not fit above the tall air handler so it was installed in the return air duct.	As discussed above, the GAHP was large and difficult to get into its place due to sloped ground and tight spaces. The indirect tank was quite tall and could have issues in many small homes. The cost of the brass fittings was higher than expected. I know many (brass fittings) will not be needed in a non-experimental setup, though.
What were the challenges during plumbing of hydronic loops and indirect tank?	Location for the pump and pressure tank	Nothing out of the ordinary.
What were the modifications to gas/vent/electrical infrastructure?	Location of the Gas connection on the unit. Difficult to open service panels with gas and venting in place.	The other big hassle which will drive up installation costs was all of the ductwork modifications needed to get the coils moved around. The easiest place for the hydronic coil is right above the evaporator coil and, failing enough space there, before the furnace. Other than the power needed for electric backup heat, no major modifications to gas, vent, or electrical infrastructure.
What are your recommendations for improved/simplified installation?	Not to use an electric air handler. A cased water coil can be retrofitted to most applications if kept under 17" height 17-1/2" wide and 20" deep. Other sizes would also be required for other applications, this being the most common size. 90%+ furnace cabinets are now 35" tall leaving room for a cased evaporator and space for a cased water coil.	Make the outdoor unit modular or able to be transported on a (large tire) two-wheel dolly. Allow the indoor coil to be installed wherever is easiest for the contractor. Offer a kit of needed hydronic parts (pump, expansion tank, valves, brass fittings, etc). Even better would be some pre-assembly, e.g. if I ordered a PEX-A kit the water storage tank connections would terminate with a PEX-A fitting and all I need to do is add the tubing.
The initial estimate was for X man-hours and Y for equipment to install prototype system. Do you think this was a conservative estimate/good estimate/under estimate?	Good estimate	Under estimate
Do you anticipate the installation costs for this system to be greater/lower/similar to standard gas water heater and gas furnace?	Similar	Greater

Do you anticipate the installation costs for this system to be greater/lower/similar to tankless gas water heater and condensing furnace?	Similar	Greater
Do you anticipate the installation costs for this system to be greater/lower/similar to electric heat pump water heater and electric heat pump?	Greater	Similar
Given your experience with the prototype system, what challenges remain for successful deployment in retrofit and new construction installations?	Higher BTU out-puts in our region, if it's new Construction I wouldn't see installation issues as we build our ductwork to fit the equipment other than the extra plumbing. Having the equipment to move the GHP to the install location could be an issue for most contractors.	Some of the time and installation costs with the prototypes are disproportionately high because of the data monitoring needs. Many hours of time were lost to CP controls issues / software rebuilds / uploading / thermostat rebooting time.
Would you recommend this technology to customers? If not, what improvements do you want to see?	I would if it fits the customer needs and budget. I would like to see it have the ability to cool as well so there are not two large units in the backyard. Variable speed solution pump and condenser fan motor	Not at this time.

5.0 Task 4: Codes and Standards Analysis

The goal of this work was to perform a codes and standards analysis concerning the residential-sized gas-fired absorption heat pump (GAHP). Under this task, GTI reviewed codes and standards relevant to performance/efficiency, health and safety, emissions and environmental concerns, and installation requirements. The focus of this study was on the U.S. market, however as needed, relevant comparisons to international codes and standards were be made. Based on the completed review, no major roadblocks with codes and standards are expected. A report detailing GTI's review of codes is provided in Appendix C.

6.0 Task 5: Market Assessment & Analysis

Figure 11 outlines the research scope for the market assessment and analysis. The Market Research task included five phases. The qualitative portion consisted of in-depth, on-camera interviews with HVAC contractors, followed by on-line interviews with consumers. Findings from the qualitative portion were used to guide the development of the quantitative phase, again with contractor interviews and an on-line consumer discrete choice study. Findings from the first four phases, along with relevant market data, guided an attempt at forecasting sales volume.

6.1 Qualitative Study

Summary results for the qualitative portion are outlined below. Generally, the GAHP concept was very well received by both contractors and home owners and the importance of energy efficiency appears to be a growing. Use of ammonia as the refrigerant was not a major concern, especially

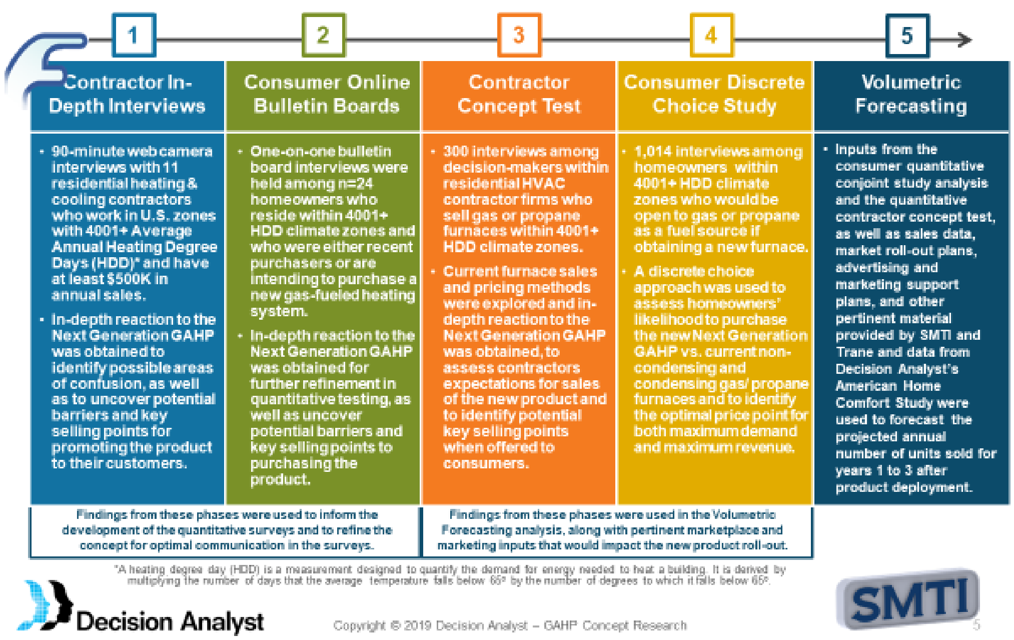

Figure 11: Research Design

since all of the refrigerant remains outside. Not unexpected, the total installation cost will be very important.

Contractor In-Depth Interviews:

- Believe installation is reasonable based on diagrams provided and overall discussion
- May take somewhat longer to install versus a standard furnace (depending on plumbing and kits provided by OEM supplier)
- Energy and operating cost savings appear strong
- Need to ensure no confusion with electric heat pumps
- Need to discuss and educate on ammonia as a refrigerant but not seen as an issue
- Adding combi (domestic hot water) feature well received
- Weight and size not identified as a barrier
- Installation diagrams tested clear and appear doable
- Questions about reliability and warranty (most prefer 10+ years)

Consumer Online Bulletin Boards:

- Initial reactions generally positive, keying in on cost savings, quiet operation, robust cold weather heat supply, DHW option
- Several question on technology itself and how it works
- Expect hesitations on cost for many but not all
- Gas utility incentives will help
- Several asked about ability to provide air conditioning
- Question areas identified include outdoor operation, ammonia and hydronic plumbing

6.2 Quantitative Study

The quantitative phase surveyed 300 contractors. Questions centered around current business practices and reactions to the new technology, and included their review of technical installation diagrams. The study revealed a strong favorable reaction, with 3 in 5 saying they “definitely would” be likely to offer the GAHP to their customers. Overall, 92% were somewhat or definitely likely to support the new technology.

The project surveyed 1,014 homeowners in the United States as part of a product concept test, obtaining data on consumer purchase habits for HVAC, as well as their reactions to the gas absorption product. The survey also included a forced-choice style test to generate a price-demand curve (based on total installed cost) for market penetration, shown below (Figure 12). The forced-choice (“conjoint”) exercise gave them a series of screens showing three currently available fuel efficiency configurations (AFUE 80%, 92% and 96%), as well as the new GAHP product (AFUE 140%). The screens showed the various attributes of each option and also had varying prices and brands for each. Respondents were required to select the one choice that they preferred. Given that each respondent saw ten of these forced-choice screens that made just over 10,000 selections available to create the quantitative dataset.

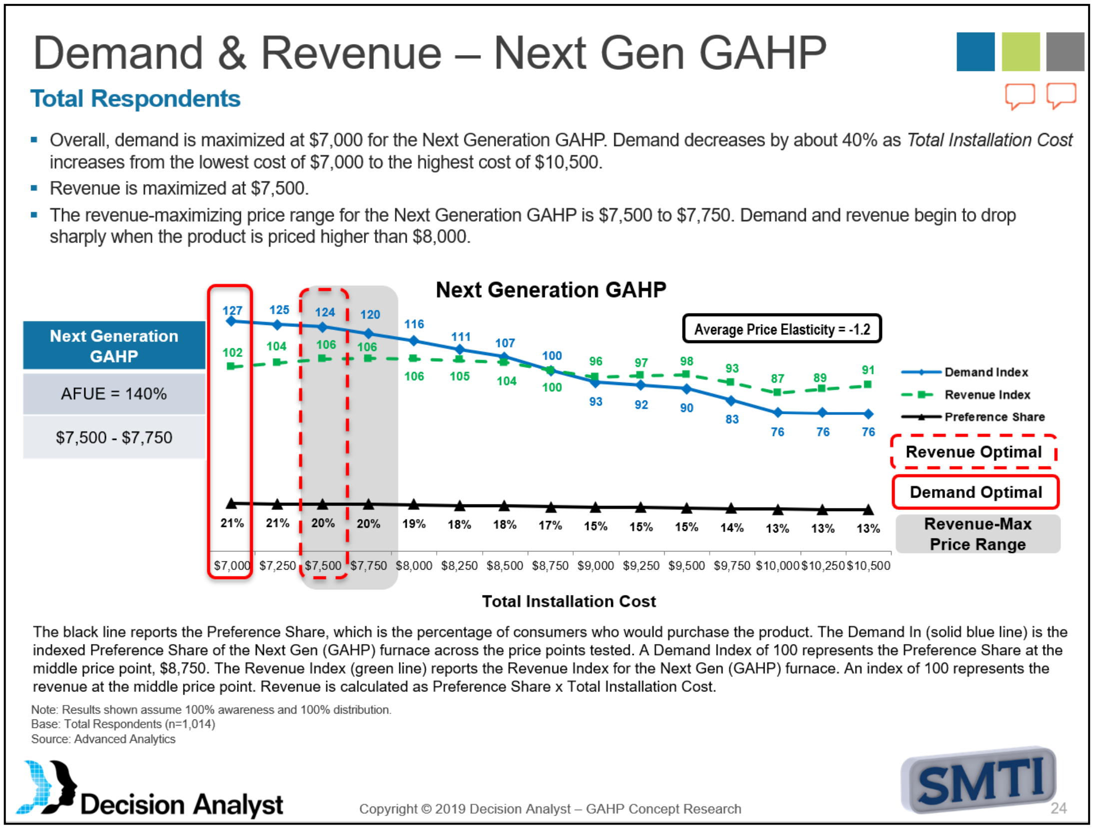

Figure 12: Price Demand Curve for Market Penetration

Not all US consumers were targeted in the survey. The survey was limited to people who have natural gas or propane available in their homes, who live in a climate with at least 4,000 HDD (heating degree days), and households with at least $75,000 income.

The market penetration can be used to project the potential sales of GAHPs as a percentage of all gas-furnace sales. Overall, gas-furnace sales in North America by 2021 are expected to be approximately 3.7 million units. Removing 15% for new construction (an entirely different set of considerations) and focusing only on the selected geographical and income targets, the price-demand curve (the "Preference Share" line in the chart below) suggests GAHP potential sales into furnace replacement situations ranges from 140,000 to 219,000 units per year depending on the total installed cost.

It is important to note that this is a potential number; not a sales projection. Potential sales assumes ideal market exposure; specifically that all furnace-buying consumers in the target population are made fully aware of, and are offered, the product. This ideal scenario will not be achieved in the early years of the product's life cycle.

7.0 Task 6 & 8: Manufacturing Process & Demonstration

7.1 Sealed System Process/Equip/Tooling Definition

Key Component Assembly Demonstrations:

***Absorber, Condenser & Desorber**:* Several assembly methods for the absorber, condenser and desorber components were conceptualized. A detailed review of these methods was performed to identify and move forward with a best approach. An assembly method was down selected from the initial concepts and design of a semi-automated (for demonstration purposes) system as completed. The system designed allows for the assembly of absorber, condenser and desorber heat exchangers and only requires an adjustment to fixturing. The result was assembly equipment that is flexible to both system size and component design.

The conceptual assembly system was then developed in SolidWorks to allow for the review of the assembly steps and equipment requirements. Tools were then fabricated from this modeling for the bench top assembly demonstration of the Absorber, Condenser and Desorber. It should be noted that the assembly demonstrations were completed with the "10K" GAHP components, due to the size being more appropriate for a bench top demonstration. The semi-automated assembly demonstration was also human powered (simulating motor drives and actuators).

The bench top assembly demonstration jig for the Condenser of the 10k btu/hr sized unit was completed and assembly trials were run successfully, with a projected assembly time of 7 minutes. The absorber and desorber were then completed with assembly times of 18 minutes and 4 minutes, respectively. These assembly times and techniques were documented in videos shared with DOE project management personnel (videos confidential).

As a follow-on to these assembly demonstrations, simple bench-top tooling was designed to improve the design for manufacturing of the heat exchanger shells and automation design for exchanger assembly was completed.

Solution pump: The best approach for assembling the solution pump was evaluated. This evaluation allowed for the identification of assembly steps, tools and design modifications to improve the speed and ease of assembly that will be required for a production unit. Sixteen distinct assembly steps were identified during this process. Bench top assembly took 10.5 minutes. Parts and fasteners were designed out of the component where possible to simplify the assembly and new technologies to reduce cost of the solution pump assembly were investigated. Multiple assembly jigs and tools were identified to reduce positioning errors and quality issues during the assembly of the solution pump.

Process/Equip/Tooling Definition & Vendor Identification/Make-Buy:

A cost model of the 80K sealed system used to determine "Make/Buy" decisions for the initial manufacturing model based on volume for year one and beyond was completed. This cost model served as a guide to size capital requirements of the SMTI manufacturing process. Most of the components in the sealed system are fabricated from carbon steel tubing. The equipment to process and fabricate these tubular components was identified and volume tube costs were established. SMTI received volume production quotations for all components that will be out-sourced and costed all internally fabricated parts and assembly processes. The projected manufacturing cost of the sealed system at 50,000 units/year is within 5% of our target cost.

Using the capital equipment requirements, the overall size of the facility has been sized at approximately 60,000 ft^2 based on year 3 production requirements. The capital equipment/tooling budget is about 10% higher than the original estimate. This includes what is needed for an initial launch and then to scale volume over the first five years.

7.2 Balance of System Process/Equip/Tooling Definition

SMTI and the commercialization partner worked to further the development of the Balance of System parts and the indoor air handler unit (AHU).

GAHP Balance of System:

An evaluation was completed to determine where the commercialization partner's existing inventory of parts and equipment had overlap with the parts and equipment that make up the balance of system parts. This included framing, paneling, fans and motors. By using existing inventory, the higher volumes of other products can be leveraged to reduce the manufactured cost of the balance of system parts.

By the time the pre-commercial prototypes were fabricated, the units incorporated finalized cabinetry, a production fan-motor-duct assembly and more robust hydronic plumbing. The use of the production fan-motor-duct assembly did require the cabinetry to grow in length by 2 inches and was determined to be an acceptable trade-off to allow for use of the high volume, lower cost parts.

Indoor System:

Design of the hydronic coil within the AHU and reducing the total envelope size of the AHU to the size of the legacy furnace equipment (40" tall max) was completed. First prototypes of this AHU were built for the pre-commercial prototype build (Figure 13 – left image). Testing with the prototype hydronic coil showed that it was sufficiently sized to supply the required heat from the hydronic loop to the indoor space with warm supply air. Review of this first design found a major issue which was that the AHU did not allow for a side return air system. These first prototype AHUs require bottom entry (typical for electric heat pumps) while side entry is required for replacement of most furnaces. Based on this fact, an initial redesign was completed to allow for side return/entry to the AHU (Figure 13 – right image). Further design improvements are needed to reduce the size of the furnace to meet the height requirements of current furnace products (33"). This reduced furnace height has been driven, at least partially, by the increase size of evaporator coils for air conditioning systems as they try and reach higher SEER ratings.

BOS Manufacturing Cost/Capital Requirement:

Evaluation of the manufactured cost of the balance of system parts (cabinetry, controls, fans, motors, condensing heat exchanger, hydronic loop) on the outdoor unit was completed by Trane.

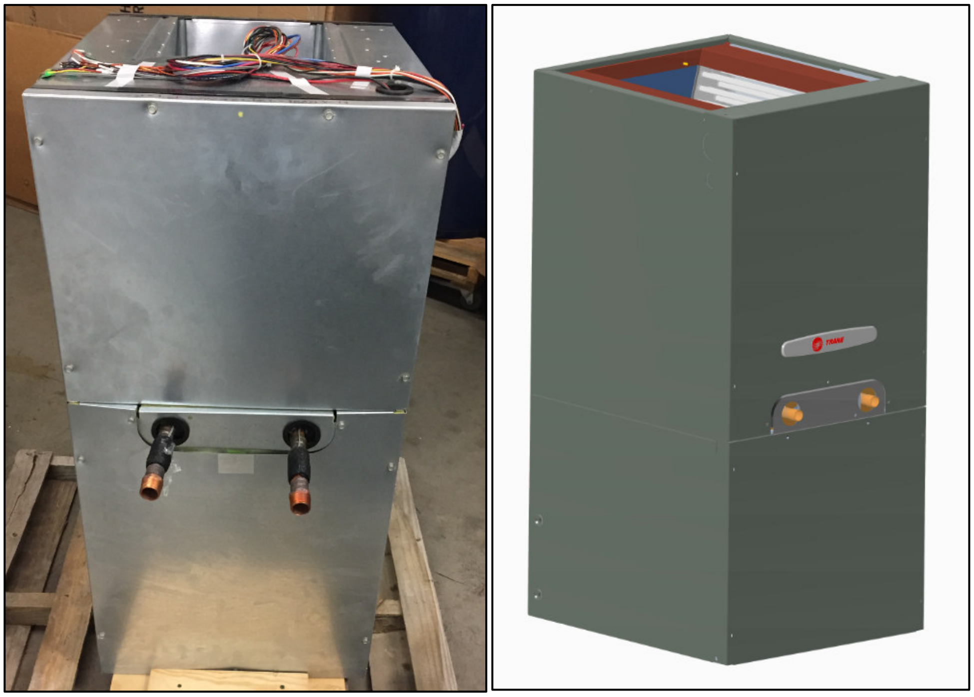

Figure 13: Legacy Height Hydronic Air Handler prototype (left) and design with side return (right)

CapEx estimates for the balance of system parts and air handler mnufactured cost estimates were also developed.

The manufactured cost of the GAHP (sealed system and balance of system) are within 10% of target at a volume of 50,000 units per year, with the sealed system coming in below target and the balance of system coming in above target. The capital equipment/tooling estimate for the sealed system is within expectations. For the balance of system, as configured, the capital equipment budget came in a bit lower than expectation.

8.0 Task 9: Reliability Assessment

8.1 ANSI Z21.40.1 Testing

Fall 2018 prototype evaluation

SMTI performed an evaluation of the construction related sub-sections and found that the prototype GAHPs were in compliance with the standard. There are a few areas within the sub-sections where it was determined that improvements were needed for a final commercial product. This includes how insulation is attached, finalizing the controls and internal cabinetry for the controls, finalizing cabinet design and improving the design of the screen on the combustion ventilation.

ANSI combustion safety testing was completed at SMTI and the prototypes passed all tests except for the blocked vent test discussed in the corrective actions section. Rain and wind testing was not completed due to the requirement of specialty test equipment, but is not expected to be a problem based on the type of combustion system used (forced-air premix) and general very short venting that is all at the same pressure.

Corrective Actions Resulting from ANSI Testing: Combustion related ANSI testing was completed in the fall of 2018 prior to shipment of the prototypes to the field test sites. Testing showed that the combustion system failed the blocked vent test because the combustion products went sour (CO above 400 ppm) before the unit lost flame sense. For the prototypes, a second pressure switch was added to turn the gas off if the pressure got above a specific value that would be indicative of a blocked vent.

The combustion system vendor added a pressure tap to their mixer design that relies on the negative pressure from the suction side of the blower rather than the pressurized outlet side of the blower to activate a pressure switch. This is a potential solution for the combustion system to return to only using one pressure switch while meeting the ANSI test requirement.

Fall 2019 prototype evaluation

ANSI combustion safety testing was completed at SMTI on the final two pre-commercial prototypes and they passed all tests. These prototypes still used the two air proving switches as additional work was still required by the combustion system supplier to develop the negative pressure port on the mixer.

Component 3x Operating Pressure Test: SMTI completed 3x operating pressure (450 psig x 3) tests on all of the sealed system heat exchangers which is a requirement for the ANSI standard. A spare set of heat exchangers was fabricated as part of the fall 2019 built to facilitate this testing.

The condenser, desorber-leveling chamber, evaporator, refrigerant heat exchanger and solution heat exchanger were successfully hydrostatically pressure tested up to the 1500 psig (150 psi above the 3x requirement of 1350 psig). The absorber component failed the hydrostatic test. The failure point was identified as a braze joint on the solution pump storage tank. This braze joint is not reflective of the design to be used in a production system. Regardless, an evaluation of the full component was completed and design adjustments were implemented to improve the robustness of the current and production design.

8.2 Reliability Test Plan

DFMEAs were completed to help identify design weaknesses before developing a reliability test plan. Sealed system, combustion system and balance of system DFMEAs were completed. From this work, reliability test plans were developed by the individual groups. The goal of these reliability test plans was to clearly define goals and metrics to enable the successful commercialization and release of a GAHP product. The reliability work outlined in the plan will extend beyond the scope of this project.

Prototype Accelerated Life Testing (ALT): The fourth unit of the fall 2018 build was installed in a reliability test cell where it as allowed to operate in an accelerated fashion with the goal of accumulating 4000+ hours of operation at the end of the project (Figure 14). The test cell fabricated is an enclosure that will result in operation of the unit down to lower year round temperatures than would be experienced if the unit were installed within or external to the laboratory facility at SMTI. Operation conditions (target supply water temperature) were targeted to stress the unit and allow for the identification of design issues or limitations.

Figure 14: Beta 7 installed in ALT Room

As of the end of the project, the ALT unit had accumulated over 4200 hours of operation. As of the writing of this report, the unit has accumulated another 1000+ hours of operation with the goal of reaching 9000+ hours by the end of the year.

To date the ALT unit has helped in the identification of system and component issues. These have included the following:

- A pump wear issue that results in loss of pumping performance after 1000+ hours of operation. Design updates developed that have been implemented on existing systems operating at SMTI and in the field that resolved the issue.
- Generation of non-condensable gases still above an acceptable level. This has resulted in adjustment to the corrosion inhibitor package to reduce the generation of these gases.

Component Level Accelerated Life Testing: The GAHP developed by SMTI has three components that are critical to the long term life and reliability of the sealed system. These components include the two moving parts (solution pump and electronic expansion valve (EEV)) and the desorber (which contains the gas burner and is subject to the most severe temperature and pressure cycling).

- For the solution pump, fabrication of an ALT test stand and four pumps was completed. The four pumps are currently undergoing continuous operation testing to identify potential issues and limitations. The goal of this test stand is to build confidence in the solution pump design and its ability to achieve an operating life of 40,000 hours.
- For the Desorber, conceptual design of a test stand to provide thermal and pressure cycling was completed. This facility will allow for the cyclic testing of at least three (3) desorbers. Fabrication of this test stand was beyond the scope of this project.
- For the EEV, SMTI is working with the manufacturer to ensure proper operation and function over the life of the valve. A product specification document was developed for this valve. An

in-depth discussion with the manufacturer was held at the AHR Orlando Expo in February 2020. Additional discussion and communication about requirements and reliability are continuing beyond the scope of this project.

8.3 Pre-Commercial Prototypes

Fabrication of the two pre-commercial prototypes was completed at SMTI with the commercialization partner providing the balance of system content and Beckett providing the combustion system content. The BOS content included all of the framing and paneling, the evaporator fan motor assembly, solution pump motor and the GAHP control board. The combustion system content provided by Beckett included combustion control boards and a combustion assembly that integrated the gas valve, blower, mixer, burner manifold, burner, ignitor and flame sense rod into one sub-assembly. These units represent a significant step forward in the overall design of a commercial GAHP system. . Figure 15 presents several images of the completed first unit. It should be noted that seven prototypes were fabricated. Two were fabricated for this project and five additional units were fabricated for a follow-on gas industry funded field demonstration.

Figure 16 presents results from testing of PC01 through PC07 at 100%. The units were tested over a range of ambient (5-47°F) and hydronic return (100-120°F) temperatures. The plot shows that all units achieved COP_gas values above the 1.4 target (most at or close to 1.45) at the design ambient and hydronic return water temperatures of 47°F and 100°F, respectively. The plot also shows the expected result that performance is highest at warmer ambients and lower return water temperatures.

