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FINAL PROJECT REPORT

Compressed Gas Full Fills With a Complete Smart Fueling System

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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

Compressed Gas Full Fills with a Complete Smart Fueling System is a final report for the Developing Innovative Low Emission Natural Gas Engine and Vehicle Technology for Medium- and Heavy-Duty Vehicles project (500-18-003) conducted by National Renewable Energy Laboratory. 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 research project demonstrated improved full fills of compressed natural gas (CNG) vehicles using vehicle monitoring and data transmission technology. This technology communicates fuel status to the station, where a smart dispenser and station controller receive data from vehicles to more accurately control CNG fills; a pre-cooling expander then applies the pressure differential between the vehicle and stationary storage to cool the CNG beyond a typical Joule-Thomson cooling. Together, these technologies enabled the station to safely add more fuel to the vehicle before the pressure limits of the CNG tank were reached. By eliminating under-filling, it may be possible to reduce the number of high-pressure storage vessels onboard a CNG vehicle resulting in a reduced capital cost of between 5 percent and 25 percent.

The vehicle monitoring system included a temperature sensor in each storage vessel in addition to the standard pressure sensor already in most vehicles. The data were then monitored and transmitted using a Wi-Fi transmitter. The smart station controller monitored all nearby vehicles with Wi-Fi transmission capability while simultaneously monitoring all station dispensers. While the team was unable to reprogram a commercial dispenser, the project validated the smart controller's capability to enable more complete fills by providing the dispenser with a new filling target using this real-time transmission of vehicle data.

The pre-cooling piston expander was controlled by linear motors and generators. The motors controlled the speed and stroke of the piston expander to adjust the flow-rate of gas to the vehicle. The expander reached peak efficiencies of 73 percent with hydrogen and about 40 percent with CNG. Furthermore, the project demonstrated that the expander is a net positive energy producer and could lower the energy costs of CNG and hydrogen fueling stations by offsetting some of the power consumed by the compressor.

Keywords: compressed natural gas, hydrogen, full fills, expander, chiller, communications, smart dispenser

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Executive Summary

While utility-served natural gas plays a small role as a transportation fuel in California, that gas demand for the natural gas vehicle (NGV) sector is expected to grow nationally at an annual average rate of 2.3 percent in 2024. Programs including the Low Carbon Fuel Standard and the federal Renewable Fuel Standard incentivize the use of biomethane in NGVs from waste streams such as landfills, wastewater treatment plants, municipal solid waste, and dairies to decarbonize the transportation sector. However, the California Air Resources Board's recently adopted Advanced Clean Fleets Regulation will phase in zero-emission technologies across vehicle fleets over the next two decades. A decline in fossil gas and biomethane as a transportation fuel is expected in the long term as fleets comply with this regulation. Natural gas vehicle adoption in interim years may still occur, however, so research to improve the efficiency, cost, and performance of natural gas engines can still deliver near-term benefits for applications where zero-emission vehicle options are not yet available.

Project Purpose and Approach

A major barrier to NGV adoption is its higher initial cost (compared with diesel vehicles) from required on-board fuel storage and handling components. Compressed natural gas (CNG) on-board storage systems are also routinely over-sized because of difficulties in completely filling the cylinders. In a typical station, CNG vehicles are filled from either stationary storage at around 4,200 to 4,500 pounds per square inch (psi), or directly from a CNG compressor. The gas from the station flows into the vehicle, where it is recompressed by additional gas flowing into the cylinder. The goal of this process was to get enough gas in the cylinder so that it settled at 3,600 psi at 70 degrees Fahrenheit (21 degrees Celsius). However, the temperature of the cylinder changed throughout the fill, which created additional uncertainties.

Current dispensers can only indirectly measure the pressure onboard a vehicle, so provide incomplete information about the state of the vehicle fill; this makes it impossible to fill gaseous vehicles accurately and consistently to 100 percent. This challenge is made even more difficult since the fuel onboard the vehicle heats up due to recompression. This recompression makes measuring the quantity of fuel onboard the vehicle even more difficult and can also prevent full fills entirely on warm days when the vehicle cylinder can reach the maximum pressure limit of 4,200 psi before the vehicle is full. These problems are inherent in the physics of using a gaseous fuel as opposed to a liquid fuel and are tied to changes in temperature when a gas is either compressed or expanded.

