



→ Adsorption Gas Heat Pump Lab Tests

Project Number ET24SWG0008

GAS EMERGING TECHNOLOGIES (GET) PROGRAM
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Executive Summary

The Manufacturer A's "First Beta" prototype gas-fired adsorption heat pump water heater (AHPWH) was evaluated based on the U.S. Department of Energy (DOE) test procedure outlined in 10 CFR Part 430 Subpart B. The scope of work also included measuring carbon monoxide (CO), carbon dioxide (CO₂), and nitrogen oxides (NO_x) emissions to assess compliance with South Coast Air Quality Management District (SCAQMD) regulations for residential water heating equipment.

Following commissioning of the unit, the AHPWH demonstrated a First Hour Rating (FHR) of approximately 22.2 gallons under direct firing mode, achieving a firing rate of 9.6 kBtu/hr (2.8 kW). Manufacturer A, in comparison, achieved an FHR of 51 gallons at a higher firing rate of 25 kBtu/hr (7.3 kW). Therefore, the medium draw pattern was implemented and determined based on Manufacturer A's testing. This discrepancy between the performance testing and the testing performed at Manufacturer A's facility was due to manufacturing issues that prevented firing the unit at its full rate at GTI Energy's laboratory.

Under the medium draw pattern, the AHPWH achieved a Uniform Energy Factor (UEF) of 0.68 and a recovery efficiency of 69%. This UEF, although below DOE guidelines for uniform operating conditions, reflects acceptable early-stage performance aligned with medium draw requirements.

Manufacturer A provided additional information on design changes and in-house unit testing for context in the Appendix A section. The GET Program did not independently confirm these changes or this data, but the trends from the First Beta to the Second Beta unit show an improvement in overall COP performance.

To achieve a UEF exceeding 1.0 in the next beta prototype, comprehensive improvements in reactor design, insulation strategies, and component integrity are recommended. Technoeconomic analysis suggests that achieving a UEF of 1.1 could lead to substantial reductions in natural gas consumption, CO₂ emissions, and utility costs, aligning with federal and California's decarbonization objectives.

Introduction

Manufacturer A has been advancing the development of the gas-fired AHPWH through successive iterations, including the First, Second, and Third Alpha prototypes, followed by the First Beta prototype, which is the current effort. This project looks at evaluating the performance of the Manufacturer A “First Beta” prototype AHPWH sized for residential applications. The evaluation was conducted through standard test methods within a R&D laboratory, which specifies methods for determining the UEF and FHR of residential water heaters. The scope of work also included measuring CO, CO₂, and NO_x emissions to assess potential impacts towards emission limitations, such as those from the SCAQMD and CSA/ANSI Z21.10.1-19 for residential water heating equipment.

Motivation

The U.S. DOE increased the minimum performance criteria (UEF) for the gas water heaters starting from May 2029, as shown in Table 1. For instance, the 50-gallon gas-fired storage water heater with medium draw should have a minimum UEF of 0.62. The new regulation will be effective in May 2029. Also, gas storage water heaters are eligible for tax credits if they have > 0.81 UEF for tanks less than 55 gallons and > 0.86 UEF for tanks greater than or equal to 55 gallons [1].

Table 1: Minimum UEF requirements for residential water heaters.

Entity			DOE [2]	ENERGY STAR [3]
Fuel	Type		Efficiencies	
			> 2024	> 2023
Gas	Storage	50 gal	0.56 – 0.63	0.81 – 0.86
		75 gal	0.76 – 0.78	0.86
	Instantaneous		0.80 – 0.81	0.95
Electric	Storage	50 gal	0.90	2.2 for 120 V HP 3.3
		75 gal	2.0 – 2.2	

In California, water heating accounts for approximately 25% of residential energy consumption [4]. To address this, the state’s Title 24 Building Energy Efficiency Standards require the use of high-performance appliances in both new construction and retrofitted homes. Highly efficient water heaters, such as heat pumps and condensing models, not only reduce electricity and natural gas demand but also help alleviate strain on the electrical grid, particularly during peak load periods. These technologies play a critical role in improving energy reliability, minimizing the risk of rolling blackouts during heatwaves, and lowering utility bills for households.

California has established some of the most ambitious climate goals in the nation, including achieving carbon neutrality by 2045 and significantly reducing greenhouse gas emissions from the building sector. To support these objectives, initiatives like TECH Clean California provide incentives and rebates that promote the adoption of high-efficiency water heating technologies, aiming to deliver long-term energy savings and advance energy equity.

In alignment with federal initiatives and California's decarbonization strategies, focus has shifted to the development and demonstration of highly efficient Thermal Heat Pumps (THPs) for residential water heating, such as adsorption and absorption water heaters. These advanced systems are a promising solution for reducing energy consumption, supporting grid stability, and accelerating the transition to low-carbon, high-efficiency residential buildings. Among several technologies, Manufacturer A gas-fired AHPWH is a promising unit that uses the adsorption phenomena to lift thermal energy from the ambient to buffer tank, aiming to achieve energy efficiency more than 1.0.

System Description

The Manufacturer A unit is a gas-fired AHPWH that uses a salt matrix with ammonia as a working pair. It is an effective integration between a condensing storage water heater and heat pump effect using adsorption technology, aiming to achieve a gas energy efficiency of more than 1.0. The unit can operate in direct-fire mode for high capacity (34 kBtu/h - 10 kW) loads when required, with efficiencies aligning with a condensing water heater.

For the heat pump effect, the appliance uses ammonia, a natural refrigerant with zero ozone depletion plus zero global warming potential (GWP) that is suitable for all climate zones. The reactor (adsorber) is the main component of the unit, which is a heat exchanger filled with a salt matrix. Note that the salt matrix lifespan may vary depending on the material of the heat exchanger, the presence of gas and/or material impurities, the frequency of maintenance and cleaning checks, and the temperature extremities during subsequent cycles. When operating in heat pump mode, the water heater undergoes three main processes:

1. Reactor Heating – Desorption Phase
 - The burner generates steam within the boiler, initiating the desorption cycle.
 - As steam flows into the reactor at temperature around 284°F (140°C) to release (regenerate) ammonia from the nanoporous structure of the salt matrix.
 - Inside the reactor (heat exchanger), the steam condenses, transferring latent heat to the salt matrix, while the resulting condensate returns to the boiler via gravity, forming a self-circulating water loop known as the Reactor Heating Loop. This circulation is driven by density and temperature-induced buoyancy differences.

- Steam expansion volume is balanced through a communication tube that connects to a buffer tank, which incorporates an expansion chamber to accommodate pressure and volume changes.
 - The desorbed ammonia vapor, at high pressure (typically ~290 psi (~20 bar)), condenses on the cooler reactor walls, releasing heat that is transferred to the buffer tank (i.e., heat of condensation).
 - The condensed ammonia then flows by gravity into the receiver and evaporator, where it can be reused in the adsorption cycle.
 - Additionally, residual heat in the flue gases exiting the boiler is recovered through a flue gas heat exchange coil, while the remaining thermal energy is used for defrosting the evaporator.
2. Pump Loop – Reactor Cooling
- During this phase, the reactor is actively cooled using the Pump Loop (PL) – a closed, pumped water circuit that circulates coolant between the buffer tank and the reactor coil. This loop ensures efficient sensible heat removal from the reactor, preparing the salt matrix for the adsorption process.
3. Heat Lifting – Adsorption Phase
- During this phase, the burner remains inactive.
 - A circulation pump drives water from the bottom of the buffer tank through the Reactor Coil, maintaining the reactor at a low operating temperature.
 - Under these conditions – typically around 140°F (60°C) and 58 psi (4 bar)—the salt matrix adsorbs ammonia vapor coming from the evaporator.
 - The heat released during the adsorption process is transferred to the circulating water, which then returns to the buffer tank through the communication tube.
 - Simultaneously, ammonia evaporates at low pressure and temperature in the evaporator, drawing low-grade heat from the ambient environment, which sustains the adsorption-driven heat transfer cycle (i.e., free energy lifted from the ambient by the adsorption reactor).

Therefore, the heat of adsorption, heat of condensation, and flue gases heat are recovered by the water in the tank, as illustrated in Figure 1, aiming to achieve an energy efficiency more than 1.0. The design parameters are outlined in Table 2.

Figure 1: Schematic diagrams of the Manufacturer A First Beta prototype

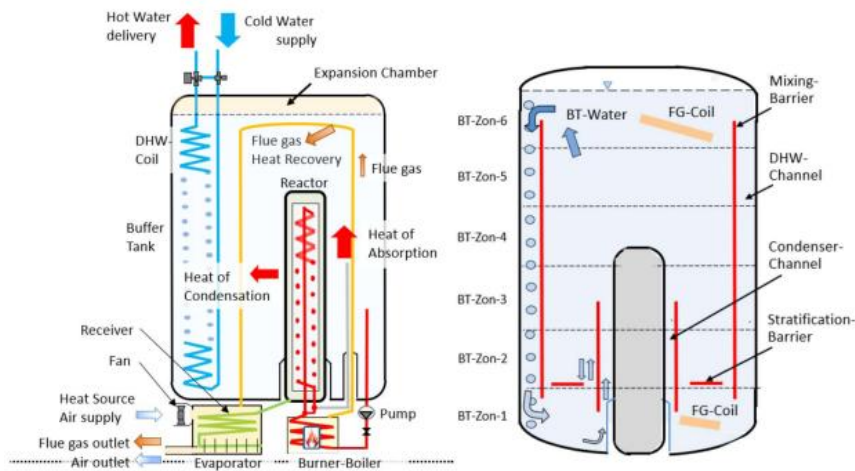


Image Source: Manufacturer A.

Table 2: First Beta prototype design parameters.

Parameter	Value
Tank Size	~ 40 gallon (150 liter) water
Footprint	28x28 in
Height	59 in
Burner Output Range	5 – 34 kBtu/hr (1.5 – 10 kW)
Ammonia Charge	3.3 Lb (1.5 kg)

Manufacturer A has developed this technology through First, Second, Third Alpha, and First Beta prototypes.

Figure 2 depicts the First and Second Alpha prototypes and the First Beta prototype. The unit was sized for residential applications in North America with a hybrid design, of both up to 6.8 kBtu/hr (2 kW) peak output from the sorption module and up to 34.1 kBtu/hr (10 kW) peak auxiliary output from the steam boiler. The unit targeted an efficiency of ≥ 1.25 UEF and a target FHR of more than ~50 gallon (190 L) of hot water.

Figure 2: Pictures show the technological progress of Manufacturer A.



