CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Demonstration of Water Recovery from Hot, Humid, Industrial Exhaust Gases

October 2024 | CEC-500-2024-099

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Agreement Number: PIR-15-013

ACKNOWLEDGEMENTS

The authors thank the California Energy Commission and the Utilization Technology Development program for their support of this project to demonstrate efficient water recovery from hot, humid industrial exhaust gases. The authors also thank Steve Richmond, Serguei Zelepouga, James Clark, and the team at United States Gypsum Corporation for their generous and constant efforts to bring this technology into the industrial workplace. Being the first site to demonstrate a new technology requires foresight, motivation, and a willingness to take on additional work. The United States Gypsum team has been an excellent demonstration site with highly professional manufacturing site support. Michael Sams of AMSEnergy, Olexiy Buyadgie of Wilson Engineering, and Jonathan Maya are also thanked for their diligent efforts to design, model, and build the demonstration unit. And, finally, the authors thank the staff of the United States Gypsum Plaster City, California, facility for their project support.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

This is the final report for the *Demonstration of Water Recovery from Hot, Humid Industrial Exhaust Gases* project (PIR-15-013) conducted by the Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project included the detailed industrial design and thermal and heat transfer modeling of a thermal ejector-based system to recover water from hot, humid exhaust gases generated in industrial facilities. The project focused on modeling, designing, and fabricating a skid-mounted system to recover 100 gallons of water per hour from exhaust gas vented from a United States Gypsum Corporation wallboard plant in Plaster City, California. The skid processes a small portion of the exhaust gas from the stack, and returns the cooled, drier, processed exhaust gas to the stack.

Baseline measurements on the demonstration plant stack have been matched with the demonstration unit design and equipment. Demonstration testing was carried out over a six-month period. The team collected operational data and then added that data with analyses to this Final Report. The demonstration unit is designed to optimize performance over the full range of ambient air temperatures. Five operating regimes have been identified, and the controls of the fans and heat exchangers are set to work in these various regimes. Details of the five regimes are presented in this report. This approach allowed the project team to optimize system performance and minimize power required per gallon of water recovered.

This Final Report includes the *Measurement and Verification* report from subcontractor Tetra Tech. A *Technology Transfer Plan* is also included to provide information on the path toward commercialization of the demonstration water recovery technology.

Keywords: water recovery, exhaust gas, humid gas, high water content, hot exhaust gas, water and hydrocarbon recovery

Please use the following citation for this report:

Rue, David, Sandeep Alavandi, and John Wagner. 2024. *Demonstration of Water Recovery from Hot, Humid Exhaust Gases*. California Energy Commission. Publication Number: CEC-500-2024-099.

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Introduction

Water is becoming an increasingly valuable and expensive resource. The cost of water has been rising at an average rate of 6 percent a year nationwide for several decades. That trend is expected to continue and to escalate. Water costs in California can already be as high as $10 to $20 per thousand gallons. The technology demonstrated in this project has been found to recover water at under $5 per thousand gallons at 73 degrees Fahrenheit (°F) (23 degrees Celsius, °C) and under $1 per thousand gallons at 60°F (16°C) or below. Specifically, this project recovers water from industrial combustion point sources producing exhaust gases with high water concentrations. Good candidate processes include drying, agricultural, and commercial cooking operations. Hundreds of facilities in California are excellent candidates for deployment of this technology. Saving even modest amounts of water will help ease the burden on scarce water resources while saving money for industrial facility operators.

Project Purpose

This project demonstrated cost–effective water recovery from hot, humid industrial exhaust gases as an added benefit from natural gas combustion. The demonstration will be conducted by a team of experts in industrial heat transfer and in design of the thermally driven ejector-based technology for water recovery. United States Gypsum Corporation (USG) in Plaster City, California, served as host site. The goal was to design, fabricate, and demonstrate the modular Clean Liquid Water by Ejector-Assisted Recovery (CLEAR) water recovery technology and to confirm a payback period of less than four years.

Project Approach

The demonstration unit has been modeled, designed, and built. The demonstration was delayed because the pandemic prevented movement, installation, and commissioning of the demonstration unit. The project team recognized that it had not acquired the necessary data as the end of the initial contract period approached. However, delays did not prevent building the demonstration skid. The travel bans and lockdowns caused by the COVID-19 pandemic prevented installation and data collection. Once travel was allowed in May 2020, the team was able to transport and install the demonstration unit in early June 2020 and begin collecting data. A request was made of the project's natural gas industry co-sponsors to provide carry-over funding after June 2020. This funding allowed the team to collect at least six months of data and to work with USG engineers on scale-up designs. This data is included in this Final Report fulfilling the demonstration data requirement of the CEC contract.

The demonstration unit consists of two heat exchangers containing the thermal ejectors. To operate smoothly, the demonstration unit is controlled over multiple regimes that are defined by the ambient air temperature. The operating regimes have been determined based on typical conditions at the USG plant in Plaster City, California. The temperature ranges for the regimes are:

- Regime 1 – ambient air below 73°F, (23°C)—power to fans on both heat exchangers decreased as ambient air temperature drops
- Regime 2 – ambient air between 73°F (23°C) and 86°F (30°C)
- Regime 3 – ambient air between 86°F (30°C) and 94°F (34°C)
- Regime 4 – ambient air between 94°F (34°C) and 107°F (42°C)
- Regime 5 – ambient air above 107°F (42°C)—both heat exchangers off—no water recovery

The test plan was designed to collect data based on the existing conditions in real time. No true baseline data is possible because ambient air temperature cannot be controlled. Baseline data becomes a function of ambient air temperature. Also, ambient air conditions change over the course of a day and from day-to-day. Given this situation, data was collected over two-hour intervals and averaged over that period. Water recovery and data analysis regarding power required per gallon of water recovered was carried out over the full range of ambient air temperatures at the demonstration site for a six-month period. This serves as a solid basis for scale-up and techno-economic analyses.

The water recovery demonstration unit was operated continuously over a six-month period covering ambient air temperatures form 58°F (14°C) to over 115°F (46°C). Operations were stable and the control algorithms switched successfully between operation ambient temperature regimes. Power consumption in kilowatt-hours (kWh) and specific power consumption in kWh per gallon (kWh/gallon) of water decreased with decreasing ambient air temperature. The average yearly temperature in Plaster City, California is 73°F (23°C) with summer days being the hottest and winter nights being the coldest. With arbitrary electricity cost of 6 to 10 cents per kWh, the demonstration unit data found the required specific power consumption to be lower than the cost to operate the water recovery system when ambient air temperature is at or below the yearly average temperature. These results were confirmed by an independent measurement and verification process. A technology development plan has been prepared to evaluate the options for scale up and application to other industrial processes. Initial scale-up work will be carried out by Gas Technology Institute in partnership with USG and AMSEnergy.

Project Results

The project team found that:

- Two heat exchangers operated in five regimes provided a stable and efficient way to recover water as a function of ambient air temperature.
- The energy cost for water recovery is a function of temperature, with the cost in kWh/gallon decreasing with decreasing ambient air temperature.
- At ambient air temperatures below 73°F (23°C), the value of recovered water is greater than the energy cost required to recover the water from the USG flue gas.

- The energy cost, at 6 cents per kWh, to recover water was under $1 per thousand gallons at 65°F (18°C) and approximately $16 per thousand gallons at 95°F (35°C) and above.

Technology Transfer

The demonstration testing confirmed the cost of water recovery is lower than the cost of water purchased in many locations at temperatures below 73°F (23°C). This does not account for the capital, labor, maintenance, and cost of money expenses. The project team is working with USG and vendors to lower the system costs and optimize the system on scale-up. USG is interested in using this technology for water recovery at multiple locations. The team is also working to locate a vendor to package, sell, install, and support the technology at locations in California and around the country where exhaust gases with high water content are currently vented to atmosphere.

Benefits to California

California consumes roughly 9 percent of all water in the United States, an amount approximately equal to 10 trillion gallons per year. The project team estimates that for just 100 facilities in California recovering only 40 gallons of water per hour, a total of 35 million gallons of water can be recovered per year. With larger and smaller systems adopted throughout the State at full deployment, as much as a billion gallons of water can expected to be recovered per year.

CHAPTER 1: Project Objective

This project demonstrated cost-effective water recovery from hot, humid industrial exhaust gases as an added benefit from natural gas combustion. The demonstration was conducted by a team of experts in industrial heat transfer and in design of the thermally driven ejector-based technology for water recovery. United States Gypsum Corporation (USG) in Plaster City, California, served as host site. A portion of the very large stream of hot, humid exhaust gas from USG's kiln was sent to the water recovery system known as CLEAR (Clean Liquid Water by Ejector-Assisted Recovery) for water recovery.

The team designed, fabricated, and demonstrated the modular CLEAR water recovery technology and confirmed a payback period of less than four years. Specific project goals included:

- Design of a modular CLEAR system scalable to a wide range of commercial and industrial dryers and furnaces of different scales and with varying exhaust gas water contents.
- Fabrication and installation of a CLEAR demonstration unit at USG, processing as much as 10,000 cubic feet per minute of hot, humid exhaust gas and recovering as much as one ton of clean water per hour.
- Operation of the CLEAR demonstration unit at stable conditions for up to six months at the demonstration site.
- Completion of a technology package including plans for CLEAR process scaling and deployment, assessment of multiple industrial and commercial applications, cost analysis with projected payback period, and a product readiness plan.

Natural gas is the fuel of choice in most industrial and commercial processes because gas is clean, reliably available, and cost-effective for heat generation. Combustion engineers and heat transfer experts have long worked to optimize natural gas process efficiency. Less common is obtaining additional services from the same natural gas. Additional services can include decreasing emissions, operating sensors, controlling process atmospheres, and, in the case of this demonstration, collecting water from the exhaust gas for reuse.

Natural gas combustion with a small amount of excess air produces an exhaust gas with approximately a 12 percent volume of water. A number of processes, including industrial and agricultural dryers, commercial cooking facilities, and various chemical processes, produce exhaust gases containing 20 to 50 percent volume of water. While water recovery from exhaust gas is an attractive additional service, the relatively simple recovery of water is almost never practiced because water is available at prices too low to cover the cost of the added equipment. Two factors are changing this historical situation. First, in California and other states, water resources are becoming scarcer and water prices are rising dramatically. There is a need to conserve precious fresh water supplies. Second, the CLEAR technology offers a less expensive way to recover water from hot exhaust gas. The CLEAR process uses the thermal energy in the hot, humid exhaust gas to drive an ejector-based closed-loop refrigeration cycle. This type of refrigeration cycle is well known and highly engineered but not commonly used because vapor compression refrigeration cycles have much higher coefficient of performance (COP) values. For water recovery, the thermally driven ejector refrigeration cycle used in the CLEAR technology is much more attractive because the electricity used to drive a compressor in the vapor-compression cycle is replaced with heat energy used to drive a generator in the ejector refrigeration cycle.

All natural-gas-fired furnace exhaust gases contain water, but drying and cooking process exhaust gases have much higher water concentrations. These exhaust gases are much more attractive for cost-effective water recovery by the CLEAR process. For that reason, the demonstration was conducted with a hot, humid exhaust gas from the USG sheetrock kiln.

The jet compression era started in 1838, when the Frenchman Pelletan was granted a patent for the compression of steam by means of a jet of motive steam. In 1858, the French engineer Henry-Jacques Giffard developed a steam-water injector, which served as a fluidic pump for his successive airship's steam engine. Further on, the injectors gained widespread application specifically as a boiler feeding system for steam trains.