This research project addressed both NGV capital costs and the total costs of ownership barriers by developing and demonstrating a smart fueling system with a full suite of technologies that consistently enable NGV full fills. This smart fueling system could also ease the technical challenges of both dispensing uncertainties and the heat of compression from consistently underfilling NGVs. By eliminating underfilling, it may be possible to significantly reduce the number of high-pressure storage vessels onboard an NGV, resulting in lower capital costs of between 5 percent and 25 percent. These smart vehicle technologies can also help reduce the number and frequency of vehicle stops for refueling, which would also increase productivity.

The project approach followed by GTI Energy (GTI) and its team members involved developing the hardware to cool the CNG during filling and more precisely determine when a tank is truly full. In parallel, the GTI team developed software that provides communication between a CNG dispenser and the vehicle it is filling. Embedded in the software are new algorithms that use measured temperatures and pressures to control the fill rate. The gas cooling technology includes a unique gas expander system, designed by the GTI team during this project, which uses the cooling effect of gas expansion to cool the gas that is pumped into vehicle tanks.

Key Results

The new hardware and software developed during this project were fabricated and successfully demonstrated in a GTI laboratory. When combined, these technologies can improve the quality and consistency of CNG fills which, based on industry experience, can currently be underfilled by 10 percent to 25 percent using existing dispensers and fueling technologies.

The expander that was developed and tested was a first-of-its-kind design that utilized a large linear motor to control and produce power as gas expanded at pressures up to 12,000 psi for hydrogen and 6,000 psi for CNG. The expander constantly adjusted the expansion ratio to maintain efficient expansion of the gas stored at a CNG or hydrogen fueling station as it flowed into and filled the target vehicle cylinders. The expander reached thermal efficiencies as high as 73 percent and produced power at efficiencies between 50 percent and 60 percent. Compared with conventional precooling technologies using vapor compression refrigeration systems that consume power and must run regularly to keep the coolant and heat exchangers cold, the expander is a promising alternative because it is a net producer of power and supplies cold gas instantly upon startup using the high-pressure differential that already exists between the station and the vehicle storage cylinders. While these are promising preliminary results, both efficiencies can be further improved by optimizing both some of the components and the operating characteristics of the expander design.

The smart station components successfully demonstrated that communication between an NGV and the fueling station could increase full fills across a broad spectrum of conditions. The communication equipment enabled the use of the expander (or other cooling technologies), which help lower the delivered gas temperature to the vehicle. Without this communication, it would be difficult or even impossible to accurately determine the filling state onboard the vehicle.

Knowledge Transfer and Next Steps

These positive research results will continue to be shared with vehicle dispenser manufacturers and fleet owners through published reports, papers, journal articles, and through presentations and meetings with both vehicle manufacturers and users. This included presenting the technology to stakeholders at the Natural Gas Vehicle Technology Forum (2021 and 2023) and speaking to stakeholders about the project benefits at the Advanced Clean Transportation Exposition, which GTI attends annually. The team also worked with multiple dispenser manufacturers and vehicle integrators about the smart station components and the significant benefits of precooling.

The benefits to California from this technology and the wider use of NGVs in medium-duty and heavy-duty fleets will be cleaner air (from reduced emissions of nitrogen oxides and particulate matter compared with diesel emissions) and lower greenhouse gas emissions from biomethane. Additionally, the smart dispenser and vehicle technology has applications for emerging zero-emission hydrogen fuel cell vehicles as a possible alternative to line-of-sight communication, which can be expensive and easily damaged. The expander was also tested as a direct replacement to commercial hydrogen chilling systems with high capital and operating costs. By implementing these technologies for hydrogen, the capital and operating costs for hydrogen stations could be reduced.

CHAPTER 1: Introduction

While utility-served natural gas plays a small role as a transportation fuel in California, gas demand for the natural gas vehicle (NGV) sector is expected to grow nationally at an annual average rate of 2.3 percent in 2024 (SoCalGas et al., 2022). Programs such as the Low Carbon Fuel Standard and federal Renewable Fuel Standard incentivize use of biomethane derived from waste streams such as landfills, wastewater treatment plants, municipal solid waste, and dairies to decarbonize the transportation sector. However, the California Air Resources Board's recently adopted Advanced Clean Fleets Regulation phases in zero-emission technologies across vehicle fleets over the next two decades. A decline in fossil gas and biomethane as a transportation fuel is therefore expected in the long run as fleets comply with this regulation. NGV adoption in interim years may still occur, however, so research to improve the efficiency, cost, and performance of natural gas engines can still have near-term benefits for applications where zero-emission vehicle options are not yet available.