Assessment Objectives

The main goal of this test plan is to advance the development of the First Beta prototype of Manufacturer A AHPWH designed and fabricated at the Manufacturer A facility for residential application. This goal is achievable by:

1. Procuring and commissioning the residential-scale prototype Manufacturer A unit.
2. Experimentally measuring the FHR and UEF values of the unit.
3. Measuring CO, CO₂, and NO_x emissions.
4. Assessing the technoeconomic performance of the unit.

Test Plan

The test plan was designed to commission the system based on Manufacturer A’s recommendations and to evaluate its energy efficiency. The following tasks were performed according to Table 3:

Table 3: Task descriptions.

Task	Description
1	Develop the test plan and prepare the unit for testing.
2	Commissioning the unit at operating conditions.
3	Evaluate the 1 st Beta unit under the US DOE standard for domestic hot water.
4	Perform a technology assessment to estimate energy/emission reductions and cost savings relevant to California.
5	Develop the draft/final report.

Calculations

To estimate the increase in the tank temperature and energy added to the water in the buffer tank during the direct firing period (commissioning phase), the volume-weighted average approach was applied using Equation 1 and Equation 2.

Equation 1: Volume-weighted average tank temperature, °F.

$$\overline{T_{tank}} = a_1 \times T_{BT1} + a_2 \times T_{BT2} + a_3 \times T_{BT3} + a_4 \times T_{BT4} + a_5 \times T_{BT5} + a_6 \times T_{BT6}$$

where

$\overline{T_{tank}}$ = mass-weighted average water tank temperature, °F

T_{BTi} = buffer tank water temperature in each zone, i, °F

$a_{1 \rightarrow 6}$ = the water percentage in each zone equivalent to 0.16, 0.16, 0.16, 0.16, 0.18, and 0.18, respectively

Equation 2: Energy added or removed from the water in the buffer tank, kBtu.

$$E_{wt} = V \left(\rho c_p \overline{T_{tank}}(final) - \rho c_p \overline{T_{tank}}(initial) \right)$$

where

V = volume of buffer tank, ft³

ρ = density of buffer tank, lb/ft³

c_p = water specific heat, kBtu/lb.°F

The performance of the first beta Manufacturer A water heater will be measured based on the US DOE standard. The natural gas energy input will be calculated using Equation 3.

Equation 3: Accumulated natural gas energy input, Btu/hr.

$$\dot{Q}_{gas} = \sum V_g \cdot \frac{P_a}{P_s} \cdot \frac{T_s}{T_a} \cdot HHV \cdot \frac{1}{\Delta t}$$

where

V_g = natural gas volume, ft³

P_a = actual line pressure and barometric pressure using weather data, psia

P_s = standard pressure of 14.969 psi

T_a = actual line temperature, R

T_s = standard temperature of 520°R

HHV = natural gas heating value (measured daily), Btu/ft³

Δt = data logger time-step of 5 seconds

Electricity consumption of the heat pump (blower and pump) will be directly measured using a Wattnode.

The useful energy output can be calculated from the mass flow rate and temperature difference across the system. It will be calculated according to Equation 4.

Equation 4: Useful energy delivered from the unit, Btu.

$$\dot{Q}_u = \sum \dot{V}_{DHW} \cdot c_{p_w} \cdot \rho_w \cdot (T_{DHW} - T_{c_w})$$

where

\dot{V}_{DHW} = domestic hot water flow rate, gpm

c_{p_w} = water specific heat at the average temperature of each draw, Btu/lb.°F

ρ_w = water density at the average temperature of each draw, lb/ft³

T_{c_w} = city water temperature, °F

T_{DHW} = domestic hot water temperature, °F

During the commissioning phase, the prototype was shaken down in the laboratory. Energy and mass balances were conducted during the commission process based on the average tank temperature, natural gas consumption, and combustion efficiency.

The tank was filled up with city water at 58°F. The volume of water in the tank and the tank's temperature will be measured. The direct-firing mode was activated, and the tank was heated up to the cut-off temperature. Both the gas consumption and flue gas properties were measured during the heating process.

The combustion efficiency based on the flue gas composition and temperature was calculated using Equation 5.

Equation 5: Combustion efficiency.

$$\eta_{combustion} = \frac{\dot{Q}_{gas} - \dot{Q}_{flue}}{\dot{Q}_{gas}}$$

The energy and mass balance across the system was computed using Equation 6.

Equation 6: Energy and mass balance.

$$\sum_{start}^{cut-off} V_{gas} HHV = \frac{m_{water,tank}}{time} \cdot (c_{p_{tank,final}} \cdot \overline{T_{tank,final}} - c_{p_{tank,initial}} \cdot \overline{T_{tank,initial}}) + \dot{Q}_{flue} + \dot{Q}_{loss}$$

\dot{Q}_{flue} (kBtu/hr) is the energy content remaining in the flue gas leaving the heat pump and \dot{Q}_{loss} (kBtu/hr) is the standby losses calculated from the tank temperature decay, and it can be estimated using

Equation 7.

Equation 7: Standby losses from the tank temperature decay, kBtu/hr.

$$\dot{Q}_{loss} = \frac{m_{water,tank}}{time} \cdot c_p (\overline{T_{tank,final}} - T_a)$$

where

T_a = ambient temperature, °F

The uniform energy factor (UEF) measured the overall efficiency of the water heater according to Equation 8 and Equation 9.

Equation 8: UEF.

$$UEF = \sum_{i=1}^N \frac{M_i c_{p_i} (125 - 58)}{Q_{dm}}$$

where

M_i = mass withdrawn for the i th draw ($i = 1$ to N)

N = total number of draws in the draw pattern

T_{DHW} = domestic hot water temperature, °F

Equation 9: First-hour rating computation.

$$F_{hr} = \sum_{i=1}^n \frac{M_i^*}{\rho}$$

where

M_i^* = mass of water removed during the i th draw of the first-hour rating test, gal

n = number of draws that are completed during the first-hour rating test

The modified daily water heating energy consumption is computed according to Equation 10.

Equation 10: Modified daily water heater energy consumption, kBtu.

$$Q_{dm} = Q_{da} + Q_{HWD}$$

The difference between the daily water heating energy consumption value and the daily water heating energy consumption for 67°F temperature difference is calculated according to Equation 11.

Equation 11: The difference between the daily water heating energy consumption value and the daily water heating energy consumption for 67°F temperature difference, kBtu.

$$Q_{HWD} = Q_{HW,67°F} - Q_{HW}$$

The energy required to heat the water over a 67°F temperature rise is calculated according to Equation 12.

Equation 12: The energy required to heat the water over a 67°F temperature rise, kBtu.

$$Q_{HW,67°F} = \sum_{i=1}^N \frac{M_i c_{p_i} (125 - 58)}{\eta_r}$$

where

M_i = mass withdrawn for the i th draw ($i = 1$ to N), lb

c_{p_i} = the specific heat of water for the i th draw ($i = 1$ to N), kBtu/lb.°F

The energy required to heat the water over a specific draw is calculated according to Equation 13.

Equation 13: The energy required to heat the water over a specific draw, kBtu.

$$Q_{HW} = \sum_{i=1}^N \frac{M_i c_{p_i} (\bar{T}_{del,i} - \bar{T}_{initial,i})}{\eta_r}$$

where

$\bar{T}_{del,i}$ = the average water outlet temperature measured during the i th draw, °F

$\bar{T}_{initial,i}$ = the average water inlet temperature measured during the i th draw, °F

The adjusted daily water heating energy consumption is calculated according to Equation 14.

Equation 14: The adjusted daily water heating energy consumption, kW.

$$Q_{da} = Q_d - (67.5°F - \bar{T}_{a,standby,2}) UA \tau_{standby,2}$$

where

$\bar{T}_{del,i}$ = the ambient temperature during the 24-hour simulated-use test when water is not being withdrawn from the water heater, °F

UA = standby heat loss coefficient of the storage tank

$\tau_{standby,2}$ = the number of hours during the 24-hour simulated-use test when water is not being withdrawn from the water heater

The daily water heating energy consumption is calculated according to Equation 15.

Equation 15: The daily water heating energy consumption, kBtu.

$$Q_d = Q - \frac{V_{st} \rho c_p (\bar{T}_{24} - \bar{T}_o)}{\eta_r}$$

where

V_{st} = the storage capacity of the water heater, ft³

\bar{T}_{24} = mean tank temperature at the end of the 24-hour simulated-use test, °F

\bar{T}_o = mean tank temperature at the beginning of the 24-hour simulated-use test, recorded one minute before the first draw is initiated, °F

The recovery efficiency of the heat pump is calculated according to Equation 16.

Equation 16: The recovery efficiency of the heat pump.

$$\eta_r = \frac{M_1 c_{p1} (\bar{T}_{del,i} - \bar{T}_{initial,i})}{Q_r} + \frac{V_{st} \rho_2 c_{p2} (\bar{T}_{max,1} - \bar{T}_o)}{Q_r}$$

where

M_1 = total mass removed from the start of the 24-hour simulated-use test to the end of the first recovery period, lb

$\bar{T}_{max,1}$ = the maximum mean tank temperature recorded after the first recovery period, °F

Q_r = total energy used by the water heater between cut-out prior to the first draw and cut-out following the first recovery period, including auxiliary energy such as pumps, kBtu

The annual energy consumption is calculated according to Equation 17.

Equation 17: The annual energy consumption, kBtu.

$$E_{annual} = 365 \times \frac{V \cdot \rho \cdot c_p \cdot 67}{UEF}$$

For the emissions testing, the corrected exhaust gas pollutant concentration in 3% oxygen is estimated using Equation 18. A Horiba PG-300 stack gas analyzer was used to measure the CO, CO₂, and NO_x concentration throughout the testing.

Equation 18: Exhaust gas pollutant x measurement corrected at 3% O₂.

$$c_{x_{3\% O_2}} = c_x \cdot \frac{20.9 - 3}{20.9 - O_2\%}$$

where

c_x = exhaust gas pollutant x measurement, ppm

$O_2\%$ = exhaust gas oxygen measurement, %

x = pollutant subscript

Besides the UEF test performed at GTI Energy laboratory, Manufacturer A used another key performance indicator (KPI) to assess the unit's energy efficiency, as shown in Appendix A.

Installation and Commissioning

The Manufacturer A unit was installed at GTI Energy's Water Heaters laboratory and commissioned per the Manufacturer A installation instructions and guidelines per Figure 3

and Figure 4. The Domestic Hot Water (DHW) lab setup consists of 3 valves built and installed to simulate the FHR and 24-hr UEF draw tests. The water heater was equipped with the required sensors and instrumentations to measure its energy efficiency and emissions. The commissioning test includes:

- Heating the tank using the direct firing to ensure temperature stratification can be established without water draws.
- Cooling down the tank to estimate the standby losses and assessing the insulation material used to insulate the tank.