Figure 15: Pre-commercial Prototype Unit

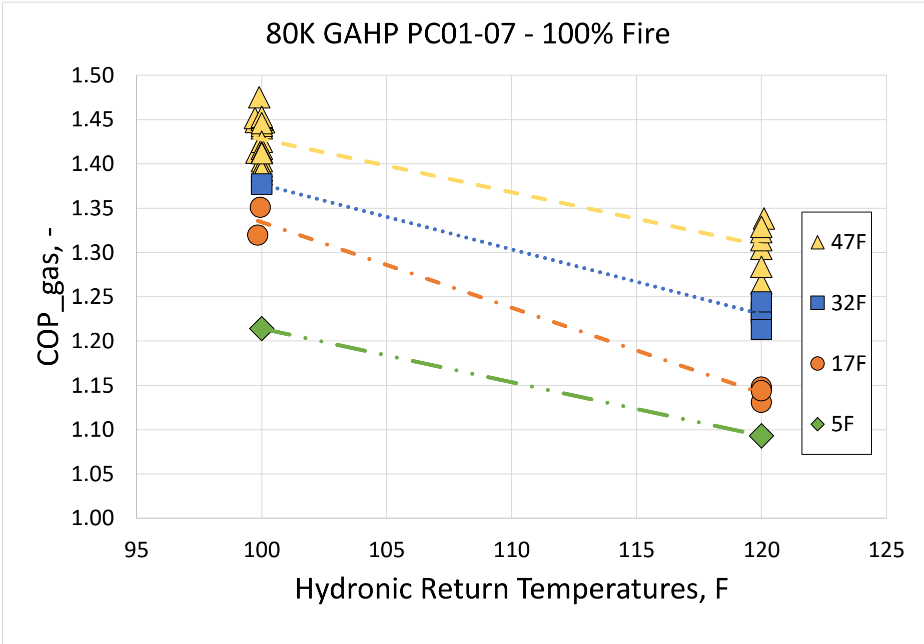

Figure 16: Pre-commercial Prototypes 1-7 COP_gas Values at 100% fire

The performance of these prototypes is slightly improved from those built in the fall of 2018. The increase experienced is a result of addressing component limitations previously identified. This included minor adjustments to the absorber and SHX components, which provided the added bump in performance.

In addition to the prototype GAHP assembled but SMTI, the commercialization partner fabricated prototype hydronic AHUs that would be installed in tandem with the GAHP so that performance of the full system is optimized. Figure 13 presents an image of one of this prototype. The use of properly designed indoor equipment (thermostat, AHU and indirect DHW tank) are critical to maximizing performance and value of the GAHP to the end user.

9.0 Task 10: Techno-Economic Analysis

Energy, operating cost and emissions modeling covering 9 cities, 5 climate zones and 3 load profiles was completed by GTI. Table 4 presents specific details of the cities, climate zones and load profiles of the homes modeled. Table 5 presents the home sizes, type and foundation requirements for the buildings modeled in the 9 selected locations. Table 6 presents the space and water heating equipment modeled for each location. This includes both gas and electric based heating systems.

Table 4: Locations and Design Heating Loads modeled

	Zone	City	Population	Btu/hr DHL-1	Btu/hr DHL-2	Btu/hr DHL-3
1	7	Fargo, ND	122,000	80,000	60,000	
2	6	Minneapolis, MN	730,000 *	80,000	60,000	45,000
3	6	Rochester, NY	206,000	60,000	45,000	
4	5	Chicago, Ill	2,700,000	80,000	60,000	45,000
5	5	Philadelphia, PA	1,570,000	60,000	45,000	
6	5	Denver	730,000	60,000		
7	4	Portland, OR	670,000	34,000		
8	4	Louisville, KY	620,000	60,000		
9	3	San Francisco, CA	900,000	34,000		

** Includes St. Paul*

Table 5: Buildings modeled in each location

<table>
<tr><th>City</th><th>Climate Zone</th><th>Building 1 DHL-1</th><th>Building 2 DHL-2</th><th>Building 3 DHL-3</th><th>Type</th><th>Foundation</th></tr>
<tr><td>Fargo, ND</td><td>7 -dry</td><td rowspan="9">3000 sq-ft</td><td rowspan="5">2400 sq-ft</td><td rowspan="2"></td><td rowspan="9">2-story, 4-bed, 3 bath, 2-car attached garage</td><td rowspan="6">unfinished basement</td></tr>
<tr><td>Rochester, NY</td><td>6-moist</td></tr>
<tr><td>Minneapolis, MN</td><td>6-moist</td><td rowspan="2">1800 sq-ft</td></tr>
<tr><td>Chicago, IL</td><td>5-moist</td></tr>
<tr><td>Philadelphia, PA</td><td>5-moist</td><td rowspan="5"></td></tr>
<tr><td>Denver, CO</td><td>5-dry</td><td rowspan="4"></td></tr>
<tr><td>Portland, OR</td><td>4-marine</td><td>slab</td></tr>
<tr><td>Louisville, KY</td><td>4-moist</td><td>unfinished basement</td></tr>
<tr><td>San Francisco, CA</td><td>3-marine</td><td>slab</td></tr>
</table>

Table 6: Heating Equipment Modeled

Case	Space Heating	Water Heating
Baseline Gas	80% AFUE Furnace, autosized for max heating load	62 EF, 47.5 gal storage water heater
Better Gas	95% AFUE Furnace, autosized for max heating load	62 EF, 47.5 gal storage water heater
GAHP Combi	45 MBH min., autosized for peak heading load	65 gal indirect storage tank
Standard Electric	7.7 HSPF Heat Pump, autosized to meet cooling load*	92 EF, 59.4 gal electric storage water heater*
Best Electric	10 HSPF Var. Speed Heat Pump, autosized for max heating load*	92 EF, 59.4 gal electric storage water heater*
*Standard BEopt 2.8 options (unmodified)		

Part load and cycling losses were factored for all equipment modeled. Part load ratio equations were developed for the GAHP which included a minimum modulation level of 25% and cycle time off of 45 minutes. Defrost requirements of the heat pump equipment (gas and electric) and its impact on system performance were accounted for in the equipment modeling.

Location specific utility (gas and electric) pricing and grid emissions were used in the analysis. Table 7 presents this information. The table highlights the very low cost of natural gas in all locations which makes the economics more challenging for advanced gas heating technologies that have a higher initial cost. It should also be noted that the electrical grid emissions are based on marginal grid emissions values. This is because load is being added to the electric grid when replacing standard gas heating equipment with advanced heating equipment that requires more electrical energy. The increase in electrical requirements would require the addition of generation at the margin as it would not be typically covered by the baseload electrical generation.

SMTI established total installed cost estimates for each competing system (conventional space and water heating equipment). A survey of published data and pricing as well as data collected during Task 5 were used to establish pricing and installed costs. Figure 17 is a plot of the total installed cost of different space heating equipment as a function of nominal output capacity. Some interesting takeaways are the very low installed cost of an 80% furnace, the cost of the GAHP being in line with that of a standard electric heat pump (EHP) on an output basis, and the very high cost of cold climate EHPs.

SMTI then used the energy, operating cost and emissions results from GTI's modeling to complete a techno-economic analysis. This analysis resulted in over 100 plots and figures for the cases investigated. For brevity, only one of these cases is reviewed below and is followed by a summary of the results for the entire study.

Table 7: Utility Pricing and Emissions

Location	Gas Winter Price ($/Therm)	Annual Average Electricity Price ($/kWh)	Electric Grid CO2e* (lbms/MMbtu)	Gas CO2e Emissions (lbms/Mmbtu)
Chicago	$ 0.76	$ 0.125	627	148
Denver	$ 0.69	$ 0.121	588	
Fargo	$ 0.67	$ 0.102	618	
Louisville	$ 0.98	$ 0.105	585	
Minneapolis	$ 0.77	$ 0.127	618	
Philadelphia	$ 0.98	$ 0.139	496	
Portland	$ 1.10	$ 0.107	527	
Rochester	$ 1.05	$ 0.176	386	
San Francisco	$ 1.14	$ 0.174	362	
*Non-baseload (marginal) power plants				

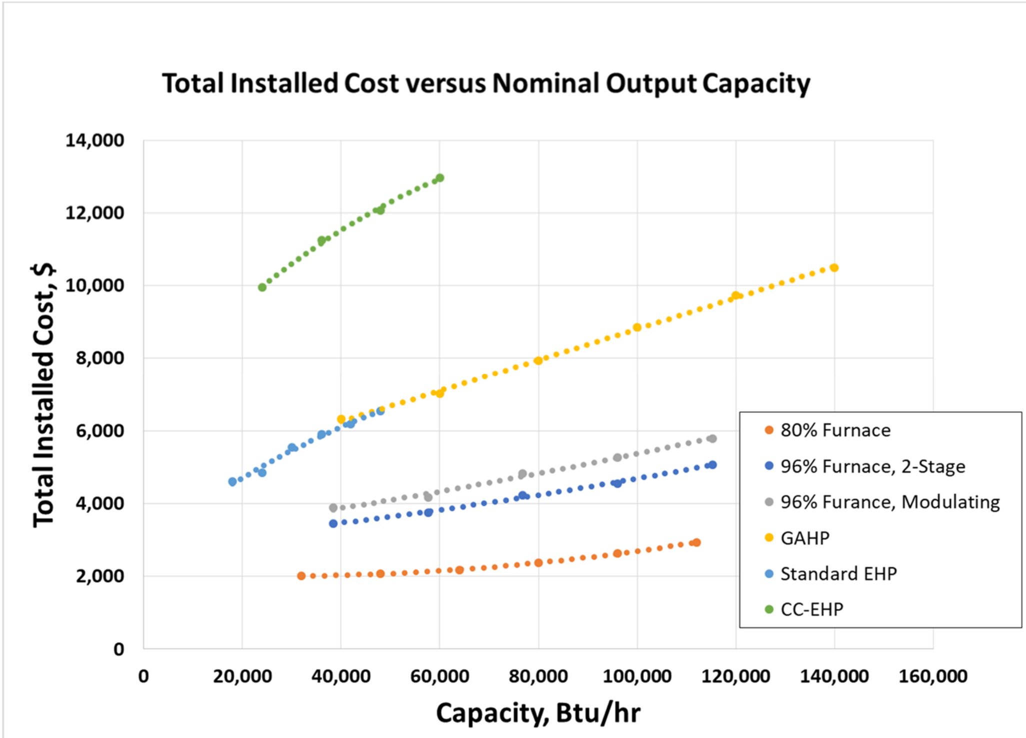

Figure 17: Total installed cost versus output capacity

Chicago (DHL-1) Results:

Gas only and total operating cost results are presented in Figure 18. The figure contains plot with utility pricing as is ($0.76 per Therm, $0.125 per kWh) and plots assuming propane ($2.00 per Therm, $0.125 per kWh). Looking as gas cost only, the GAHP is 47 and 38% lower in comparison to the non-condensing and condensing systems, respectively. For the total annual operating cost the GAHP is 34% and 23% lower in comparison to the non-condensing and condensing systems, respectively. The reduced savings for total operating cost is due to the higher parasitic power requirement of the GAHP system. The GAHP is always a lower cost option in comparison to the electric heat pump options. It should be noted that this analysis was extended to intermediate gas prices of $1.25 and $1.50 per Therm but is not included for brevity as previously noted. Results are similar and highlight the sensitivity of natural gas pricing.

A comparison of annual CO2e emissions are presented in Figure 19. The figure on the left presents CO2e emissions with utilities as is and the figure on the right assumes that there is 20% renewable natural gas (RNG) in the pipeline. Looking only at the plot of utilities as is, the GAHP offers 34%, 25% and 49% lower emissions in comparison with baseline gas, better gas and best electric, respectively. This result is counter to many claims that moving to an all-electric based economy will reduce CO2e emissions. In many of the cases investigated, the CO2e emissions are greater than the baseline heating system. This is an indication that the best electric systems available would actual make CO2e emissions worse if implemented. It is important to remember that in colder climates the heating requirement is significantly larger than that of the cooling

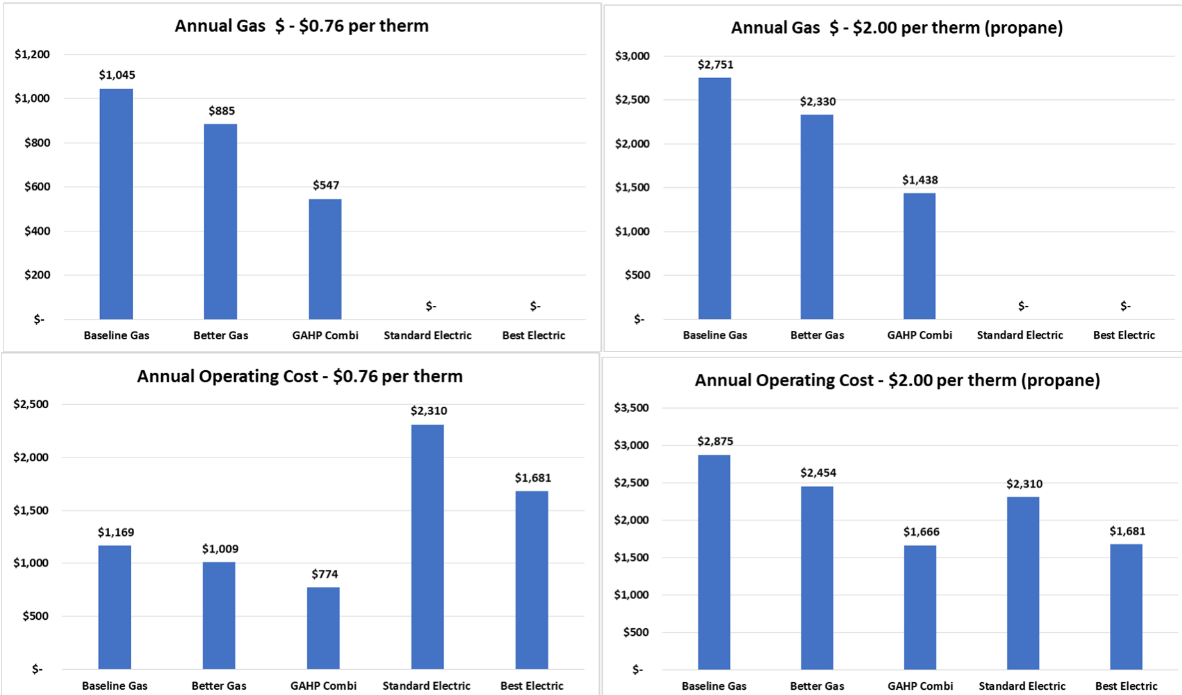

Figure 18: Gas Only and Total Annual Operating Cost, Chicago

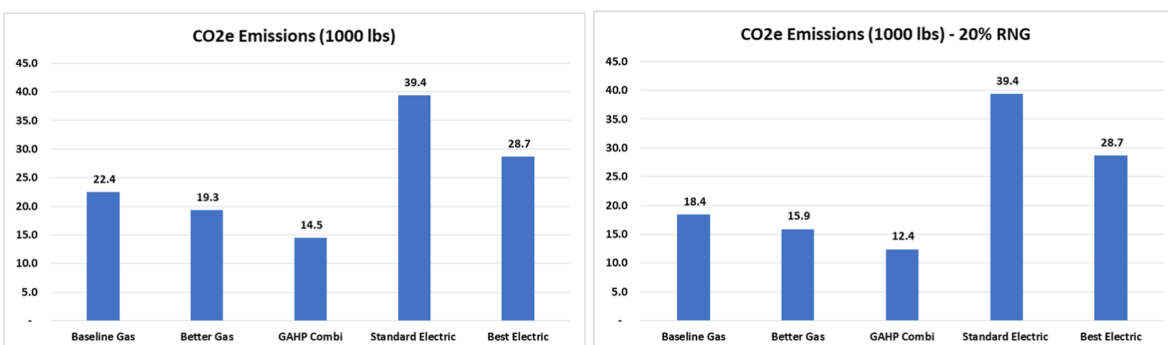

Figure 19: CO2e Emissions Comparison with utilities as is and 20% RNG, Chicago

requirement which would require additional power generation (marginal grid operation) and utility service upgrades that are beyond the scope of this study.

The simple payback was calculated versus the baseline and better (2-stage and fully modulating) gas heating equipment. The use of incentives ($500, $1000 & $1500) to reduce the payback time for the GAHP was also investigated. The following plots focus only on comparisons with the baseline gas heating system. Figure 20 presents payback result for no incentive and a $1000 incentive for the GAHP. If a bar is not show, there is no payback. The plots show that the GAHP offers the lowest payback. The plots also show the sensitively of payback and that today's natural gas pricing makes it very difficult from a sales perspective for all advance technologies (including condensing furnaces) to provide a reasonable economic payback. Payback becomes more acceptable as gas prices increase above $1.25 per therm.

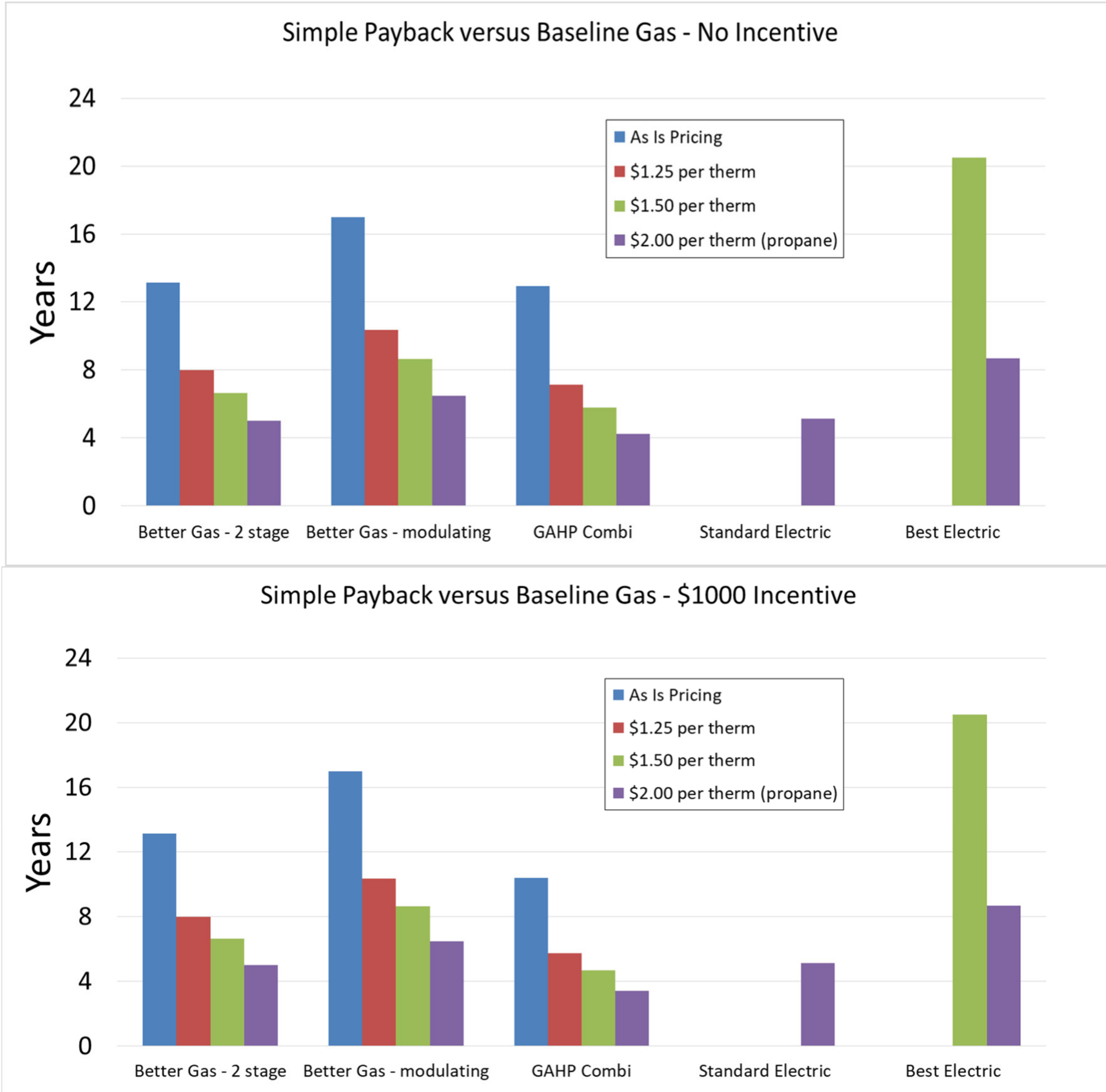

Figure 20: Payback Comparison with no incentive (top) and $1000 incentive (bottom), Chicago

The total product life and internal rate of return (IRR) were the last two items investigated as part of this techno-economic investigation. Both calculation assume a 15 year product life. It was assumed that gas and electric utility costs had inflation rates of 2 and 3%, respectively, for the total product life calculations. No incentives were assumed. Figure 21 contains plots for the total product life and IRR. The total product life plot shows that the GAHP system offers the lower total cost in comparison with all systems. The cases looking at higher gas prices show that this savings, pertaining to other gas systems, increases as the gas price increases. The IRR results show that the GAHP offers the highest rate of return versus the baseline gas system for all heating systems investigated. The IRR increases with increased gas prices as the GAHP saves more on an annual basis.

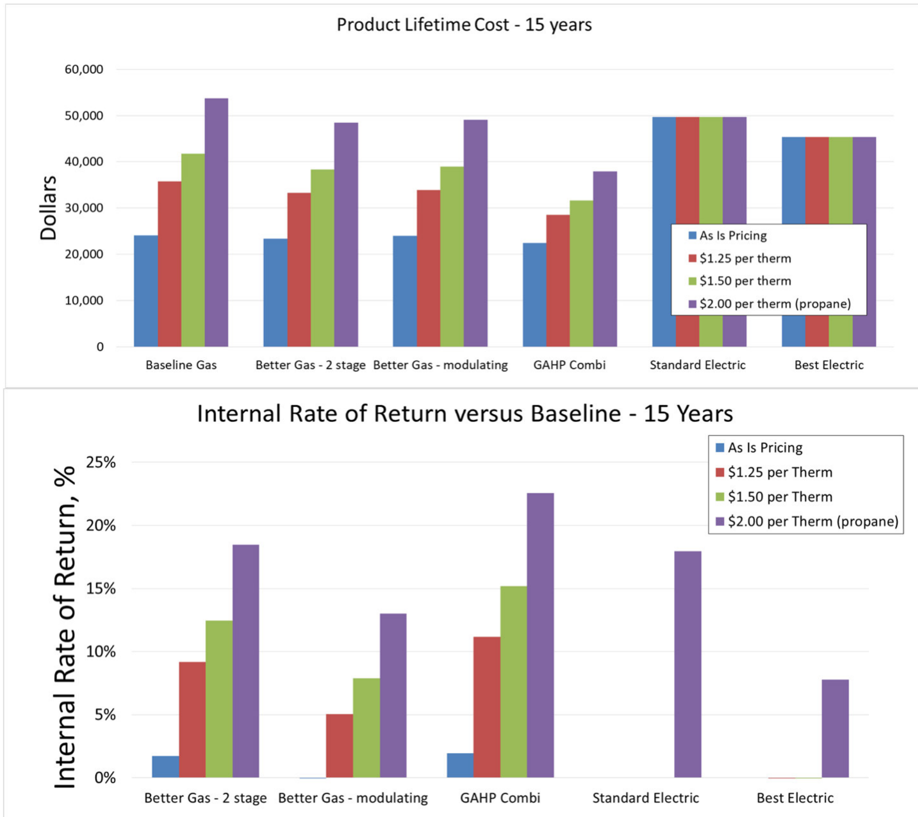

Figure 21: Product life cost (top) and IRR (bottom), Chicago

Summary for all locations investigated:

Key takeaways from the detailed study were that the GAHP offered the following.

<u>GAHP Combi natural gas savings:</u>

- 36 to 43% compared to condensing
- 46 to 50% compared to non-condensing

<u>GAHP Combi operating cost savings for design heating load 1 (DHL-1):</u>

- 21 to 29% compared to condensing
- 32 to 39% compared to non-condensing

<u>GAHP Combi carbon emissions savings:</u>

- 23 to 33% compared to condensing
- 34 to 41% compared to non-condensing
- 22 to 61% compared to cold-climate EHP

The study also showed that the payback for investing in a GAHP system is highly sensitive to the price of natural gas. However, the GAHP almost always had a better payback than condensing option and was better than the electric options for all natural gas cases and most propane cases.

10.0 Summary and Technology Status

The goal of this project was multifold and the project team was able to advance the design of the GAHP and system to a pre-commercial status by addressing the goals outlined in the statement of work.

The GAHP underwent significant design for manufacturing advancements in an effort to reduce cost to projected targets and improve manufacturability of component and system designs (1) while minimizing impact on GAHP performance. Compliance was demonstrated with the ANSI Z21.40.1 standard (2) with the remaining items open due to test facility requirements beyond those currently available to SMTI. A detailed manufacturing plan and facility layout for the GAHP were completed (3). Production cost estimates were within 10% of target at a volume of 50,000 units per year and CapEx requirements were within prior target estimates (4). A reliability test plan was developed (5). Reliability testing was completed on an 80K ALT unit which has accumulated 5000+ hours to date. Reliability testing was initiated on the solution pump and planning was completed for the desorber and EEV. A field demonstration was completed in La Crosse, WI that highlighted the potential of the GAHP system and many of the potential pitfalls if the GAHP and system are not controlled properly (6). A detailed Techno-economic analysis was completed that highlighted the potential energy, cost and CO2 emissions savings potential of the GAHP in comparison with more conventional gas and advance electric heat pump technologies (7). And lastly, a market research study was completed that showed that there is significant potential in the market for a reasonably priced GAHP technology.

SMTI’s commercialization efforts are continuing to develop beyond this project with a focus on proving out the reliability of the GAHP and all of its sub-components. The reliability test plan developed as part of this project will serve as the guide for this work. In addition to this, SMTI is continuing to refine the design of the GAHP (sealed system and balance of system) before the production design is locked down. Manufacturing facility planning and requirements continue to be refined as CapEx requirements are balanced between manufacturing needs and funding needs to get the product in the market.