In 1900, the Englishman Charles Parsons studied reducing pressure by an entrainment effect from a steam jet. In 1901, Parsons introduced the first ejector for air suction from the condenser to create a vacuum. The first steam jet refrigeration system was created by the French engineer Maurice Leblanc, who developed the Ejector Refrigeration System (ERS) in 1907 to 1908. Ejectors produced a high velocity steam jet (about 1200 meters per second). Based on Leblanc's design, the first commercial system was introduced by Westinghouse in 1909 in Paris. Although the efficiency of the steam jet refrigeration system was low, it was still attractive, as water is safe, and the system can run using low-grade exhaust steam from a steam engine. From 1910 onwards, steam jet refrigeration systems were used mainly in breweries, chemical factories, warships, etc. In 1926, the French engineer Follain improved the machine by introducing multiple stage vaporization and condensation of the suction steam. Between 1928 and1930, ERS were used for air-conditioning of American factories, cinemas, ships, and railcars. Westinghouse, Ingersoll Rand, and Carrier started producing these systems in 1930. Although these systems were replaced by more efficient vapor absorption systems using lithium bromide water, some east European countries (such as the former Czechoslovakia and the Union of Soviet Socialist Republics, or USSR) manufactured ERS as late as the 1960s.

The follow-up research was focused on ERS improvement, since the ejector principle can also be used to provide refrigeration using more efficient fluids other than water, i.e., refrigerants such as CFC-11, CFC-21, CFC-22, CFC-113, CFC-114, etc. In 1950, Dr. V.S. Martynovskiy of the Odessa Technology Institute of Food and Refrigerating Industry (USSR) started researching ERS with hydrofluorocarbon and hydrochlorofluorocarbon working fluids. The first closed loop vapor jet refrigeration systems were developed by USSR engineers S.Z. Zhadan (1954) and I.S. Badylkes (1961). Refrigerants other than water could achieve temperatures as low as –148°F (–100°C) with a single stage of compression. The advantage cited for this type of system is simplicity and robustness, while difficult design and economics composed main disadvantages. The ideal working fluid for ERS and a reliable feeding pump was not found.

Main application areas of steam jet refrigeration systems in the 1950s to 1970s remained air-conditioning for submarines, and industrial cooling for chemical and textile works. In the early 1980s, the ERS with low boiling point refrigerants were successfully introduced for temperature control operation in the foundry industry, abundant with waste heat, where the cooling needs neglected the low efficiency and noise level of ERS. Further research concentrated on various computational fluid dynamics (CFD) modelling of the ejector as an important process for the ejector's flow part perfection; however, this work did not bring a big gain to the real ERS efficiency.

By the end of the 20th century, ejector refrigeration systems were found among compression, sorption, and thermoelectric refrigerating systems, fighting for the highly competitive global refrigerating systems market, where economic factors play the greatest role. The beginning of the 21st century opened a new era for the low-grade-heat activated refrigerating system, including the ejector, with a focus on both economic benefits and ecological safety.

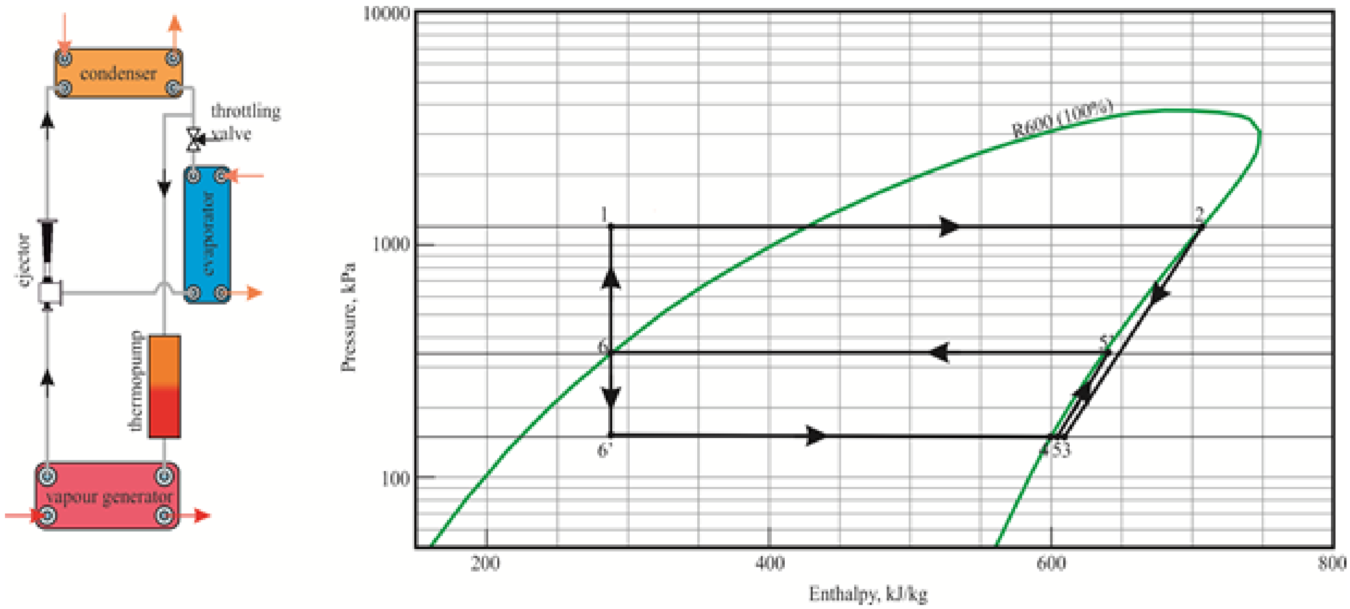
Like many heat-driven cooling systems, the Ejector Cooling System (ECS) employs two thermodynamic cycles simultaneously—power and refrigeration. Unlike existing refrigeration cycles activated at the expense of mechanical work or electricity, work is produced in separate cycles regardless of energy quality factor. Figure 1 shows the schematic diagram of the ECS and its thermodynamic cycle. The heat from an external source is supplied to the vapor generator, where the working fluid is evaporated at high temperature and pressure. The working fluid heads to the ejector where it expands in the ejector nozzle and entrains the refrigerant vapor from the evaporator. The vapor mixture is compressed in the diffuser part of the ejector and directed to the condenser, where it condenses. Part of the condensed fluid is throttled back to the evaporator, where it evaporates at low pressure and temperature, producing the valuable cooling. The balance of the condensed working fluid is directed by the thermal pump and feeds the generator to repeat the cycle. The COP of ECS is determined by equation (1): Equation 1 COP of Ejector Cooling System:

$$COP^{ERS} = \frac{Q_{eva}}{Q_{gen}} = \frac{q_{eva} G_{eva}}{q_{gen} G_{gen}} = U \frac{q_{eva}}{q_{gen}}$$

Credit: Gas Technology Institute

where: Qeva is cooling capacity, Qgen is heat consumed in the vapor generator, qeva/qgen is specific heat of evaporation, U is entrainment ratio, and Geva and Ggen are working fluid mass flow rates in the evaporator and the vapor generator. Equation 1 does not count the pump work. If the system is equipped with a mechanical pump, the COP of ECS will be essentially lower, taking into account the efficiency of the pump. An effective pump workload uses 3 to 12 percent of the total heat consumed.

Figure 1: Schematic Diagram and Thermodynamic Cycle of the ECS



1-2 – liquid heating and its evaporation in the vapor generator, 2-3 working vapor expansion in the ejector nozzle, 3-4 and 4-5 – vapor mixing in the ejector, 5-5' vapor mixture compression in the ejector, 5'-6 vapor condensing, 6-6' liquid throttling to the evaporator, 6-1 liquid pumping to the vapor generator.

Credit: Gas Technology Institute

Considering the high cost of electricity and its generation from the heat of the same potential as used to activate the ECS's vapor generator, it reduces the system's COP by more than a factor of two. With the thermal pump employed in the system, the COP decreases by 3 to 12 percent maximum, depending on the working media used.

For cooling production, an innovative self-regulated ECS was proposed, and developed by Wilson Engineering (Wilson). During 2014 to 2015, the prototype of this ECS was built and tested in the Wilson laboratory, with a COP obtained for various operating parameters on a level of 70 to 90 percent. Various tests at off-design conditions were performed with the performance drop on a level of 20 to 30 percent.

CHAPTER 2: Design and Fabrication

The project team made two trips at the start of the project to review USG's kiln stack for testing and to coordinate activities with USG plant and engineering staff. The first trip was made by Gas Technology Institute (GTI) engineers. In November 2017, the second visit to the USG plant was made by Nancy Wellhausen of Tetra Tech and engineers from Wilson Engineering. Ms. Wellhausen was able to determine the best way to conduct stack measurements, and she prepared a detailed testing plan. The Wilson engineers were able to understand the site location and the space available for the skid-mounted water recovery demonstration unit. Space on-site was not a problem, but the demonstration unit must be designed to fit on a skid for delivery to the host site.

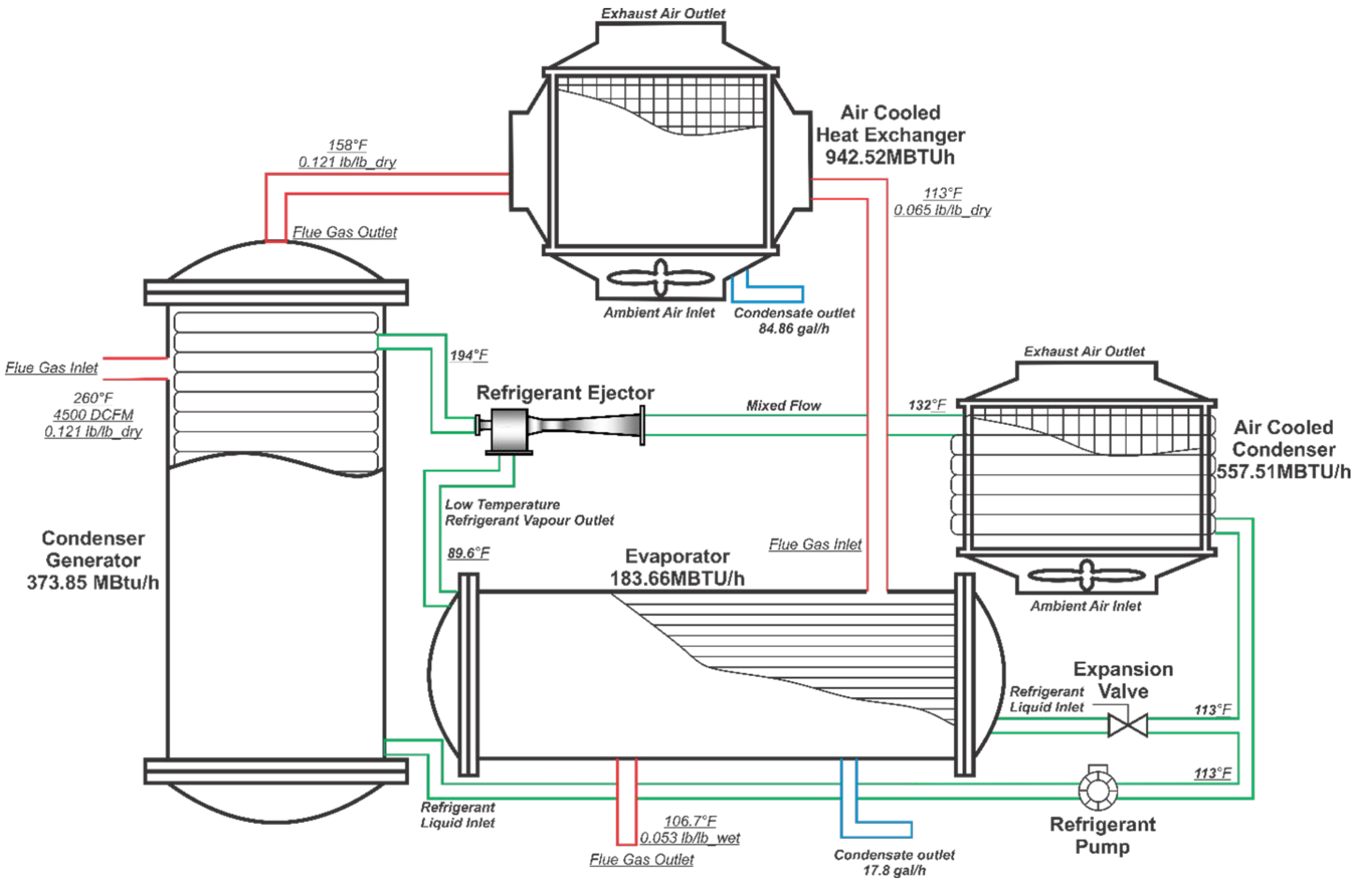
USG recently completed changing out the burners on the Line 3 dryer and tuned the drying furnace. USG then commissioned an independent testing company to measure emissions from Line 3 and other plant locations. The project team acquired a copy of the Line 3 dryer exhaust gas analysis. Wilson used this data for their initial, detailed water recovery system design. This design was delivered to GTI. The design was incomplete but gave an outline of the overall system design. GTI worked with Wilson to complete the design, ready for assembly. Figure 2 shows the simplified layout of the water recovery demonstration unit. A plan called for three thermal ejector units operating at different temperatures, but, in the interest of clarity, only a single unit is shown. GTI shared this design with the other members of the project team. After comments and reviews, the team was ready to begin system fabrication drawings, equipment purchase, and fabrication.