Figure 3: Piping and Instrumentation Diagram (P&ID) for the First Beta prototype.

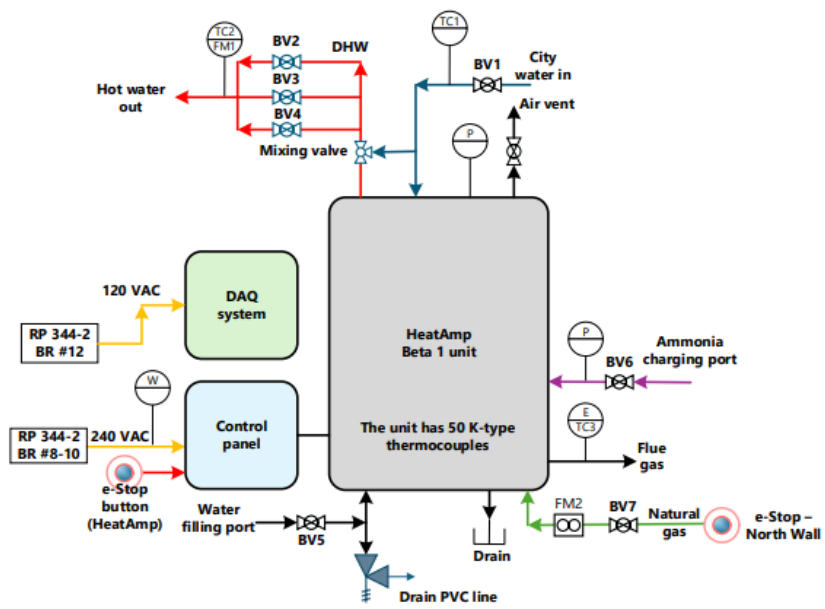


Figure 4: Photo of the First Beta prototype installed at GTI Energy laboratory.



Direct Firing Test

After filling the tank with city water and pressurizing to 34 psi(g) (2.3 bar(g)) per OEM installation guidelines, the firing rate was adjusted to be about 2.5 kBtu/hr (7.25 kW) by controlling the blower speed. Figure 5 plots the buffer tank temperature, while

Figure 6 shows the firing rate during this period. The top tank temperature increased from 74°F (23.6°C) to 133°F (56°C) in about 51 min. The tank temperature stratification was successfully established. It was estimated that the gas energy consumed during this period is about 21.1 kBtu (6.2 kWh), while approximately 60% of this energy was used to heat up the water in the buffer tank. The volume-weighted average approach (Equation 1 and Equation 2) was applied to estimate the increase in the tank temperature and energy added to the water in the buffer tank during the direct firing period.

Figure 5: Temporal tank temperatures during the tank heating using the direct firing mode.

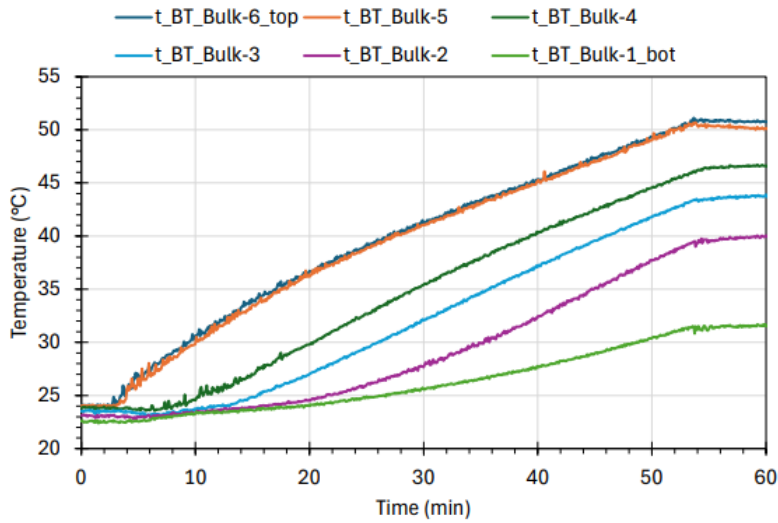
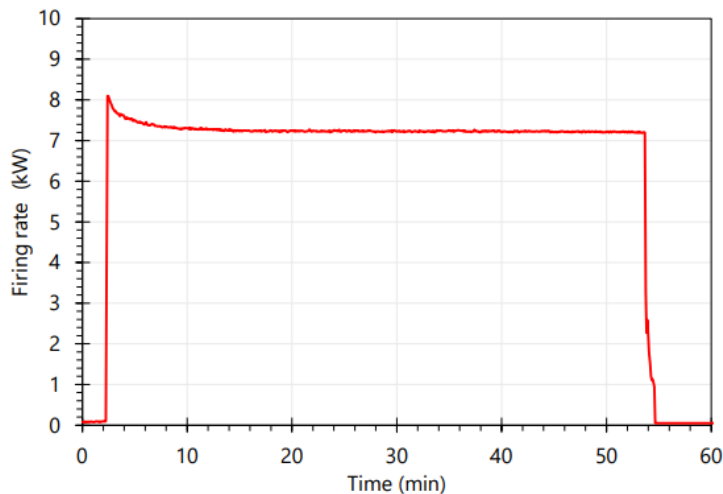


Figure 6: Temporal firing rate profile during the direct firing operation mode.



Buffer Tank Standby Test

Following the heating test, the burner was deactivated, and the temporal evolution of the tank temperatures was recorded over an extended duration, as depicted in Figure 7. A mass-weighted average temperature was subsequently computed and is presented in Figure 8 alongside the ambient temperature. The analysis revealed that the water temperature decreased by approximately 21.6°F (12°C) over the first 24 hours, equating to a cooling rate of 0.9°F (0.5°C) per hour. During this period, the reduction in water energy was measured at roughly 7.1 kBtu (2.09 kWh), and the heat transfer coefficient of the tank was determined to be approximately 5.79 Btu/hr·°F (11 kJ/hr·°C). This comparatively low heat transfer coefficient indicates the effectiveness of the tank's insulation.

Figure 7: Temporal buffer tank temperature profiles during the cooling down test.

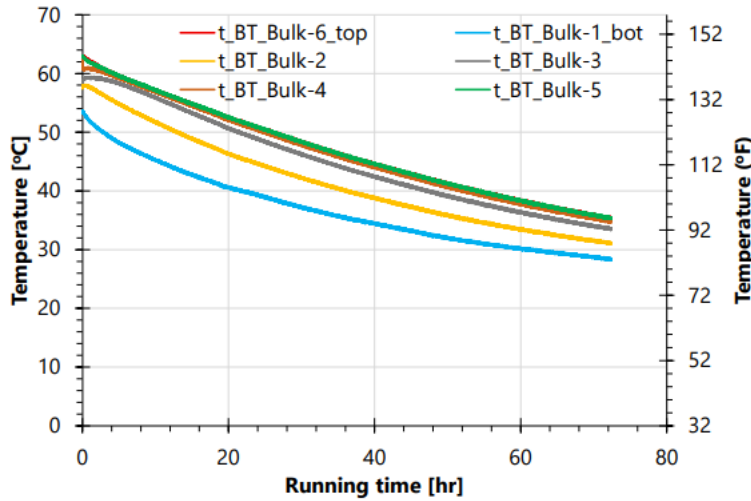
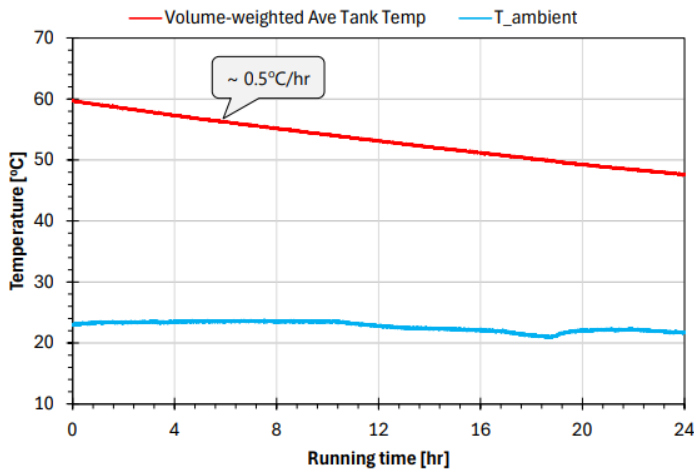


Figure 8: Temporal profiles for the mass-weighted average tank temperature and ambient temperature.



Standard Lab Testing

The DOE Standard Lab Testing for water heaters refers to a set of uniform procedures established by the U.S. DOE to measure the energy efficiency of residential water heaters. These procedures ensure comparability across different brands and models by testing products under consistent, controlled conditions. The purposes are to ensure accurate energy labeling, such as EnergyGuide labels, support ENERGY STAR qualification, enable enforcement of federal minimum energy conservation standards. The FHR and UEF values are the main evaluation parameters extracted from this standard test.

First Hour Rating (FHR) Testing

FHR is a key performance metric for water heaters, especially residential storage water heaters. It measures how much hot water (in gallons) a water heater can supply in the first hour of operation when starting with a fully heated tank. The test was performed by following the following steps:

1. The city water is conditioned to be about 58°F (14.4°C) during the test.
2. Fully heat the water heater at a firing rate of 9.6 kBtu/hr (2.8 kW) to ensure the water heater is fully charged. The setpoint temperature for the tank temperature at level 4 was 143.6°F (62°C).
3. The mixing valve was adjusted to deliver about 125°F (51.7°C) at the beginning of the withdrawal.
4. After 1 hour from the burner turned off, the test started by drawing hot water at a rate of 3 GPM (11.4 LPM), and the maximum discharge temperature was recorded.
5. The draw stopped when the discharge water temperature reached 15°F (8.3°C) less than the maximum temperature.
6. The second draw started after the recovery cycle ended when the tank setpoint temperature reached back to 143.6°F (62°C). Then, the hot water was drawn at the same rate until the discharge water temperature reached 15°F (8.3°C) less than the maximum temperature.
7. The previous step was repeated within the 1st hour, after the amount of delivered water was calculated.
8. The FHR is the amount of water withdrawn from the tank during the 1st hour starting from the beginning of the test.

Figure 9 shows the cumulative withdrawn hot water and the corresponding hot water temperature during the FHR test. About 10.49 and 11.71 gallon (39.7 and 44.2 L) were withdrawn during the 1st and 2nd draw. The duration of the recovery period between the two draws was about 39 min. The FHR value was estimated to be about ~22.2 gallon (84 L) at an average direct firing rate of around 9.5 kBtu/hr (2.8 kW). Table 4 listed information about the two draws performed during the 1st hour. It should be noted that the FHR value will be higher when the burner operates at a higher firing rate. Manufacturer A performed a similar test at their facility at a firing rate of 25 kBtu/hr (7.3 kW) and reported an FHR of 51 gallon (193 L), indicating that the 24-hr simulated UEF testing can be performed using medium draw pattern.