References

[1] Garrabrant et al (2013), Development & Validation of a Gas-Fired Residential Heat Pump Water Heater-Final Report, DOE DE-EE0003985, OSTI 1068205.
[2] Garrabrant, M., Stout, R., Glanville, P., Keinath, C., and Garimella, S. (2013), Development of Ammonia-Water Absorption Heat Pump Water Heater for Residential and Commercial Applications, Proc. of the 7th Int'l Conference on Energy Sustainability, Minneapolis, MN.
[3] Glanville, P., Vadnal, H., and Garrabrant, M. (2016), Field testing of a prototype residential gas-fired heat pump water heater, Proc. of the 2016 ASHRAE Winter Conference, Orlando, FL.
[4] Garrabrant et al (2015), Low-Cost Gas Heat Pump for Building Space Heating-Final Report, DOE DE-EE0006116, OSTI 1328433.
[5] Glanville, P., Keinath, C., Garrabrant, M., Development and Evaluation of a Low-Cost Gas Absorption Heat Pump, Proceedings of the 2017 ASHRAE Winter Conference, Las Vegas, NV.
[6] Garrabrant, M., Stout, R., Keinath, C., Glanville, P., (2016) Experimental Evaluation of Low-Cost Gas Heat Pump Prototypes for Building Space Heating, 16th International Refrigeration and Air Conditioning Conference at Purdue.
[7] ANSI Z21.40.1 Performance Testing & Rating Gas-Fired Air-Conditioning and Heat Pump Appliances
[8] Geoghegan, P., Shen, B., Keinath, C., Garrabrant, M., (2016), Regional Climate Zone Modeling of a Commercial Absorption Heat Pump Water Heater–Part 1: Southern and South Central Climate Zones, 16th Int. Refrigeration and Air Conditioning Conference at Purdue.
[9] Sharma, V., Shen, B., Keinath, C., Garrabrant, M., Geoghegan, P., (2017), European Regional Climate Zone Modeling of a Commercial Absorption Heat Pump Water Heater, 12th IEA Heat Pump Conference, Rotterdam.

Appendix A: Cold Ambient Modulating Gas Valve Assessment and Test Report

Prepared by Glanville, P. and Sutherland, B. of GTI

Edited by Keinath, C. and Garrabrant, M. of SMTI

Milestone Goal: The goal of Milestone 2.4 was to experimentally demonstrate successful ignition and operation of a cold-climate gas valve down to -20°F and successful 4:1 modulation of said cold-climate gas valve down to 0°F. Under this task, the Gas Technology Institute (GTI) sought to meet this target with off-the-shelf hardware with modifications, if necessary.

Summary of Results: Using a modified climate chamber, GTI evaluated off-the-shelf combinations of components from three major suppliers: Honeywell, EBM-Papst, and SIT. These gas valves were rated for a minimum -15°C/5°F (Honeywell) and 0°C/32°F (SIT, EBM-Papst). An overall summary of results are as follows:

- **Modulation of 4:1 at 0°F:** By calibrating combustion at the nominal 47°F condition, all combinations were able to modulate firing rate at 0°F, however some equipment exhibited flame stability and/or excessive CO emissions at the 25% firing rate and, in some cases, the 50% condition. It is worth noting that not all combinations of gas valves, venturis, and blowers were rated to cover the intended modulation range (13,750-55,000 Btu/hr), namely the venturis for the SIT and Honeywell have lower rated limits of 17,000 Btu/hr. Of all combinations evaluated to date, the SIT was most able to retain good combustion stability over the modulation range.

- **Full-Fire Cold Start at -20°F:** Using the same calibration from operation at 47°F, two of the three product combinations evaluated were fired from a cold start in a -20°F environment. The combination of components from Honeywell as tested had sufficient instabilities during the 0°F modulation tests that GTI requires additional time to understand if these are due to how it is being tested (including erroneous setup/operation) or if they are inherent to the equipment. Equipment combinations from EBM-Papst and SIT were able to ignite and sustain combustion from a -20°F cold start, however each had poor combustion (high CO emissions, moderate noise).

From these results, GTI can confirm that:

4) Off-the-shelf combinations of components (blower, gas valve, venturi mixer, controls) are, for the Gas Absorption Heat Pump's (GAHP) target operation, able to support 4:1 modulation at 0°F and sustain ignition from a -20°F cold start. This is despite the components' operation below their rated ambient temperature.

5) Auxiliary heating within the GAHP enclosure for cold starts at -20°F will not be necessary.

6) For components evaluated, using pneumatic control or a zero governor valve to maintain fuel/air mixing ratios, modifications may be necessary to maintain acceptable CO emissions and operational noise at these low ambients. GTI will explore these modifications with additional testing and the inclusion of electronically-controlled gas valves.

Background: Premixed combustion systems, wherein fuel and combustion air are mixed upstream of the burner and pressurized with a blower, have several demonstrated advantages for gas-fired equipment. These include:

- **Modulation:** Variable speed blower control permits variation of the heating rate to the process, allowing for 4:1 turndown or greater to facilitate continuous process modulation. This fine control is often advantageous over discrete staging of individual or multiple burners, as is common with induced/natural draft equipment.
- **Emissions:** Pressurizing the fuel/air mixture allows the use of low-NO_x burner designs whose flameholders have appreciable pressure drops, including woven/knitted fiber sheets, sintered fiber mats, ceramic/metallic foams, and other flameholders intended to decrease flame temperatures and NO_x emissions.
- **Efficiency:** Similarly, the pressurization permits the use of more tortuous heat exchangers and the aforementioned premix burners with increased surface heat flux permits compact, more efficient heat transfer.

With these advantages, premix combustion systems are commonly deployed as part of high-efficiency gas-fired equipment, primarily for condensing boilers and more recently for gas-fired heat pumps, the subject of this study. These premixed combustion systems are comprised of five main components: the gas valve/regulator assembly, the blower, the fuel/air mixer, the premix burner, and the combustion controls (including ignition, gas valve, and blower speed controls). While the premix burner can vary widely from application to application, the modulating gas train (gas valve, blower, fuel/air mixer, ignition sense/control) is typically one of two configurations: pneumatic control and electronic control. Both cases permit modulation by adjusting the natural gas flow with the blower speed, in an attempt to maintain the air/fuel ratio (lambda, λ) over the modulation range. The predominant pneumatic control systems generally maintain λ over the modulation range very well, however more modern electronic (or “gas adaptive”) gas trains offer more precise control. The two differ generally as follows, in how gas flow varies with blower speed:

- **Pneumatic Control:** Once λ is set relative to a fixed blower speed and source fuel pressure, using a manual adjustment on the pneumatically-controlled gas valve, the ‘zero governing’ feature of this gas valve assures a neutral fuel pressure on the suction side of the fuel/air mixer, adjusting to the blower suction through a pneumatic signal. A simplified diagram from vendor EBM-Papst is shown in Figure A1. Within the gas valve, a diaphragm/spring assembly adjusts based on said pneumatic signal to maintain a desired outlet fuel pressure independent of the flow rate/upstream pressure, as shown in the diagram in Figure A2 from vendor Maxitrol. Often this desired outlet pressure is 0” W.C. gauge, as a ‘zero governor’.

  Pneumatic control for premix combustion gas trains is very common, its performance is reliably documented by numerous condensing boilers, commercial condensing water heaters, and other commercially-available equipment. Additionally, the gas absorption heat pumps (GAHP) under development in this study have, to date, used pneumatically-controlled gas trains (Figure A3). While not an issue for boilers and water heaters installed indoors, GAHPs installed outdoors must operate over a very wide range of ambient operating conditions, potentially below those that the available gas trains are certified to operate, generally down to -15°C or 0°C (5°F or 32°F). At lower temperatures, down to 0°F (-18°C) or -20°F (-29°C), the operation can be affected in several ways:

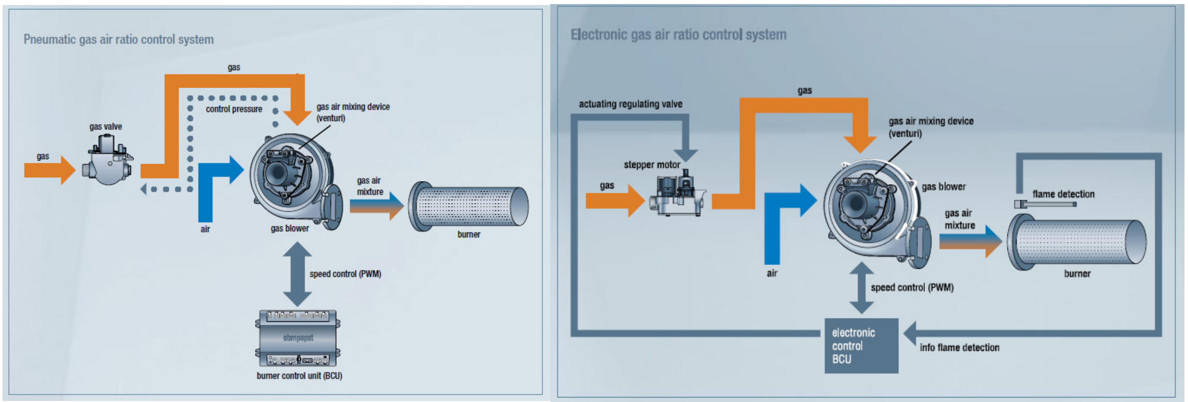

Figure A1: Diagrams of Pneumatically vs. Electronically-Controlled Gas Trains (Source: EBM-Papst)

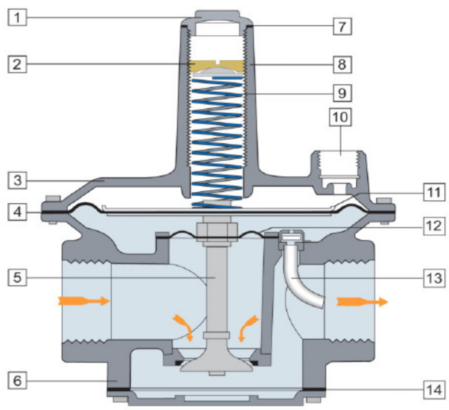

Figure A2: Diagram of “Zero Governor” Valve (Source: Maxitrol)

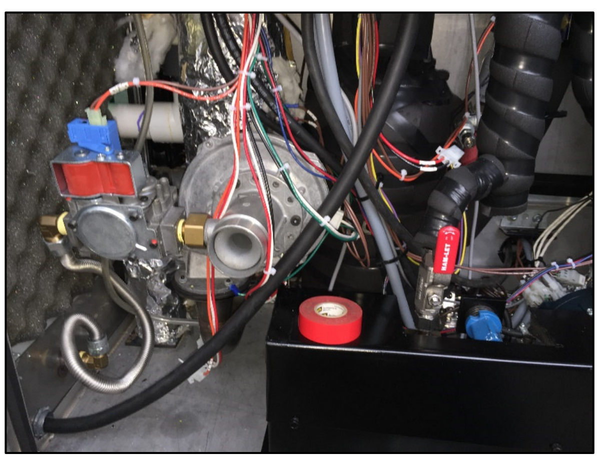

Figure A3: Pneumatically-Controlled Gas Train in “Beta” GAHP Unit

- **Poor Performance:** The proportional control of the gas valve, in response to the pneumatic signal, is non-linear with very cold temperatures. This is in part due to changes in material properties with temperature (spring stiffness, diaphragm hardness) and the changing properties of air, for example air is 15% more dense and 14% less viscous from 70°F down to -20°F. Additionally gas trains typically have a natural de-rating with cold temperatures as openings contract (orifices, slots, gaps, etc.). As a result, in cold environments premix combustion systems may lose the ability maintain desired air/fuel ratios and, in some cases, fail to sustain ignition.

- **Failure:** At very cold temperatures, seals of mating parts may no longer function. Also the diaphragm may weaken due to hardening/stiffening and springs may fracture, resulting in leakage and potentially permanently damaging the hardware.

- **Electronic Control:** Coming from the boiler industry and from Europe, where tight excess air control and ability to handle wide ranges gas quality ("gas adaptive" systems) are important, many vendors offer electronically-controlled gas trains. In this arrangement (Figure A1), a central controller receives input from the blower (speed) and from the burner/combustion chamber (typically temperature) to adjust a stepper motor-controlled gas valve to adjust fuel input to the gas train. For a given λ, the controller maps the detected heat output as a function of air flow through the blower and attempts to maintain λ as the system modulates. As the control of the gas valve is decoupled from the blower speed by the electronic controller, the loss of capacity and air/fuel ratio control may be feasible. Like pneumatically-controlled gas valves, these electronically-controlled gas trains are certified for operation as low as -25°C (-13°F), however the robustness of the programmed constant-λ curves down to and below this range is unknown. This newer product category, slowly being introduced to North America, is reportedly expensive relative to the common pneumatically-controlled gas trains, however the specific cost is unknown.

Test Plan: In evaluating the ability of off-the-shelf and, if necessary, modified premix combustion systems to meet the Task Goals, the project team will attempt to address the following research questions:

- Can one or multiple off-the-shelf pneumatically-controlled premix combustion systems meet the Task Goals of 4:1 modulation at 0°F and stable ignition at -20°F?
  - If not, what is the minimum supplemental heating (electric resistance) necessary to achieve the Task Goals?
  - Are there simple modifications to the components that either expand the operating envelope of the gas train or acceptably reduce performance at high ambient temperatures by shifting the operating envelope?
- Can one or multiple off-the-shelf electronically-controlled premix combustion systems similarly meet the Task Goals?
  - If so, what is a possible λ curve calibration procedure for the GAHP and what is the expected equipment cost to an OEM?

Methodology: In order to facilitate reliable operation the GAHP's combustion system while installed outdoors in a cold climate, GTI will demonstrate the safe operation of a modulating gas train (gas valve, blower, fuel/air mixer, ignition sense/control) in a climate chamber. A "dummy desorber" was provided by SMTI for testing, which was used as a fluid-cooled heat exchanger for testing. Additionally, SMTI provided a representative premix burner to be used in all testing. The desorber (Figure A4) was plumbed with a water/glycol mixture, insulated, and installed within the walk-in climate chamber. For the purposes of testing, the downstream condensing heat exchanger (CHX) and venting were simulated as back-pressure with a variable restriction and during steady operation, the desorber was maintained at a temperature sufficient to keep the desorber in a 'non-condensing' mode. The chamber itself, rated for

Figure A4: "Dummy Desorber" with pre-heating tankless Water Heater (Left), Cold Climate Chamber (Right)

ambient temperatures down to -40°F, was modified to a) accommodate flue products out to the analyzer bank, b) bring in the approximately 12 CFM of combustion air necessary for the setup, and c) minimize the internal heat gain from the setup to the chamber.

For all off-the-shelf hardware configurations, the sequence of test operations proceeded as follows with all measurements noted in Figure A5 running continuously:

1) The climate chamber was brought to 47°F, a typical mild-winter rating point. The CCGT was fired at nominal 55,000 Btu/hr and the flue segment coolant was introduced into the flue segments at approximately 120°F. The controlled flue restriction, coolant flow rate, and gas valve/mixer settings were set such that the exit flue conditions are 300°F and with 5% O_2 (dry basis). Steady state was held at this baseline configuration point for no less than five minutes.
2) Holding the Simulator conditions fixed, the system was shut down and restarted at least two times to verify successful ignition. Additionally, the following was performed:
    a. Continuous modulation of 4:1 was demonstrated from 55,000 Btu/hr to 13,750 Btu/hr and back to 55,000 Btu/hr
    b. Startup ignition was verified at 25% and 50% peak input.
    c. The lower modulation point below 4:1 was identified at the point of flame loss through gradual reduction in firing rate.
3) The chamber conditions was gradually brought down to 0°F and, upon reaching stable environmental conditions the tests outlined in Item #2 were repeated starting with a cold desorber shell.
4) If Item #3 showed successful performance, 4:1 modulation, the chamber conditions were brought further down to -20°F and the unit will be fired at the original settings for 55,000 Btu/hr to demonstrate successful startup ignition and firing.

As outlined the test plan, once all equipment configurations received were evaluated through steps #1-#4 and if none successfully met the Task Goals, the project team would evaluate modifications as necessary to reach required performance, including but not limited to: issues with hot-surface ignitor,

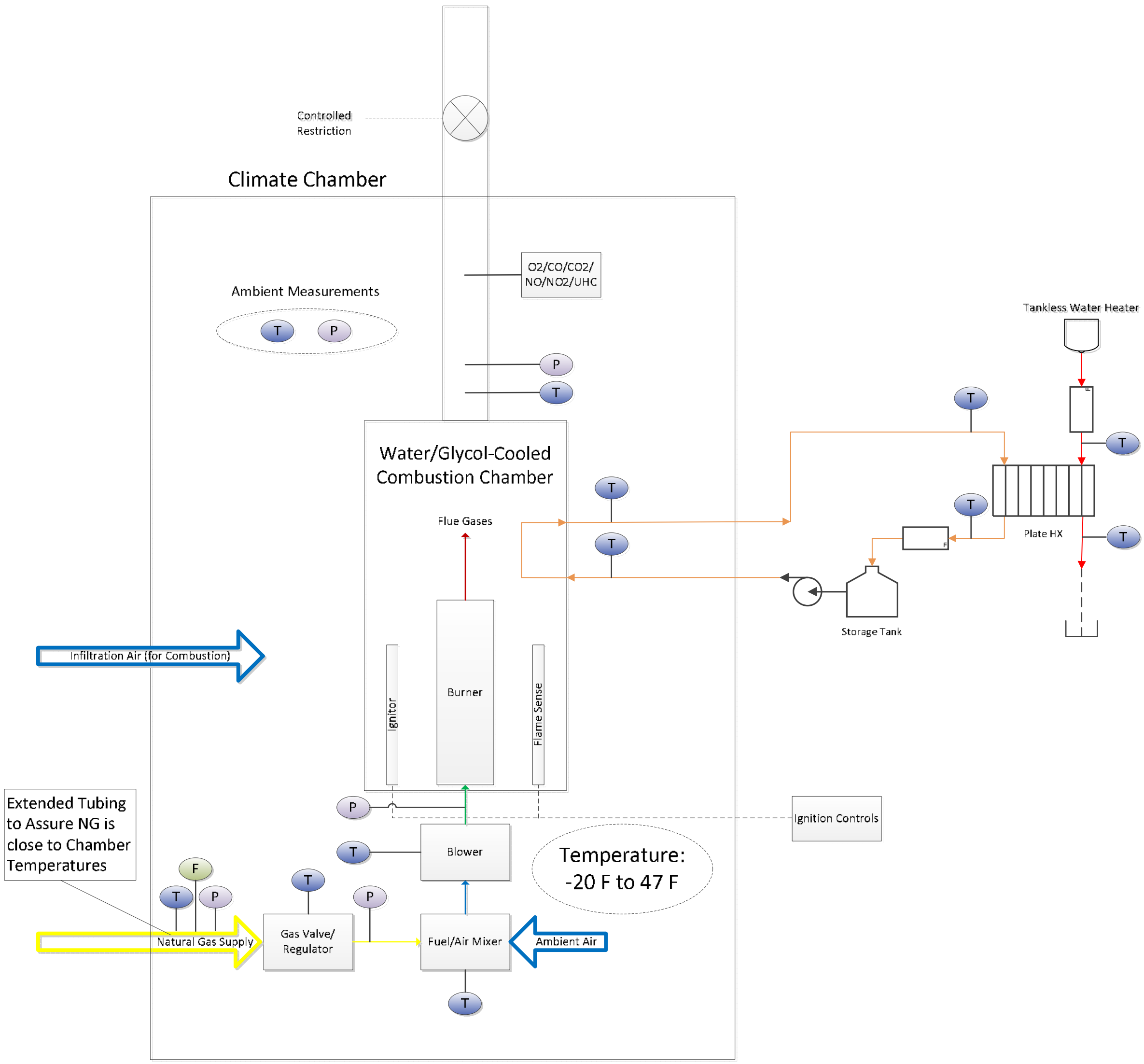

Figure A5: Diagram of CCGT Simulator

physical modifications of fuel/air mixer, over-sizing gas regulator, dynamically adjusting flue-side back pressure, dynamic adjustments to fuel/air ratio and blower speed, and other changes. Additionally, if the pneumatically-controlled options do not work, the opportunity for resistance heating would be explored to aid in startup.

Measurements performed for each test performed by STI are outlined in Figure A5 and summarized in Table A1. These measurement include the following:

- Natural Gas Inlet: flow (dry test meter), pressure (transducer), temperature (thermocouple), and HHV (calorimeter)
- Ambient Air Inlet: temperature/pressure as measured volume-averaged within chamber
- Blower: Outlet pressure (transducer), and speed (as controlled/measured with tachometer)

- Combustion Chamber: temperature difference (thermocouple) and flow (turbine meter) of chamber coolant.
- Flue Gases: temperature (thermocouple), back pressure (transducer), and speciation (gas analyzers)

Equipment Tested:
For each system evaluated, the following hardware was consistent:

- The premix burner provided by SMTI
- While the blower will be operated manually through a custom blower speed controller, the ignition controls/flame sense as integrated with each gas valve will use a standard, off-the-shelf controller (e.g. Capable Controls) for each test
- The "dummy desorber" settings for inlet water/glycol temperature and flow rate, back pressure at flue exit, they were determined with the first configuration and held consistent throughout the remainder of testing (see Figure A6)

Working with suppliers of premix combustion components, GTI solicited the following hardware:

1) **SIT -** SIT is an Italian manufacturer of gas control components, claiming to be the world market leader in controls for boilers, space heaters, and fireplaces. For this program GTI solicited a set of hardware from SIT:

- An identical set of hardware as used by the GAHP prototypes, which includes:
    - A *390* model fuel/air mixer with a rated capacity of 5 – 25 kW (17,000 – 85,300 Btu/hr)

Table A1: Summary of Measurements

Measurement Type	Measurement Point	Instrument	Notes
Natural Gas	Dry Test Meter	Model: Elster AC-250	Dry Test Meter
	Pressure Transducer	Model: Dwyer 668-7	Pressure Transducer
	Thermocouple	K-Type Thermocouple Model: KQXL-116U-12	Thermocouple
	N/A	Model/Data Source: N/A	N/A
Ambient Air	Thermocouple	K-Type Thermocouple Model: KQXL-116U-12	Thermocouple
Combustion Blower	Pressure Transducer	Model: Dwyer 616D	Pressure Transducer
	Embedded Tachometer	N/A	Embedded Tachometer
Exhaust Gases	Thermocouple	K-Type Thermocouple Model: KQXL-116U-12	Thermocouple
	Pressure Transducer	Model: Dwyer 620	Pressure Transducer
	Horiba Gas Analyzer	Model: PG-300	Horiba Gas Analyzer
"Dummy" Desorber	Thermocouple	K-Type Thermocouple Model: KQXL-116U-12	Thermocouple
	In-line Turbine Flow Meter	Model: Omega FTB4607	In-line Turbine Flow Meter

Figure A6: Uninsulated (Left) and Insulated (Right) Test Setup within Chamber

- An *848 Sigma* model gas valve, with pneumatic 1:1 air/fuel control, with a 0°C (32°F) lower temperature rating
- An *NG-40* premix blower, with a max speed of 9,600 rpm, 64.7 CFM, and max outlet pressure of 12.4” W.C.

- Additionally, SIT indicated they have a “low temperature” (-25°C or below) assembly under development, however SIT was unable to provide a sample and indicated that this may change over the next six months.

2) **EBM-Papst -** EBM-Papst is a German manufacturer of electric motors and fans, leading in these markets. They have a complete line of premix combustion controls and have a growing North American presence, with an R&D facility in Connecticut. To date, EBM-Papst was able to provide the following components to GTI (Figure A7):

- An assembly based on the *NRV118* blower, including:
  - *NRV118* blower, max speed of 9,000 rpm, 57 CFM, and max outlet pressure of 11.2” W.C.
  - A standard venturi, ranging from 3-23 kW (10,250 to 78,500 Btu/hr) output
    - Note that while the smaller venturi is perfect for the GAHP, a larger venturi is anticipated from EBM-Papst, to cover 5-28 kW (17,000 to 95,550 Btu/hr) output
  - A zero governor-based gas valve *GB-ND 055 E01*, with a 0°C (32°F) lower temperature rating

- An assembly based on the *NRV77* blower, including:
    - *NRV77* blower, max speed of 14,000 rpm, 53 CFM, and max outlet pressure of 8.8" W.C.
    - A standard venturi, ranging from 2-15 kW (6,800 to 51,200 Btu/hr) output
        - This venturi is too small for the GAHP, so the larger venturi for this blower is anticipated, to cover 5-28 kW (17,000 to 95,550 Btu/hr) output
    - The same model gas valve as the *NRV118*

- In addition to other sizes of venturis for both NRV118 and NRV77, GTI was unable to secure the *electronically-controlled* gas valve based on the *F01* model line. While it was unable to do so initially, EBM-Papst has committed to providing GTI with a compatible *F01* valve for the *NRV118* platform and support direct control of the stepper motor from their own supplier. Testing of this valve will be performed as part of an extended study.

Figure A7: Photo of Honeywell (Left) and EBM-Papst (Center, Right) Assemblies

3) **Honeywell -** Honeywell is a major OEM supplier in the U.S. and Canada, dominating conventional gas controls and also providing a complete line of premix combustion controls, building on their expansive industrial and commercial-sized products. Honeywell was able to provide GTI with the following assembly:

- An *FIME* blower, *PX118* model, max speed of 7,000 rpm, 56 CFM, max outlet pressure of 10.4" W.C.
- A *VK81* series gas valve, with pneumatic 1:1 air/fuel control, a -15°C (5°F) lower temperature rating
- A standard venturi *45.900.444-003* model, output range from 5 to 27 kW (17,000 to 92,000 Btu/hr)

Honeywell does have a series of electronically-controlled gas valves, however they do not have offerings in the residential sector.

<u>Results:</u>
SIT System: For the 47°F ambient simulated condition, a number of test fires were performed to verify ignition at multiple modulation points. These are summarized in Table A2 and Table A3, which other than moderate observed noise, a low hum, the SIT system operated well and was readily calibrated. At low fire

(25%), the noise increased and was coincident with a sharp increase in CO emissions, an indication of a lifted and impinging flame. It would require additional effort to calibrate the “dummy desorber” to simulate the actual operating conditions, namely the hotter desorber walls (> 250°F), so with the cooler ~120°F, these high CO emissions were treated as an artifact of a) the difficulty in matching the back pressure of the actual GAHP system and b) the cooler desorber shell walls. Follow-on efforts may attempt to address this directly, however, as shown the SIT system is able to:

1) Successfully achieve a sustained ignition at all firing rates and ambient temperatures and,

2) As shown in Figure A8 and Figure A9, the SIT system is able to successfully modulate from 4:1 and back, at 47°F and 0°F, with moderate noise as noted at the low firing rates.