After the project team acquired the full plant emissions analysis, the report was used to help guide the project team on expected variations in Line 3 emissions over time.

The demonstration unit was agreed to be located at the flue stack on USG's Line 3 drying furnace. USG shared exhaust duct information from another USG plant to assist in the development of the initial design. The burners USG replaced have this drying furnace serving as a duplicate of a drying furnace at another USG plant. Tetra Tech was tasked to complete a plan for making baseline flue measurements once the demonstration unit is installed.

The project team was not sure if this demonstration would require a modification to the plant's air quality permit. The air quality permit modification forms were sent to USG to see if air quality permit modifications would be necessary. USG undergoes regular plant environmental inspection, and this permit review process was combined with the plant inspection and testing. The forms were submitted to the State of California. After significant delay, the decision was made that no air quality permit modifications were required as long as the installation was temporary. To meet this requirement, the team decided to mount the system on a moveable skid.

Figure 2: Simplified Initial Water Recovery System Design Showing Heat Exchangers and Thermal Ejectors



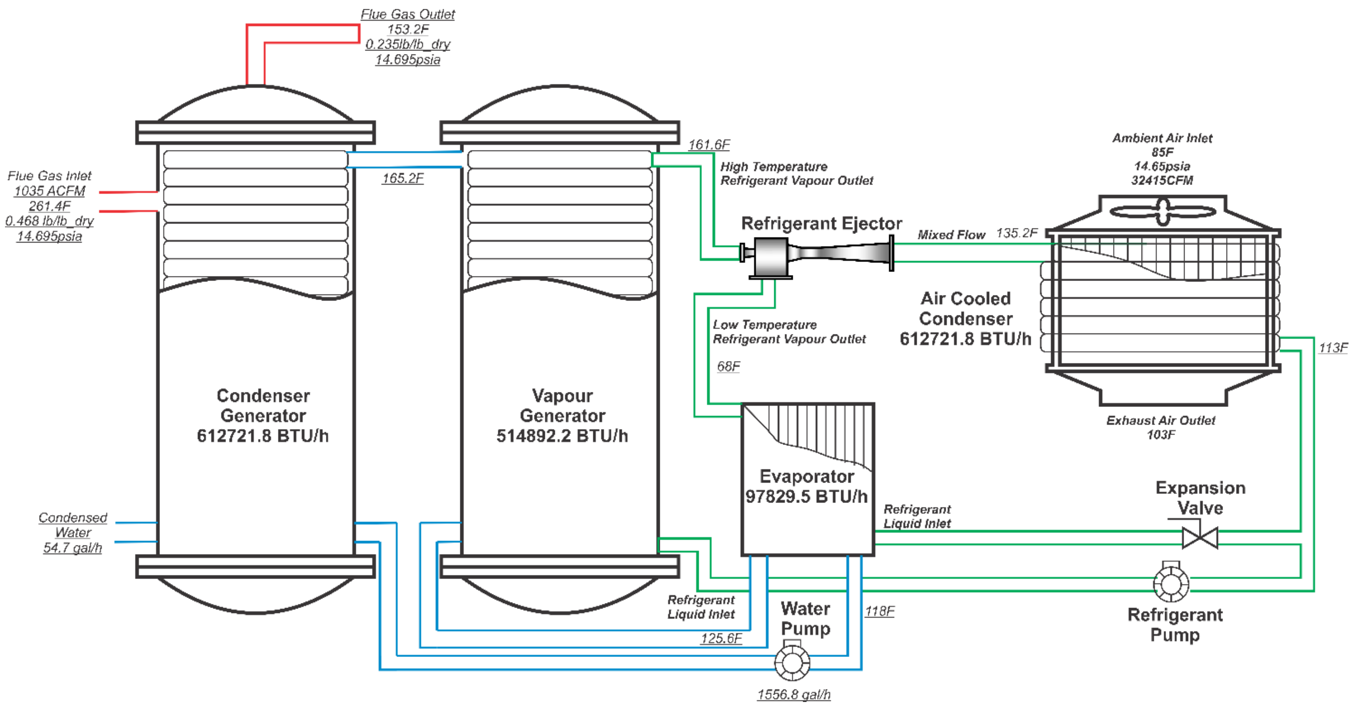
Credit: Gas Technology Institute

With completion of the field test agreement, the Wilson subcontract, and the demonstration test plan, the team moved forward with arranging plant coordination, demonstration unit siting, and data gathering needed for test unit design.

USG engineers expressed concerns about the system design. In particular, they were concerned about the amount of ambient air flow needed for cooling the heat exchangers. The team worked to redesign the system to minimize the needed ambient air flow rate and to reduce the size and power demand of the blowers.

After extensive discussions and review, the project team developed a design that consumes low power and requires no outside plant utilities except for small amounts of power to operate fans and pumps. The fans replace the much larger, energy-consuming blowers in the early designs. Figure 3 shows the layout agreed to by GTI, Wilson Engineering, and USG.

Figure 3: Second Water Recovery Unit Design



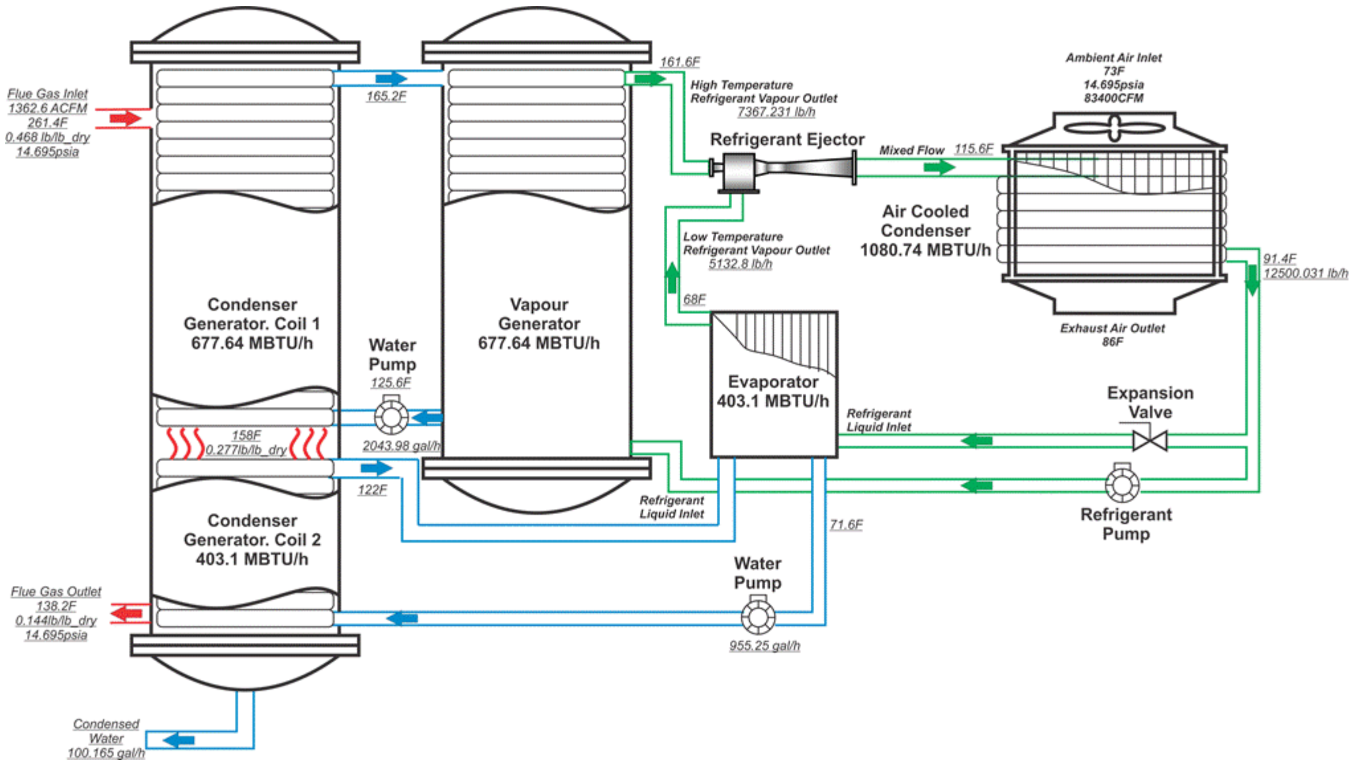
Credit: Gas Technology Institute

The project team engaged in the detailed system design and scoping of the equipment needed. This work proceeded after design approval by the full team.

After extensive discussions and review, the project team continued to work with the design that consumes low power and requires no outside plant utilities except for a small amount of power to operate fans and pumps. Figure 4, updated from earlier sketches with more detail, shows the layout agreed to by GTI, Wilson Engineering, and USG. Figure 5 provides a more detailed process flow diagram with all streams specified. Figure 6 provides a layout of the water recovery system using two skids to transport the system to the USG site by truck. In this system design, the two air-cooled condensers are large and take up one skid. All other components and flow control valves, along with pumps and fans, are positioned on the second skid.