It is important to note that the UEF test was performed in heat pump mode, while the FHR test was conducted in direct firing mode. Although this deviates from the DOE's standard

testing protocol which requires consistency in operating mode across both tests, the team's R&D methodology at this stage involves characterizing system performance under heat pump mode. This approach is intended to inform optimization strategies targeting the medium draw pattern use case.

Figure 9: Withdrawn water and discharge hot water temperature during the FHR test.

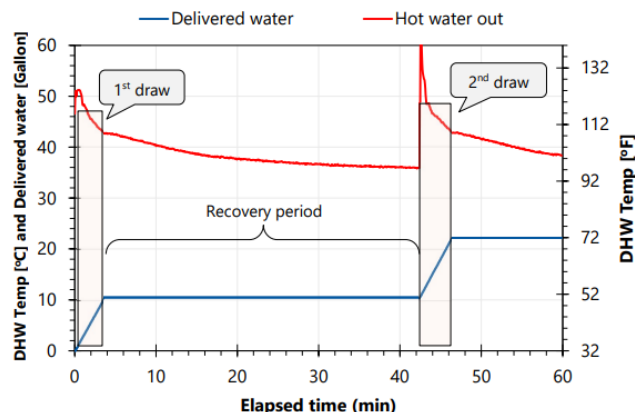


Table 4: Summary of the FHR test.

Draw No.	Collected Water, Gal (L)	Duration (min)	City Water Inlet Temp, °F (°C)	Starting Temp, °F (°C)	Ending Temp, °F (°C)
1	10.49 (39.7)	3.61	58.8 (14.9)	124.2 (51.2)	108.9 (42.7)
2	11.71 (44.3)	3.83	57.9 (14.4)	124.7 (51.5)	109 (42.8)

24-Hour Simulated UEF Testing

The 24-hour simulated UEF testing, which is the U.S. DOE standard method, is used to evaluate the energy efficiency of residential water heaters under realistic daily usage conditions.

While the FHR value was estimated using the direct firing mode, the UEF test was performed using the heat pump mode because it is the main goal of this effort. Based on the FHR value of 51 gallons that was measured at the Manufacturer A facility, the water heater was tested using the medium draw pattern shown in Table 5. The inlet cold water temperature was conditioned to be $58^{\circ}\text{F} \pm 2^{\circ}\text{F}$ ($14.4^{\circ}\text{C} \pm 1.1^{\circ}\text{C}$) during the test. The desorption scheme was selected (see Table 6) based on the Manufacturer A's recommendation. The solenoid valves were adjusted to deliver 1.7 GPM (6.4 LPM) and 1.0 GPM (3.8 LPM) during the test, according to the draw pattern. The amount of delivered hot water, the gas consumption, the ambient temperature, the inlet cold water temperature, and the outlet temperature were recorded during the 24 hours. The test was repeated twice to ensure accuracy, reliability, and reproducibility of results.

Table 5: Medium Usage Draw Pattern for 24-hour simulated UEF testing.

Draw No.	Draw Start Time, hh:mm	Volume, Gal (L)	Flow Rate, GPM (LPM)
1*	0:00	15.0 (56.8)	1.7 (6.4)
2*	0:30	2.0 (7.6)	1.0 (3.8)
3*	1:40	9.0 (34.1)	1.7 (6.4)
4	10:30	9.0 (34.1)	1.7 (6.4)
5	11:30	5.0 (18.9)	1.7 (6.4)
6	12:00	1.0 (3.8)	1.0 (3.8)
7	12:45	1.0 (3.8)	1.0 (3.8)
8	12:50	1.0 (3.8)	1.0 (3.8)
9	16:00	1.0 (3.8)	1.0 (3.8)
10	16:15	2.0 (7.6)	1.0 (3.8)
11	16:45	2.0 (7.6)	1.7 (6.4)
12	17:00	7.0 (26.5)	1.7 (6.4)

*Denotes draws in the first draw cluster.

Table 6: Desorption scheme for the heat pump mode operation.

Schedule	Blower Speed	kBtu/hr (kW)	Min	kBtu (kWh)
Step-1	17	7.68 (2.25)	6	0.768 (0.225)
Step-2	12	5.15 (1.51)	4	0.343 (0.101)
Step-3	11	4.44 (1.30)	4	0.296 (0.087)
Step-4	11	4.44 (1.30)	42	3.11 (0.910)
Total Desorption Energy (kWh)			56	4.51 (1.322)

Figure 10 shows the relationship between the volume-weighted average tank temperature and the firing rate of the burner over 24 hours. The unit successfully operated continuously, and the heat pump (desorption and adsorption phases) repeated 8 times. The average water tank temperature follows a cyclical pattern, rising steeply during firing events (desorption periods) and gradually declining afterward during the adsorption periods. Each peak in temperature occurs just after a firing event, typically reaching around 125.6–132.8°F (52–56°C), while the minimum tank temperature before desorption phase tends to drop to around 111.2–114.8°F (44 – 46°C). The consistent temperature cycles and peak firing rate indicate the system is stable and operating as intended. The burner appears to maintain a good temperature range for domestic hot water supply, avoiding overheating or excessively low temperatures.

Table 7 lists the parameters of each draw and the total energy consumption and total hot water delivered by the unit. Analysis of this data indicated that the 1st Beta Manufacturer A water heater can deliver a total of 28.22 kBtu (8.27 kWh) of hot water by consuming about 36.88 kBtu (10.81 kWh) of natural gas over 24 hours. This means that the energy efficiency of the unit is about 77%.

Figure 10: Temporal profile of the firing rate and average tank temperature during the 24-hour test.

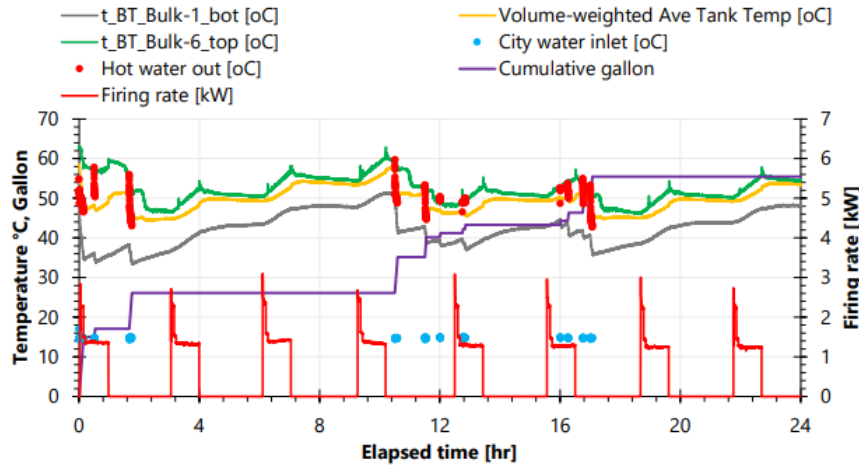


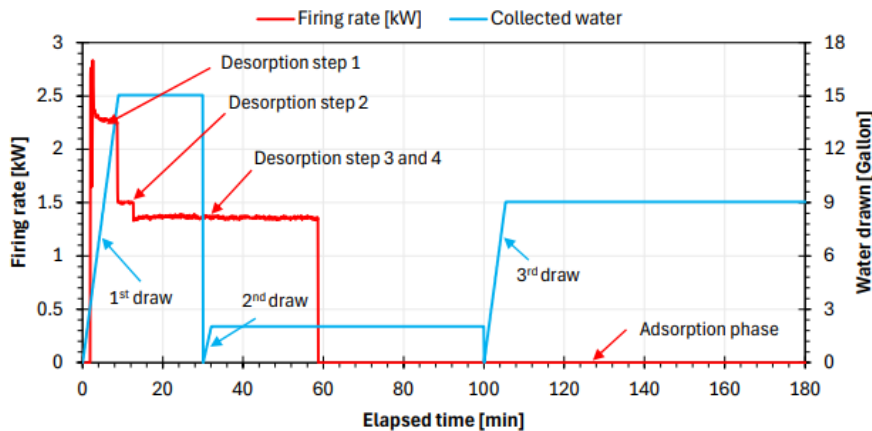
Table 7: Energy consumption and delivered water energy for each draw.

Draw No.	DHW Out, Gal (L)	DHW In, °F (°C)	DHW Out, °F (°C)	Avg. Tank Temp Start, °F (°C)	DHW Out, kBtu (kWh)	Gas In, kBtu (kWh)
1	14.94 (56.55)	58.5 (14.7)	121.3 (49.6)	137.1 (58.4)	7.78 (2.28)	2.56 (0.75)
2	2.01 (7.61)	58.8 (14.9)	126.1 (52.3)	118.9 (48.3)	1.13 (0.33)	2.22 (0.65)
3	9.06 (34.30)	58.8 (14.9)	116.1 (46.7)	123.6 (50.9)	4.31 (1.26)	14.29 (4.19)
4	8.99 (34.03)	58.6 (14.8)	124.0 (51.1)	136.2 (57.9)	4.88 (1.43)	0.00
5	5.05 (19.12)	59.0 (15.0)	118.0 (47.8)	123.3 (50.7)	2.47 (0.72)	0.00
6	1.04 (3.94)	59.9 (15.5)	119.8 (48.8)	116.8 (47.1)	0.52 (0.15)	1.52 (0.45)
7	1.05 (3.97)	59.9 (15.5)	117.9 (47.7)	115.9 (46.6)	0.50 (0.15)	0.38 (0.11)
8	1.00 (3.79)	58.6 (14.8)	121.1 (49.5)	114.8 (46.0)	0.50 (0.15)	4.93 (1.44)
9	1.04 (3.94)	60.1 (15.6)	123.0 (50.5)	122.4 (50.2)	0.54 (0.16)	1.08 (0.32)
10	2.08 (7.87)	59.0 (15.0)	125.1 (51.7)	122.5 (50.3)	1.14 (0.33)	1.10 (0.32)
11	1.94 (7.34)	59.2 (15.1)	126.9 (52.7)	124.3 (51.3)	1.09 (0.32)	0.00
12	7.15 (27.07)	58.6 (14.8)	115.2 (46.2)	121.6 (49.8)	3.35 (0.98)	8.80 (2.58)

Draw No.	DHW Out, Gal (L)	DHW In, °F (°C)	DHW Out, °F (°C)	Avg. Tank Temp Start, °F (°C)	DHW Out, kBtu (kWh)	Gas In, kBtu (kWh)
Total	55.36 (209.5)				28.22 (8.27)	36.9 (10.8)

Figure 11 presents a detailed view of the first three hours of the UEF test, during which the first heat pump cycle and the first draw cluster were completed. The heat pump cycle was initiated when the buffer tank temperature in zone 4 dropped below 140°F (60°C), which was set in the control system. During the desorption phase, steam was generated slightly above 284°F (140°C), corresponding to a tank pressure of 52.2 psi (3.6 bar), to facilitate the regeneration of ammonia from the salt matrix. Reaching this temperature is indicative of a successful desorption process. The desorption phase lasted 52 minutes, followed by a 10-minute reactor cool-down period and an adsorption phase lasting 1 hour and 54 minutes, resulting in a total heat pump cycle duration of 3 hours. Within this cycle, three water draws were conducted, with an average delivery temperature of approximately 122°F (50°C), which complies with standard performance requirements.