Table A2: SIT Components Start-up Fire – Temperatures and Firing Rate

Ambient Target (°F)	Firing Rate (% of Max.)	Gas Inlet Temp. (°F)	Air Inlet Temp. (°F)	Average Shell Temp. at Start (°F)	Average Firing Rate (Btu/hr)
47	100%	47.0	45.5	89.4	56,180
	50%	46.9	45.3	79.7	26,065
	25%	44.4	44.7	72.0	12,580
0	100%	-1.5	-2.5	65.1	57,880
	50%	-0.9	-2.0	61.9	27,000
	25%	-1.2	-2.6	67.6	13,240
-20	100%	-17.2	-19.2	67.3	57,335

Table A3: SIT Components Start-up Fire – Gas Analysis

Ambient Target (°F)	Firing Rate (% of Max.)	O2 (%, dry)	CO2 (%, dry)	CO (ppm)	NO (ppm)	Note
47	100%	6.2	8.4	156.3	6.9	~5,600 rpm
	50%	Data Unavailable				
	25%	6.1	7.1	4,700	8.6	~ 1,700 rpm; Moderate Oscillatory Noise
0	100%	5.2	9.0	50.2	10.0	Moderate Noise
	50%	3.9	8.8	5,080	15.0	
	25%	6.2	5.2	573	1.2	
-20	100%	6.1	8.1	588	6.1	Moderate Noise

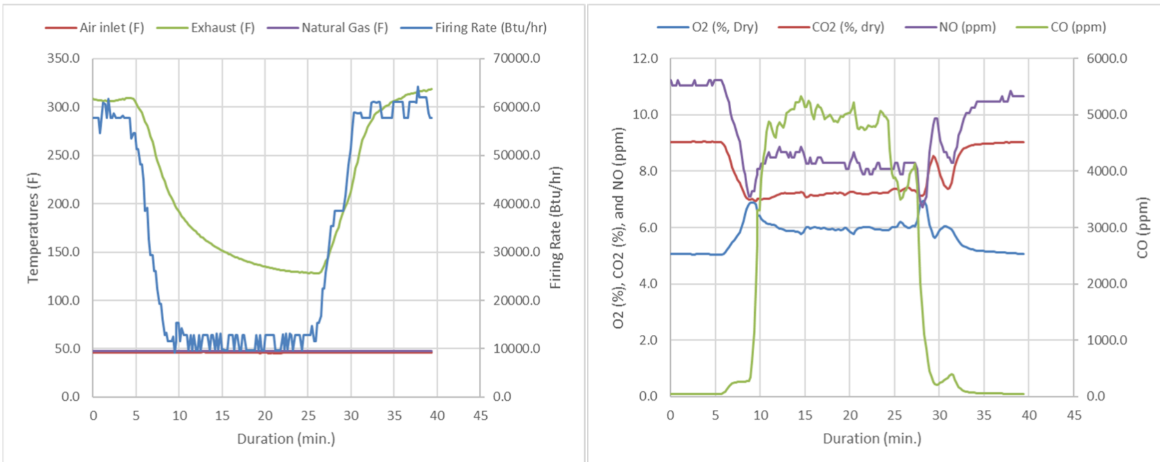

Figure A8: SIT Initial Modulation Test at 47°F

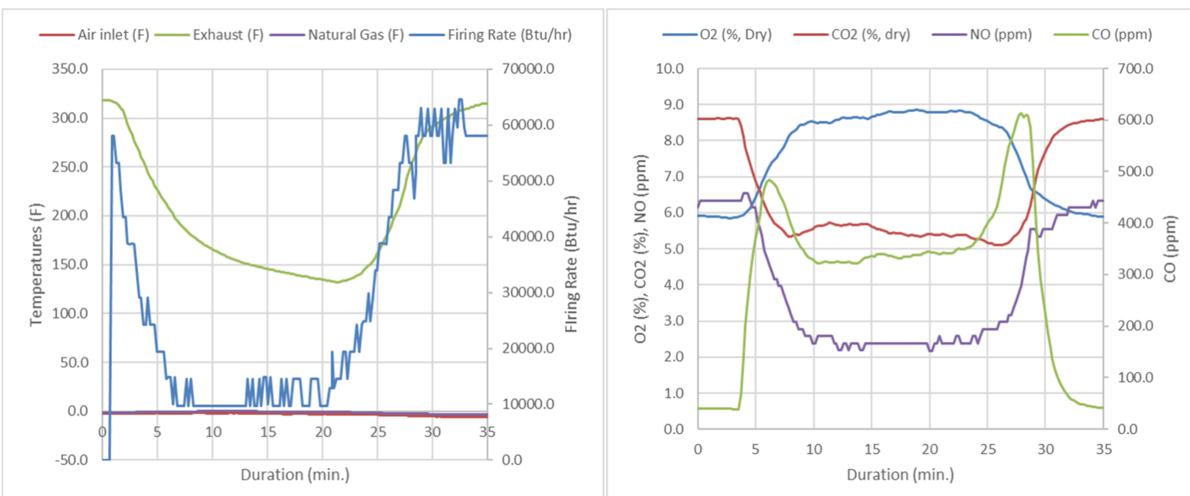

Figure A9: SIT Initial Modulation Test at 0°F

EBM-Papst System: The following presents findings from the EBM-Papst blower, exclusively for the *NRV118* assembly (Tables A4 and A5). GTI was not successful in calibrating this assembly to the "dummy desorber", however data suggest this is feasible for these components. The EBM-Papst assembly was able to ignite and sustain ignition at the operating points, including 100% fire at -20°F, however GTI had continued difficulty dialing in the gas valve/blower/venturi for the 50% and 25% cases. GTI is awaiting additional equipment from EBM-Papst and plans to spend more time testing the *NRV118* and *NRV77* assemblies, including the integration with an electronically-controlled *F01* series gas valve.

As shown in the modulation tests at 0°F with no active adjustments (Figure A10) versus active adjustments while operating (Figure A11), it is feasible to hold stable combustion with acceptable CO emissions (<100 ppm air free). The assembly is able to hold successful ignition at all operating points and can modulate at the nominal and cold conditions, however the correct settings for the 'dummy desorber' were not yet identified.

TableA4: EBM-Pabst Components Start-up Fire – Temperatures and Firing Rate

Ambient Target (°F)	Firing Rate (% of Max.)	Gas Inlet Temp. (°F)	Air Inlet Temp. (°F)	Average Shell Temp. at Start (°F)	Average Firing Rate (Btu/hr)
47	100%	47.6	47.2	88.9	52,470
	50%	Able to ignite, but back pressure issues create erroneous measurements			
	25%				
0	100%	0.0	-0.5	89.6	64,545
	50%	Not Performed Yet			
	25%				
-20	100%	-16.2	-17.2	60.6	63,170

Table A5: EBM-Papst Components Start-up Fire – Gas Analysis

Ambient Target (°F)	Firing Rate (% of Max.)	O2 (%, dry)	CO2 (%, dry)	CO (ppm)	NO (ppm)	Note
47	100%	5.8	8.7	42.9	7.5	~5,500 rpm
	50%	Able to ignite, but back pressure issues create erroneous measurements				
	25%					
0	100%	5.7	8.7	49.2	7.9	Investigating overfire
	50%	Not Performed Yet				
	25%					
-20	100%	5.4	8.9	53.1	8.6	Investigating overfire

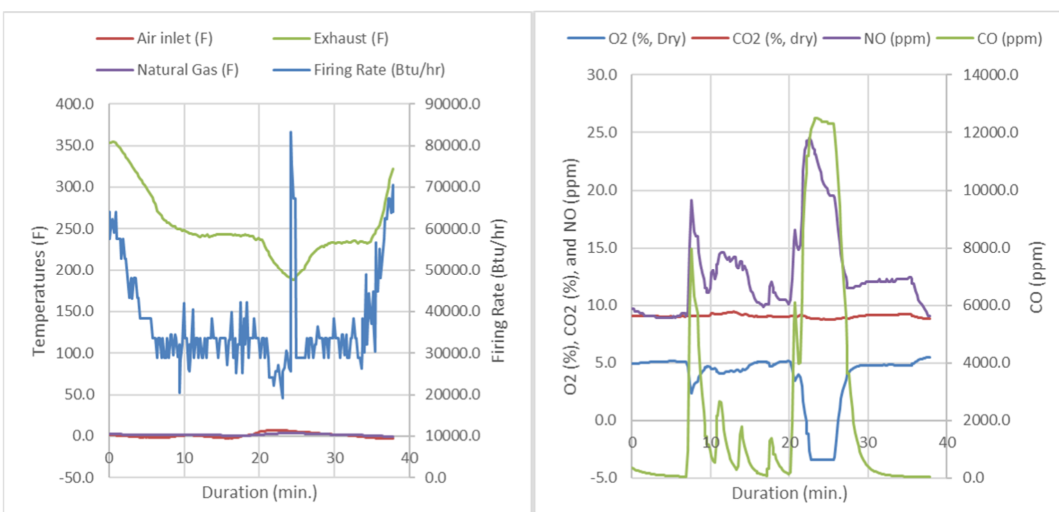

Figure A10: EBM-Papst Initial Modulation Test at 0°F without Adjustments

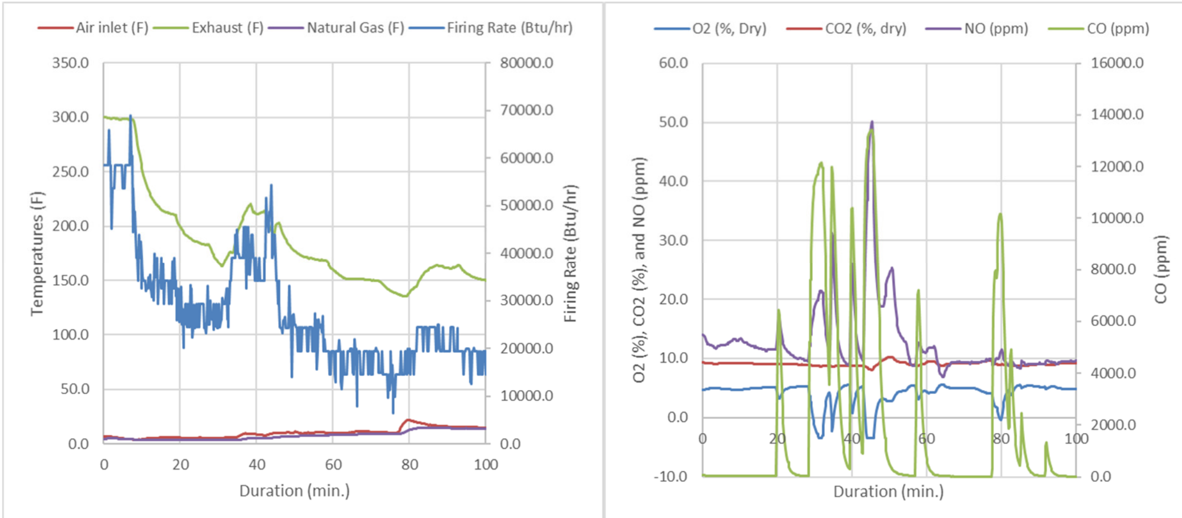

Figure A11: EBM-Papst Initial Modulation Test at 0°F with Adjustments

Once identified, potentially using different venturi/blower combinations and/or the electronic gas valve, GTI expects that settings held from the 47°F condition will result in successful operation as the SIT equipment have shown.

Honeywell System: Similar to the EBM-Papst assemblies, GTI was not able to operate the Honeywell assembly successfully based on initial settings. The assembly was able to ignite at all cases for 47°F and 0°F, however the assembly appears to have greater difficult with operating below 50% modulation. GTI plans to continue to investigate the Honeywell assembly.

Conclusions and Next Steps: The SIT component testing was completed and demonstrated successful operation to achieve the task milestone. This included successful 4:1 modulation at 0°F, and ignition and operation down to -20°F. This evaluation builds confidence in the gas valve currently being used by SMTI. Certification of this valve at even colder temperatures (-35°F) is needed as part of long term development. Over the near term, GTI will continue to perform tests to provide a complete dataset per the test plan and to fully answer the research questions, including:

- *Assure Dataset Completeness:* For data presented in this report, GTI may repeat tests to address issues and data gaps as noted.
- *Refined Approach to EBM-Papst Assembly:* In addition to continuing to refine the initial settings of the EBM-Papst *NRV118* assembly, to assure stable operation with acceptable CO emissions when modulating, GTI will solicit additional components from EBM-Papst to assure the correct assembly is used for the GAHP application. This includes additional venturis for the *NRV118* and *NRV77* blowers and an electronically-controlled *F01* series gas valve with independent control of the stepper motor.
- *Determination of Honeywell Assembly*: Using lessons learned from the EBM-Papst assembly evaluation, GTI will evaluate the Honeywell assembly and, if necessary, make minor modifications to permit successful startup ignition at 50% or lower firing rates.

Appendix B: Baseline Field Demonstration M&V Report

Prepared by Glanville, P., Suchorabski, D., and Mensinger Jr., M. of GTI

Edited by Keinath, C. and Garrabrant, M. of SMTI

Scope of Field Demonstration

In this field demonstration of "beta" prototypes, gas absorption heat pump (GAHP) combi and space heating-only systems, the project team intends to focus on prototype reliability, installation practices and issues, and on system performance under "real world" operating conditions. New prototypes, built for this project, will be installed at a closely monitored location at field sites in the metropolitan area of La Crosse, WI. This test is planned as follows:

- The performance baseline of existing water heater and space heating equipment will be captured during a portion of the 2017-2018 heating season at the two closely monitored residences in the La Crosse, WI suburban region.
- Next generation "Beta" GAHP units, built by SMTI in cooperation with the commercialization partner, were be installed in advance of the 2018-2019 heating season and continue to operate throughout the end of this season. Due to the nature of the individual sites selected and the variety sought with results, Site A will be installed as a GAHP combi system while the Site B will be installed as a heating-only GAHP system (no water heating function).

Field Test Plan: Monitoring Goals and Methodologies

As a field demonstration of a pre-commercial technology, and using past successful monitoring practices from prior field monitoring of similarly constructed pre-commercial GAHP units, the overall monitoring goals are to quantify the following:

- Pre-commercial GAHP system reliability and performance, with monitoring of both the heat pump cycle and its interaction with the space heating and DHW delivery.
- Quantifying delivered efficiency versus prior laboratory testing, comparing results to laboratory measured AFUE of 139% per ANSI Z21.40.4
- Identifying installation issues and other barriers to market entry, particularly focusing on residential installation/infrastructure issues.

Through achieving these monitoring goals, at the conclusion of this early-stage, closely monitored GAHP field study, the project team seeks to answer the following research questions:

1. Under installed conditions in a space heating-only and combi-arrangement, how do the GAHP delivered efficiency and System Coefficient of Performance (COP) vary with ambient conditions and part-load operation? How do they differ from prior laboratory GAHP testing of these same prototypes at GTI and SMTI?
2. Compared to the comparable baseline monitoring of residential space heating and combi-systems by GTI in other regions, what therm savings can gas utilities anticipate from the GAHP?
3. What GAHP retrofit installation issues could present barriers to market adoption and what are the benefits over existing high-efficiency space heating/combi equipment?

Site Selection Process

GTI solicited individuals for participation in the GAHP demonstration project via a DOE flyer in affiliation with the commercialization partner. The flyer informed participants of the minimum requirements of the house and typical use patterns that are appropriate for the study. GTI sent an online 41-question application to the volunteers that covered the critical aspects of the host site criteria GTI received three surveys that met the requirements to be the GAHP Combi Field Site. GTI developed the following criteria of the ideal host site:

- At least three or more occupants
- Existing gas-storage water heater
- Single-family residential site
- Space to accommodate both current water heater and indirect tank
- Simple installation and removal of equipment
- "Friendly" Host Site, meaning willingness to cooperate fully with all aspects of the demonstration.

A GTI employee screened these homes adhering to a defined inspection procedure to verify and propose space requirements for the installation of the GAHP prototype, an additional water heater tank, and all plumbing connections. Additionally GTI verified that the house is equipped with an existing gas furnace. The recruitment flyer, web survey, and the inspection form are all displayed at the end of the report. The selected two sites (Table B1 and Figures B1 and B2), Sites A and B are located in La Crosse and Onalaska respectively.

Measurement Methodology and Hardware Specification

This measurement methodology and hardware specification is intended to reliably collect data in support of answering the aforementioned research questions, while generating high quality datasets for future analysis. Using methods from prior GAHP field monitoring, the following metrics will be quantified over the field monitoring periods:

- COP of the GAHP over the course of an on-cycle as a function of ambient air temperature & humidity, hydronic return temperature, and other installation factors.
- Develop GAHP output and projected AFUEs for range of outdoor temperature bins. Extrapolate to annual energy savings.
- Disaggregate natural gas from electricity inputs, for total GAHP power draw
- Assess impact of part-load performance and DHW loading.
- Chart and quantify robustness of absorption cycle startups, as a function of loading and ambient conditions.
- Track end-user interaction through adjustment of thermostat setting (if any).

Table B1: Site Details

Site	Home Details	Occupants	Existing HVAC	Existing DHW Equipment
Site A	Two-story, 1973 build, 2,451 sf	2 Adults	Gas Furnace, Dual stage, 100 kBtu/h input, 96.7% AFUE	Standard Gas Storage, 40 kBtu/h, 40 gal.
Site B	Two-story, 1978 build, 1700 sf, full basement	2 Adults	Gas Furnace, Single stage, 80 kBtu/h input, 78% AFUE	Standard Electric Resistance, 80 gal

Figure B1: Photos of Site A

Figure B2: Photos of Site B

GAHP Monitoring

During these monitoring periods, for continuously monitored data points, the Logic Beach *Intelliogger IL-80* datalogger will be used, connecting to project participants via a Verizon Wireless cellular modem. The *IL-80* will send datasets to GTI via FTP on a weekly basis, backing up data onto GTI's servers, and also storing data onto its 128 MB onboard memory card. To prevent data loss due to power surge and/or temporary power loss, the datalogger will be powered via surge protection and an Uninterrupted Power Supply (UPS). With this datalogging platform, to quantify the aforementioned performance metrics, the following data will be collected on a continuous basis:

Baseline DHW and Space Heating Performance (All Sites) – Figure B3

- Indoor Air Temperature (Multiple Locations)
- Outdoor Air Temperature
- Natural Gas Flow (Domestic Water Heater)
- Natural Gas Flow (Furnace Space Heating)
- Space Heating Electric Power Use
- Space Heating Return Air Temperature
- Space Heating Supply Air Temperature (X4)
- DHW Inlet and Outlet Temperatures
- DHW Flow

GAHP Combi with expansion DAS module (All Sites) – Figure B4

- Indoor Air Temperature (Multiple Locations)
- Outdoor Air Temperature (one point, on evaporator coil)
- GAHP Natural gas flow
- GAHP Gas valve state (open/closed)
- Total GAHP power use
- GAHP Loop water flow
- Space Heating Loop supply and return temperatures at Hydronic Air Coil
- Hydronic Air Coil air flow speed setting (Low/Mid/High)
- Hydronic Air Coil supply and return air temperatures
- DHW Inlet and Outlet Temperatures
- DHW Flow
- DHW Loop supply and return temperatures at Tank Coil (Pre Site/A Only)
- GAHP hydronic return and supply temperatures
- GAHP outlet flue gas temperature
- Select GAHP internal temperatures: Evaporator inlet/outlet, Desorber Shell

These data are recorded on a continuous basis by the *IL-80* with a variable frequency algorithm. Data are taken every 15 seconds if a hot water draw is detected or the GAHP is firing, otherwise data are taken every 2.5 minutes using the instrumentation outlined below.

The following data will be acquired from third party sources:

- Daily outdoor high/low temperature and barometric pressure– using available weather station data in proximity to installation site
- Natural gas heating value – solicited from local utility company on daily basis
- Average ambient dew point/dry bulb temperatures from local weather station(s)

During GAHP pre-shipment laboratory testing, field commissioning, and/or field spot audits, the following data will be collected at least once by lab or field personnel:

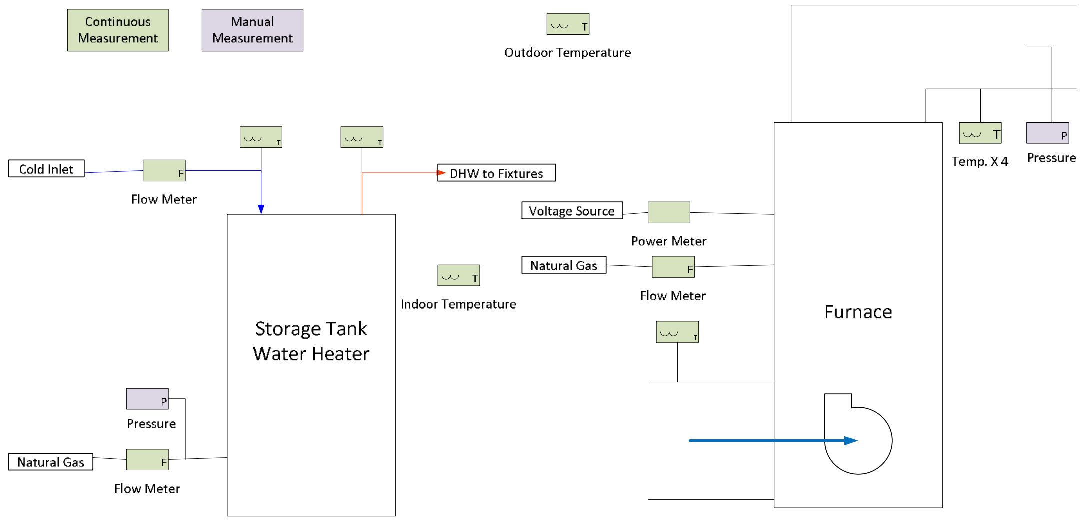

Figure B3: Diagram of Baseline Monitoring Instrumentation

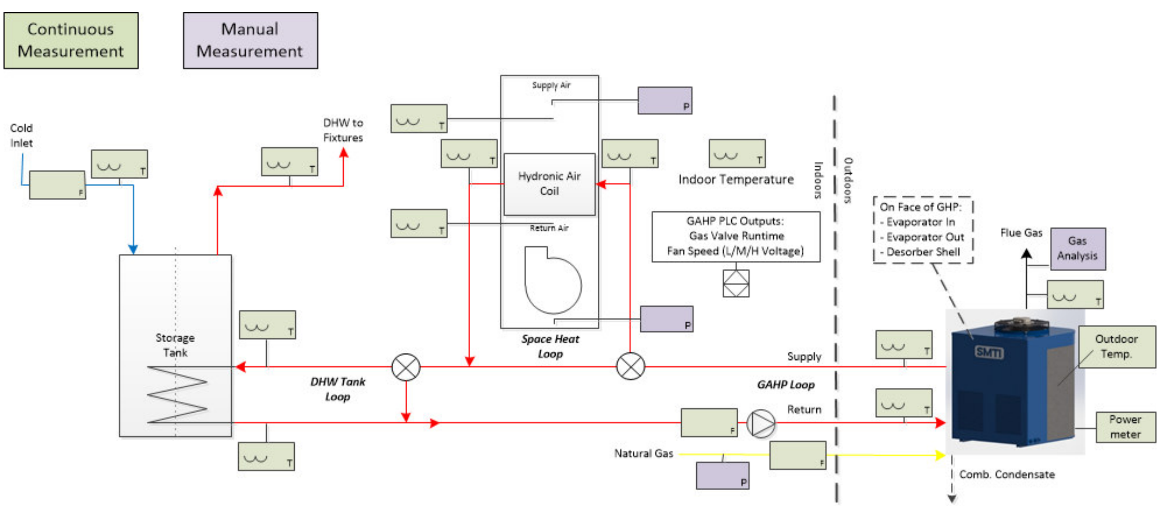

Figure B4: Diagram of Instrumentation Locations – GAHP Detail (Combi Version)

- Inlet natural gas pressure (at meter), as measured at field installation using mechanical pressure gauge.
- Excess air level in flue gases, as measured at field installation using a portable combustion analyzer.
- As the flue gas exit temperature from the desorber has been shown to be directly proportional to ambient temperature and the hydronic return temperature, this temperature map will be generated for each unit during pre-shipment laboratory testing
- Tank storage volume, measured during pre-shipment laboratory testing or provided by manufacturer.
- Mass or volume of glycol added to GAHP loop as fraction of glycol/water mixture.

During the installation of instrumentation and datalogging equipment, the following requirements will be met:

- The water meters will be installed with lengths of straight pipe in compliance with manufacturer recommendations.
- Immersed thermocouples for water inlet/outlet temperatures will be installed at locations as close to those required by the standard method of test as allowable. Associated piping will be insulated to minimize heat loss/gain between the GAHP and the point of measurement.
- The *Wattnode* power meter must be powered by the same circuit as the GAHP
- The 12" cellular modem antenna will be installed to maximize signal quality, as verified during commissioning.

The indoor temperature will be acquired via wired thermocouples placed proximate to the home's thermostat(s). Additionally, temperatures will be measured close to the datalogger. During the GAHP phase, an external data logger will be placed outside the home to gather outside air temperature for future data reduction. When the GAHP is installed, outdoor air temperature will be monitored continuously as opposed to derived from third party weather data. **Error! Reference source not found.** summarizes the data collection points for the Baseline phase of Sites A and B.

Due to the timing of the project initiation with respect to the end of the 2017-2018 heating season, the project team was unable to finalize Field Test Agreements (FTAs) and installation contractor agreements until the end of March. To capture as much of the heating season as possible, the project team received agreement from Site A and Site B to install non-invasive state loggers with on-board memory on the furnace gas valves to track furnace activity. This limited form of data collection, approximately five weeks, was a bridge to the point at which the complete baseline data package was installed by the installation contractor and GTI subject to the FTA.