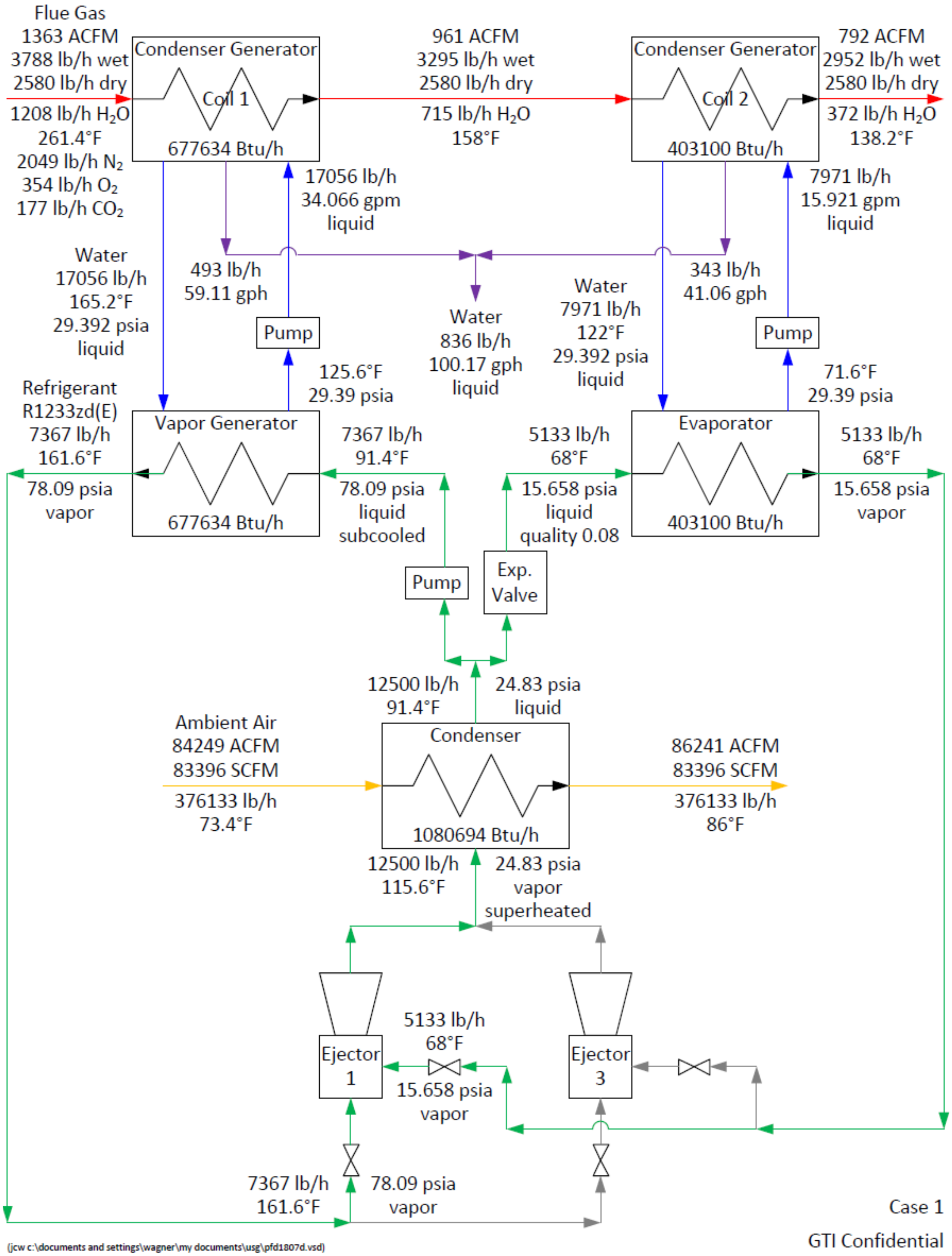
As discussed previously, GTI worked with Wilson Engineering to complete the system design for presentation to USG. Following several revisions, agreement was received on the approach. GTI and Wilson then met to plan the final design conditions. The challenge was to recover 100 gallons of water per hour when the ambient air temperature is constantly changing. To make a system that is operable, the team agreed to use three ejectors, each optimized to a range of ambient air temperatures. The lowest temperature ejector was optimized for 73°F (23°C) ambient air. The average annual temperature (day to night and around the full calendar) is 73°F (23°C). The system was designed to generate 100 gallons of water per hour at this average yearly temperature of 73°F (23°C). Water yield will be lower at higher ambient air temperatures. While water yields will decrease with increasing ambient air temperature, the demonstration unit will gather all the data needed to design a commercial-scale water recovery system.

Figure 4: Second Demonstration Unit Design Showing More Detail



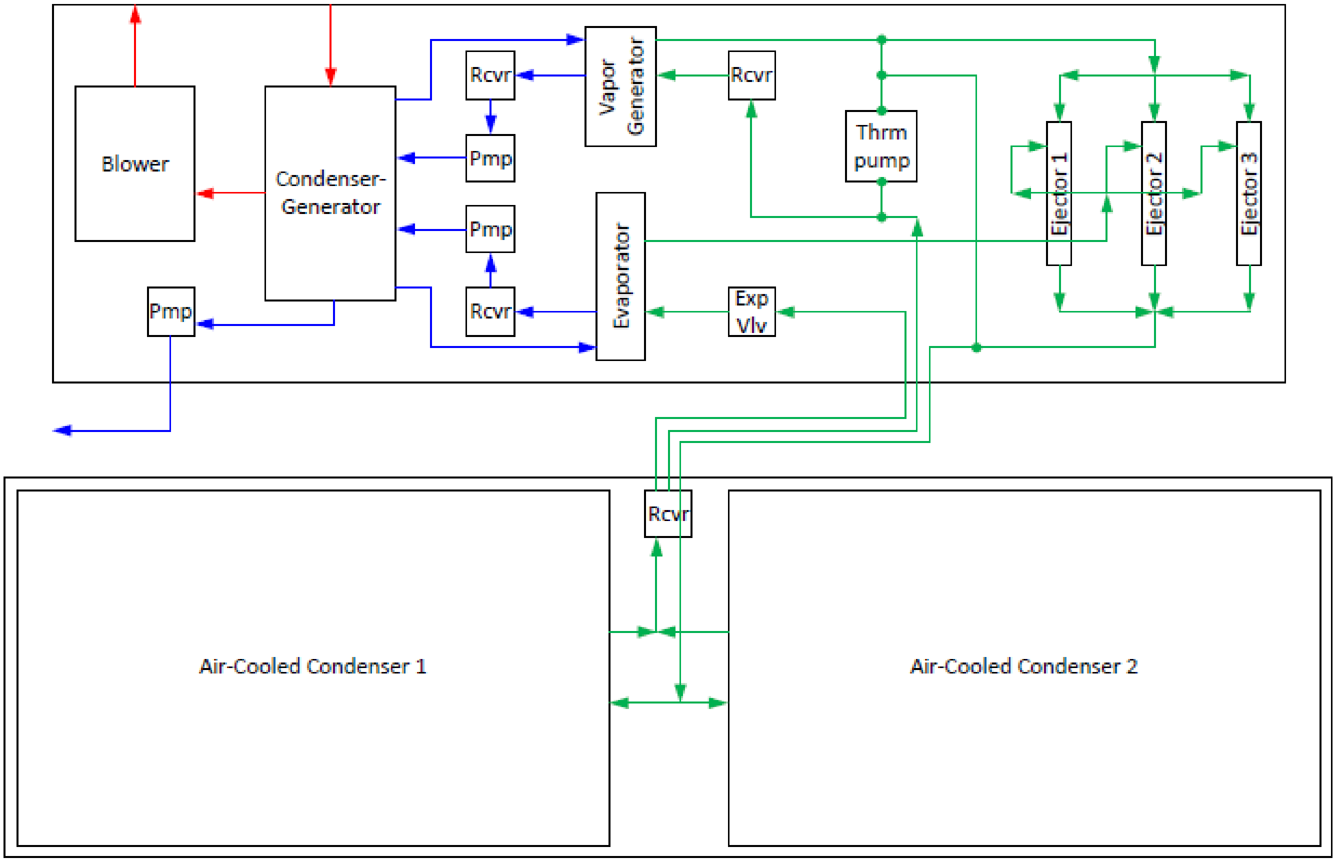
Credit: Gas Technology Institute

Figure 5: Streams and Flow Rates for Second Water Recovery System Design



Credit: Gas Technology Institute

Figure 6: Top View of Skid Layout for the Second Water



Recovery Demonstration Unit Design

Credit: Gas Technology Institute

The team simplified the system design and began ordering the major component heat exchangers. The Piping and Instrumentation Diagram was completed by Wilson and modified by GTI. Further modifications were undertaken to reduce the system footprint, simplify the layout, and make scale-up more practical. Discussions continued with California vendors for overall system assembly. A vendor was identified to complete the on-site erection and assembly. This vendor, Maya's Mechanical Service, had worked with USG in the past and provided all needed mechanical and electrical capabilities to complete the job.

There were four heat exchangers in the system. These heat exchangers are the largest and most expensive system components. Quotes were received for all four heat exchangers. Detailed heat transfer calculations were conducted to make sure the heat exchangers can do the needed heat transfer and phase changes. All heat exchangers are based on available models with required modifications. Design included access panels to allow for heat exchanger tube cleaning.

The length of this project provided the team the opportunity to carefully improve the system design. The team developed a third and final water recovery system design. This version uses the same four heat exchangers but in a different configuration. The thermal ejectors were moved inside the heat exchanger shells to save space and reduce equipment size and cost.

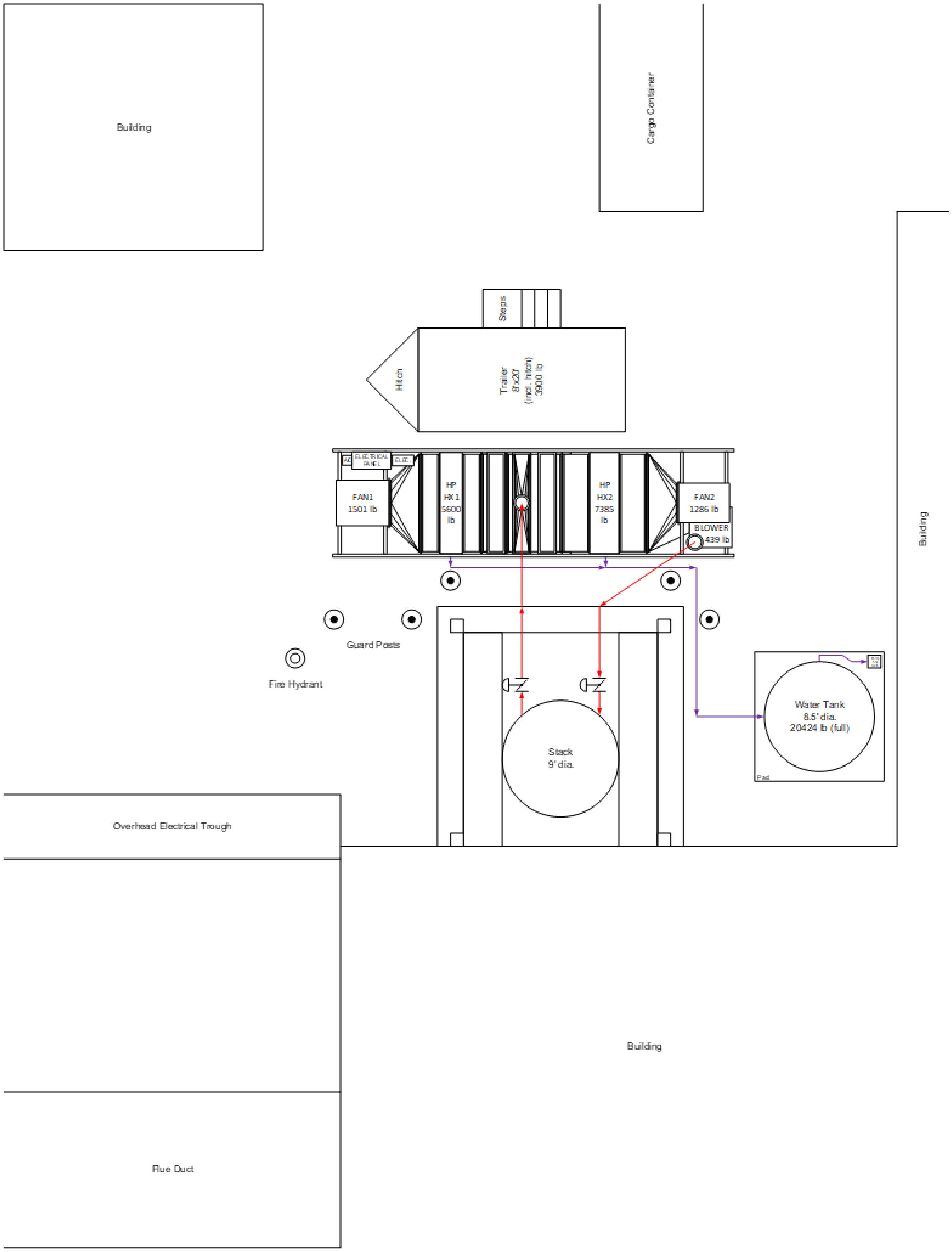
This modification lowered design cost and size while decreasing the energy demand for fans. The entire system could now be placed on one skid instead of on two skids, as in the first and second configurations. Other benefits of this change included:

- Elimination of the water-cooling loop
- Avoidance of the close temperature pinch point
- Simplification of the sensor package and controls
- Increased operation stability when switching between ambient air temperature regimes
- Elimination of the large gas-to-gas air cooled condenser

Figure 7 shows the system layout relative to the exhaust stack on the USG Line 3 demonstration site. Figure 8 provides a side view of the skid with all equipment mounted.