Figure 11: Delivered water and firing rate profile during the first three hours of the 24-hour test.



To better understand the heat pump operation mode, the third cycle where no water draw event is plotted in

Figure 12 and Figure 13. This plot presents the detailed thermal and operational behavior of a thermochemical heat pump cycle.

Figure 12 shows the buffer tank temperatures and the firing rate profile to indicate the duration of the desorption and adsorption period. The cycle is divided into three distinct phases: desorption, reactor cool down, and adsorption. The reactor cool-down period and the adsorption period start at the same time. However, the reactor cool-down lasts for 10 min while the adsorption period lasts for 114 min. During the desorption stage, the burner is active, reaching up to about 8.5 kBtu/hr (2.5 kW), indicating burner operation to heat the reactor and enable desorption. As expected, the temperatures of the water in the buffer tank steadily increase during the desorption period while the burner is on. Importantly, the water temperature at the bottom of the buffer tank reached around 118.4°F (48°C) at the end of the desorption period. This value is relatively high to facilitate the adsorption process and continuously lift thermal energy from the ambient during this period.

Figure 12: Temporal profile of the buffer tank temperatures and firing rate for the third cycle during the standby period and no water draw.

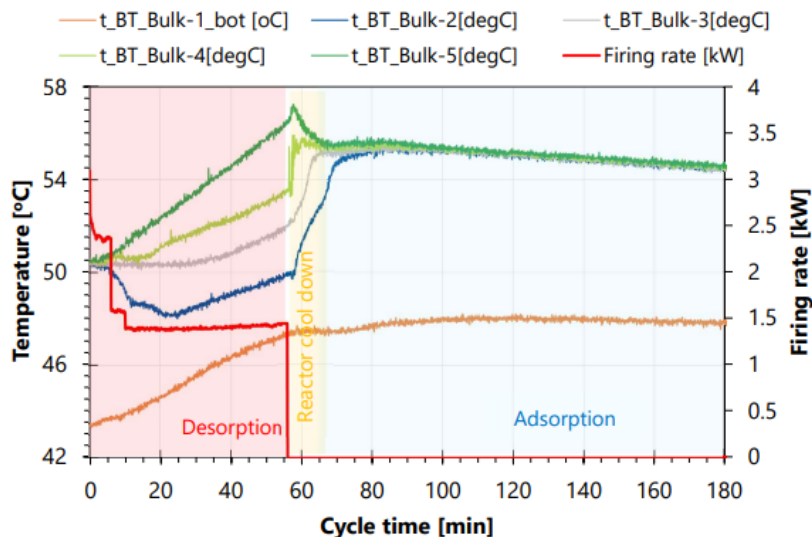


Figure 13 shows the volume-weighted average tank temperature and firing rate as a function of cycle time. The average tank temperature rises from approximately 120.2°F (49°C) to just over 127.4°F (53°C), indicating heat transfer (heat of condensation) from the desorption process to the tank. This corresponds to the actual energy gained by the water in the buffer tank of about 2.66 kBtu (0.78 kWh). This indicates energy efficiency during the desorption phase of roughly 59%, based on the ratio of recovered energy to the input energy [2.66 kBtu (0.78 kWh) out of 4.5 kBtu (1.32 kWh)]. After the end of the desorption phase, the reactor cool-down phase and the adsorption phase start together. For the

reactor cool down period (~56–66 minutes), the burner turns off and the tank temperature continues to rise slightly, indicating residual heat transfer from the reactor to the tank and also the adsorption process. During the adsorption phase (~56–180 minutes), the burner remains off, and the system continues the adsorption phase. The tank temperature initially peaks just above 129.2°F (54°C), then gradually declines at a rate of approximately 0.9°F/hr (0.5°C/hour), as annotated in the plot. The same rate was observed during the standby period (see Figure 8), indicating that the heat pump is not able to lift enough thermal energy from the ambient environment to exceed the standby losses which is in the same order of magnitude of the commercially available gas storage water heaters. It should be mentioned that the same behavior was observed in the other seven heat pump cycles. The main reason behind this trend is that the bottom zone of the tank was measured to be about 118.4°F (48°C) at the beginning of the adsorption process. This relatively high hot water temperature is not suitable to facilitate the adsorption process for a long period, preventing the reactor from efficiently lifting thermal energy from the ambient environment.

Figure 13: Temporal profile of the volume-weighted average tank temperature and firing rate for the third cycle during the standby period and no water draw.

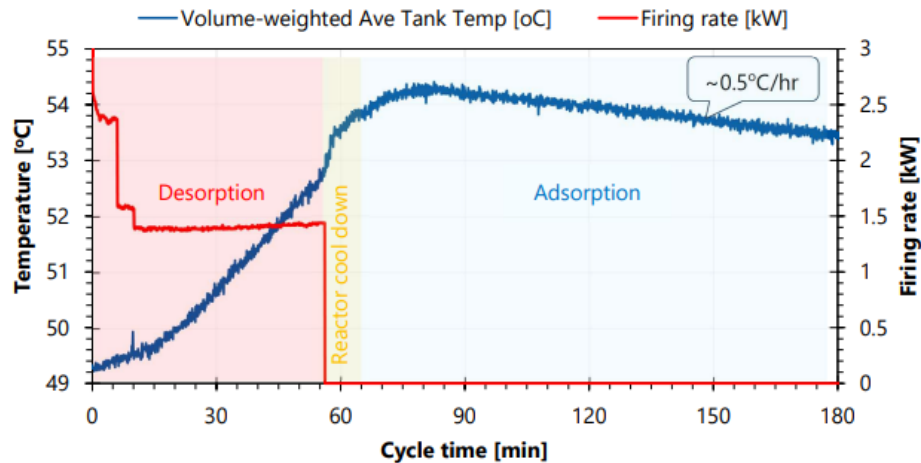


Figure 14 presents the ammonia and ambient temperature for one heat pump cycle. After the desorption (regeneration) process, the ammonia is regenerated and condensed in the ammonia receiver. At the beginning of the adsorption process, the salt matrix has the capacity to adsorb ammonia from the receiver, and this is indicated by the sharp decrease in the ammonia temperature. Interestingly, the ammonia temperature went below the ambient temperature and started to increase afterward. This process slowed down after a short period of time, because the water temperature in the bottom layer of the tank is not low enough to facilitate more ammonia to be adsorbed by the reactor. This trend is consistent with the buffer tank temperatures as well.

Figure 14: Temporal profile of the ammonia and ambient temperature for the third cycle during the standby period and no water draw.

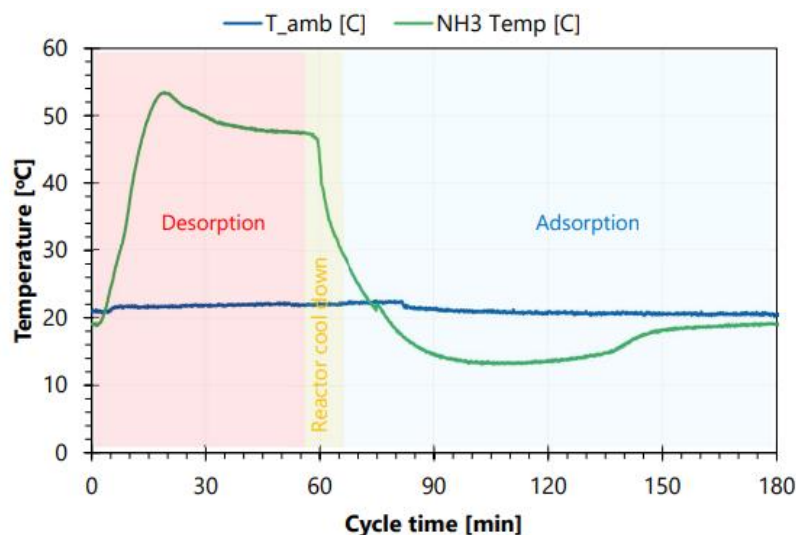


Table 8 summarizes the key parameters derived from the measurements collected during the 24-hour simulated UEF test. Over this period, the water heater delivered approximately 55.36 gallons (209.5 L) of hot water, aligning with the expected performance, at an average delivery temperature of 121.28°F (49.6°C), thereby meeting the standard requirements. The tank's standby heat loss coefficient was estimated at 7.14 Btu/hr·°F (13.5 kJ/hr·°C), indicating relatively low thermal losses during standby periods. The recovery efficiency and UEF were calculated to be approximately 68.9% and 0.68, respectively. These relatively low energy efficiency values are primarily attributed to suboptimal operation of the heat pump mode, which is a result of inadequate tank temperature stratification.

The coefficient of performance (COP) is also estimated to be about 0.77. The COP is defined as the ratio between the energy delivered by the unit and the fuel consumption during the test. It does not consider the difference between the initial and final tank temperature, and this is the reason why it is higher than the UEF value.

Table 8: Estimated parameters from the 24-hour UEF testing.