Data Quality Control and Safety Precautions

Using automated data quality control during weekly data uploads, GTI will identify and resolve issues with data collection in a swift manner, minimizing data loss. Data from each site will be downloaded, analyzed, and reviewed on a regular basis to spot issues, trends, and identify needs for field servicing of datalogging equipment or the GAHPs.

As the GAHP is a pre-commercial prototype and as a result, is not a certified product for residential installations, during this field demonstration the datalogger will send out automated warning emails to key staff from GTI and SMTI to prompt action and, if necessary, field servicing if the following conditions are observed, however unlikely:

- *Operating Cycle:* Not to indicate an operating issue, the datalogger will announce on-cycles of the GAHP for the team to log in to watch the unit "live", if desired.
- *Freezing loop temperatures* - If the return hydronic temperatures drop below 45°F and the unit is operational, an alarm will be sent out.
- *Excessive heating* – If the hydronic supply temperature exceeds 150°F or if the desorber shell temperature exceeds 370°F, this represents an off-design operating condition which could result in a GAHP automatic shutdown due to excessive high-side pressures. The GAHP controls can recover from this event, however following email notification, GTI/SMTI may arrange for a site visit to investigate this overheating event.

Table B2: Configuration for Baseline Sites A and B

Logger	Signal Type	Baseline Phase - Signal	Baseline Phase - Name	Instrument	Measures
	DENT	Dry Contact	Dry Contact - Furnace Gas Valve Stage 1	CT @ Gas Valve	Gas Flow
	DENT	Dry Contact	Dry Contact - Furnace Gas Valve Stage 2	CT @ Gas Valve	Gas Flow
IL-80	Digital	pulses, 40 p/cf	Pulses - Furnace Gas	AC-250	Gas Flow
		Pulse, 8 p/Wh	Pulses - Furnace Total Power	Electric Meter	Electric Meter
		pulses, 40 p/cf	Pulses - Water Heater Gas	AC-250	Gas Flow
		Pulse, 75.7 p/gal	Pulses - DHW Water Meter	Water Meter	FTB4607
	Analog	TC, T Type	Temperature - Indoor Thermostat Temperature (#1)	Wireless, wired TC	Wireless, wired TC
		TC, T Type	Temperature - Utility Room Air	Beaded wire TC	Wireless, wired TC
		TC, T Type			
		TC, T Type	Temperature - DHW Hot Water Outlet (To Fixture)	6" T-type Therocouple	TC Probe
		TC, T Type	Temperature - DHW Cold Water Inlet	6" T-type Therocouple	TC Probe
		TC, T Type	Temperature - Furnace Return Air	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #1	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #2	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #3	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #4	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - WH Flue Gas	6" T-type Therocouple	Gas Flow

Logger	Signal Type	Baseline Phase - Signal	Baseline Phase - Name	Instrument	Measures
	DENT		Dry Contact - Furnace Gas Valve Stage 1	CT @ Gas Valve	gas Flow
IL-80	Digital	Pulses, 40 p/cf	Pulses - Furnace Gas	AC-250	Gas Flow, needs connections
		Pulse, 6 p/Wh	Pulses - Water Heater Total Power	Electric Meter	Electric Meter, 240VAC, 2 phase
		Pulse, 8 p/Wh	Pulses - Furnace Total Power	Electric Meter	Electric Meter
		Pulse, 75.7 p/gal	Pulses - DHW Water Meter	Water Meter	FTB4607
	Analog	TC, T Type	Temperature - Indoor Thermostat Temperature (#1)	Wireless, wired TC	Wireless, wired TC
		TC, T Type	Temperature - Utility Room Air	Beaded wire TC	Beaded wire TC
		0-2.2 V			
		TC, T Type	Temperature - DHW Hot Water Outlet (To Fixture)	6" T-type Therocouple	TC Probe
		TC, T Type	Temperature - DHW Cold Water Inlet	6" T-type Therocouple	TC Probe
		TC, T Type	Temperature - Furnace Return Air	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #1	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #2	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #3	Beaded wire TC	Beaded wire TC
		TC, T Type	Temperature - Furnace Supply Air #4	Beaded wire TC	Beaded wire TC
		~~TC, T Type~~	~~Temperature - WH Flue Gas~~	~~6" T-type Therocouple~~	~~Gas Flow~~

- *Defrost Event:* If conditions indicate a defrost cycle is underway, including a sharp shift negative in evaporator superheat, the datalogger will alert the team of the defrost event.

In the event of a loss of GAHP functionality at the field site, GTI will work to inform SMTI in a swift manner to assure SMTI can return the host to regular heating/hot water service.

Data Analysis

With continuously monitored data sampled at the aforementioned frequency of every 15 seconds during hot water draws or GAHP on-cycles, and otherwise at every 2.5 minutes during standby, datasets will be downloaded on a weekly basis and analyzed with custom programming, yielding the following data as summarized in frequent reporting:

Prototype Field Test:

- Operating conditions: indoor/outdoor temperatures and, when applicable, inlet water mains temperature and return/supply room air temperature.
- Load characteristics: Hourly space heating loads (as served by GAHP), fraction of operation at part load and GAHP modulation.
- Heat pump system conditions: hydronic return/supply temperatures, evaporator inlet/outlet temperatures, desorber shell temperature and, cycle startup "health".
- Heat pump output: heating capacity, heat pump cycle COP, GAHP system COP (including combustion losses).
- GAHP Activity: daily/weekly natural gas consumption, daily/weekly electricity consumption, power draw in both "standby" and "active" modes, average daily firing rate, operating hours at various firing stages.
- Energy efficiency: Weekly "Annualized Fuel Utilization Efficiency".
- System servicing
- Hot Water Characteristics: daily draw volumes, draw rates, draw durations, draws per day, delivered hot water temperature, delivered energy of hot water.
- Water heater recovery cycling: Cycles per day/week, cycle duration, hot water consumed between cycles, thermostat temperature at cycle cut-in/cut-out.
- GAHP Combi Controls: fraction of on-cycles for DHW, space heating, or combination; modulation response to DHW-priority.
- Comfort loss events, "cold blow" (supply air below 100°F) or loss of hot water (extended draws below 105°F).

With analysis of the data recorded as outlined in Table B3, beyond the reporting of raw data statistics the following calculations will be used to address the primary Research Questions of this field demonstration:

- Loads (output): Heat delivered to GAHP loops calculated as $\dot{Q}_{loop} = 60 \cdot \dot{V}_{loop} C_P \rho (T_{sup} - T_{rtn})$ and for space heating $\dot{Q}_{SHL} = 60 \cdot \dot{V}_{SHL} C_P \rho (T_{sup,coil} - T_{rtn,coil})$ [=] Btu/hr; for $C_P \rho$ evaluated at an average of return/supply temperatures; DHW loads calculated as $Q_{HW} = V_{HW} C_P \rho (T_{w,o} - T_{w,i})$ [=] Btus; for $C_P \rho$ evaluated at $T_{w,o}$.

- Natural gas input: $Q_{NG} = V_{NG} \cdot HHV \left(P_B + \frac{P_{NG}}{13.595}\right)/29.93$ [=] Btus; evaluated for each cycle and converted to a firing rate as a rolling average over each cycle, $\dot{Q}_{NG}$, adjusting HHV for elevation as needed.
- Heat Pump output rate: $\dot{Q}_{GAHP} = 60 \cdot \dot{V}_{GL} C_P \rho \left(T_{sup,GAHP} - T_{rtn,GAHP}\right)$ [=] Btu/hr; for $C_P \rho$ evaluated at $T_{rtn,GAHP}$ for each time step.
- Steady State COP_{Gas}: $COP_{Gas} = \dot{Q}_{GAHP}/(\dot{Q}_{NG})$, averaged over 5 minute periods with weekly averaged firing rates for $\dot{Q}_{NG}$.
- Simple AFUE: $AFUE_{simple} = \sum(\dot{Q}_{GAHP} \cdot t_{step}) / \sum(Q_{NG})$; where the time step t_{step} sums the average GAHP output on an hourly basis.
- Combined Delivered Efficiency: $DE = \sum\left(Q_{HW} + \dot{Q}_{SHL} \cdot t_{step}\right) / \sum(Q_{NG} + Q_{elec} * 3.412)$; calculated on a weekly basis.

Table B3: Measurement Points and Variables

Measurement Type	Measurement Point	Variable	Units
Continuous Measurement	Gas Valve Runtime	N/A	
	Natural Gas Flow	V_{NG}	ft^3
	Water Flow: GAHP Loop (GL)	$\dot{V}_{GL}$	GPM
	Power Consumption	Q_{elec}	Wh
	Outdoor/Indoor Temperature	$T_{out,db}$, $T_{in,db}$	°F
	Supply Air Temperature	$T_{air,sup}$	°F
	Return Air Temperature	$T_{air,rtn}$	°F
	Evaporator In Temperature (NH_3)	$T_{evap,i}$	°F
	Evaporator Out Temperature (NH_3)	$T_{evap,o}$	°F
	Hydronic Supply Temperature (GAHP, Tank, Coil)	$T_{sup,GAHP}$, $T_{sup,Tank}$ $T_{sup,Coil}$	°F
	Hydronic Return Temperature (GAHP, Tank, Coil)	$T_{rtn,GAHP}$, $T_{rtn,Tank}$ $T_{rtn,Coil}$	°F
	Desorber Shell Temperature	T_{des}	°F
	Flue Gas Outlet Temperature	T_{FG}	°F
	Cold Water Inlet Temperature	$T_{DHW,cold}$	°F
	Hot Water Temperature to Fixtures	$T_{DHW,hot}$	°F
Batch Measurement	Inlet Fuel Pressure	P_{NG}	in. WC
	Excess air level, as dry stack O_2	n_{O2}	%, dry
	Flue Gas Outlet, Desorber Temperature	$T_{FG,Des}$	°F
	Tank storage volume	V_{tank}	gal.
	Glycol Mass Percent	$\%_{glycol}$	N/A
3rd Party Data	Outdoor Temperature	$T_{OD,db}$	°F
	Outdoor Humidity	$T_{OD,dp}$	°F
	Barometric Pressure	P_B	in. Hg
	Natural Gas HHV	HHV	Btu/scf

Figure B5: Simplified GAHP Heat Flow Diagram

Qualitative Data

Using the questions outlined below, some of which were answered during the recruitment/screening phase, GTI will perform surveys before and after the GAHP system installations with host sites and installation contractors. The results of this survey will be reported in full at the close of the demonstration task.

Table B4: Pre/Post Questions for Host Sites

Pre – Host Questions*	Post – Host Questions

• Any recent weatherization? (New doors, windows, insulation, etc.)
• How would you describe hot water in your sufficient, inadequate, etc.?
• How would you describe heating in your home, comfortable, drafty, etc.?
• What is a typical winter monthly gas bill?
	• Any change in occupancy or change to building envelope over the study?
	• How frequently, if at all, did you change DHW/heat thermostat settings?
	• How satisfied were you with:
	  ◦ Hot water availability, temperature consistency
	  ◦ Heating comfort, temperature consistency
	  ◦ Prototype system nuisances: noise, vibrations, unit failures, other
	• Have you observed a change in utility bills, gas/electric/water?
	• If competitively priced, how likely are you to purchase the system in 2/5/10 years?
	• Based on your experience, what premium would you be willing to pay - $1000/$1500/$2000?
	• What do you view as the best feature of the technology: Energy/Cost Savings, GHG Emissions Reduction, Improved DHW/heating comfort, Other?
	• How likely are you to recommend this technology to friends and family?
	• Unsolicited Comments on performance, test experience, recommendations to team

Table B5: Pre/Post Questions for Contractor

Pre – Contractor Questions*	Post – Contractor Questions

• Describe Company (No. employees, % residential/commercial, etc.)
• What fraction of business is retrofit vs. new construction?
• What fraction of heating/DHW systems are:
  ◦ DHW: Emergency vs. non-emergency replacements, gas/electric, storage/tankless, Gas - min. efficiency vs. EnergyStar vs. condensing, Electric – standard vs. heat pump, have/don't have water softeners
  ◦ Heating: Forced-air vs. hydronic/radiant, boilers vs. furnaces, gas/electric, Gas – < 83% vs. > 90% efficient, Electric – standard vs. heat pump, single vs. multi-zone thermostats, prevalence of "smart" thermostats
• What are common issues/challenges with:
  ◦ Gas/venting/electric upgrades
  ◦ Condensate management, with/without neutralization
  ◦ Retrofitting larger, different footprint equipment
  ◦ Managing noise and other customer nuisance complaints
	• Recall challenges during installation, including:
	  ◦ Placement/siting of GAHP, tank, hydronic air coil
	  ◦ Plumbing of hydronic loops and tank
	  ◦ Modifications to gas/vent/electrical infrastructure
	  ◦ Recommendations for improved/simplified installation?
	• You initially estimated XX man-hours and YY for equipment to install the prototype system, do you:
	  ◦ Think this was a conservative estimate or a good estimate?
	  ◦ Can you identify efficiencies in labor or materials that you would use in the future?
	  ◦ Were their characteristics of the site that made the installation easier/more difficult than expected?
	• Do you anticipate installation costs for this system to be greater/lower/similar to:
	  ◦ Standard gas water heater and gas furnace
	  ◦ High-efficiency gas water heater and condensing gas furnace
	  ◦ Tankless gas water heater and condensing furnace
	  ◦ Electric heat pump water heater and electric heat pump
	• Is the system as more favorable for customers with: gas, propane, or electric heating – or equal?
	• Given your experience with the prototype system, what challenges remain for successful deployment in retrofit and new construction installations?
	• Would you recommend this technology to customers? If not, what improvements do you want to see?

Baseline Monitoring Results

Domestic Hot Water

Per the Federal Standard, homes with medium and large DHW usage are estimated to consume 55 and 84 gal/day respectively. Sites A and B with two occupants each, are expected to be towards the lower end. However, DHW usage is highly behavioral and these standard consumption values were derived from datasets with large ranges in DHW consumption.

At Sites A and B, the DHW consumption is very different from site to site. Site A has a highly erratic consumption pattern, with two periods of extended vacation, highly variable DHW consumption between 50-100 gal/day during an extended period, and a brief period with very high DHW consumption, exceeding 200 gal/day in one instance. Site B has are relatively steady DHW consumption pattern of less than 50 gal/day, with slightly greater consumption on weekend days.

Seen in Figure B6, consumption at Site A would be difficult to properly design for, primarily the middle period with very high consumption. Speculating, this could be temporary increases in occupancy (e.g. visitors), intermittent high-usage behavior (e.g. filling hot tubs), or some combination. The GAHP combi system, with a nominal output of 80,000 Btu/hr, certainly can handle this load – 200 gal of DHW in a day represents operation on an equivalent full load hour basis of approximately 90 minutes, however it is critical (a) how quickly the DHW volume is consumed and (b) if a space heating load is overlaid on top of the DHW load. While no special preparation will be made for Site A to accommodate these high usage events, beyond setting expectations with the host, the project team will closely follow this site once the combi system is operational.

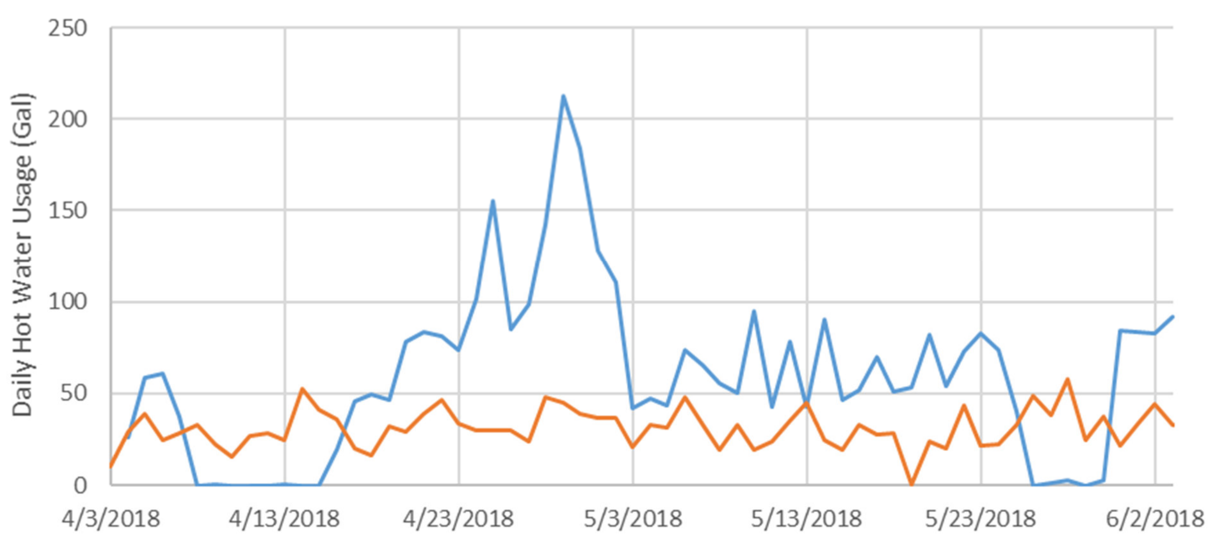

Figure B6: DHW Consumption at Sites A (Blue) and B (Orange)

Concerning DHW energy consumption, the water heaters are Site A (low efficiency gas storage) and Site B (low efficiency electric storage), the DHW energy intensity is shown in Figure B7. With a larger dataset, both sites have better linear fits, as the impact of transient energy storage from one day to the next is lessened. This normalized energy input will be the primary basis of determining site specific DHW energy savings. Figure B8 and B9 show the DHW draw patterns of typical days at Sites A and B, which indicate a higher thermostat set point of ~135°F at Site A and a more moderate set point of ~125°F at Site B.

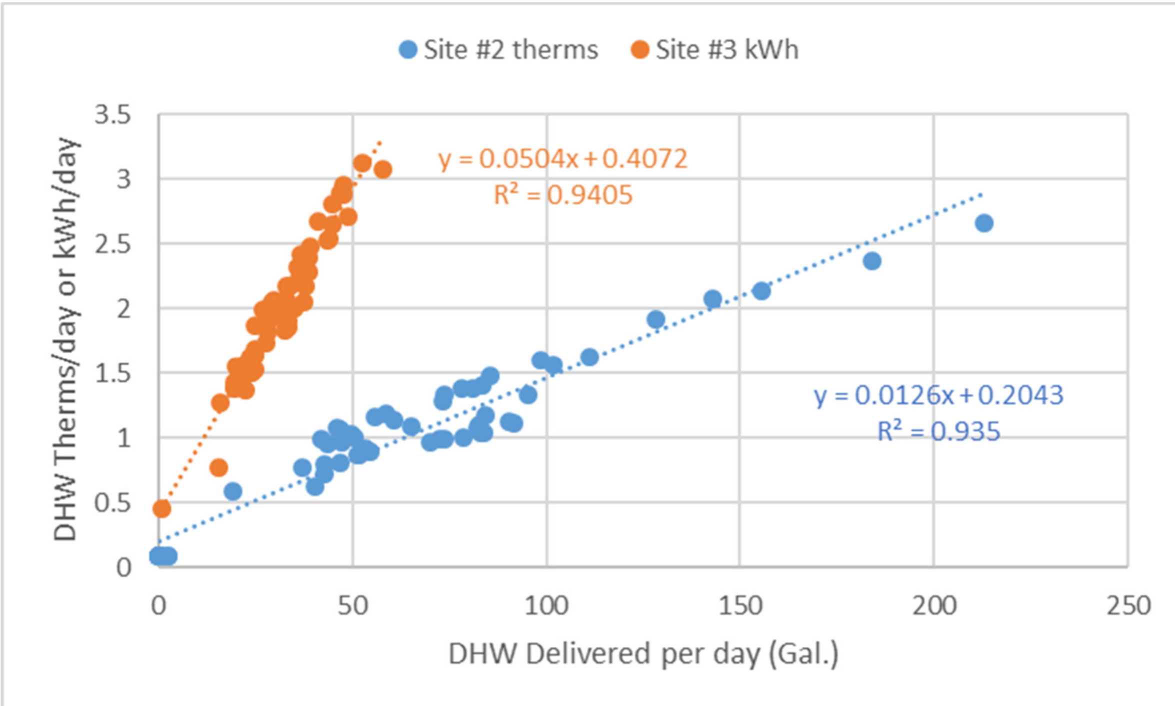

Figure B7: Site A and B DHW Energy Consumption Normalized by Loading

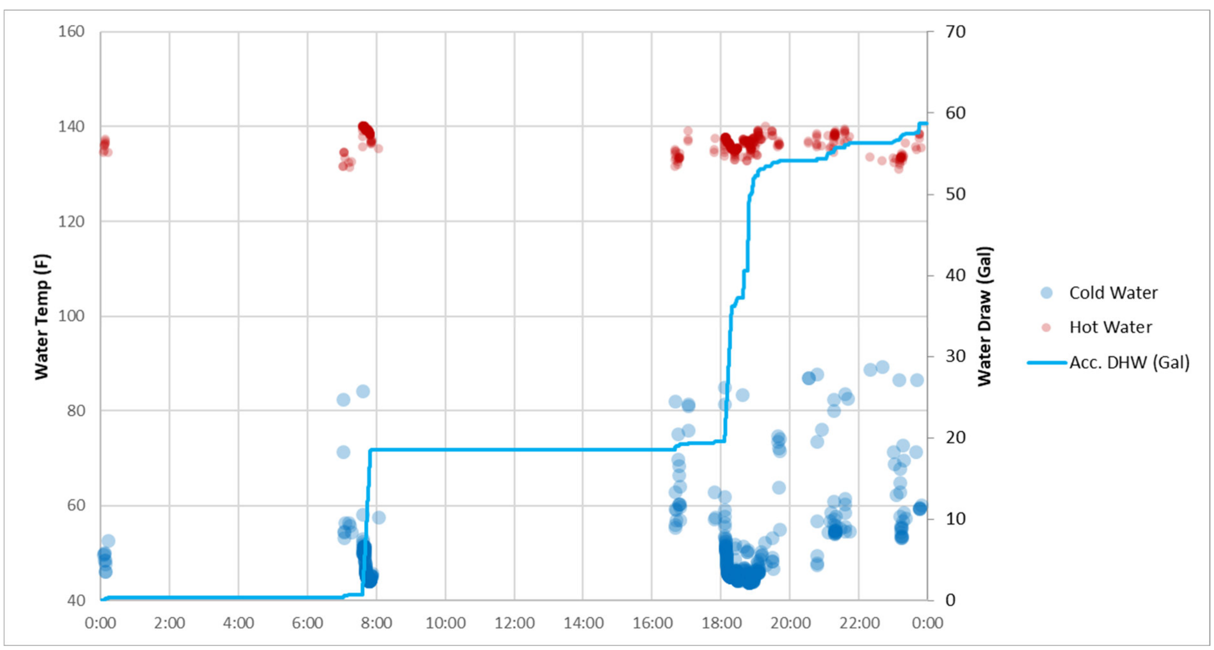

Figure B8: DHW Draw Pattern at Site A

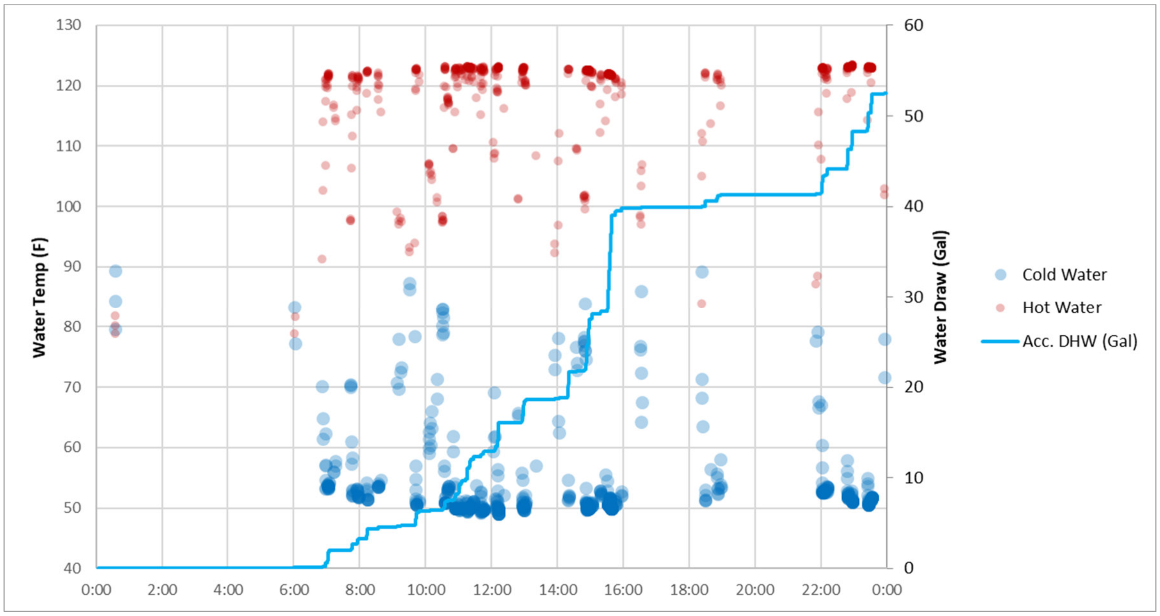

Figure B9: DHW Draw Pattern at Site B

Space Heating

Daily energy flows as a function of outdoor temperatures for Sites A and B are shown in Figure B10 and Figure B11. Here, as the monitoring period covers the end of the heating season, periods of low/no furnace activity are clear based on daily furnace gas input. Noting that Site B DHW energy input is in kWh/day, the relatively steady DHW energy input at Site B contrasts with the large variation in DHW gas input at Site A.