The project team realized that time had been lost in changing and improving the demonstration unit design and layout. While those changes represented significant technology improvements, time was becoming an important factor. All equipment, components, wiring, and sensors were ordered. The team learned that the heat exchangers with integral, internal thermal ejectors were the longest delivery item. The heat exchangers were ordered as quickly as possible, and constant pressure was exercised to accelerate completion and delivery. Figures 9, 10, and 11 show the heat exchanger frames, the thermal ejector tubes before installation, and the completed heat exchangers being unloaded at the site of the selected fabricator, Maya’s Mechanical Service (Maya’s) in Baldwin Park, California, which served as the assembly point.

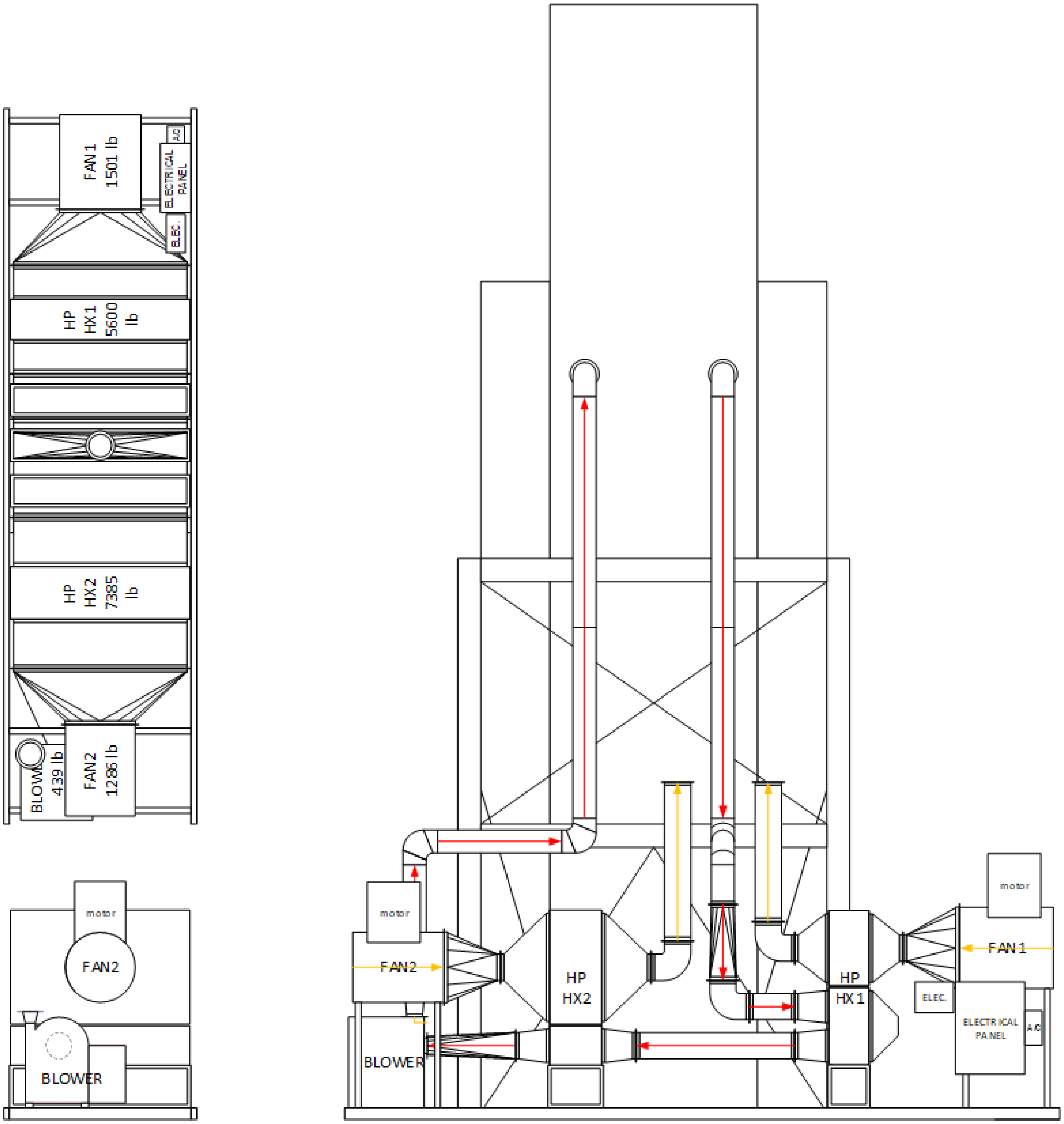
Figure 7: Final Water Recovery System Design From Above



Showing Equipment in Relation to USG Line 3 Exhaust Stack

Credit: Gas Technology Institute

Figure 8: Side View of Final Water Recovery Demonstration Unit Equipment Layout



View looking south toward stack
(isolation valves not shown)

Credit: Gas Technology Institute

Figure 9: Heat Exchanger Frames Under Construction

Credit: Gas Technology Institute

Figure 10: Heat Exchanger Thermal Ejectors Before Installation

Credit: Gas Technology Institute

Figure 11: Completed Heat Exchangers Being Unloaded at Maya’s Mechanical Service in Baldwin Park, California

Credit: Gas Technology Institute

Delays in heat exchanger fabrication were experienced in December 2019, with shops closed the second half of the month for the Christmas holiday. All other components had been ordered and had arrived at Maya’s. As components arrived, they were assembled by Maya’s technicians per drawings prepared by GTI engineers. Photographs of the skid under construction and with components included are shown in Figures 12, 13, 14 and 15. The final pieces to be completed were the transition pieces, the ductwork connecting the heat exchangers and ducts to and from the stack. The transition pieces were completed after delivery of the heat exchangers. The electrical boxes were completed and mounted on the skid. The final wiring was installed, and the skid wiring was then completed for power and sensors. All sensors and process control components were calibrated as much as possible off-site. A full set of drawings was completed by GTI engineers and supplied to the fabricators at Maya’s.

Figure 12: Skid Electrical Boxes

Credit: Gas Technology Institute

Figure 13: Skid Side View With Heat Exchangers and Transition Pieces Installed

Credit: Gas Technology Institute

Figure 14: Skid Before Wiring Installation, End View Showing Fan

Credit: Gas Technology Institute

Figure 15: Completed Demonstration Skid Ready for Transport to USG Host Site

Credit: Gas Technology Institute

The electrical box and electrical wiring are shown in Figures 16 and 17.

Figure 16: Electrical Panel for Skid Control

Credit: Gas Technology Institute

Figure 17: Electrical Box on Skid Showing Sensor Wiring to Boards

Credit: Gas Technology Institute

The tank for storing collected water from the demonstration unit was installed at USG (Figure 18).

Figure 18: Water Storage Tank on Concrete Pad

Credit: Gas Technology Institute

CHAPTER 3:
Results and Discussion

Stack measurements were made by Tetra Tech on the Line 3 exhaust stack. These measurements provided baseline conditions for input into the demonstration skid design. A summary of the results is presented in Table 1. The baseline results are similar to the values obtained by the USG contracted stack analysis earlier in the project. Three full analyses were conducted, and the results were averaged.

Table 1: USG Line 3 Baseline Stack Analyses

Parameter	Units	Kiln #3 Stack			
		O-1	O-2	O-3	AVG
Test Date:	mm/dd/yy	01/03/2020	01/03/2020	01/03/2020	
Test Time:	hh:mm	10:54 – 11:24	10:53 – 12:23	12:52 – 13:22	
Sampling Data					
Stack Temperature	°F	248	250	250	249
Moisture	%	43.1	44.0	43.5	43.5
Sample Volume	dscf	24.3	25.3	33.3	27.6
Oxygen	% v/v	18.1	14.7	17.0	16.6
Carbon Dioxide	% v/v	2.01	3.29	2.52	2.61
Gas Velocity	ft/min	2,128	2,175	2,140	2,147
Stack Flow Rate	acfm	135,347	138,363	136,110	136,607
Stack Flow Rate	dscfm	56,294	56,549	56,072	56,305

dscf = dry standard cubic feet; % v/v = percent volume/volume; ft/min =feet per minute; acfm = actual cubic feet per minute; dscfm = dry standard cubic feet per minute
Credit: Gas Technology Institute

Baseline testing confirmed the expected flue gas temperature of approximately 250°F (121°C) and water content of 43.5 percent by volume. These match anticipated demonstration skid input parameters used for system design. Kiln operation uses a large excess volume of air to dry the board product. This is illustrated in the high concentration of oxygen and low concentration of carbon dioxide in the flue gas. Overall, the flue gas analyses matched expected results.

While the demonstration skid assembly was being completed, the project team developed a testing plan. The flue gas temperature and composition is fairly steady at the USG host site, but ambient air temperature changes over a wide range throughout the year, from under 50°F (10°C) (winter nights) to over 110°F (43°C) (summer days). The water recovery process rejects heat to the environment by heating ambient air. This leads to higher process efficiency as input ambient air temperature drops. The water recovery system is designed to work in real-world conditions. The two double heat exchangers are operated with one heat exchanger operating over the full range of temperatures, and the other heat exchanger operating over a lower ambient air temperature range.

The demonstration was carried out on the Line 3 drying kiln of the USG plant in Plaster City. The kiln runs at constant conditions, and the project team processed approximately 1 percent of the exhaust gas. For these reasons, the team could assume exhaust gas flow rate, composition, and conditions are constant into the demonstration unit. The only true independent environmental variable is the ambient air temperature. This variable is critical because all heat must be rejected into the environment via ambient air flowing through the demonstration unit.