A major barrier to NGV adoption is its higher initial cost when compared with diesel vehicles due to its required on-board fuel storage and handling components. This project addressed this barrier by developing and demonstrating a smart fueling system that included a full suite of necessary technologies that enable consistent NGV full fills. These technologies include a smart vehicle and dispenser, an advanced full fill algorithm, and cost-effective gas pre-cooling (using a near-isentropic-free piston expander/compressor). This combination of technologies sought to solve the technical challenges of both dispensing uncertainty and the heat of compression from underfilling. By eliminating underfilling, it may be possible to significantly reduce the number of high-pressure storage vessels onboard a natural gas vehicle, which could reduce capital costs by between 5 percent and 25 percent.

CHAPTER 2: Project Approach

This project was conducted with oversight from the National Energy Renewable Laboratory, which led a consortium of the United States Department of Energy, the California Energy Commission (CEC), and the South Coast Air Quality Management District. The project team included staff members from GTI Energy (GTI) and the University of Texas Center for Electromechanics. It was divided into three technical tasks, with multiple subtasks.

Expander Compressor Simulation and Design

The objective of this task was to complete the preliminary design and analysis of the expander/compressor and smart compressed natural gas (CNG) station.

The project team developed a dynamic simulation of the expander/compressor in MATLAB Simulink, a graphical programming environment for modeling, simulating, and analyzing multidomain dynamical systems, to evaluate the performance and control strategies of the expander/compressor components and assembly. Tradeoffs such as expander diameter, stroke length, and frequency were evaluated to maximize system efficiency, as well as a control methodology for valves and other electronic components on the system. This simulation was integrated into the smart station simulation to evaluate performance in several filling scenarios.

The project team developed and analyzed a solid model of the expander/compressor to determine the mechanical and thermal performance of both key components and the full system. Performance analyses of these components were then fed into the simulation to both refine their accuracy and better estimate expected system efficiencies.

Key components such as valves, actuators, and seals were designed and integrated into the expander solid models. These critical components underwent extensive thermal and structural finite-element analysis to ensure they could handle the required pressures and temperatures expected in the expander, as well as computational fluid-dynamic analysis to minimize pressure drops and efficiency losses within the expander.

A test apparatus for testing and validating the performance of key components was then designed and built. This test apparatus validated and improved the performance of these components. Results from this testing were used to improve assumptions in the simulation.

Lastly, an economic analysis of the expander/compressor was conducted to determine whether the cost and expected performance of the system provided value for the NGV industry. Assumptions made about the savings and benefits of the expander/compressor were validated using industry input from project partners to ensure the soundness of the analysis.

Component Testing, Detailed Design, and Fabrication

Key components such as the expander inlet and outlet valves were tested to validate that their performances met expected requirements. Testing included flow, leaks, durability, and other critical design criteria that directly impacted the performance and efficiency of the expander/compressor; communication components for the smart vehicle and dispenser were also selected and tested.

A prototype version of the control system was tested using bench-scale and key components just described. The testing validated that the components operated accurately and within the timeframe necessary to both meet the simulated performance and efficiently control the expander/compressor.

The testing and analysis data of the controls and key components were used to improve the solid models and refine the simulation used to estimate full system performance and efficiency. Results from the refined simulation and key component analysis were used to make final design improvements to the expander before finalizing the detailed design.

Major components of the expander/compressor and smart station were then purchased, and the expander/compressor fabrication, assembly, and installation began. This included the necessary data acquisition used to validate the performance and efficiency of the expander/compressor.

Commission, Testing, and Demonstration

The expander/compressor was commissioned. This process included testing and verification to ensure that individual components such as control valves, data acquisition, and safety features of the test loop were operating properly. This also included simulating fault conditions to ensure that tests shut down safely if an error occurs.

The test loop and expander/compressor were pressure- and leak-tested using nitrogen. Following successful pressure and leak testing, the expander was operated at low pressures to verify the performance and operation of the full test loop.

Following successful commissioning and inert gas testing, the system was tested using natural gas in a smart CNG station. The testing slowly ramped up operating pressures to ensure the expander/compressor was operating safely and efficiently in a range of test conditions. Steady state efficiencies were measured and recorded for each of the test conditions. Testing continued until the unit was tested at full design pressure and flow rates.

The fully verified expander/compressor was then used within the smart CNG station to fill a test vehicle from near empty to full to verify that the dynamic performance of the expander/compressor met project targets and could deliver a full fill under extreme operating conditions.