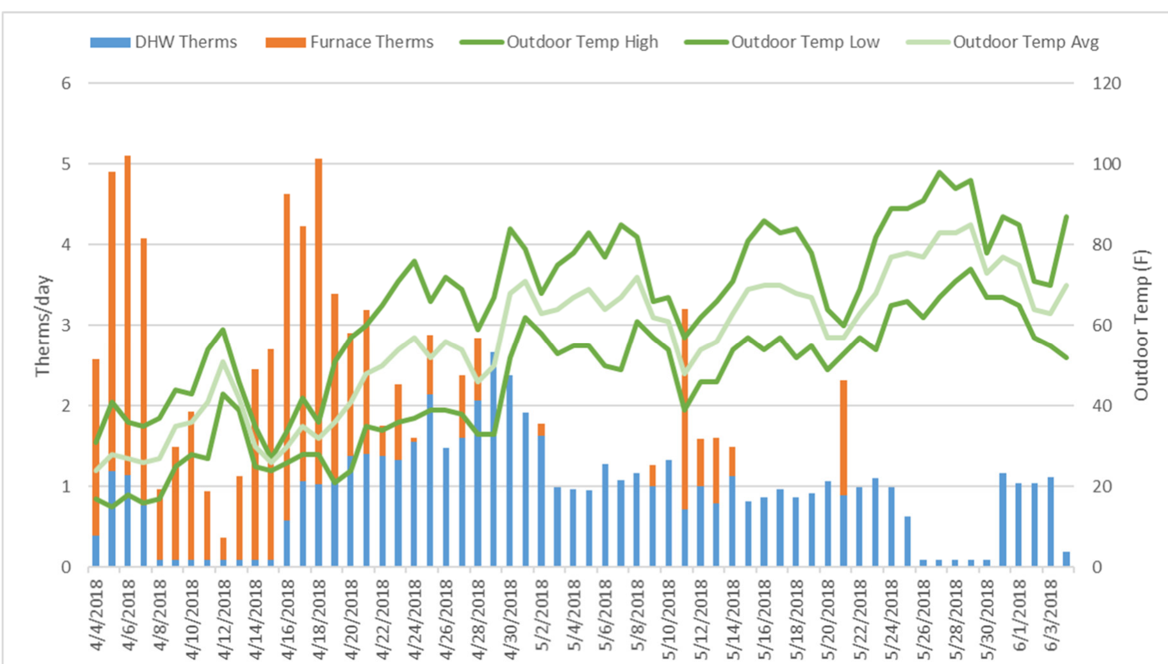

Figure B10: Site A – Daily Energy Flows

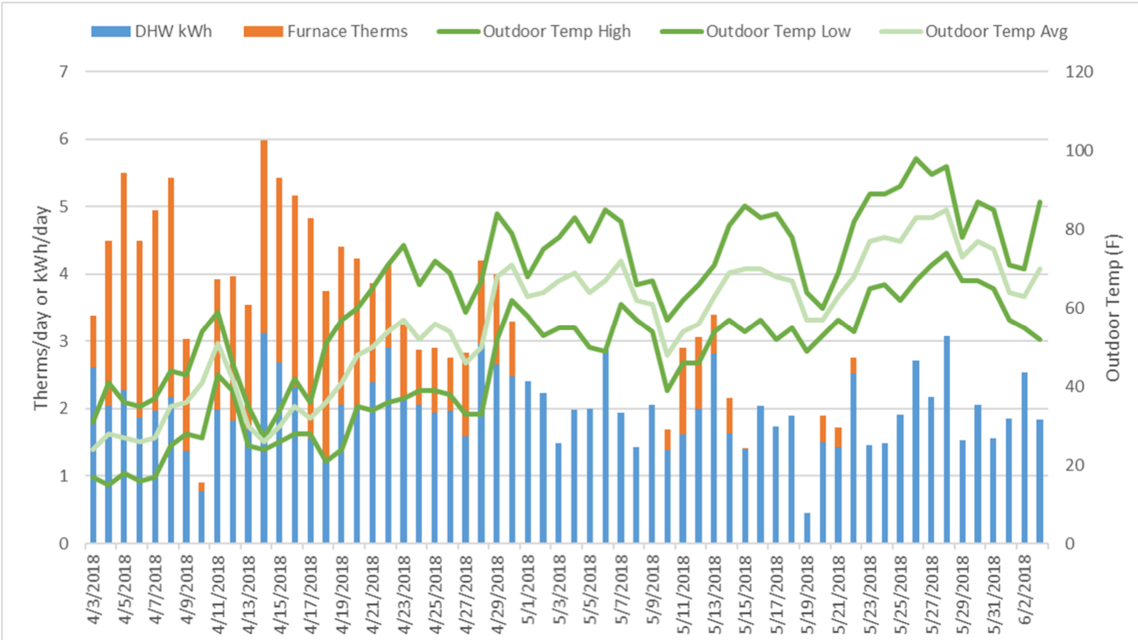

Figure B11: Site B – Daily Energy Flows

Normalizing furnace gas consumption with outdoor temperatures during the monitoring period is shown in Figure B12. During the shoulder season, as the furnace cycles less frequently and may not operate for a portion or entirety of a warmer day, the linear fits are poorer. Using the 1981-2010 climate normal of 7,194 HDD/year, Site A and B would consume 582 and 534 therms/year for space heating respectively.

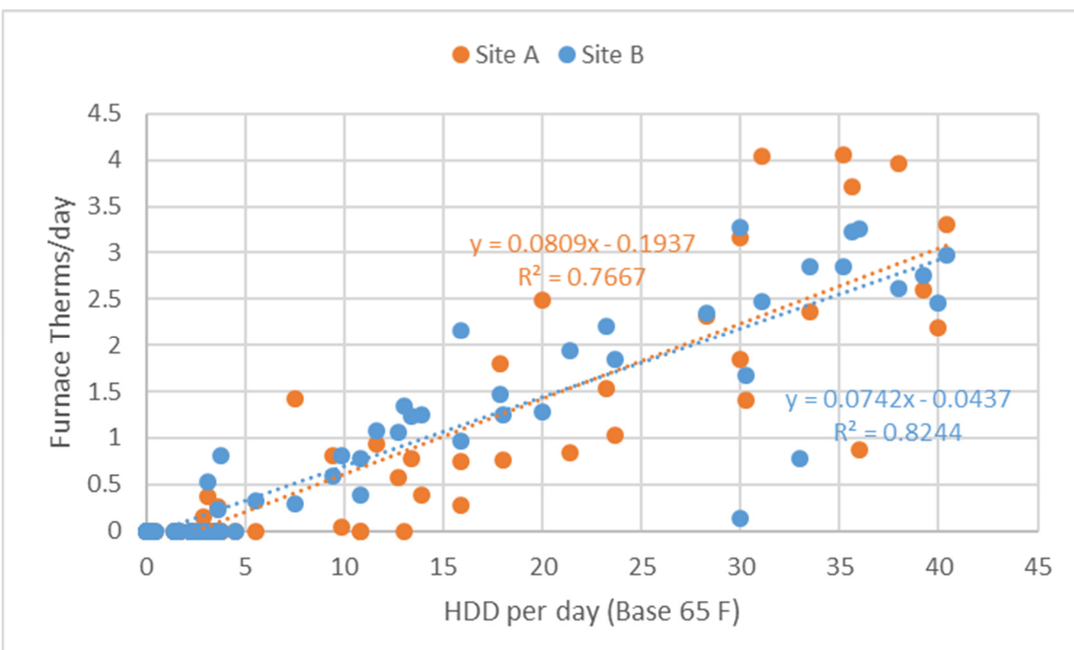

Figure B12: Site A and Site B Space Heating Load – Baseline Measurements

Concerning other factors, the power draw of the two furnaces are as follows:

- Site A had a cycle median furnace power draw of 103 W, with an overall range of 216 W to 94 W
- Site B had a cycle median furnace power draw of 148 W, with an overall range of 161 W to 123 W

Air temperatures during active heating periods for Sites A and B are shown in Figure B13 and B14, indicating that cycle start and ending temperatures measured at the thermostat, showing up to a 10°F setback at Site A and up to a 7°F setback at Site B. Both homes employ advanced thermostats which is evident in the behavior of the furnaces. Additionally the supply and return air temperatures are shown for each furnace on-cycle 30 seconds after cycling on and at the cycle end.

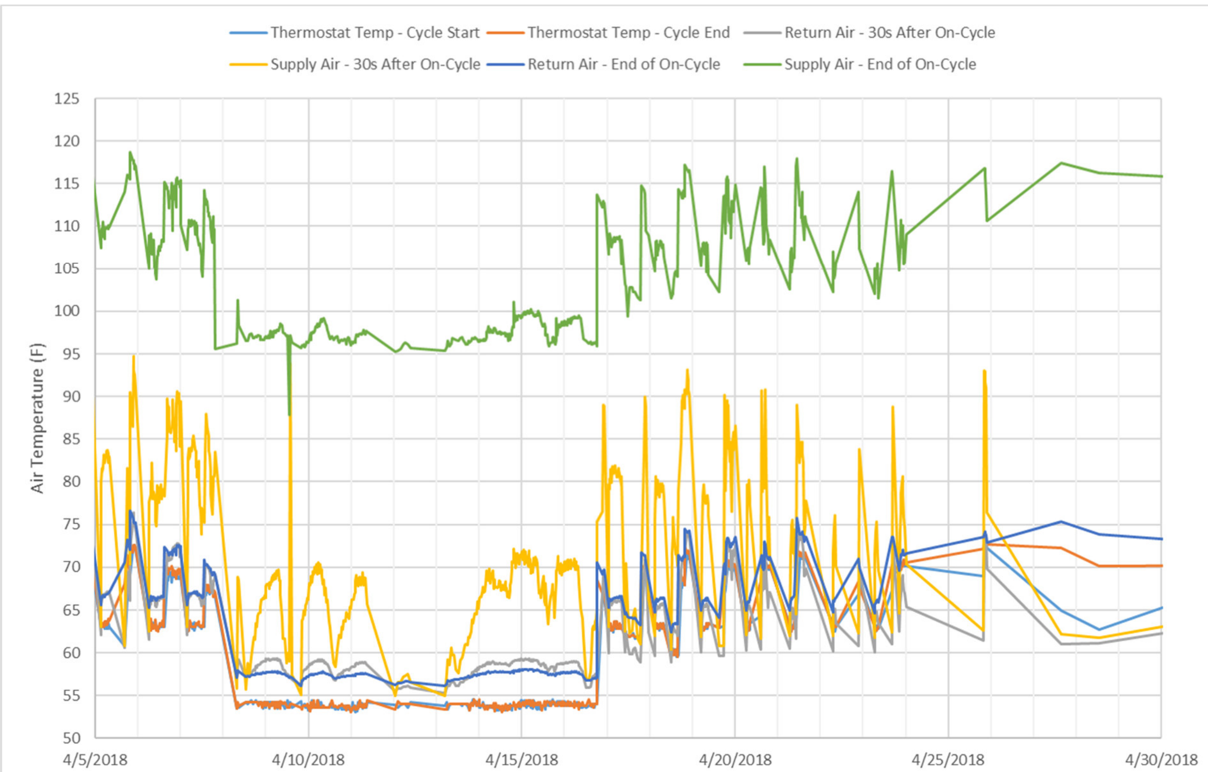

Figure B13: Air Temperatures at Site A – Active Heating Portion

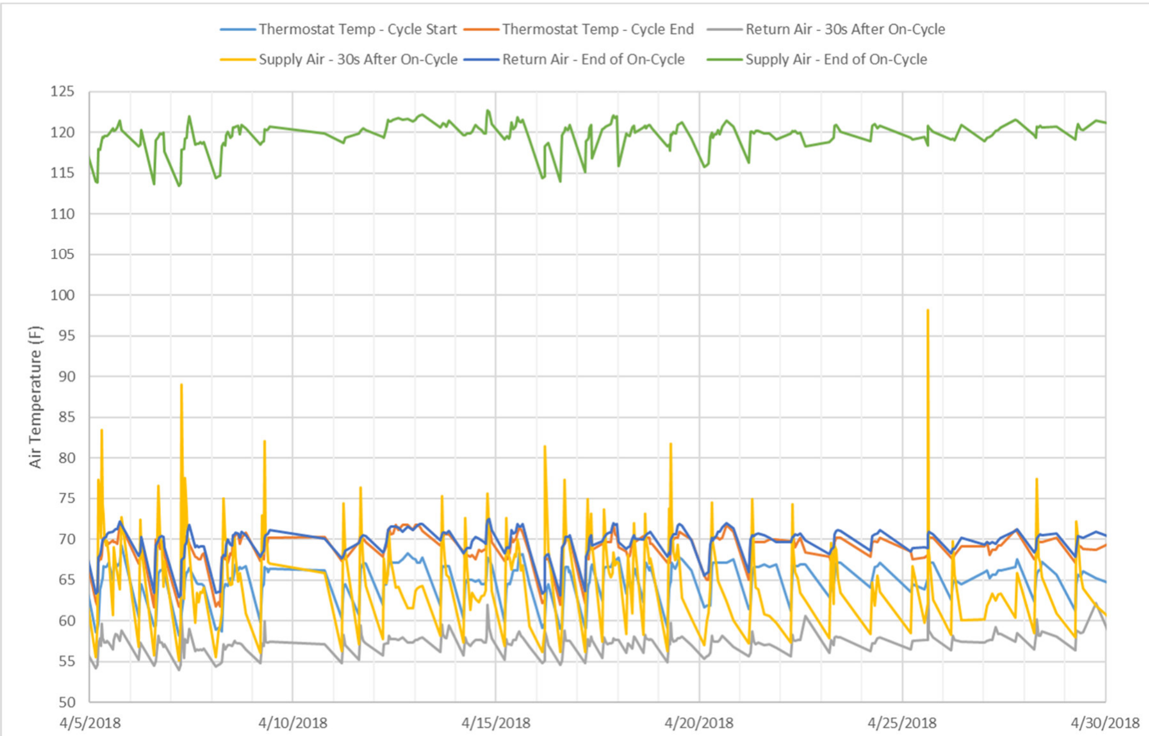

Figure B14: Air Temperatures at Site B – Active Heating Portion

Conclusion

In this baseline field demonstration report, the authors outline the motivation for and methodology used to monitor and characterize GAHP heating-only and combination space/water heating systems at single family homes in La Crosse, WI. Additionally the baseline data collected from each site is analyzed and reported to establish a basis of comparison for pre/post assessment of GAHP energy savings. The primary conclusions for DOE Sites A and B were:

- *Both Sites will be Adequately Served by GAHP:* Based on the past operation of a prototype GAHP combi system[1] and the data reported in this report, the project team anticipates that:
    - The peak estimated on-cycle space heating output at Site A and B are 69,600 Btu/hr and 32,900 Btu/hr respectively, both below the nominal 80,000 Btu/hr output of the GAHP. While the baseline period monitored only captures the late heating season, La Crosse, WI experienced an abnormally cold Spring. April had 765 heating degree days in 2018, compared to the climate normal of 499. While Site A is close, it is expected that the GAHP will operate more frequently and, depending on the thermal response of the building in peak winter, may operate with a less aggressive setback, both

[1] Glanville, P. et al., "Laboratory and Field Evaluation of a Gas Heat Pump-Driven Residential Combination Space and Water Heating System", Proceedings of the 2018 ASHRAE Winter Conference.

expected to address possible capacity issues. The project team will closely monitoring this post-GAHP installation and commissioning.
    - Output DHW and space heating temperatures from the GAHP combi/heating-only system will be adequate for each site, based on baseline measurements.
- *Baseline of DHW Energy:* Using the normalized energy consumption by daily DHW draw (Figure), the energy savings from the GAHP combi system for DHW output will be determined, noting that comparisons for Site B with an electric water heater will be performed on a “site energy” and “source energy” basis.
- *Baseline of Space Heating Energy:* With the energy consumed by the furnaces at Sites A and B, normalized by weather in Figure, with “pre-baseline” measurements and estimates in **Error! Reference source not found.** as well, the energy savings from GAHP space heating operation will be judged by these baselines.

Site Recruitment, Screening, and Inspection Materials

Recruitment Flyer

U.S. DEPARTMENT OF ENERGY   UTD Utilization Technology Development

gti

Demonstration Opportunity

A consortium of natural gas utilities, Utilization Technology Development (UTD) and the U.S. Department of Energy are sponsoring the demonstration of an innovative gas-fired heating technology.

The Gas Technology Institute (GTI) is seeking a host site to demonstrate a novel Gas Heat Pump (GHP) in the La Crosse, WI region. Following a brief baseline monitoring period, GTI will install and monitor the performance of the GHP unit over two winter heating seasons.

Opportunity

Requirements

- Single-Family residential site with existing gas furnace for central forced-air heating.
- Home is 1,200 sf or larger and has a 4' X 4' outdoor space to locate the GHP near the home.
- La Crosse, WI region

Equipment / Installation

- All equipment/installation costs will be covered by the project.
- No financial contribution required from the Host Site.
- At close of project, existing furnace will be replaced with a new furnace.

Timeline

- Baseline monitoring installed in Jan. 2018 for Pre Site, Mar., 2018 for Site A & B.
- GHP installation will be installed in Feb. 2018 (Pre Site), Aug. 2018 (Site A & B).

Questions?

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paul.glanville@gastechnology.org

An innovative technology, the pre-commercial Gas Heat Pump (GHP) delivers heat to the home and, potentially, hot water with half the energy required by standard gas-fired equipment. As an air-source heat pump, it works by transferring ambient heat to the home through a hydronic air coil and as hot water through an indirect tank. With a planned market entry in 2-3 years, this pre-commercial GHP field demonstration is a critical step in the evaluation of this technology.

The Technology

The typical residential gas-fired central furnace has an Annual Fuel Utilization Efficiency (AFUE) of 80%, with 'condensing' efficiency furnaces reaching up to 95-98% AFUE. As the next step in energy savings, a novel pre-commercial Gas Heat Pump (GHP), developed by a start-up company Stone Mountain Technologies with current support from Trane, has a projected 140% AFUE, significantly reducing the natural gas consumed by home heating and its resulting impact on climate change.

This GHP achieves this best-in-class efficiency by capturing useful heat from the outdoor environment, using a *vapor absorption cycle*, driving this refrigerant effect similar to home A/C, electric heat pumps, and refrigerators. At the heart of the GHP is a 'thermal compressor', which is driven by an efficient gas burner. This packaged GHP is designed for outdoor installation, linking to the home's ductwork through a hydronic air coil and can also provide hot water via an indirect tank.

The Opportunity

The project will assess the performance of the GHP and collect customer feedback through a field demonstration at three homes. This information will identify barriers to market for this product, including installer/consumer familiarity with the technology. Lessons learned and results will then shape a marketing program to help build awareness and support the GHP commercialization.

GTI is seeking three host sites to demonstrate the technology in the La Crosse, WI region. Interested host sites should fill out the brief survey at this web address, (please send photos of current furnace/water heaters using the email to the left):

https://www.surveymonkey.com/r/TMP6PLH

Site Screening Web Survey

Welcome!

Thank you for volunteering to be a potential host site for the Utilization Technology Development, U.S. Department of Energy and Gas Technology Institute (GTI) project to demonstrate residential Gas Heat Pumps (GHP) in the La Crosse, WI region. The project will assess the performance of the GHP and collect customer feedback through a field demonstration. This information will identify barriers to market for this product, including installer/consumer familiarity with the technology. Lessons learned and results will then shape a marketing program to help build awareness and support the GHP commercialization.

Please complete the below brief survey to help us understand the details of your particular host site. Please have the make/model of your current furnace & water heater available and photos of their location (if possible).

Thank you for your participation – we're excited to be getting underway!

1. Occupant Name
2. Address
3. Telephone (Mobile)
4. Telephone (Work)
5. Email Address
6. Number of Occupants and Ages
7. Has there been a change in family size over the last 2 years?
    a. If yes, please explain.
8. What year was the house built?
9. What is the house square footage?
10. How many total rooms?
    a. Bedrooms
    b. Bathrooms
    c. Foyers/Hallways
    d. Kitchen
    e. Family Room
    f. Dining Room
    g. Laundry Room
    h. Additional rooms (ex. Loft, Mud Room, Home Office, and etc.)
11. Which of the following style of homes identifies your house:
    a. Ranch
    b. Split level
    c. Two story
    d. Three story
    e. Other (please specify)?
12. Which of the following types of construction describes your home:
    a. Stucco

   b. Wood
   c. Aluminum
   d. Vinyl
   e. Brick
   f. Brick and wood/aluminum/vinyl
   g. Other (please specify)?

13. Does your home have the following:
    a. Slab
    b. Crawl Space
    c. Basement
    d. Other (please specify)
14. Any recent weatherization? (New doors, windows, insulation, etc.)
15. Do you plan on occupying your home for at least the next 18 months consecutively?
16. Does your home currently have a gas-fired storage water heater?
    a. Manufacturer
    b. Model
    c. Btu/h
17. Approximate age of water heater?
18. Where is the water heater located?
19. Can an additional water heater be located adjacent to the existing unit?
20. Does the water heater share a vent with another gas fired appliance?
    a. Yes
    b. No
21. How would you describe hot water in your sufficient, inadequate, etc.?
22. Does your home currently have a gas-fired furnace (if no, ignore questions 23-26)?
    a. Manufacturer
    b. Model
    c. Btu/h
23. Approximate age of furnace?
24. Where is the furnace located?
25. Is the furnace room heated?
26. How would you describe heating in your home, comfortable, drafty, etc.?
27. Does your home have central air conditioning?
    a. Yes
    b. No
28. Where on the property is the A/C condenser located?
    a. Left of house
    b. Right of house
    c. Back of house
    d. Other (please specify)

29. Approximately how many feet from the A/C condenser to the air handler?
30. What type of thermostat is in the home (standard, programmable, wireless, “smart”)?
31. Where is the thermostat located?
32. Which best describes the HVAC ducting type:
    a. Standard duct (press fit)
    b. Spiral duct (fitting required)
    c. Flexible duct
    d. Rectangular duct
    e. Other (please specify)
33. Does HVAC ducting enter the attic?
34. Where are exposed sections of HVAC ducting located?
35. Are you willing to pay natural gas, water, and electricity costs during the demonstration? (Note: these are expected to be less than your current cost.)
    a. Yes
    b. No
36. What is a typical winter monthly gas bill?
37. Is cell phone coverage an issue at your property?
38. Will you allow accessibility to the site for a preliminary site visit, equipment installation, project decommissioning (prototype removal and new furnace installation), and, if necessary, troubleshooting?
    a. Yes
    b. No
39. Are you willing to have your hot water and furnace usage monitored? This will include water volume and temperatures, indoor air temperatures, gas and electric energy consumed by the equipment.
    a. Yes
    b. No
40. Would you be willing to participate in homeowner surveys?
    a. Yes
    b. No
41. Will you allow photos of the installation to be published?
    a. Yes
    b. No

Site Inspection Form

Location

Name: ____

Address: ____

City: ________________________________ State: ________________ Zip: ___________

Telephone (Home): (____)___________ (Work): (____)___________ Ext.________

Telephone (Mobile): (____)___________

Email: ____

GAHP Installation Site(s)

Please provide a quick sketch of the water heater location include, dimensions, and any constraints (Include Doors, windows, etc.):

Mechanical Room:

Outdoors: If more space needed, use back of sheet

Water Heating Equipment:

Water Heater Type: Electric Storage NG Storage Tank-less

Other: ____________________

Model No.: __________________________

Serial No.: ___________________________

Capacity: ____________________________

Input (Btu/h): _________________________

Fuel Type: ___________________________

Manifold Pressure (“WC): ________________

Year Installed: ________________________

Current Tstat Setting (F): _________________

Room for second water heater:

Water Heater Name Plate Picture: ☐

Water Heater Location Picture: ☐

Water Heater Piping Picture: ☐

Room for second water heater: Yes No

Does the installation appear to be up to code (piping/venting/combustion air./etc.)?

Space Heating Equipment

Furnace Type ___________________________
Model No. _____________________________
Serial No. ______________________________
Input (Btu/h) High: _______________ Low: ____________________
Output (Btu/h) High: _______________ Low: ____________________
Air Temp Rise (F) High: _______________ Low: ____________________
Design Max Outlet (F) High: _______________ Low: ____________________
Manifold Pressure ("WC) High: _______________ Low: ____________________
Current Tstat Setting (F) Day: ________________ Night: ___________________
Year Installed ___________________________
Furnace Name Plate Picture: ☐
Furnace Location Picture: ☐
Furnace Duct Picture: ☐
Room for second air handler: Yes No
Does the installation appear to be up to code (piping/venting/combustion air/etc.)?

Site Characteristics

What year was house built? ____

What is the approximate square footage? _____________________________________

Total number of rooms in home? ____

Which of the following style of homes identifies your house: Ranch Split Level

Two story Three story Other (please specify) _____________________________

Which of the following types of construction describes your home: Stucco Wood

Aluminum Vinyl Brick Brick and wood/aluminum/vinyl

Other (please specify)___________________________

Does your home have the following: Slab Crawl Space Basement

Other (please specify)___________________________

Any recent weatherization? (New doors, windows, insulation, etc.) ______________________

Do you plan on occupying your home for at least the next 18 months consecutively?
Yes No

Water Distribution

Describe the piping: (Check all that Apply)

☐ Copper ☐ Galvanized Steel ☐ CPVC ☐ Polybutylene ☐ PEX

Is the hot water distribution system insulated? ☐ Yes ☐ No

IF YES, What is the approximate percentage of pipes insulated? ______ %

Type of insulation used: ☐ Fiberglass ☐ Black closed-cell foam

HVAC

Which best describes the HVAC ducting type: Standard duct Spiral duct
Flexible duct Rectangular duct Other (please specify)___________

Does HVAC ducting enter the attic? Yes No

Where are exposed sections of HVAC ducting located?