The demonstration unit consists of two heat exchangers containing the thermal ejectors. To operate smoothly, the demonstration unit was designed to be controlled over multiple regimes that are defined by the ambient air temperature. The operating regimes have been determined based on typical conditions at the USG plant. The temperature ranges for the regimes are:

- Regime 1 – ambient air below 73°F (23°C) — power to fans on both heat exchangers decreased as ambient air temperature drops
- Regime 2 – ambient air between 73°F (23°C) and 86°F (30°C)
- Regime 3 – ambient air between 86°F (30°C) and 94°F (34°C)
- Regime 4 – ambient air between 94°F (34°C) and 107°F (42°C)
- Regime 5 – ambient air above 107°F (42°C) — both heat exchangers off—no water recovery

The test plan was designed to collect data based on the existing conditions in real time. No true baseline data is possible because ambient air temperature cannot be controlled. Also, ambient air conditions change over a day and from day-to-day. Given this real-world reality, the team collected data continuously (once a minute) and then aggregated the collected data over two-hour intervals and averaged over that two-hour period. Ambient air temperature does not change much over two-hour periods, so this approach provided an artificial but reasonable single data point for each two-hour period. The same process was then repeated over the next two-hour period, etc. This process was continued throughout the demonstration period. Thus, a large number of data points were collected covering the full range of ambient air temperatures in Plaster City. The data was analyzed and presented in a number of formats as it was collected. The control approach was outlined as follows:

- For Regimes 1 through 4, the flue gas flow rate was held steady.
- For Regimes 1 through 3, Heat Exchanger 1 (HX 1) was controlled by regulating its flue gas outlet temperature by adjusting its ambient air flow rate, while for Regime 4, its ambient air flow rate was held steady, and its flue gas outlet temperature was allowed to vary.
- For Regime 1, Heat Exchanger 2 (HX 2) was controlled by regulating its flue gas outlet temperature by adjusting its ambient air flow rate, while for Regime 2, its ambient air flow rate was held steady, and its flue gas outlet temperature was allowed to vary.

A more detailed description of the operation of the demonstration unit in different regimes is presented in Table 2. This scheme was developed as a way to maximize water recovery and minimize fan power as the ambient air temperature changes. A general statement is that the power required per gallon of water recovered decreases as the ambient air gets cooler because each cubic foot of air can carry away more heat. Taking advantage of this situation is impractical in other water recovery technologies but is an inherent advantage of the CLEAR water recovery technology. The Plaster City climate is very hot compared to other California and United States (U.S.) locations, so the CLEAR technology performance is expected to be better in terms of power per ton of collected water in most other locations.

Table 2: Planned Demonstration Unit Operating Regime Control Scheme

	Regime 1	Regime 2	Regime 3	Regime 4	Regime 5	
Flue Gas Flow Rate	Constant	Constant	Constant	Constant	Zero	
Heat Transfer/Water Recovery	Constant	Varying	Zero	Zero	Zero	Stage 2
Ambient Air Flow Rate	Varied	Constant	Zero	Zero	Zero	Stage 2
Ambient Air Exit Temperature	Constant	Constant	N/A	N/A	N/A	Stage 2
Flue Gas Exit Temperature	Constant	Varying	Constant	Varying	N/A	Stage 2
Heat Transfer/Water Recovery	Constant	Constant	Constant	Varying	Zero	Stage 1
Ambient Air Flow Rate	Varied	Varied	Varied	Constant	Zero	Stage 1
Ambient Air Exit Temperature	Constant	Constant	Constant	Constant	N/A	Stage 1
Flue Gas Exit Temperature	Constant	Constant	Constant	Varying	N/A	Stage 1

62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118

Credit: Gas Technology Institute

The demonstration test regimes may be found to be not ideal. The test plan calls for data to be collected for sufficient time (several weeks) and then reviewed. If the operating ambient air temperatures described in Regimes 1 through 5 need to be changed, they can be changed for optimum performance. Optimum performance is defined as the lowest amount of power needed per gallon of water recovered. This second optimized demonstration period was maintained throughout the remainder of the demonstration period.

The demonstration unit was operated as follows:

- Operation was fully automatic with manual override available. Data was collected and transmitted via internet hotspot to GTI for post-processing.
- The control points were temperatures of flue gas leaving HX 1 and HX 2.

- No adjustment of operating modes or control points was needed except when switching from the first data collection period to the optimized demonstration period.
- Data and calculations were in two-hour blocks with data averaged over the time period.

The demonstration unit was equipped with a large number of sensors. Some sensors are needed for process control while other sensors are needed for determination of process performance. The data that was collected and averaged in two-hour periods included: HX 1 and HX 2 inlet and outlet air temperatures, flue gas inlet and outlet temperatures, flue gas humidity, water flow rates, air pressure, air flow rates, total system power, flue gas blower power, and fans 1 and 2 power and speed.

To determine demonstration unit performance and to gather the data needed to calculate system scale-up to commercial scale, the collected data was processed in several ways. The data is reported in the following formats:

- Calculated – Air temperature rise and flue gas temperature drop through HX 1 and HX 2 as a function of ambient air temperature
- Calculated – Air and flue gas approach delta temperature as a function of ambient air temperature for HX 1 and HX 2
- Calculated – Heat transfer rate for HX 1 and HX 2 as a function of ambient air temperature
- Calculated – HX 1, HX 2, and total water rate (gallons per hour) as a function of ambient air temperature
- Calculated – Total, blower, fan 1, and fan 2 power as a function of ambient air temperature
- Calculated – Energy (total, blower, fan 1, fan 2) per gallon of water as a function of ambient air temperature
- Calculated – Fan energy per gallon of water for HX 1 and HX 2 as a function of ambient air temperature

The skid was completed in February 2020 and was ready to transport from Maya's facility in Baldwin Park, California, to USG in Plaster City, California. For nearly a year the lockdown from the COVID-19 crisis prevented moving the skid or sending GTI engineers to USG to work with installation contractors to connect the skid to the USG stack and get the unit operational. The project was successfully completed but took longer than anticipated for a number of reasons. The most important reason was the modification of the thermal ejector system layout to improve process efficiency, reduce equipment size and complexity, and to lower capital costs. A timeline of events is shown:

- The project timeline was disrupted when the project team took time to re-design the water recovery system. This was ultimately an excellent decision because the improved design consumes far less power, is less capital-intensive, is more compact, and can be scaled much more easily.

- The project team experienced delays in the supply chain for the thermal ejectors when suppliers delayed production. This issue was resolved, and all components were delivered and vetted. The skid was fully assembled and was checked for operability.
- The demonstration skid was ready to be moved in February 2020, but the COVID-19 lockdown and USG plant restrictions prevented movement and installation of the skid.
- The requested invoice delays totaling approximately $60,000 were for mechanical and electrical installation of the skid at the demonstration site (USG's Plaster City plant). The project team wrote quotes for the mechanical and electrical installation work, but the contractors could not do the installation work and bill the project team because the skid could not be delivered. However, this work was completed by early 2021 and billing completed after the skid was moved.
- The project team made strong efforts to acquire the desired demonstration testing data. This was needed to fulfill the CEC contract. It is also needed because GTI's demonstration partner, USG, is very interested in the technology. USG needs this data to evaluate means to scale the technology and deploy the water recovery technology across their plant system.
- With these goals in mind, the project team requested and obtained support from natural gas industry partners to continue collecting data from the demonstration skid for at least six months following completion of the CEC project.

The project team was not able to acquire the required data by the end of the contract period. However, six months of operational data was acquired with gas industry support. The travel bans and lockdowns caused by the COVID-19 pandemic prevented installation and data collection. The project's natural gas industry co-sponsors generously provided carryover funding after June 2020. This funding allowed the team to collect six months of data and to work with USG engineers on scale-up designs.

The USG wallboard plant Line 3 in Plaster City served as the demonstration site for the nominal 100 gallon per hour water recovery demonstration system. Figure 19 provides a photograph of the plant site. The kiln is located on the left side of the road in the picture.

Figure 19: Demonstration Site – USG Plant, Plaster City, California

Credit: Gas Technology Institute

The exhaust gas for line 3 is located outside the building. The stack is shown in Figure 20. The water recovery system had to be installed so that plant staff and contractors could access the stack when needed.

Figure 20: USG Plant Line 3 Exhaust Stack

Credit: Gas Technology Institute

Figure 21 shows the water recovery system in place along with the trailer used to house the programmable logic controller (PLC) and data acquisition systems. The heat exchanger fan is shown at the end of the water recovery system.

Figure 21: Water Recovery System in Place with Trailer

Credit: Gas Technology Institute

The water recovery system was attached to the stack as shown in Figure 22. One duct brought exhaust gas from the stack to the water recovery system. The other duct returned exhaust gas after cooling and water recovery to the same stack at a higher position.

Figure 22: Water Recovery Unit Attached to Line 3 Exhaust Stack

Credit: Gas Technology Institute

Figure 23 provides an overview of the physical placement of the water recovery system. The unit on its skid was positioned next to the Line 3 stack with sufficient spacing to allow access to the stack when required by plant staff or contractors.

Figure 23: Water Recovery Unit in Place Next to Line 3 Exhaust Stack

Credit: Gas Technology Institute

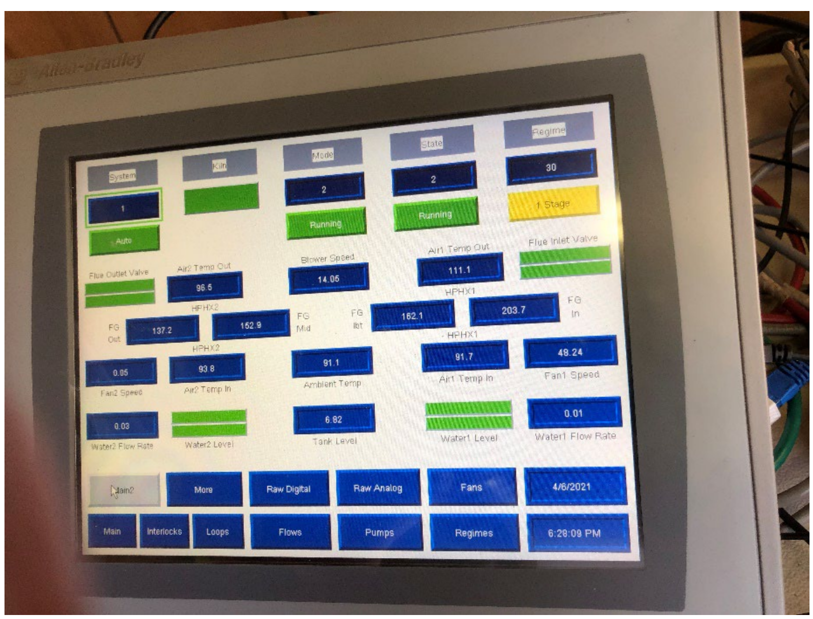
After the water recovery system was installed, the project team took the photograph in Figure 24. This photograph provides a scale to show the size of the equipment.

Figure 24: GTI and USG Project Team

Credit: Gas Technology Institute

All sensor data was sent to the PLC. This data was stored for later analysis. Control input data was collected by the PLC allowing for remote process control and monitoring. Figure 25 shows the process control screen on the human-machine interface (HMI). The PLC and HMI were located inside the trailer during the demonstration test. At the end of the project, the PLC and HMI were provided to USG will full operating instructions. USG will construct a housing for these instruments and for the sensor connections.