CHAPTER 3: Results

Expander Compressor Simulation and Design

The objective of this task was to complete the preliminary design and analysis of the expander/compressor and smart CNG station.

Simulate Performance and Control of Expander Compressor in Smart Station

A major goal of this task was to develop and simulate a novel CNG expander that could be used to pre-cool CNG before it is pumped into an NGV, with the goal of achieving fuller fills. The use of an expander is attractive because it can produce power, offsetting the power consumed by the compressor (instead of adding to the station's power consumption by using a traditional chiller).

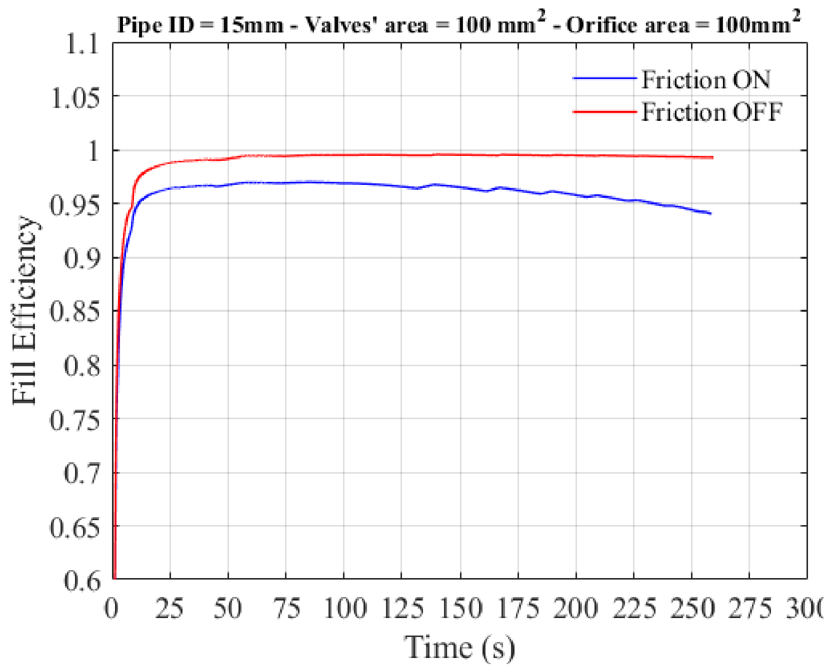
The team created a thermodynamic simulation in MATLAB Simulink using real gas properties from the National Institute of Standards and Technology's REFPROP computer program. The simulation used a high-pressure gas supply to feed CNG into two opposing expansion chambers through controlled inlet and discharge valves. A controlled amount of gas first enters the expansion chamber at high pressure through the supply valve. The supply valve then closes so the gas can expand as the piston increases the volume of the expansion chamber. After the gas is fully expanded, the discharge valve is opened, and the piston pushes the gas out of the expander. The gas then flows to a simulated vehicle, entering an adiabatic (occurring without either loss or gain of heat) cylinder.

At the start of the project, the team simulated an expander efficiency of about 75 percent, though the goal was to achieve nearly 100 percent efficiency with a lossless expander before calculating and adding in losses. Reaching 100 percent ensured that both the simulation's thermodynamics and controls were working properly.

Valve timing was identified as a likely cause of the low efficiency, so the team focused on refining the valve control equations to minimize losses caused by under- or over-expansion. These valve equations were critical to the system operation because they calculated how much mass must enter the expansion chamber to achieve ideal expansion. In other words, the gas pressure in the expansion chamber would start at the inlet pressure and end at the discharge pressure just as the piston reached bottom dead center. That way gas would not enthalpically flow in or out of the expander when the discharge valves opened, resulting in efficiency losses. Ultimately the team achieved a maximum simulated isentropic efficiency of about 99 percent, seen in Figure 1. The team determined that this efficiency is sufficient to demonstrate that the nearly lossless simulation and expander controls were working properly. The remaining 1 percent of losses was likely a combination of unavoidable valve pressure drop in the simulation design and some remaining valve timing issues that were nearly impossible to eliminate due to the highly dynamic operation of the expander and the wide range of operating pressure ratios as the vehicle was filled.

Figure 1 shows the lossless simulation of expander efficiency compared with the simulation, with friction added. The frictionless expander achieved an efficiency of 99 percent, while the addition of friction dropped the efficiency to 94 percent.