Siting

Is the existing water heater close/adjacent to an exterior wall? Yes No

Is there space for an additional indirect storage tank? Yes No

Could be GAHP be installed adjacent to the property? Yes No

Available space for 4’ x 4’ unit with 18-24” clearance? _________________________

Is there access to mechanical room without stairs? Yes No

Narrowest doorway/hallway from exterior to mechanical room? ______________

Site potential DAS space ____

____

Electrical Connection

Are electrical outlets near the water heater location? ___________________________

Are electrical outlets near the furnace location? _______________________________

Are electrical outlets available for data monitoring enclosures? ___________________

Does the site have 208 or 480 VAC service? ___________________________________

How close is the existing water heater to the main panel? ________________________

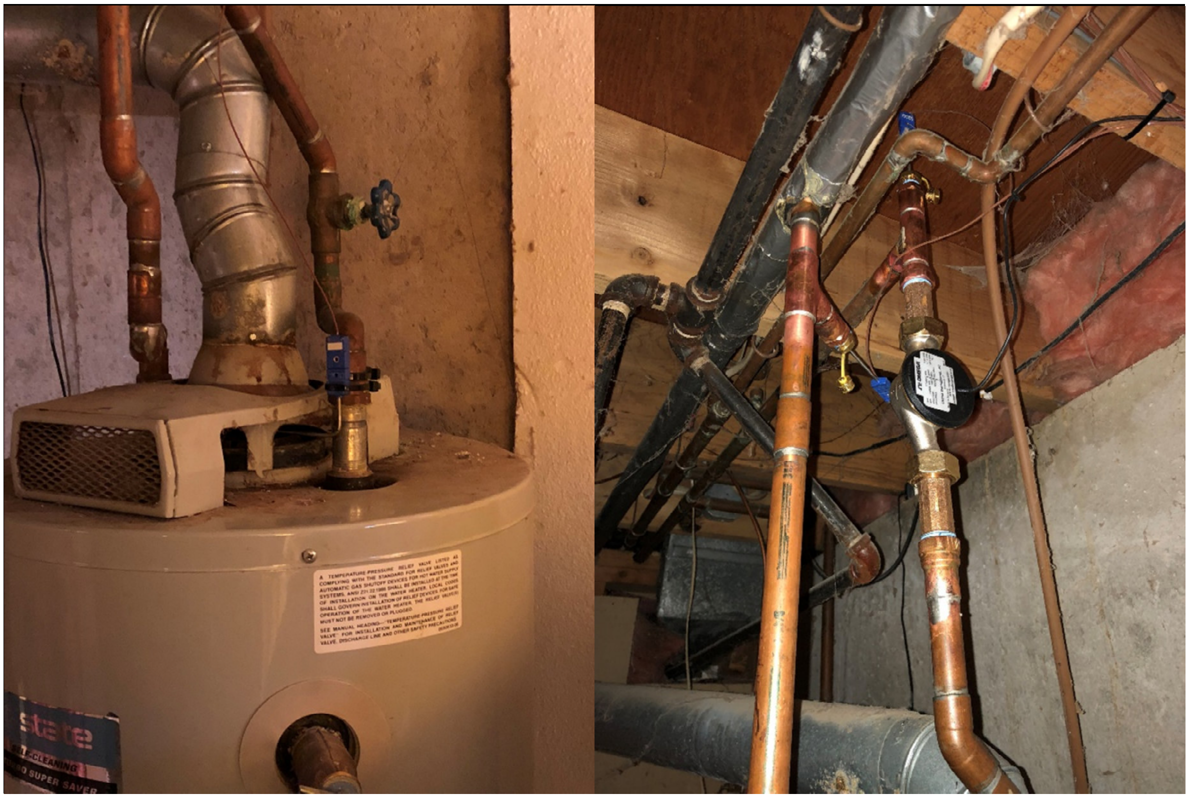
How close is the existing furnace to the main panel? ____________________________

Photo Checklist

- Water Heater(s), Nameplate(s), space for add'l equipment
- Furnace(s), Nameplate(s), space for add'l equipment
- Potential location for wall-mounted GTI Data Monitoring Enclosures
- Mechanical Room details, distances, access
- Rooftop equipment, access, potential locations for equipment
- Exterior of building, locations for ground-mounted equipment
- Photos of piping/ductwork
- Photos of exterior of building and GHP site locations

Baseline Installation Photos

Site A



Site B


A.O.Smith

Appendix C: Codes and Standards Review Report

Prepared by Glanville, P. of GTI

Edited by Keinath, C. and Garrabrant, M. of SMTI

Task Goal:

The goal of this Task 4.1 is to perform a codes and standards analysis concerning the residential-sized gas-fired absorption heat pump (GAHP). Under this task, the Gas Technology Institute (GTI) will consider codes and standards relevant to performance/efficiency, health and safety, emissions and environmental concerns, and installation requirements. The focus of this study is the U.S., however as needed, relevant comparisons to international codes and standards will be made.

Disclaimer: This codes and standards analysis is not exhaustive and is intended for informational purposes only.

Definitions and Boundary Conditions:

First, it is useful to distinguish between a *code* and a *standard*, as both will be discussed here:

- A **code** is enforceable by law or contract, written by a government or a government approved body. An example is the National Fuel Gas Code (NFPA 54). Often "model codes", like NFPA 54, are referenced by Authorities Having Jurisdiction (AHJ) and thus, enforceable by law.
    - For example, the state of Louisiana (an AHJ), adopted the International Fuel Gas Code (2015 version) without amendments and thus, is enforceable by Louisiana state law.
- A **standard** is a set of definitions and guidelines, written by an organization or government body. These may be used by industry or by government in the development of regulations.

After the relevant codes & standards are discussed, a few selected AHJs will be reviewed to highlight the diversity of regional and local requirements, specifically: the City of Chicago, the City of Seattle, and the State of Massachusetts.

List of Acronyms:

The organizations in this analysis referenced include:
ANSI – American National Standards Institute
AQMD – Air Quality Management District
ASHRAE – American Society of Heating Refrigeration and Air-Conditioning Engineers
CARB – California Air Resources Board
CGA – Canadian Gas Association
CSA – Canadian Standards Association
DOE – Department of Energy
DOT - Department of Transportation
EPA – Environmental Protection Agency
IAPMO - International Association of Plumbing and Mechanical Officials
ICC – International Code Council
I/NFGC – International/National Fuel Gas Code
IIAR – International Institute of Ammonia Refrigeration
IMC/UMC – International/Uniform Mechanical Code
IPC/UPC – International/Uniform Plumbing Code

IRC – International Residential Code
NFPA – National Fire Protection Association

Boundary Conditions:
Relevant features of the gas-fired absorption heat pump are as follows:

- **Size/Weight:** Appx. 4' tall with 3' X 4' footprint; ~600 lbs. shipping weight
- **Firing Rate:** Nominal 55 kBtu/hr input, 4:1 modulation (continuous), 1/2" gas line
- **Venting:** 1.5" PVC, short rise above GAHP, condensate disposal into limestone gravel pit below frost line or through a heat-traced line to a drain
- **Electrical:** 120 VAC, 15A service
- **Sealed System:** Approximately 2.5 gallons of aqua-ammonia (20 lbs), approximately 50% NH_3 by mass, contains trace corrosion inhibitor chemicals, commonly 40-60 psig at room temperature when idle
- **Combi System:** GAHP connects to indirect storage tank for domestic hot water (DHW) and/or hydronic air handler (HAH) for space heating with a closed hydronic loop, charged with propylene glycol/water mixture. Note that the term "combi" is used here for combined space and water heating, where others may use "combo".
- **Installation Type:** Outdoors, low-rise residential detached/attached, 18" clearance from adjacent exterior wall

This is codes and standards analysis will, through a review of relevant materials, identify the impact on aspects of GAHP development, certification, and installation, with a focus on a few key areas:

- **Product Performance:** This includes the rated capacity and efficiency as defined by standards or required by regulation.
- **Product Safety:** This includes requirements for product design and construction, safe use of Ammonia (NH_3) and other materials.
- **Installation and Maintenance:** As a residential product, the requirements for installation, siting, infrastructure (gas, electrical, etc.), and maintenance are discussed in this section.
- **Environment:** This includes policy and requirements for the GAHP concerning direct (e.g. NO_x, CO) and indirect (refrigerant) emissions.

Comparable Product:
The Robur Corporation, through their U.S. division, has sold the *GAHP-A*, a natural gas-fired gas absorption heat pump using the NH_3-H_2O working pair since 2004, certified for the U.S. and Canada in 2006. While this product is sized for applications ~50% larger than the GAHP discussed, with a nominal 123.5 kBtu/hr output at 45°F ambient and 122°F supply (Source: Robur), and differs in other ways (e.g. often is non-residential and it is a non-modulating device), it provides a useful comparison at several junctures in this analysis by way of its own experience with U.S./Canadian codes & standards and is thus introduced here.

Figure C1: Robur *GAHP-A* (Source: Robur)

<u>Product Performance:</u>

Efficiency – ANSI Z21.40.4/CGA 2.94

The GAHP, when applied in residences, will most likely carry an Annual Fuel Utilization Efficiency (AFUE) rating as defined by ANSI Z21.40.4 / CGA 2.94 *Performance Testing and Rating of Gas-Fired, Air-Conditioning and Heat Pump Appliances*. This standard was first published in 1996 and has been continuously reaffirmed without major revisions/updates since, in 2002, 2012, and most recently in 2017. The standard is currently undergoing a major revision in its current cycle, the following information may not apply to the GAHP once certified[2]. A high-level summary of this test method is as follows:

- The scope is broadly defined concerning "factory-made, space-conditioning, unitary heat pumps which utilize gas as the primary fuel". There are no minimum or maximum sizes identified (input or output), nor is it restricted to reversible (heating/cooling) devices, with provisions for heating-only or cooling-only equipment. Additionally, there is flexibility concerning heat source/sink, with air, ground water (open), and geothermal (closed) type systems, even including provisions for multiple modes of heat rejection in cooling modes (cooling tower, desiccant dehumidifiers, etc.).
- The test procedure uses a "bin method" to use several discrete steady state rating points and a define calculation methodology to generate estimated seasonal efficiencies for a given climate zone. There are seven steady state rating points, where this GAHP is operated at three firing rates (high, low, intermediate), and the ambient temperature varies from 47°F, 35°F, 17°F, and 7°F and a return water temperature of 95°F. An optional cycling degradation coefficient can be determined with a defined procedure at the 35°F condition. If not performed, a default cycling degradation coefficient can be used. Generally, the test procedure aligns with ASHRAE 37 *Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment*.
- The calculation of seasonal energy efficiency, as an AFUE, includes several adjustments. As an Air-to-Water heat pump, this GAHP has a) the auxiliary electricity from the circulator pump estimated, b) the same is applied to the indoor supply air fan, and c) an attempt is made to credit/debit the

[2] **Note:** GTI will update this section with developments concerning this standard in the Final Draft

heating/cooling capacity based on the inefficiency of the supply air fan. All of these adjustments reflect a dated approach to estimating system losses/gains and dated equipment (blowers, pumps, etc.) and will be updated in the current revision.

- While the test method is broadly applicable in scope, the calculation of seasonal performance is specifically limited to "residential air-source appliances" and cut-off for products "with a maximum rated heating capacity of less than 65,000 Btu/hr (19 kW) for heating-only heat pumps". Technically, this GAHP is outside this limitation at an 80,000 Btu/hr, however this procedure is used for research purposes nonetheless[3]. A standard bin method is used to estimate building loads for multiple outdoor temperature conditions (depending on climate zone). Below is an example of the "Beta 2" GAHP undergoing this procedure at GTI in 2017[4], noting that this reflects the performance of an older generation prototype. The resulting AFUE and annual seasonal heating electricity consumption (ASHEC) reflect the GAHP's operating efficiency (gas basis, HHV) and power consumption.
- The standard includes an informative appendix, ANSI Z21.40.4a / CGA 2.94a, to assist users in estimating annual operating costs and other performance metrics based on the aforementioned test procedure.

Output data for Region IV								Note: G_1<G_v<G_2; Case No. BL(Tj) v.s. Q_1 and Q_2									
j	T(j)	nj/N	BL(Tj)	Q_1	G_1	E_1	Case	G_v	E_v	Q_2	G_2	E_2	HLF	PLF	Output(kBtu)	Gas (kBtu)	Elec (kWh)
1	62	0.132	3.1	20.7	13.9	0.84	I	5.0		86.3	50.6	1.19	0.15	0.79	2121	1804	110
2	57	0.111	8.2	20.5	14.0	0.85	I	7.3		85.0	51.2	1.19	0.40	0.85	4755	3816	231
3	52	0.103	13.3	20.4	14.2	0.85	I	10.0		83.8	51.8	1.18	0.65	0.91	7170	5451	328
4	47	0.093	18.5	20.2	14.3	0.86	I	12.9		82.5	52.3	1.18	0.91	0.98	8964	6482	387
5	42	0.100	23.6	18.3	13.1	0.85	II	16.1	0.87	78.9	55.5	1.13	1.00	1.00	12317	8413	453
6	37	0.109	28.7	18.5	13.6	0.86	II	19.6	0.89	78.1	55.5	1.14	1.00	1.00	16344	11163	506
7	32	0.126	33.9	18.7	14.0	0.87	II	23.4	0.91	77.3	55.6	1.14	1.00	1.00	22266	15397	600
8	27	0.087	39.0	18.9	14.4	0.87	II	27.5	0.94	76.5	55.6	1.15	1.00	1.00	17704	12483	426
9	22	0.055	44.1	19.1	14.8	0.88	II	31.9	0.97	75.7	55.7	1.15	1.00	1.00	12665	9144	277
10	17	0.036	49.3	19.3	15.2	0.88	II	36.5	1.00	74.9	55.7	1.16	1.00	1.00	9254	6859	187
11	12	0.026	54.4	19.2	15.4	0.89	II	41.5	1.03	73.6	56.3	1.15	1.00	1.00	7379	5624	140
12	7	0.013	59.5	19.0	15.5	0.89	II	46.7	1.07	72.3	56.9	1.15	1.00	1.00	4038	3166	72
13	2	0.006	64.7	18.9	15.7	0.89	II	52.2	1.10	71.1	57.4	1.15	1.00	1.00	2024	1634	35
14	-3	0.002	69.81	18.7	15.8	0.90	III	58.0		69.80	58.0	1.14	1.00	1.00	728	605	12
15	-8	0.001	74.9	18.6	16.0	0.90	III	64.1		68.5	58.6	1.14	1.00	1.00	391	306	16
		Cost HSPF	12.34		Gas seasonal COP	1.39			AFUE	139	%		Seasonal total		128121	92346	3780
		Source fuel HSPF	10.77						ASHEC	3780	kWh				SHO	SHGEC	SHEEC

Figure C2: Example of ANSI Z21.40.4 Calculation Results for Older GAHP Unit

For seasonal efficiency, there are other test methods directly applicable to this GAHP, most notably:

- *ASHRAE 40 – Methods of Testing for Rating Heat Operated Unitary Air-Conditioning and Heat Pump Equipment*: Most recently a 2014 version, updating a 2002 version of the standard, this standard is intended as a reference and not to be directly used for testing. Like ANSI Z21.40.4, it references ASHRAE 37 extensively with respect to test tolerances and conditions, however it does not specify operating conditions for the testing. For this GAHP, it can be tested using a "coolant heat-transfer fluid flow method", similar to ANSI Z21.40.4. As a reference method, where no test conditions are specified, this method is otherwise unusable in practice though its methods generally align with those in ANSI Z21.40.4. At time of writing, it is expected that this method will undergo a major revision in parallel to or after ANSI Z21.40.4.

[3] As with other standards of the time, this method was developed primarily for gas-fired A/C equipment, as a result there oversights with respect to heating-only equipment, such as in Section 8.1 determining that a product is "residential" if its cooling capacity is less than 65,000 Btu/hr OR its heating-only capacity is less than 65,000 Btu/hr.
[4] Glanville, P., Keinath, C., and Garrabrant, M. 2017. "Development and Evaluation of a Low-Cost Gas Absorption Heat Pump", proceedings of the 2017 ASHRAE Winter Conference, Las Vegas, NV.

- *EN 12309: Gas-fired Sorption Appliances for Heating and/or Cooling with a Net Heat Input Note Exceeding 70 kW:* In Part 4 of this standard, a thorough and specific treatment of the GAHP as a product category, the test method outlined determines a Gas Utilization Efficiency (GUE, a COP_{Gas} on LHV basis) is determined on a rating point and seasonal basis, in addition to a seasonal primary energy ratio and estimates of annual electricity inputs. As defined in Europe, this GAHP is *monovalent* in that heating will be supplied **only** by the heat pump, and it will operate without supplemental/backup gas/electric heating. With provisions for heat pumps designed for lower temperature supply water (radiant heating, etc.), this GAHP would be rated with a design supply temperature of 55°C (131°F) and with several test conditions with dynamic operation from -10°C (14°F) to 12°C (54°F).

Note: GTI will update this section, including a more expansive critique of this test method and potential for adoption alternative approaches used by ASHRAE 37, EN 12309, and concerning electrically-driven equipment.

Notes on Robur GAHP-A

The GAHP-A is certified in the U.S. and Canada to meet the requirements of ANSI Z21.40.4 / CGA 2.94. While this product is required is defined by the European Union to meet specific minimum energy efficiency targets (>110%, including all energy inputs on LHV basis), the unit is certified as "A+" per EN 12309 and as a result has a seasonal efficiency of greater than 110% but less than 125%. Similarly, Robur publishes the efficiency of the GAHP-A in high temperature and low-temperature mode at multiple ambient/water temperature rating points. In the U.S. and Canada, such requirements on efficiency do not exist yet and as a result, the GAHP-A is not required to and does not publish any efficiency metrics from ANSI Z21.40.4.

Combined Space and Water Heating

These standards referenced above only apply to unitary heating and cooling equipment and, for this GAHP, only concern operation in space heating mode. While limited, there are standards in use or under development that concern combined space and water heating equipment ("combi"). Currently, no standards directly cover the application of gas-fired heat pumps to combined space and water heating systems.

- *CAN CSA P.9-11: Test Method for Determining the Performance of Combined Space and Water Heating Systems (Combos)* - Adopted in 2012 and reaffirmed in 2015, this is the only standard in use in North America concerning these types of systems. Highlights of this standard are as follows, as they relate to this GAHP:
  - Scope: P.9 applies to forced-air, packaged combi systems with up to 300 kBtu/hr input for boiler-based systems and 250 kBtu/hr input for water-heater-based systems. Subject to interpretation, this GAHP could be considered a "Hot Water Boiler" as per this definition and thus applicable to this standard:

Hot water boiler — a self-contained gas- or oil-burning appliance for supplying hot water for potable use and space heating applications.
Note: *Hot water boilers have the following characteristics:*
(a) *hot water is circulated for heating purposes and then returned to the boiler; and*
(b) *they operate at water pressures not exceeding* 1.10 MPa *(160 psi) and water temperatures not exceeding* 121 °C *(250°F) at or near the boiler outlet.*

  - This GAHP would be considered a "Type B" system, with variable space heating output, however as the standard is not intended to cover heat-pump-based equipment. The 'combo

unit', when testing the space heating mode, is wholly contained within a climate chamber to simulate a static indoor environment. As such, this standard has no provisions for testing a heat-pump driven combi system.
  - The space heating and water heating performance tests are handled separately, with a "One Hour Hot Water Delivery Test" and a 24-hour simulated use test, not unlike how individual water heaters are rated.
  - Finally, sections 7.14 and 7.15 define test procedures to quantify the DHW capacity with and without a simultaneous call for heat and a one-hour delivery rating with a concurrent call for space heat. For this GAHP, as currently controlled to operate in DHW ***or*** space heating modes, these concurrent tests would yield the same results as those for DHW-only mode. System standby losses are also quantified as part of the DHW simulated use test.
- *ANSI/ASHRAE Standard 124-2007 (R2016) – Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances:* This test method is substantially similar to the Canadian P.9 standard described previously, wherein a combined rating is calculated from separate space-heating and water-heating mode tests. One significant difference is that this standard specifically references space heating testing be performed as per ASHRAE Standard 103-1993 - *Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers* and does not specify space heating procedures unit to combi systems. It does, like P.9, have a means of assessing water heating capacity (First Hour Rating) and efficiency using a simulated use test and as a result, is largely a test method that combines two existing test methods: space heating as a furnace/boiler (ASHRAE 103) and water heating (ASHRAE 118.2). Also like P.9, it has no direct means of testing a heat pump-driven combi system. This standard is currently undergoing a significant revision and as a result, may differ when this GAHP is undergoing certification.

<u>Product Safety</u>

ANSI Z21.40.1/CGA 2.91

Part of the same standard from which the aforementioned AFUE rating will likely come, ANSI Z21.40.1 *Gas-fired, Heat Activated Air Conditioning and Heat Pump Appliances* defines criteria for the safe construction and operation of GAHPs overall. The standard is in two sections, concerning 1) the construction and 2) the performance of the GAHP, a brief summary follows:

- *Construction:* Much of this standard concerns the combustion system and related design features for safe operation, similar to those employed by conventional gas-fired heating equipment (e.g. boilers), specifications for construction of burners for example. Aspects of note from this standard section for this GAHP are:
  - Construction must be in compliance with relevant sections of ANSI/ASHRAE 15 *Safety Standard for Refrigeration Systems*, ANSI Z21.20 *Automatic Gas Ignition Systems and Components*, ANSI Z21.21 *Automatic Gas Valves for Gas Appliances*, ANSI Z21.18 *Gas Appliance Pressure Regulators*, ANSI/NFPA 70 *National Electric Code*, ANSI/NFPA 54 *National Fuel Gas Code*, ANSI/ASME *Boiler and Pressure Vessel Code*, among other codes and standards.
  - The GAHP must have an automatic limit control to interrupt operation if the hydronic fluid is at or above 200°F, where lower settings are acceptable [1.13.2].
  - The device's rating plate is required to have extensive information, including mass of refrigerant and absorbent contained to the nearest 0.1 lb [1.26.2].
- *Performance:* The following is a summary of test requirements relevant to this GAHP, in order as found in this standard:

- The GAHP will have to demonstrate a CO emission rate of less than 0.04% (400 ppm) air free.
- Combustion should be unaffected by presence/lack of air filters, device panels, and all flue products should discharge from designated flue.
- The burner should operate well (no flashback/blowoff) at minimum/maximum fuel pressure at 87% of the rated minimum firing rate, 85%/110% of the supply voltage, and other typical operating scenarios.
- Flue baffles and flame spreaders should demonstrate temperature tolerance as outlined in this standard.
- Temperature limit controls should prove to function correctly, limiting gas supply when desired and not when undesired, under normal and 3X working pressure scenarios.
- Pressure limiting switches should limit absorbent/refrigerant to no more than 90% of 1/5 of the "pressure corresponding to the ultimate strength of the high-side refrigerant parts". This requirement is currently under review as too restrictive.
- Combustible and otherwise flammable surfaces and electrical equipment must be shown to have temperatures below those required and, for this GAHP, if installed on combustible surfaces outdoors it must show that the flooring surface is no more than 90°F above ambient temperatures when the GAHP is operating.
- The device must demonstrate no accumulation of moisture in areas that are not drained. The combustion condensate disposal must show that flue products do not exit a condensate trap (if used) and the device can operate or detect, react to blocked condensate drainage.
- Tests are performed concerning adequate condensate disposal, insulation efficiency, and tolerance of maximum operating conditions, which for this GAHP are as follows (Table XIII from standard). Additionally, the GAHP must prove normal operation in a "simulated rainstorm", generally with a focus on proving the combustion system continues to work adequately.

Table C1: Table from ANSI Z21.40.1 / CGA 2.91

TABLE XIII

OPERATING CONDITIONS FOR STANDARD RATING AND PERFORMANCE TESTS USING *ANSI/ASHRAE 37* STANDARD

TEST		INDOOR UNIT		OUTDOOR UNIT					
		Air Entering		Air Entering				Liquid	
				Air Cooled		Evaporative			
		DB °F (°C)	WB °F (°C)	DB °F (°C)	WB °F (°C)	DB °F (°C)	WB °F (°C)	IN °F (°C)	OUT °F (°C)
Heating	Insulation Efficiency	80 (27)	75 (24)	80 (27)	75* (24)	80 (27)	75 (24)	—	80 (24)
	Condensate Disposal	80 (27)	75 (24)	80 (27)	75* (24)	80 (27)	75 (24)	—	80 (24)
	Maximum Operating Conditions	80 (27)	67 (19.5)	115 (46)	75* (24)	100 (38)	80 (27)	90 (32)	100 (38)
Cooling	Frost Accumulation	70 (21)	60 (15.5)	35 (1.5)	33 (0.5)	—	—	—	—
	Maximum Operating Conditions	80 (27)	—	75 (24)	65 (18)	—	—	—	—

* The wet bulb temperature condition is not required when testing air cooled condensers which do not evaporate condensate.

Note: As with the 40.4 method of test section, this is standard is undergoing a major revision and as a result, GTI will update this section with the final draft as this effort continues.

Ammonia

ANSI/ASHRAE 15 *Safety Standard for Refrigeration Systems* was, for most of its existence, the singular reference concerning the safe use of Ammonia in HVAC equipment, including absorption heat pumps/chillers. Most importantly, this standard limited the charge volume of this GAHP to 10 kg when installed outdoors and adjacent to a residential building, where this GAHP's NH_3 charge is approximately half of this value. Note that these values are referenced in the major mechanical codes, Section 1104.3.2 for the *International Mechanical Code (2018)* for example.