Figure 25: Water Recovery Process Control Screen



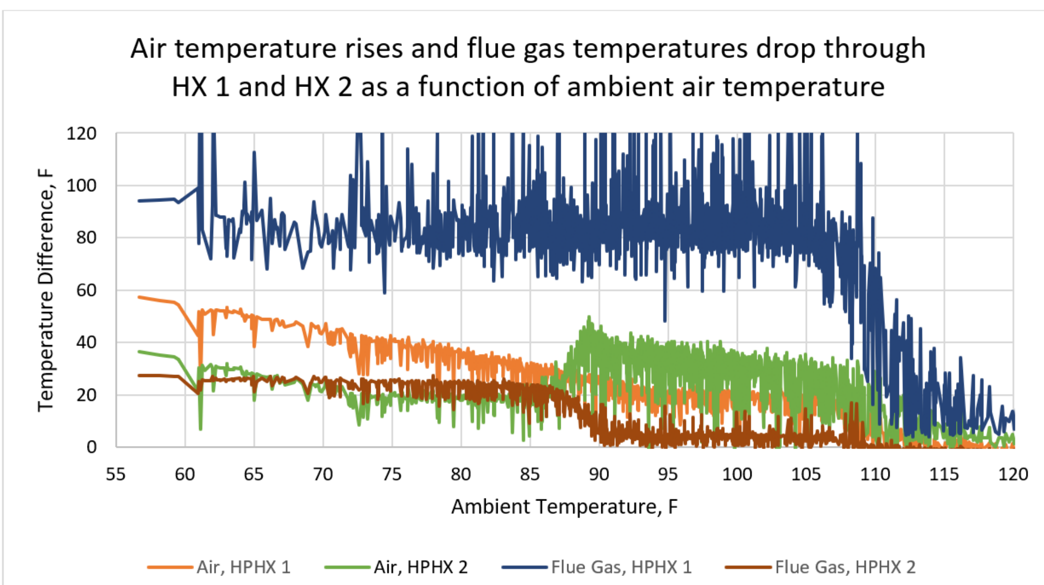
Credit: Gas Technology Institute

The water recovery demonstration was carried out over a six-month period from March to November 2021. During this time, the plant had shut down periods and there were some interruptions in exhaust gas flow. In total, more than 69,000 gallons of water were collected. Ambient air temperature ranged from under 60°F (16°C) to more than 110°F (43°C). Water collected in the storage tank was recovered by USG and used for soil dedusting.

The operating scheme for the overall system was chosen to work well with the range of ambient air temperatures at the demonstration site in Plaster City. The average annual temperature at this location is 73°F (23°C). For much of the year the daytime highs are much hotter, reaching to nearly 120°F (49°C). But even on these hot summer days nightly temperature drop to 80°F (27°C) or below. A key project goal was to determine the effectiveness of water recovery as a function of ambient air temperature. The needed volume of ambient air is significantly greater than the volume of flue gas. The efficient removal of heat in each heat exchanger increases as differential temperature rises with decreasing ambient air temperature. Since flue gas temperature and composition are nearly constant and flue gas volume is much lower than ambient air volume, the control scheme maintained a constant flue gas flow rate while ambient air flow rate was varied with ambient air temperature in the different operating regimes described.

Figure 26 confirms the effectiveness of the operating strategy. This figure shows the change in temperature of air and flue gas through HX 1 and HX 2 as a function of ambient air temperature. As ambient air temperature decreases, the temperature change for air and flue gas through the heat exchange units rises. This leads to greater heat transfer because total heat transfer is a linear function of differential temperature.

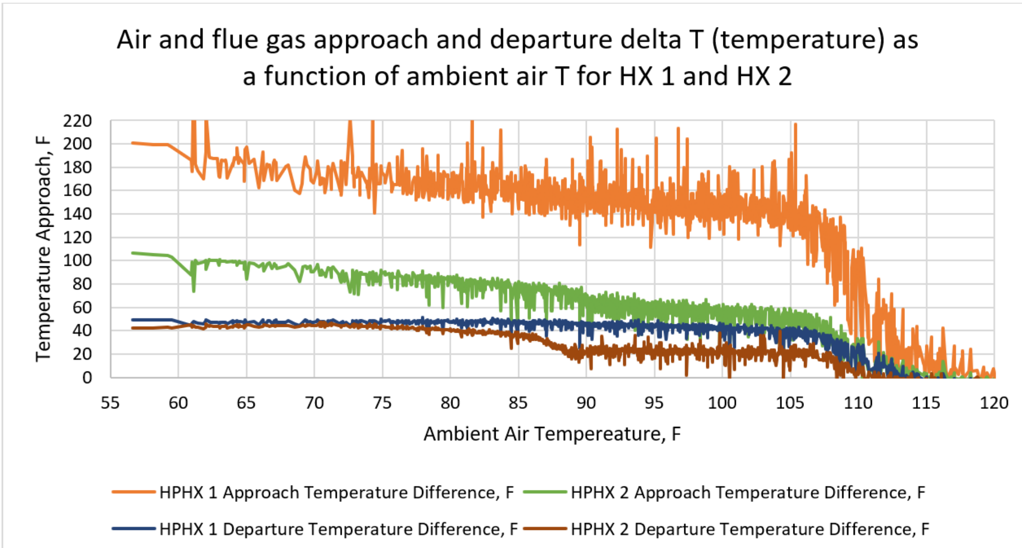
Figure 26: Air and Flue Gas Temperature Rise Through the Heat Exchanger Units



Credit: Gas Technology Institute

Figure 27 illustrates the temperature gradient effect more clearly. The data shows the temperature difference of air and flue gas approach and departure temperatures. As shown, this data confirms the increase in approach and departure temperature differentials with decreasing ambient air temperatures. The data also provides a clear indication of when the two heat exchanger units are operating with a sharp drop in HX 2 departure temperature differential at 88°F (31°C) when the regime was switched.

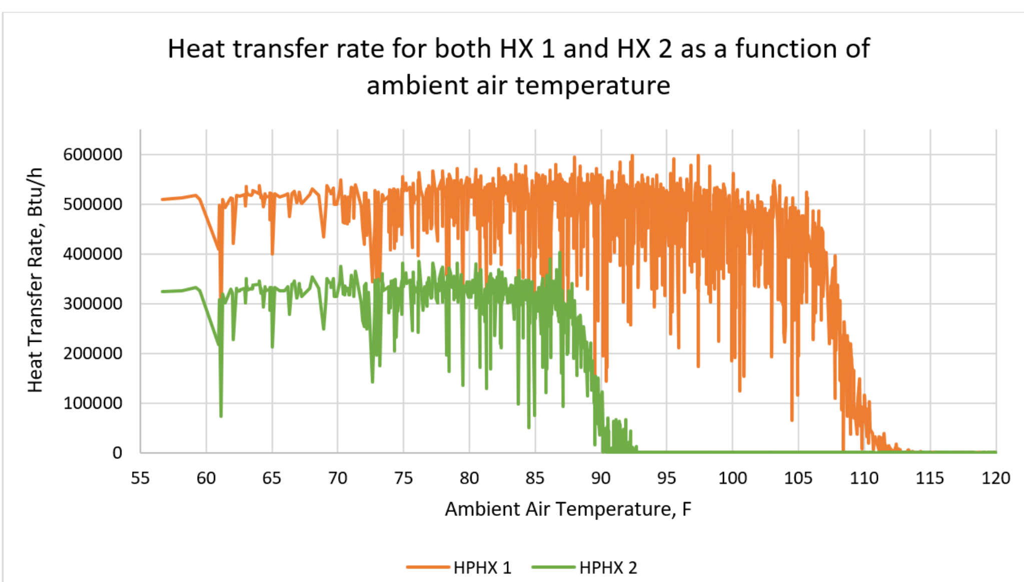
Figure 27: Air and Flue Gas Entrance and Exit Temperature Differentials



Credit: Gas Technology Institute

Figure 28 shows the heat transfer rates in the two heat exchangers. HX 2 heat transfer rate is steady over the full range of its operating temperature. This is a result of the operating strategy where the air fan speed is varied. The heat transfer rate of HX 1 is steady over most of the operating range and decreases slowly above 95°F (35°C) until the cutoff temperature of 105°F (41°C). This also reflects the operating strategy in which the fan speed for cooling air is varied with ambient air temperature.

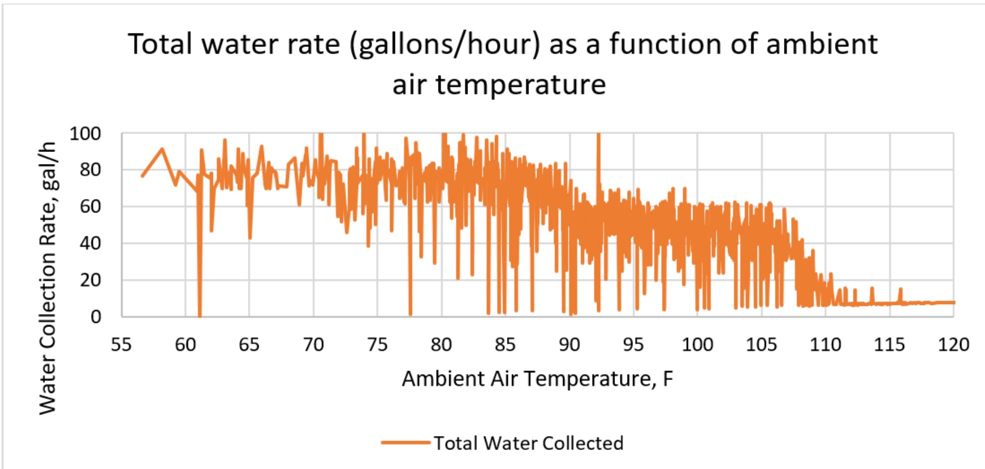
Figure 28: Heat Transfer Rates in HX Units



Credit: Gas Technology Institute

The optimum water collection rate was approximately 80 gallons per hour (Figure 29). This was held steady at temperatures up to 88°F (31°C). Water collection rates decreased at higher temperatures as the differential temperatures between ambient air and exhaust gas declined in the heat exchangers. The water collection rate could be increased at lower ambient air temperatures if a different set of regimes and operating parameters was established. The selected strategy was based on the host site weather conditions and the desire to minimize power consumptions while operating a simple control scheme.

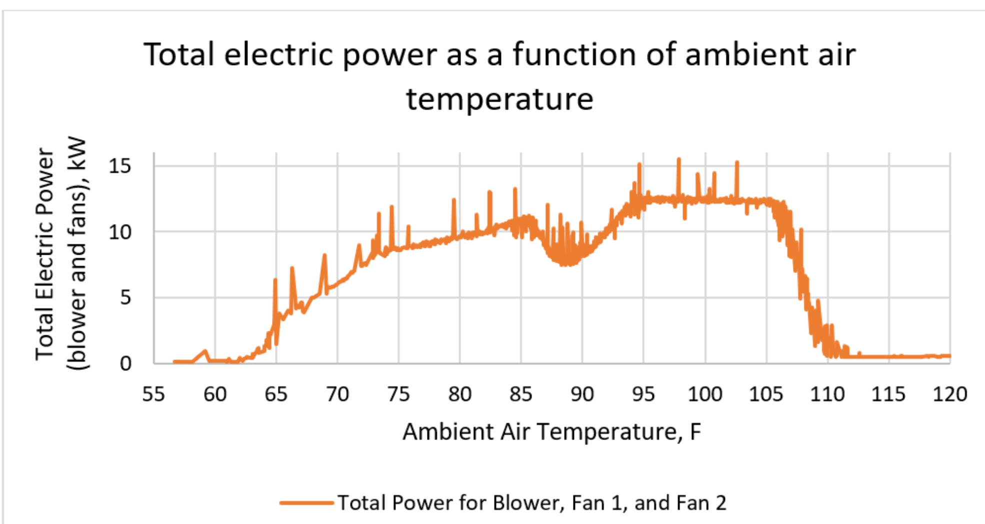
Figure 29: Total Water Collection Rate as a Function of Ambient Temperature



Credit: Gas Technology Institute

The total electrical power requirement for the blower and the two air fans is shown in Figure 30. This clearly shows the way power is used in the different ambient air temperature regimes. Total power requirement increases with increasing ambient air temperature to maintain the widest possible differential temperatures and a steady water recovery rate.