Figure 1: Lossless Simulation of Expander Efficiency



Source: GTI

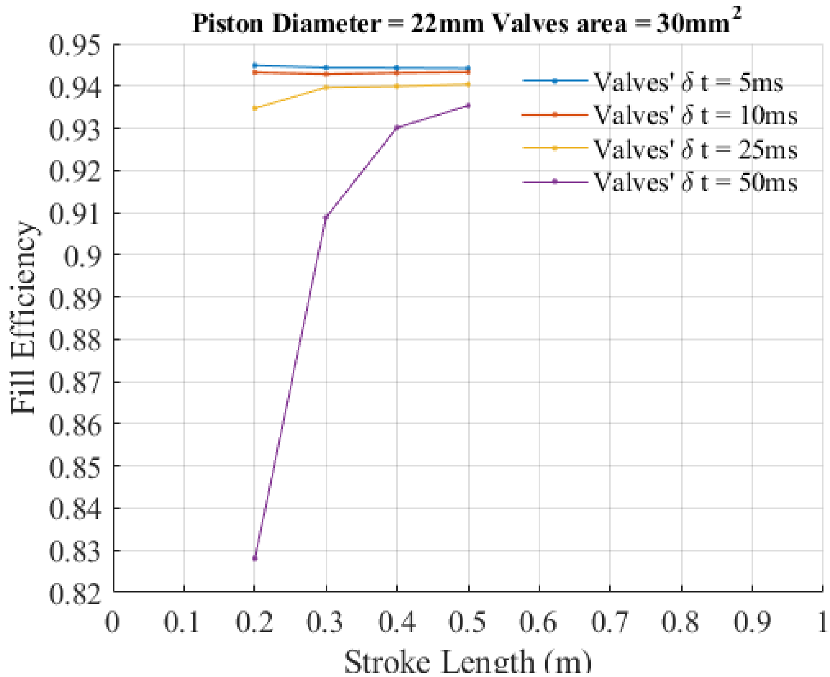
Following the successful simulation of the nearly ideal expander, the team introduced realistic friction, heat transfer, and other real-world losses expected to impact operation of the expander when filling a vehicle. The team also integrated system dynamics including inertia and motor-control forces. These variables were evaluated across a wide range of dynamic operating conditions to optimize design of the full-scale expander and aid in the selection of components such as linear motors, valves, and seals.

The team continued to simulate the dynamic performance of the expander. Using the best estimates available for dynamic forces such as friction, inertia, and valve pressure drop, the team simulated the performance of the expander across a range of operating conditions to reach the preferred design. Using the results from the simulation, the team decided to move forward with a design that used a stroke length of 500 millimeter (mm) and an expander piston diameter of 22 mm.

The 500 mm stroke length was selected based on results from an analysis that examined the impact of valve timing and speed on the performance of the expander. Based on this analysis, the 500 mm stroke length maintained relatively high levels of efficiency even with relatively slow valves requiring 50 milliseconds (ms) to open or close. Considering that the valve performance was an unknown variable at this point in the project, the team decided to start with a conservative, longer stroke length. If during testing the team determined that the valves could be actuated faster than expected, it will be possible to shorten the stroke length of the expander, which would help shorten the overall length of the expander assembly.

Figure 2 illustrates the impacts of valve timing and stroke length on the efficiency of the expander. Faster valves perform better than slow valves. Increased stroke length can also improve the performance of the slow valve since they have more time to actuate.