Recently, ASHRAE has determined that it is sensible to delegate responsibility to the use of ammonia in HVAC/R applications wholly to the IIAR, through their IIAR-2 *Standard for Safe Design of Closed-Circuit Ammonia Refrigeration Systems*. An excerpt from IIAR's statement on this topic explains[5]:

"There is no longer a technical rationale for ASHRAE 15 to maintain requirements for ammonia systems, and this proposal recommends deleting those requirements in favor of a mandatory reference to IIAR 2. The change is timely, not only because of the IIAR 2 update, but also because of ASHRAE 15's proposed recognition of Group A2L refrigerants. Deferring ammonia to IIAR 2 will avoid any risk, now or in the future, of Group A2L provisions in ASHRAE 15 inadvertently impacting ammonia, a Group B2L refrigerant, based on the shared 2L flammability classification.
In conclusion, deferring ammonia to IIAR 2 is justified because:

[5] https://www.iiar.org/iiar/WCM/Standards/ASHRAE_15_Reference_to_IIAR_2.aspx

- *IIAR 2-2014 is an ANSI approved standard that comprehensively regulates ammonia refrigeration, is recognized by all of the latest U.S. model fire and mechanical codes, and no longer relies on ASHRAE 15 for supplemental content.*
- *Ammonia is unique among 2L refrigerants. It has a self-alarming odor that can be detected at concentrations well below hazardous levels, has a gas density that is lighter than air, and is uniquely regulated by EPA and OSHA.*
- *Taking ammonia out of ASHRAE 15 will simplify integration of new Group A2L provisions.*
- *Having a single design standard will simplify design, operation and regulation of ammonia systems.*
- *IIAR now publishes a complete suite of ammonia-specific standards, all of which are standalone documents, except for IIAR 2. It makes no sense for IIAR 2 and ASHRAE 15 to continue dividing the topic of design when requirements for equipment, startup, operation, maintenance and decommissioning of ammonia systems are all independently established by IIAR standards."*

In the 4th Public Review Draft of IIAR 2-2014, a new chapter on Ammonia Absorption Refrigeration systems is to be added with updates on several relevant matters, including the following highlights pertaining to this GAHP:

- IIAR-2 adopted the same overall guidance as ASHRAE 15 had, with respect to charge volume and installation location. Packaged absorption systems for residential applications with less than or equal to 10 kg of NH_3 can be installed outdoors within 20 ft. of a building opening [4.2.2.1].
- This GAHP, with less than 10 kg of NH_3, does not *require* a means of purging air or other non-condensable gases [5.8].
- Vapor compression and liquid-vapor absorption systems must be isolated, with integration only permitted indirectly through heat exchanger [18.3].
- Within the absorption systems chapter, there are numerous exemptions for this GAHP (<10 kg NH_3) concerning other portions of this standard, including but not limited to means of field-servicing [18.9], emergency shutdown procedures [18.11], specific design requirements for piping [18.13], solution pumps [18.14], condensers [18.15], evaporators [18.16], valves [18.18], controls [18.21], and ammonia detection and alarms [18.23].

Space Heating and Potable Water Heating
This GAHP must be an indirect heating system, as the common mechanical and plumbing codes require it due to ammonia's toxicity.

- In the case of potable water heating, the *International Plumbing Code (2018)* requires that heat exchangers using an "essentially toxic transfer fluid shall be separated from the potable water by double-wall construction", additionally requiring that there be an air-gap, open to atmosphere, between the two walls [608.17.3], with a similar provision in the *Uniform Plumbing Code*.
    - Note that within the IMC, propylene glycol is noted as "essentially nontoxic" and thus permitted for use with single-wall heat exchangers, in-line with the U.S. Food & Drug Administration's legal handling of propylene glycol as "food safe"[6]. However, there may be localities that require double-wall heat exchangers for all glycols.
- In the case of the *International Mechanical Code (2018)*, references are made to ASHRAE 15 and IIAR-2, which only contain exemptions for "sealed absorption" machines and use as a "direct" refrigeration system are not possible given NH_3's B2L classification, though the opportunity for the "low-flammability" refrigerants (A2L) is shifting.

[6] CFR Title 21, Chapter 1, Subchapter B "Listing of Specific Substances Affirmed as "Generally Recognized as Safe", Section 184.1666 *Propylene Glycol*.

- All items noted here are applicable within the *International Residential Code* as well.

Thus now, and for the foreseeable future, this GAHP will require the use of an indirect heat transfer fluid between the sealed system and the generation of heated supply air and/or potable hot water.

Corrosion Inhibitors - Chromates

The need for corrosion protection within the GAHP sealed system is inherent to the technology, where the ammonia-water (or strong salt-water, such as LiBr) absorbent/refrigerant pair often create high pH environments that under high temperatures and pressures (a) have a tendency to form hydrogen, a non-condensable gas that degrades system efficiency and (b) can attack steel surfaces, promoting stress corrosion cracking and eventual failure. This is commonly addressed by the use of corrosion inhibitors, additives to the solution upon charging that regulate system pH and create passive, protective layers on wetted surfaces.

In Europe, where GAHPs are more common, the European Union has made an effort to restrict or eliminate the use of chemicals commonly deployed as corrosion inhibitors, namely chromate salts (sodium dichromate, sodium chromate, potassium dichromate, potassium chromate). This EU Regulation No. 348/2013, referred to as REACH under Annex XIV, included these substances which could last applied for used on March 21st, 2016 and passed a "Sunset Date" on September 21st, 2017 after which their use is banned. During this application window, manufacturers of absorption heating/chilling equipment have sought specific exemptions to continue the use of chromates for corrosion protection, in some cases continuing use through 2029[7]. In the run up to this regulation, Dometic, a well-known manufacturer of absorption-based refrigerators made the following public comment[8]:

"Sodium chromate is used as an anti-corrosion of the carbon steel cooling system in absorption refrigerators. Since 1925, Dometic (previously owned by Electrolux , now owned by a group of international banks) has produced some 50 million absorption refrigerators. Today, Dometic produces approximately 700.000 cooling units per year, of which 350.000 units are sold in Europe. The production is located in Sweden, Germany, Hungary and China.

The Dometic absorption cooling units are constructed in carbon steel because of its strength and good welding and cold-working properties. The refrigerant is an ammonia-water solution. The absorption cooling system is a completely closed system, which is pressurised with hydrogen or helium gas. In order to prevent corrosion of the carbon steel cooling system a small amount (about 10 grams/unit) of sodium chromate is added to the refrigerant. At this stage, despite extensive research, there are a number of scientific and technological challenges, which remain to be overcome, and where alternatives to hexavalent chromium give rise to difficult trade-offs in respect to product lifetime, product reliability and energy efficiency.

Dometic uses less than 10 tonnes of sodium chromate solution (33 w%) per year. Hexavalent chromium (sodium chromate) as an anti-corrosion of the carbon steel cooling system in absorption refrigerators is currently exempted from the requirement of Article 4(1) of the RoHS Directive 2002/95/EC and exempted from Article 4(2)(a) of the ELV Directive 2000/53/EC."

[7] Chemical Watch, "Sodium Dichromate Authorisation Application Approved by EU", April 3rd, 2018.
[8] https://echa.europa.eu/documents/10162/5eb70a3c-c0bf-403d-85b5-1dcc220c238d

Currently, in conformity with said REACH regulation, Dometic publicizes that their products contain sodium chromate as an inhibitor, but less than 1% of the total refrigerant charge[9]. While it appears that companies, particularly those in heavy industries and food processing, have been permitted to continue the use of chromates as corrosion inhibitors within absorption equipment, it also seems that the time has passed to seek such a waiver barring any changes to the regulation.

While sodium chromate and the related compounds do not have the same phase-outs planned in the U.S. like REACH, the use of these substances is heavily regulated due to their carcinogenic properties, grouped with other “hexavalent chromium compounds”. The hazardous properties of these chemicals from their use as corrosion inhibitors was famously brought to light by Erin Brockovich, regarding Pacific Gas & Electric’s use of sodium dichromate in cooling towers leading to groundwater pollution and a $333 million settlement in central California.

Notes on Robur GAHP-A

The GAHP-A is certified in the U.S. and Canada to meet the requirements of ANSI Z21.40.1 / CGA 2.91. Concerning the use of chromates as corrosion inhibitors, in discussion with a large distributor of Robur products based in the U.S. Northeast, it is their recollection that Robur continues to use chromates, thus is possible that Robur has either a) received an exemption or extension from the REACH regulation for which a record could not be found or b) such an exemption is not applicable in the U.S. and Canada. Robur’s use of chromate-based inhibitors possible based on prior patent applications[10].

Installation and Maintenance

While the GAHP shares many installation and maintenance requirements with other conventional HVAC equipment (boilers, furnaces, etc.), as a new product category it also has several unique requirements primarily concerning a) the nature of the GAHP design and b) that it is a high-efficiency combustion device installed outdoors.

Concerns with Outdoor Installation – Siting and Venting

Generally, the first concern with outdoor installations is required setbacks from the adjacent building from a safety and venting of combustion products perspective. In addition to comparisons with the commercialized Robur *GAHP-A*, this GAHP can also draw on the experience of outdoor installations of gas-fired stationary generators and so-called “gas packs”, packaged unitary A/C and gas-fired heating equipment installed outdoors. For
NFPA 54, the *National Fuel Gas Code* (NFGC), is commonly referenced by combustion equipment for safe installations, gas piping, venting, and other matters.

- For gas piping, the NFGC offers flexibility with gas piping connections, with listed connectors referencing ANSI Z21.24 and ANSI Z21.75, for indoor/outdoor gas connections and manufactured homes respectively [9.6.1]. Generally, manufacturers require a sediment trap be installed as part of the gas piping.
- For venting, the NFGC would treat this GAHP as with other “Category IV” appliances, permitting the manufacturer to define much of the specific venting requirements [12.5.1] and is generally silent on products listed for outdoor installation. The IMC (2018) specifically states exemptions for requirements of minimum vent height, leaving this determination to the manufacturer [802.6.2].

[9] https://www.dometic.com/en-us/us/about-us/our-company/sustainability/products/reach
[10] EP1304398A3, *Corrosion Inhibitor for Ammonia/Water Absorption Systems*, Filed 2001.

Additionally, the IMC requires that mechanical draft systems terminate no less than 10' from the lot line or adjacent buildings and direct the venting away from the building [804.3.3]. Guidance exists for vertical and horizontal vent terminations, however these apply to through-the-wall venting with no specific provisions for outdoor equipment [804.3.4, 804.3.5]

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Figure C3: Residential Installations of Backup Generator (L), Gas Pack (C), and GAHP (R) [Source: Generac, Broan, Robur]

Table C2:

Equipment	Example Product	Setback/Venting Requirements	Notes
Backup Generator	Generac	- No windows/openings within 5' of generator surface - 60" from nearest wall and all around, 36" if near wall has fire resistance one-hour rating - As is typical, unit has integrated venting	Installation guidance references NFPA 37 *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
Gas/Electric Packaged HVAC	Nortek *R8HE*	- 36" on all sides from combustibles, except adjacent wall which is within 6". Combustion equipment and venting face away from the adjacent building (only orientation option shown in Figure) - For ground installations, the entire venting assembly is sold as a kit and condensate disposal must use drain pit, dug for the installation. Refer to Figure.	Installation guidance states that neutralization may be required depending on state/local codes, accomplished with substituting limestone or lime pellets instead of gravel.
GAHP	Robur *GAHP-A*	- Between 18" and 32" from adjacent combustible surfaces, with venting on side opposite building. If multiples are installed, no less than 18" between units. No installations within 6' of external air intakes. - Robur's GAHP-A has a factory-installed vent kit as shown in Figure,	Robur offers guidance with respect to acoustics, but no prescriptive requirements.

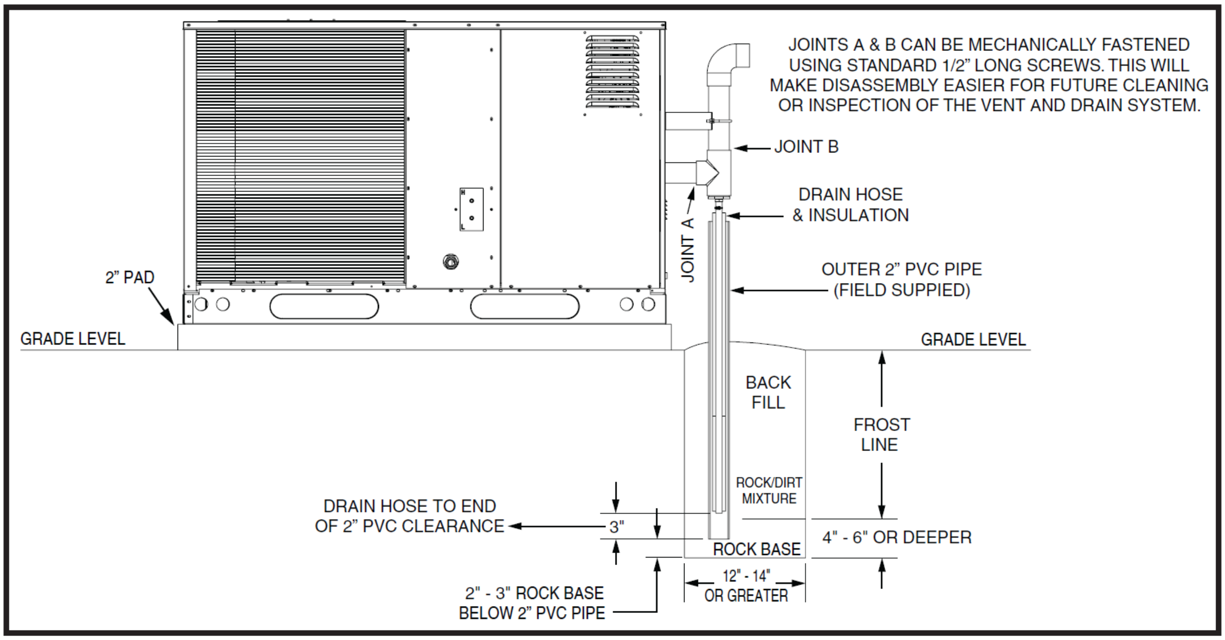

Figure C4: Vertical Well Condensate Drainage for Nortek R8HE [Source: Nortek]

While the standard is no longer recognized, there used to be a standard in use specifically for outdoor combustion equipment, CAN1-2.21 (1985, reaffirmed 2015) *Gas-fired Appliances for Outdoor Installation*. When in effect, this standard applied to similar products (including the Robur *GAHP-A*), which had the following general requirements (most of which are redundant to the Z21, appliance-specific series):

- Specific requirements concerning accessibility of flue baffles, removable insulation/panels, and other combustion components to permit cleaning, servicing, and other maintenance.
- Prescription of material selection (e.g. corrosion resistant coatings) and assembly.
- Requirements on combustion air intake openings and low-temperature rating of components with and without compartments heated by supplemental energy inputs.
- An old, and possibly impractical requirement, is that the flame be observable (pilot, main). As a note, this requirement is addressed in the modern version of the ANSI Z21.40 standards.
- Performance shall be demonstrated during a "rain test" and a "wind test" to assure successful and safe ignition/operation.

Condensate Disposal

Like many aspects of venting, the model mechanical codes (IMC and UMC), which cover the handling of condensate and, the model plumbing codes (IPC and UPC), which cover the disposal of condensate, leaves specifics up to the manufacturer guidance. Generally, the model codes are good about distinguishing between condensate formed by HVAC equipment at the evaporator coil and generated from combustion by-products. Note that the IFGC/NFGC, which covers many aspects of fuel-burning equipment installations, defers to manufacturer instructions as well. A brief summary of the ICC codes (IMC/IPC) are as follows, with minor differences noted in the UPC/UMC:

- Model Mechanical Codes: The 2018 IMC notes that approved plumbing fixtures are necessary for the collection and discharge of condensate, per manufacturer instructions. Piping needs to be made of an approved corrosion-resistant material, shall not be smaller than the drain connection at the appliance, and have a horizontal slope of at least 1% [307.1]. Requirements from the UMC are substantially similar [312.1]. Both codes are silent on approved disposal location, treatment/neutralization, and for both effectively defer to manufacturing requirements and the AHJ.
- Model Plumbing Codes: The 2018 IPC has the identical language as the IMC regarding collection and disposal [314.1], with similar parallels from the UPC to the UMC [814.1]. The plumbing codes, however, do have general provisions for disposal of corrosive wastes, which from the IPC are as follows [803.1, 803.2].

While there are no direct references to combustion condensate, an AHJ may make this connection. With similar language in the UPC [306.1, 807.3], the UPC references "undiluted condensate waste" specifically, but only in the context of specifying suitable materials for fixtures and traps, nothing regarding neutralization or disposal locations. Generally, the plumbing codes again defer to the manufacturer instructions and the AHJ. While neutralization is mentioned with regard to disposal of "special wastes", it is not tied directly to combustion condensate.

Note: While not absolute, generally speaking the ICC codes (IMC, IPC, etc.) are more widely adopted and referenced by U.S. states, with the notable exception of California.

SECTION 803
SPECIAL WASTES

803.1 Neutralizing device required for corrosive wastes. Corrosive liquids, spent acids or other harmful chemicals that destroy or injure a drain, *sewer*, soil or waste pipe, or create noxious or toxic fumes or interfere with sewage treatment processes shall not be discharged into the plumbing system without being thoroughly diluted, neutralized or treated by passing through an *approved* dilution or neutralizing device. Such devices shall be automatically provided with a sufficient supply of diluting water or neutralizing medium so as to make the contents noninjurious before discharge into the drainage system. The nature of the corrosive or harmful waste and the method of its treatment or dilution shall be *approved* prior to installation.

803.2 System design. A chemical drainage and vent system shall be designed and installed in accordance with this code. Chemical drainage and vent systems shall be completely separated from the sanitary systems. Chemical waste shall not discharge to a sanitary drainage system until such waste has been treated in accordance with Section 803.1.

Where additional guidance is noted by AHJs, states and municipal governments, generally codes address the running of condensate outdoors in a manner that does not create a nuisance (freezing on walkways, etc.). Triggered by abnormally cold winter temperatures in 2014, many state/local governments realized that indoor 'condensing efficiency' equipment were tripping on errors as disposal lines were freezing. For example, North Carolina passed a "green furnace law", which specifically permitted the disposal of combustion condensate into sanitary sewer drains[11]. This has led to the more common use of neutralizers

[11] WRAL, "Green Furnace Law Still Needs Some Tweaking", News story published on 9/17/15.

as local sanitation codes very commonly have strict requirements on the pH of disposed wastes. The following is a sampling of local requirements with respect to condensate disposal:

- **New York City:** NYC's mechanical, plumbing, and fuel gas codes all have the following language:

"Condensate from all fuel-burning appliances and associated flues shall be neutralized to a pH of at least 6 and no more than 8 prior to disposal to a sanitary system."

- **Boston (State of Massachusetts):** The MA Mechanical, Plumbing, and Fuel Gas Code all following the language from the ICC codes (IPC, etc.). No special requirements for neutralization when disposing into a sanitary sewer.
- **Seattle:** Similar to the State of MA, Seattle adopts the ICC code set as it relates to plumbing and mechanical concerns, thus no specific requirements for condensate disposal into sewers.
- **Detroit:** Detroit references the State of Michigan codes which, like Massachusetts and Seattle, reference the ICC code set.
- **Chicago:** Chicago's city code has specific language which mirrors the IPC/IMC, as follows:
    - **Mechanical Code:** *"18-28-307.1 Fuel-burning appliances; The liquid combustion by-products of condensing appliances shall be collected and discharged in accordance with Section 18-28-801, Plumbing. Condensate piping shall be of Type M copper or Schedule 40 PVC and shall not be smaller than the drain connection on the appliance. Such piping shall maintain a minimum horizontal slope in the direction of discharge of not less than one-eighth unit vertical in 12 units horizontal (1 percent slope)."*
    - **Plumbing Code:** *"18-29-803.2 Neutralizing device required for corrosive wastes. Corrosive liquids, spent acids or other harmful chemicals that destroy or injure a drain, sewer, soil or waste pipe, or create noxious or toxic fumes or interfere with sewage treatment processes, shall not be discharged into the plumbing system device for corrosive waste. No corrosive wastes which are equal or greater in corrosive action than a ph lower than 4.5 or higher than 10.0, having corrosive properties sufficient to cause damage or hazards to structures, equipment, or personnel, shall discharge into any house sewer without first discharging into a dilution tank or basin. Such devices shall be automatically provided with a sufficient supply of diluting water or neutralizing medium so as to make the contents noninjurious before discharge into the drainage system. No other waste pipe shall connect to a dilution basin. Every dilution tank used for this purpose shall be constructed of earthenware, polyethylene, propylene or glass and shall be provided with a standing waste and overflow or other approved means to ensure dilution."*

While outdoor installations of condensing equipment are rare, but occurring, namely condensing gas pack equipment (Figure C3), there are no specific code requirements around the handling and disposal of condensate for outdoor equipment and thus, the Mechanical and Plumbing codes defer to the manufacturer instructions. Where neutralization is required for condensate disposal into sanitary sewer drains, it stands to reason that the AHJ may require neutralizers as part of this GAHP's outdoor condensate disposal.

Shipping

As noted by SMTI in prior correspondence, several sections within the Code of Federal Regulations provide exemptions for shipping factory charged, sealed absorption machines containing ammonia under pressure. This includes the following:

- **49 CFR 173.306**: Here in the code, the shipment of compressed gases and associated requirements of packaging are exempted for "refrigerating machines", which for this GAHP this exemption applies, in addition to requirements referencing ANSI/ASHRAE 15:

*"Machines or components having two or more charged vessels may not contain an aggregate of more than 2,000 pounds of Group I refrigerant or **more than 100 pounds of refrigerant other than Group I**."*

- **49 CFR 173.307:** An additional exemption for shipment of compressed gases applies to "refrigerating machines" which have "12 L (3 gallons) or less of ammonia solution". This GAHP is estimated to contain 9.5 L of ammonia solution.
- **49 CFR 173.154:** Concerning shipment of hazardous corrosive materials, wherein shipment of "Ammonia Solution" is treated as a Class 8 Hazardous Substance (corrosive material). Labeling and packaging requirements are here and limitations on shipment by aircraft.

Figure C5: Removing NCs from GAHP

Maintenance

Maintenance is expected to be performed by 3rd parties, much of which involves routine aspects of conventional system components covered by other codes (e.g. servicing ignition components), however limited maintenance is expected for the sealed system. One concern worth exploring is the removal of non-condensable (NC) gases from the GAHP. This procedure is intended to vent the NCs, primarily/exclusively H_2 from the sealed system to improve performance. These NCs were previously discussed with respect to corrosion inhibitors. The process of venting NCs from prototypes has involved connecting hoses to service valves, placing the outlet of said hose submerged in water, and slowly venting the NCs until bubbles are seen to start "collapsing" – an indication that the NCs are substantially removed and NH_3 is venting. After venting NCs, the solution collected may have trace amounts of NH_3 and possibly corrosion inhibitors. A few questions arise from this process, including:

- **Certification of technician?** The U.S. EPA regulates the handling of refrigerants, hence the certification of technicians, through the efforts coming out of the "Montreal Protocol". In Title 40 of the CFR, Chapter I, Subchapter C, Part 82, Subpart F, Part 82 – Protection of Stratospheric Ozone: Recycling and Emissions Reduction, the following applies to ammonia, as it is exempt from venting prohibition requirements, specifically for absorption units [82.154]. As a result, technicians operating on the GAHP sealed system may require the same level of certification typical for HVAC maintenance (refrigerant recovery, etc.). The technicians may, depending on exemptions from IIAR-2, may require other certifications however as they do in industrial refrigeration.
- **Handling and Disposing of Solution:** The dilute ammonia solution (ammonium hydroxide) will be substantially similar to what is often referred to as "household ammonia", barring the presence of trace corrosion inhibitors and dissolved metals. Treating this substance as pure ammonia solution and ignoring trace materials, the following apply:
    - Per 40 CFR 116.4, the solution will be listed as a hazardous substance per the Clean Water Act and, as the Resource Conservation and Recovery Act (RCRA) stipulates, no amount of dilution obviates status as hazardous, however only quantities of 1,000 lbs or greater are reportable per law.

- Per 40 CRF 261.22, the solution is also deemed a corrosive waste *if* the pH is greater than 12.5.
- Some “household ammonia” solution SDS sheets note that when handling ammonia solution, one should:
    - Only handle outdoors, do not swallow and avoid inhalation, wear protective gloves/clothing/eye & face protection
    - Disposal must be done per requirements of the AHJ (see prior discussion of special waste disposal) and in one SDS case, it states “Suitably diluted product may be utilized as fertilizer on agricultural land”

Notes on Robur GAHP-A

In discussion with a distributor and installer of Robur products in the Northeast, a company with experience installing 1,000s of units over 40 years, the lead installer had the following notes regarding installation and maintenance:

- When shipped to distributor and transported to the site, the GAHP products carried no specific hazardous requirements or designation as NH_3 is low.
- Combustion condensate commonly is drained to a gravel pit, condensate does freeze sometimes but doesn’t create lasting issues.
- Generally speaking local inspectors have had no issue with the GAHP units, just unfamiliarity with the technology.
- When solution was removed from the older GAHP units (not common now), they would have to hire a hazardous material handling company for disposal because of the sodium chromate contaminate in the solution.

Environment

As a high-efficiency device, utilizing a natural refrigerant/absorbent working pair, the GAHP is an important solution for organizations seeking specific reductions in direct and indirect greenhouse gas (GHG) emissions, these fall into two primary categories:

- Those organizations seeking to reduce direct GHG emissions, through “cap-and-trade” approaches, carbon taxes/levies, and other means. This includes the State of California, Canada and several provincial governments, and numerous municipal governments (e.g. NYC).
- Those organizations seeking to limit the impact of high global warming potential (GWP) refrigerants, including the EPA, the California Air Resources Board, and ASHRAE. For this, the GAHP is ‘future-proof’, with a zero-GWP working fluid pair.

Concerning conventional emission limitations of criteria pollutants, namely CO and NO_x, this GAHP will have to demonstrate compliance with the CO emission rate outlined in ANSI Z21.40.1 and, when installed in most jurisdictions in California, meet a NO_x emission rate of 14 ng NO_x/J output, which this device has been certified to meet in 2018. Note that the GAHP exists within a gray area for most Air Quality Management Districts in California, as it is not neatly defined by Rule 1121 or 1146.2, as a result the Robur GAHP-A is said by its distributor and local reps to be exempt from Ultra Low NO_x requirements.