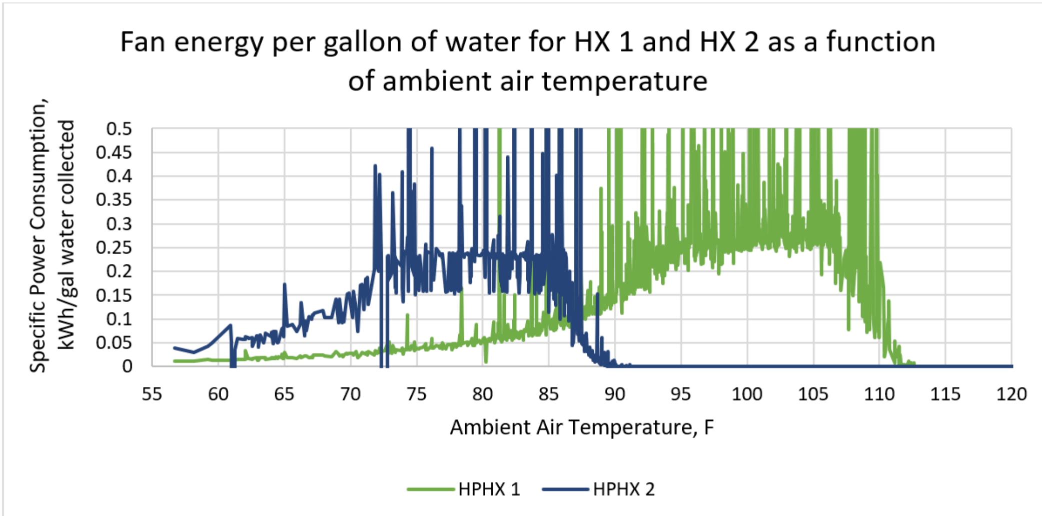
Figure 30: Total Electric Power Requirement as a Function of Ambient Air Temperature



Credit: Gas Technology Institute

Figure 31 details the power demand for the two heat exchanger fans as part of the total electric power used per gallon of collected water. The figure shows the power demand curves for the fans on the two heat exchangers as a function of ambient air temperature.

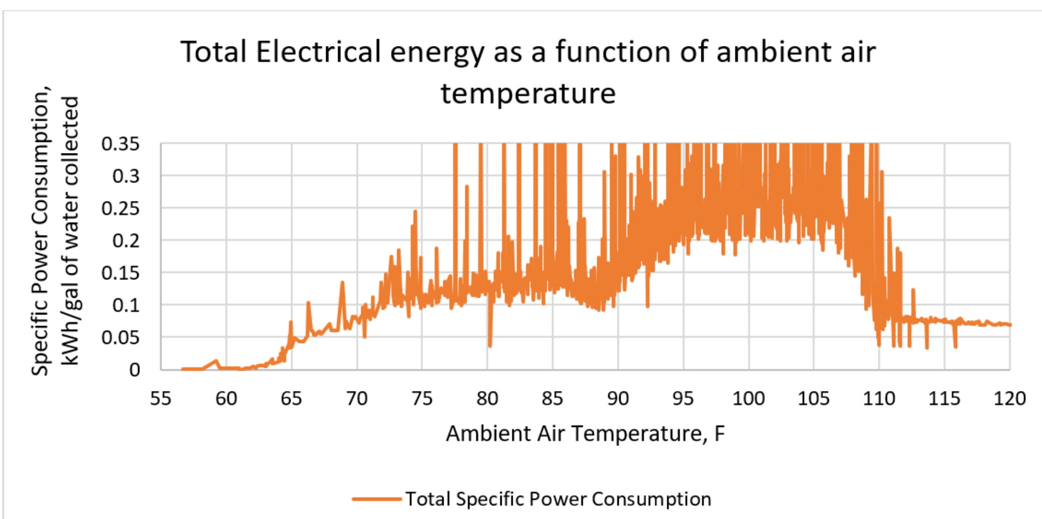
Figure 31: Fan Energy Power per Gallon of Water for HPHX 1 and 2



Credit: Gas Technology Institute

The specific power consumption in kilowatt-hours per gallon (kWh/gallon) of collected water is similar to the total power consumption and is shown in Figure 32. Again, the different ambient air temperature regimes are clear. The process operating regimes were not optimized and are expected to provide even lower specific power consumption versus ambient air temperature when optimized. Because the six-moth test period covered the summer months and not any winter months, the data is limited for ambient air temperatures below 70°F (21°C).

Figure 32: Specific Power Consumption as a Function of Ambient Air Temperature



Credit: Gas Technology Institute

The ultimate benefit of the water recovery technology will be the cost for water recovery compared with the cost of purchased water. Figure 33 shows the specific electricity cost per thousand gallons of water for electricity costs of 6 and 10 cents per kWh.

The price of purchased water varies dramatically across the U.S. Costs range from a low of $2 per thousand gallons to nearly $20 per thousand gallons. A typical cost is between $6 and $10 per thousand gallons. For temperatures below the yearly average temperature of 73°F (23°C) in Plaster City, the cost of electricity is less than the cost of purchased water. This makes the CLEAR water recovery technology attractive. This is without considering capital, financing, labor, and maintenance costs.

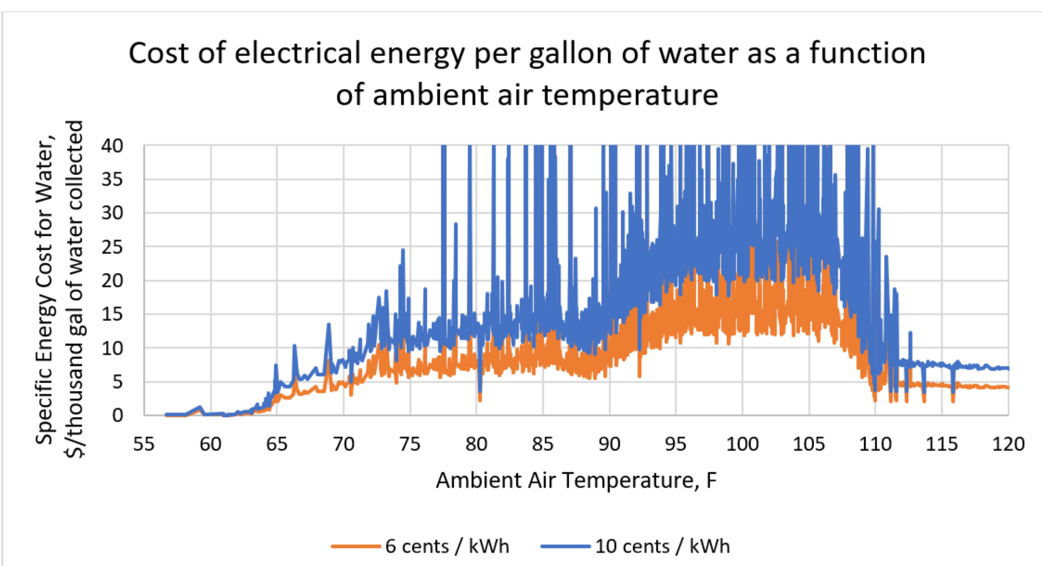
Water costs in the U.S. have been rising at an annual rate of 6 percent a year for the last 20 years. This will improve the economics of the water recovery technology in the future.

Ambient air used in the water recovery process is preheated to 130°F (54°C) to 160°F (71°C). Using this preheated air for combustion can save 2 to 3 percent of the furnace natural gas cost, another cost benefit of this water recovery technology.

Valuable water, particularly in Western States can be saved for other purposes instead of many industrial processes. While this is not an economic benefit of the water recovery process, it is a social benefit of this technology.

A full techno-economic analysis is required. While cost savings on an on-going energy cost basis clearly show the savings realized using this water recovery technology, the capital cost, and maintenance of the technology must also be considered. That techno-economic analysis is underway. Preliminary estimates have found the capital and maintenance cost is balanced against less than five years of energy cost savings. The project team believes process improvements can significantly reduce this payback period.

Figure 33: Electricity Cost per Gallon of Water as a Function of Ambient Air Temperature



Credit: Gas Technology Institute

CHAPTER 4: Technology Transfer Plan

The project team has successfully demonstrated water recovery at 80 gallons per hour over a six-month demonstration period. The demonstration was carried out at the USG wallboard plant in Plaster City, California. Water recovery efficiency improves with decreasing ambient air temperature. This is because the power needed for ambient air fans decreases as temperature drops. Using electricity prices of either 6 or 10 cents per kWh, the energy cost to produce water is found to be lower than the cost of purchased water at ambient air temperatures of 73°F (23°C) and lower.

Future development work will involve scaling the technology up and down for different market applications. Other work is needed to engineer the system so capital cost is minimized and maintenance cost is as low as possible. The engineered system will then be packaged and made available through a vendor to companies that can benefit from the water recovery and energy savings. Possible customers in California and across the country have been identified in a broad range of furnace operations in industry (die casting, foundries, minerals and ore processing, various chemical and petrochemical processes), agriculture (drying, roasting), and commercial cooking (bakeries, general cooking, chips, brewing). Scales are different from one industry segment to another, but the water recovery technology is highly adaptable and can easily be sized for all commercial and industrial applications. Hundreds of potential locations exist in California alone. Installing the water recovery technology in 100 California facilities of similar size to the demonstration furnace will result in savings of 35 million gallons of water per year, equivalent to a water recovery of 40 gallons per hour at each facility. At a savings of $5 to $10 per thousand gallons of water, the California savings from CLEAR technology deployment would be $200,000 to $400,000 per year. This savings will also help industry to be more competitive, lower natural gas demand, and reduce production along with the release of carbon dioxide.

The water recovery technology is adaptable and scalable. The heart of the technology is a series of thermal ejectors that use ambient air to cool the exhaust gas to condense water in the exhaust gas. The amount of water to be recovered is a function of ambient air conditions and the amount of water contained in a flue gas stream. A number of companies inside and outside of California specialize in fabricating, selling, and supporting recuperators for industrial applications. These companies are potential suppliers of the water recovery technology. The project team is preparing materials to present to these organizations to form a licensing arrangement. The goal is to license the water recovery technology to an aggressive company that will sell and service water recovery systems in California (and throughout the U.S.). Guidelines will be provided to enable water recovery systems to be properly sized based on ambient air temperatures ranges.

Along with direct communications with heat exchanger companies, the project team will communicate the benefits of the water recovery technology through several routes. These will include:

- The CEC final report
- The Utilization Technology Development (UTD) final report sent to natural gas company members of UTD
- Technical papers
- Conference presentations
- Discussions with vendors and heat exchanger companies at trade shows
- Summary sheets providing data on the characteristics of the radiative recuperator with secondary emitters technology

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
%v/v	percent volume/volume
acfm	actual cubic feet per minute
CEC	California Energy Commission
CFD	computational fluid dynamics
CLEAR	Clean Liquid Water by Ejector-Assisted Recovery
COP	coefficient of performance
dscf	dry standard cubic feet
dscfm	dry standard cubic feet per minute
ECS	ejector cooling system
ERS	ejector refrigeration system
ft/min	feet per minute
GTI	Gas Technology Institute
HMI	human-machine interface
HX	heat exchanger
kWh	kilowatt-hours
kWh/gallon	kilowatt-hours per gallon
PLC	programmable logic controller
T	temperature
U.S.	United States
USG	United States Gypsum Corporation
USSR	Union of Soviet Socialist Republics
UTD	Utilization Technology Development
Wilson	Wilson Engineering