Parameter	Value
Initial Average Tank Temperature	136.8°F (58.2°C)
Final Average Tank Temperature	127.4°F (53.0°C)
Average Ambient Temperature	70.1°F (21.2°C)
Average Discharge Water Temperature	121.3°F (49.6°C)
Average Inlet Temperature	59°F (15°C)
Total Gallon Delivered	55.36 gallons
UA	7.14 Btu/hr.-°F (13.5 kJ/hr.-°C)

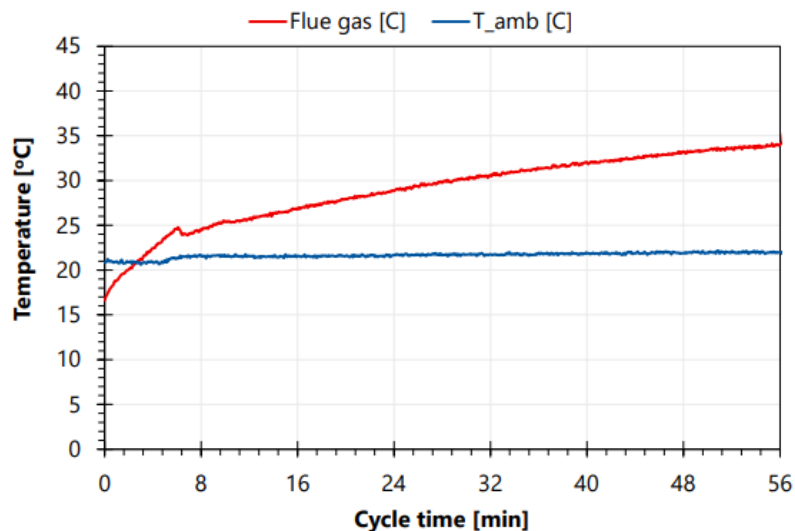
Parameter	Value
Recovery Efficiency	68.9%
UEF	0.68

Emission Test

The temperature of the flue gases was recorded during the 24-hour test.

Figure 15 plots the flue gas temperature during one heat pump cycle. The flue gases temperature steadily increases during the desorption period and reaches about 95°F (35°C), which is less than the dew point (typically 130–135°F), indicating the flue gas condensation is occurring.

Figure 15: Temporal profile of the flue gas and ambient temperature for the third cycle during the standby period and no water draw.



Flue Gas Analyzer (Horiba PG-300) was used to measuring emissions from a water heater's flue gas during the desorption periods when the burner is on. Figure 16 illustrates the corrected emissions (per Equation 18) data from the Manufacturer A water heater over a 180-minute period (i.e., one cycle), showing concentrations of NO_x (in ppm), CO (in ppm), and CO_2 (in %). At the start of the desorption period, there was a sharp spike in NO_x , reaching about 1.8 ppm, which is typical during burner ignition due to high flame temperatures. NO_x reduced as the firing rate reduced for the desorption step 2, 3, and 4. NO_x stabilized between 1.3–1.5 ppm when the firing rate was about 4.4 kBtu/h (1.3 kW) and dropped to zero during the adsorption period. CO levels showed a peak near 45 ppm at ignition but remain consistently low (around 1.3–1.5 ppm) during operation, indicating efficient combustion and minimal carbon monoxide production. CO_2 concentration rises quickly to about 14.5% at burner start-up and remains steady during the desorption phase

(around 10.4%), then drops to zero when the burner shuts off. Overall, the emissions profile suggests that the water heater operates with high combustion efficiency, exhibiting low CO and moderate, well-controlled NO_x emissions across well-defined heating cycles.

While the U.S. EPA does not directly regulate NO_x from residential water heaters, SCAQMD Rule 1121 regulates NO_x emissions from residential-type, natural gas-fired water heaters within the South Coast Air Basin, encompassing Los Angeles, Orange, Riverside, and San Bernardino counties [5]. The NO_x emission limit is 10 nanograms per joule of heat output or 15 ppmv at 3% O₂, dry. Per ASHRAE and appliance standards, the target CO emissions from gas appliances should be less than 400 ppm and the practice for safe combustion is less than 100 ppm. Table 9 lists the emissions parameters of the Manufacturer A water heater. It was found that the NO_x is less than 0.9 ng/J and the CO is less than 1.5 PPM, indicating that the new burner used in the First Beta meets the SCAQMD and ASHRAE safety standards.

Figure 16: Temporal profiles of the corrected emissions during one cycle of heat pump.

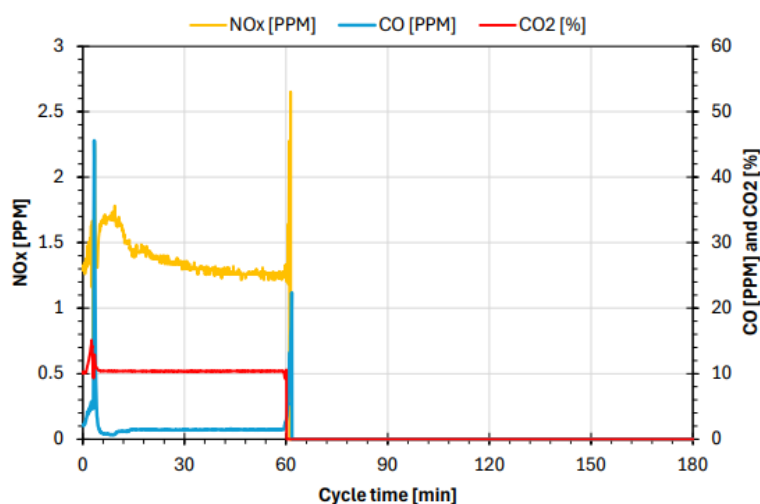


Table 9: Corrected data of the emissions test.

Firing Rate, kW	Average Emissions			
	NO _x , ppm	NO _x , ng/J	CO, ppm	CO ₂ , %
2.25	1.680	0.89	0.765	10.386
1.51	1.680	0.88	1.044	10.387
1.30	1.298	0.69	1.428	10.373

Observations and Recommendations

The analysis of the measured data revealed two key issues that prevented the First Beta prototype from achieving higher energy efficiency:

1. The energy efficiency during the desorption period is about 46%, which is relatively low.
2. The unit was not able to lift a high amount of thermal energy from the ambient environment during the adsorption phase due to the inadequate temperature stratification in the tank. Specifically, the temperature of water used to facilitate the adsorption process was relatively high (more than 113°F (45°C)).

The evaluation of the First Beta prototype identified several critical areas for improvement in both design and system controls necessary to achieve UEF greater than 1.0 under medium draw pattern. The foremost priority for subsequent prototypes is the optimization of reactor design and performance, specifically focusing on the ammonia charge, heat exchanger configuration, and salt matrix quantity. Manufacturer A will increase the salt matrix in Beta 2 version by 20%. This might enhance the adsorption process if the heat exchanger is able to cool the reactor during this period. This is also related to the temperature stratification in the tank. It should be ensured that the bottom layer of tank has a temperature of less than 104°F (40°C), and the less the better, to be able to facilitate the adsorption process and ensure the salt continuously adsorbs ammonia vapor. Additionally, ensuring the structural integrity and robustness of key components within the combustion system and heat transfer loop is essential to prevent leaks of natural gas and flue gas. Such leaks not only pose significant safety risks but also severely compromise overall unit efficiency. To mitigate these risks and avoid costly material and labor demands associated with leak detection and repair, materials such as stainless steel and cast iron can be used and also Manufacturer A must verify the leak-tightness of all critical components prior to laboratory and field testing.

Another critical issue that must be addressed to obtain $UEF > 1.0$ is sub-system optimization. For example, it was found that the energy added to the water in the buffer tank is about 46% of the gas consumption during the desorption process, and the remainder was wasted mainly due to the high thermal mass of the components. Therefore, the steam loop and interior metal compared to the tank size should be reduced using lighter material. Another key to achieving $UEF > 1.0$ is revisiting the evaporator design to ensure efficient heat transfer from the ambient environment to the tank. Proper adjustments should be made to the burner-boiler ammonia receiver to reduce heat losses and thermal mass.

Technoeconomic Analysis

In the preceding section, an engineering development pathway was developed to aim at achieving a UEF value greater than 1.0. Advancing the Manufacturer A water heater to reach a target UEF of 1.1, for example, is projected to have a substantial influence on the residential water heating market by setting a new benchmark for energy performance.

In this section, a technoeconomic analysis was conducted to estimate the potential energy savings and corresponding emissions reductions resulting from the successful development and deployment of the Second Beta prototype of the Manufacturer A water heater, designed to meet a target UEF of 1.1.

The analysis employed the BEopt (Building Energy Optimization Tool) software, developed by the National Renewable Energy Laboratory (NREL). BEopt is a modeling tool used to simulate residential building energy performance. It allows for detailed evaluation of appliance-level impacts and supports the identification of cost-optimal efficiency strategies at varying levels of whole-building energy savings, including pathways toward zero net energy homes.

The simulation assumed a typical single-family residential building with four occupants, and domestic hot water demand was modeled across Los Angeles and San Francisco, CA, representing hot and dry climate. BEopt calculated hot water usage profiles specific to each city per

Figure 17 and Figure 18, while also accounting for local utility rates. The average state natural gas rate in California is about \$1.3635/therm. A monthly fixed service charge of \$12 was applied to the two locations. Marginal and average gas costs were derived from the latest U.S. Energy Information Administration (EIA) data incorporated into BEopt. Annual hot water draw profiles for each city are illustrated in the following figures. While the draw patterns are broadly consistent across locations, peak demand levels vary by climate zone, influencing the performance impact and savings potential.

Figure 17: Delivered hot water in Los Angeles, CA.

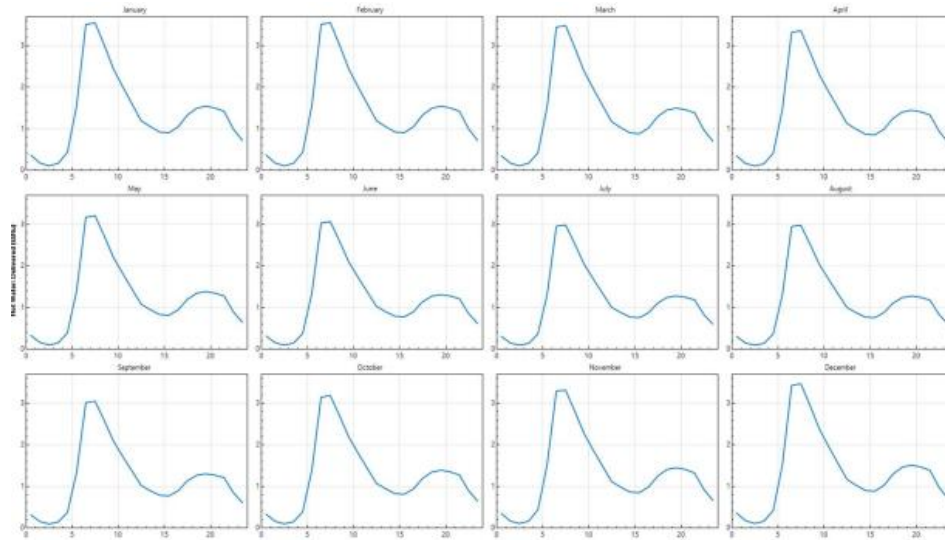


Figure 18: Delivered hot water in San Francisco, CA.

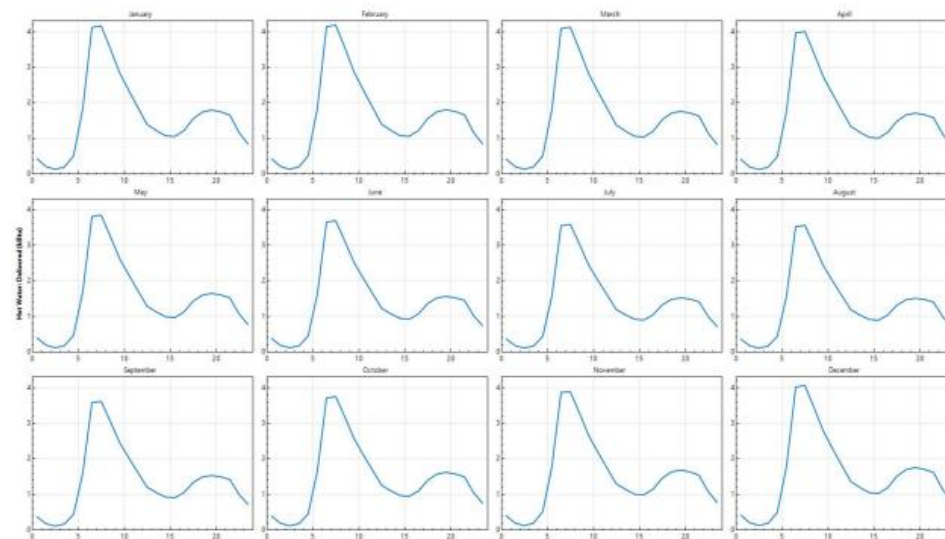
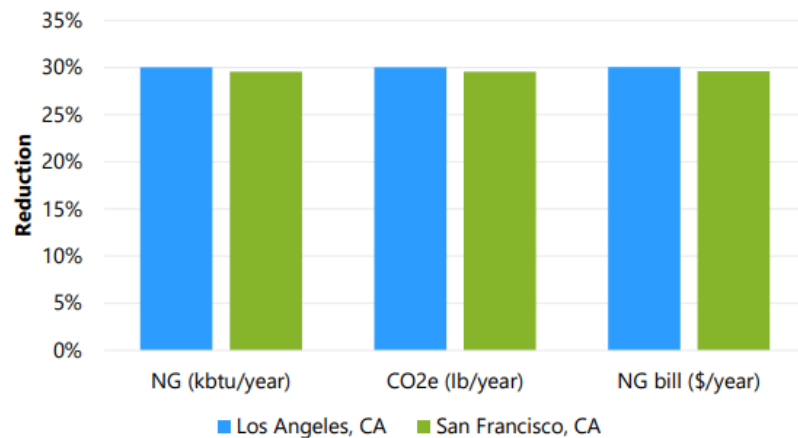


Figure 19 estimates the reduction in gas consumption, CO₂e emissions (Carbon Dioxide equivalent), and utility bills that would result from further advancing the Manufacturer A water heater to achieve a UEF of 1.1 in the 2nd Beta prototype. Los Angeles and San Francisco have a hot water load of 11,035 and 13,017 kBtu/year, respectively. This trend is mainly because the ambient temperature over the year is higher in Los Angeles (e.g., average annual ambient temperature in San Francisco and Los Angeles is 55.4°F and 62.3°F, respectively). The bar chart shown in Figure 19 illustrates the percentage improvement (reduction) achieved by advancing the Manufacturer A water heater to achieve a UEF of 1.1, compared to a gas water heater with a UEF of 0.66. The improvements are measured across three categories: natural gas usage (NG, in kBtu/year), carbon dioxide equivalent emissions (CO₂e, in lb/year), and natural gas bills (in \$/year), for the two cities. The

improvement percentages are nearly identical across the three categories for each city, implying a linear relationship between natural gas savings, emission reductions, and cost savings. Los Angeles, CA showed slightly better improvements due to the lower hot water load. The two cities show an improvement of just around 30% in all three categories, indicating a substantial efficiency gain from switching to the higher-efficiency Manufacturer A water heater. This supports the case for advancing Manufacturer A water heater technology as a cost-effective and environmentally friendly investment.

Figure 19: Technoeconomic potential of Manufacturer A unit after achieving UEF of 1.1.



Conclusions and Recommendations

The AHPWH is a promising unit that uses the adsorption phenomena to lift thermal energy from the ambient to buffer tank, aiming to achieve a COP of more than 1.0. Achieving this relatively high energy efficiency aligns with federal initiatives and California's decarbonization strategies.

The test plan of the first Beta unit was developed followed by commissioning of the water heater. The FHR and the 24-hour simulated UEF were evaluated under a medium draw pattern. The FHR was measured at approximately 22.2 gallons using the direct firing mode at a firing rate of 9.6 kBtu/hr (2.8 kW) (the fuel has a HHV of 1050 Btu/cF). This value is expected to increase at higher firing rates. However, to avoid potential damage due to suboptimal burner quality, the unit was not operated at its full capacity which is approximately 27.3 kBtu/hr (8.0 kW). In comparison, Manufacturer A conducted similar tests at a firing rate of 25 kBtu/hr (7.3 kW) and reported an FHR of about 51 gallons.

Based on these results, testing proceeded with the medium draw pattern. The experimental data indicated a UEF of approximately 0.68 and a recovery efficiency of around 69%. It is important to note that the FHR was determined using the direct firing mode, while the UEF was measured using the heat pump mode. Although this approach deviates from DOE guidelines, which require both tests to be conducted under the same operating conditions,

it is considered acceptable at this early stage of research and development. Additionally, the unit is specifically designed to meet the performance requirements of the medium draw pattern.

A detailed analysis of the experimental data was conducted to investigate the causes of the low UEF value. It was determined that only about 60% of the energy input (i.e., gas consumption) was effectively transferred to the water in the buffer tank during the desorption phase. At the beginning of the adsorption period, it was observed that the ammonia temperature in the receiver decreased and went below the ambient temperature, indicating the adsorption process is taking place. At the same time, the average tank temperature decreased with the same rate of standby losses. This trend indicates that the energy lifted by the heat pump is quite low and does not exceed the standby losses and the energy that goes to the metal inside the tank. So, the reactor was unable to lift a good amount of thermal energy from the ambient environment due to the relatively high temperature (more than 113°F (45°C)) of the tank water used to cool the reactor during the adsorption process. These findings underscore the need for improved reactor design and better temperature stratification within the buffer tank to maintain the bottom layer (zone) in the tank at low temperature (less than 104°F (40°C) and the lower the better) to facilitate the adsorption process. The appropriate material selection and thickness of insulation is required to minimize standby losses while also considering cost and manufacturability. Additionally, the evaporator design should be revised to ensure efficient heat transfer during the adsorption process. Another critical issue identified for the first beta prototype is the structural integrity of key components in the combustion system and heat transfer loop. To prevent leakage of natural gas and flue gases, which poses significant safety risks and can severely degrade system performance, robust construction is essential. Manufacturer A must ensure all critical components are leak-proof before proceeding with laboratory or field testing to avoid costly and time-consuming troubleshooting.

Manufacturer A provided additional information on design changes and in-house unit testing for the first and second beta units. The GET program did not independently confirm these changes or the test data, but the trends from the first beta to the second beta unit shows an improvement in overall COP performance.

Resolving these major issues has the potential to raise the UEF above 1.0 in the second beta prototype. Achieving this level of performance would significantly reduce energy use and carbon emissions. Technoeconomic analysis suggested that a UEF of 1.1 could result in approximately a 30% reduction in natural gas consumption, CO₂e emissions, and utility costs in California.

Appendix A: Manufacturer A Testing – First and Second Beta Prototypes

This is information provided by Manufacturer A without input from GTI Energy. The GET program did not independently confirm this.

Besides the UEF test performed at GTI Energy laboratory, Manufacturer A used another key performance indicator (KPI) to assess the unit's energy efficiency. This parameter was named as a gas-COP which evaluates the function and performance of the heat pump (the core sorption technology). While the UEF accounts for water delivery at a specific temperature and flow rate, tank thermal standby losses, and recovery efficiency, gas-COP is assessed as to how effective the burner-boiler and reactor heat up the buffer tank. Therefore, the gas-COP is defined as the heat delivered by the heat pump to the buffer tank divided by gas fuel input according to **Error! Reference source not found.**

Equation 19: Gas-COP.

$$COP_{gas} = \frac{Q_{delivered\ by\ heat\ pump}}{Q_{fuel\ input}}$$

Heat delivered by the heat pump system is represented by:

1. Delivered DHW.
2. Standby losses (energy used to keep the buffer tank ready to deliver) and
3. The net change in stored energy during the course of the test in the buffer tank (positive when energy is added, negative when heat is removed).

The gas-COP, therefore, accounts for the boiler-burner efficiency, the heat pump module COP as well as the efficiency with which heat is recovered from the flue gas, but it does not account for tank insulation performance. This is important, as Manufacturer A currently lacks the capability to incorporate high-performance foam insulation during the equipment prototyping phase.

The First Beta prototype was pre-tested by Manufacturer A between August and November 2024, prior to being sent to GTI Energy for the testing outlined in the main body of this report.

The Second Beta prototype was tested by Manufacturer A between April and June 2025 following the first Beta testing conducted at GTI Energy.

This section summarizes the results from Manufacturer A's First and Second Beta testing focusing on the performance of the heat pump (the core sorption technology) and a comparison and comments to the results from testing at GTI Energy.

First Beta Prototype Testing Results and Discussion

Baseline Heat Pump Cycling

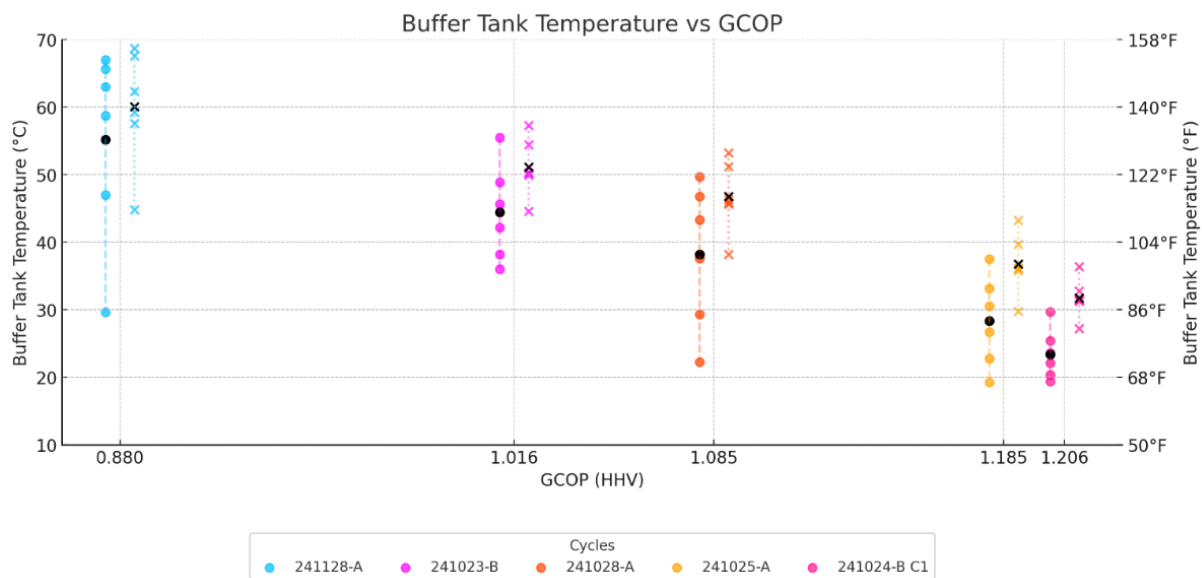
The prototype was tested at varying buffer tank temperatures and stratification levels to gain a deeper system understanding. According to the gas-COP **Error! Reference source not found.**, the baseline heat pump cycling showed gas-COP values ranged from 0.88 to 1.20 depending on the buffer tank temperature profiles.

These results suggest promising improvements compared to the earlier prototypes, but further enhancements are still needed especially at higher tank temperature profiles. To optimize DHW delivery and system efficiency, maintaining a proper buffer tank stratification with adequate temperatures at both the top and bottom of the buffer tank is essential.

The gas-COP decreased as the buffer tank temperature increased especially as temperatures in the bottom part of the buffer tank increased. As a result, during consecutive cycles over a 24-hour test as shown in Figure 10, the gradually increasing buffer tank temperatures led to a gradual reduction in each cycle’s gas-COP.

Separate from the 24-hour test, Figure 20 illustrates how the buffer tank stratification changes over a cycle and how the cycle gas-COP is influenced by the buffer tank temperature level. For each test, the six temperature measurement points on the buffer tank are plotted at both the start and the end of the cycle. Additionally, the average buffer tank temperature at the start (●) and end of the cycle (x) are shown.

Figure 20: Buffer tank temperature profile as a function of the gas-COP.*



*The data presented does not include water draws.

FHR Testing

During the FHR testing, buffer tank recovery was achieved through direct firing for maximized capacity. A mixing valve is also utilized during this testing to prevent the delivered DHW temperature from exceeding the maximum safe delivery level.

The preparatory FHR test involved water draws of 3 GPM (11.3 L/min) during the one hour stopping when the delivery temperature dropped below ~115°F (46°C). The first draw began at a buffer tank temperature (t_BT__Bulk-5) of ~145°F (63°C) and each subsequent draw started when t_BT_Bulk-5 reached ~144°F (62°C). This FHR test resulted in a 51 gallon total draw. This result aligns well with the maximum output of 25 kBtu/hr (7.4 kW) achieved by the prototype burner and corresponds to the 51 gallons lower limit of medium draw pattern standard.

The First Beta prototype was then tested at GTI Energy primarily to evaluate the performance during a 24-hour UEF test.

The results presented by GTI Energy generally showed lower efficiencies than those reported by Manufacturer A, due to the following reasons:

- While GTI Energy evaluated the system performance using the standard DOE FHR and UEF test, Manufacturer A assessed the effectiveness of adding and storing heat to the buffer tank without delivering water. Thus, these are two different approaches to evaluate the system's energy efficiency.
- Manufacturer A approach assessed one heat pump cycle. The UEF test evaluated the heat pump cycling efficiency, which is more challenging for the heat pump at this early stage of research and development.
- Manufacturer A estimated a gas-COP of about 1.2 when the average buffer tank temperature was around 86°F (30°C). To comply with the UEF test, the buffer tank (at least the top portion of it) should be maintained at more than 125°F to be able to deliver a domestic hot water at 120–125°F.
- While GTI Energy used proper insulation and the measured standby losses were comparable to the commercially available water heater, the tank insulation could be further improved.

First Beta Prototype Key Findings and Conclusions

The testing at GTI Energy provided valuable experience and insights, particularly in following areas:

- Evaluation of key parameters impacting system efficiency
- Design for burner robustness

- Verification of the control system and identification of areas for improvement
- Verification and consolidation of prototype documentation
- Verification and refinement of commissioning procedures

The following concept design conclusions were drawn from the First Beta testing and were addressed in the Second Beta prototype and its subsequent testing.

DHW Delivery Capacity (optimization for a medium draw pattern–category product)

- Buffer tank–water volume was increased.
- The vertical temperature profile of the buffer tank was improved to store more energy.
- DHW–coil length was enlarged.

Heat Pumping Efficiency and Stratification Management

- Burner–boiler adjustments were made to reduce heat loss and thermal mass.
- Reactor size was slightly increased for reduced cyclic losses.
- Reactor thermal mass was reduced for reduced cyclic losses.
- Receiver was redesigned to reduce thermal mass and cyclic losses.
- Reactor cooling loop port levels were adjusted for improved stratification.
- Stratification barrier was re–designed for improved stratification.

Direct–Firing Capacity and Stratification Management

- Burner output was increased.
- Stratification barrier to be adjusted for improved stratification.

System Robustness

- Burner redesign (i.e., material updates) for improved robustness.

Second Beta Prototype Design Updates

A Second Beta unit was developed and tested by Manufacturer A. The testing of the Second Beta prototype follows the testing of the First Beta prototype which was performed at GTI Energy and is discussed in this report. The testing of the Second Beta prototype, performed by Manufacturer A, is in alignment with the testing discussed in this report and is built on learnings from the previous work with the First Beta prototype.

The GET program has not independently confirmed these design changes.

The following adjustments were made to the Second Beta prototype that was commissioned for testing at the Manufacturer A facility.

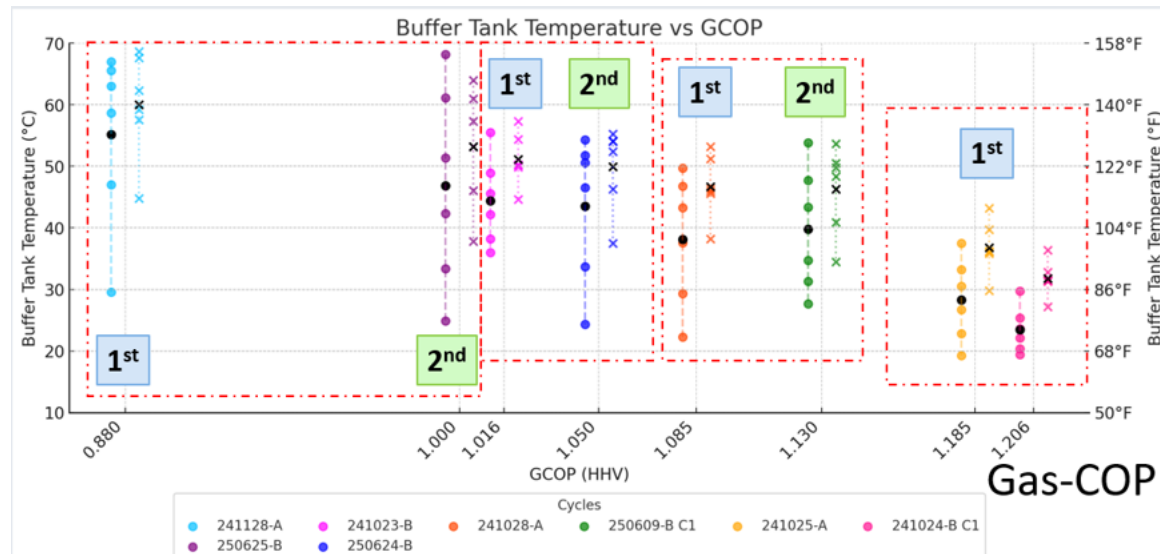
- Buffer tank & DHW-coil adjustments: enlarged (~18%) to achieve DHW-delivery at lower average buffer tank-temperatures, thereby, reducing HP cycling losses.
- Stratification adjustments: kept the buffer tank-1 bottom zone temperature low enough to ensure full flue gas condensation during consecutive HP-cycling and direct-firing.
- Reactor adjustments - salt amount increased (~19%) to reduce HP cycling losses.
- Receiver redesign - lowered thermal weight (~50%) to reduce HP cycling losses.
- Boiler adjustments - boiler coil shortened (10%) to lower the thermal weight to reduce HP cycling losses.
- Further cycle optimization (desorption power scheme, etc.).
- General design review for increased robustness.

Second Beta Prototype Testing Results and Discussion

With the design updates, significant progress was made in both the functionality and performance. The GET program has not independently confirmed the validity of these test results.

During the direct-firing test, the maximum power output achieved by the prototype burner with the current gas train was 28 kBtu/hr (8.3 kW). The preliminary estimated product target is 34 kBtu/hr (10 kW); the performance of this metric will be addressed in future prototypes. Note that the condensing efficiency during the direct-firing test resulted in a COP of 0.96.

Figure 21 presents a comparison of the First and Second Beta prototype testing. The baseline heat pump cycling showed gas COP values ranging between 1.00 to 1.13. The range is primarily attributed to variations in the buffer tank temperature profiles.

Figure 21: Comparison of First and Second Beta prototype gas COP.*

*The data presented does not include water draws.

Instead of conducting the full 24-hour simulated UEF test, individual draw clusters and their subsequent recovery periods were tested separately since the lab and prototype setups were not prepared for a 24-hour unattended operation. Preparations for the full 24-hour UEF testing are on-going.

During the most demanding first draw cluster using the medium draw pattern, the delivered DHW temperatures remained above the specified minimum values [6] when starting from an average buffer tank temperature of 127.2°F (52.9°C).

The gas COP was recorded at slightly above 1.0. During subsequent cycles, a slight drop in COP occurred due to the temperature increase in the bottom zone of the buffer tank.

The first hour rating test resulted in a total draw of 57 gallons, which falls within the medium draw pattern range.

This result aligns well with the maximum output of 25 kBtu/hr (7.4 kW) achieved by the Second Beta prototype.

Second Beta Prototype Key Findings and Conclusions

Several concept modifications were identified to address challenges in next prototype iteration. Main challenges include:

- HP cycling requires further conceptual refinements and optimization to achieve target efficiency.
- The burner-boiler robustness must be improved to avoid flue gas leakage.

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- [6] Code of Federal Regulations, Appendix E to Subpart B of Part 430—Uniform Test Method for Measuring the Energy Consumption of Water Heaters. [eCFR :: Appendix E to Subpart B of Part 430, Title 10 -- Uniform Test Method for Measuring the Energy Consumption of Water Heaters](#)