Figure 2: Valve Timing and Stroke Length Efficiency

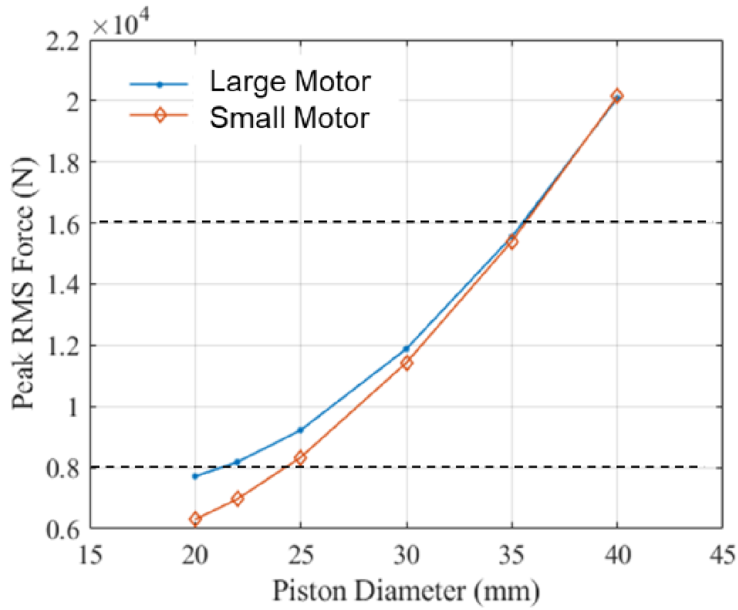


Source: GTI

Following the decision to operate using a 500 mm stroke length, the team focused on the expander diameter. At any given stroke length, the expander will operate at a fixed speed regardless of the fluid end diameters, so the diameter directly impacts both the flow through the expander and the force exerted on the motors. The goal of the analysis was to maximize the diameter in order to maximize the flow without exceeding the limits of the motors. The team ran a range of cases using diameters from about 20 mm to 40 mm. These were compared with the motor limits to determine the optimal fluid end size. Based on the analysis, the team believes the 22 mm diameter provides the best compromise between flow and motor performance. As pictured in Figure 3, the large motors should be able to operate right at their air-cooled limit (lower dotted line) while providing the maximum flow possible. The decision to operate at the air-cooled limit was made because that allowed the team to maximize the performance of the motors while simplifying the system design. However, the design also has some safety factors built in because the team can still liquid cool the motors if they overheat. This ensured that the team could fully test the design even if the real-world loads on the motors were slightly higher than the simulation.

Figure 3 shows the simulation of two motor sizes. Large motors were selected to maximize the performance using an air-cooled design. A 22 mm piston diameter was also selected to maximize flow.

Figure 3: Simulation of Two Motor Sizes



Small Motors	
Continuous Force	4 kN
Continuous Force Water Cooled	8 kN
Peak Force	20 kN

Large Motors	
Continuous Force	8 kN
Continuous Force Water Cooled	16 kN
Peak Force	40 kN

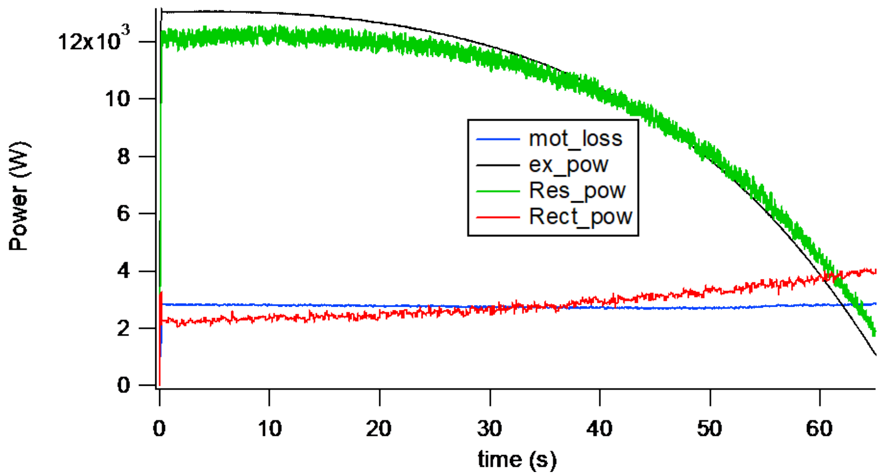
kN=kilonewton; N=newton

Source: GTI

The team further refined the simulation by looking closely at the controls and power management during expansion to ensure the motors and drives could handle electrical power requirements. This analysis included the wall power supplying the motor controllers that rectify the alternating current supply to direct current (DC). The DC power was supplied to the linear motors using insulated-gate bipolar transistors (IGBT) and a proprietary control loop that controlled the current and motion of the motors. The detailed expander dynamics and motors controls were simulated together to estimate either the true power draw or the power generation of the system.

Results from the power analysis indicate that the expander produces power. For the purposes of this project, that power was rejected using two large power resistors attached to the motor drives. Rejecting the power simplified the system design for testing; however, in the future the power can be either supplied to the CNG compressor or returned to the grid. Figure 4 shows averaged powers from the primary expander power systems. These include input power from the wall (red), expander power (black), motor losses (blue), and net power produced (green) that will go to the power resistors. Other minor losses such as valve pressure drop and friction are not shown.

Figure 4: Averaged Powers From the Primary Expander Power Systems



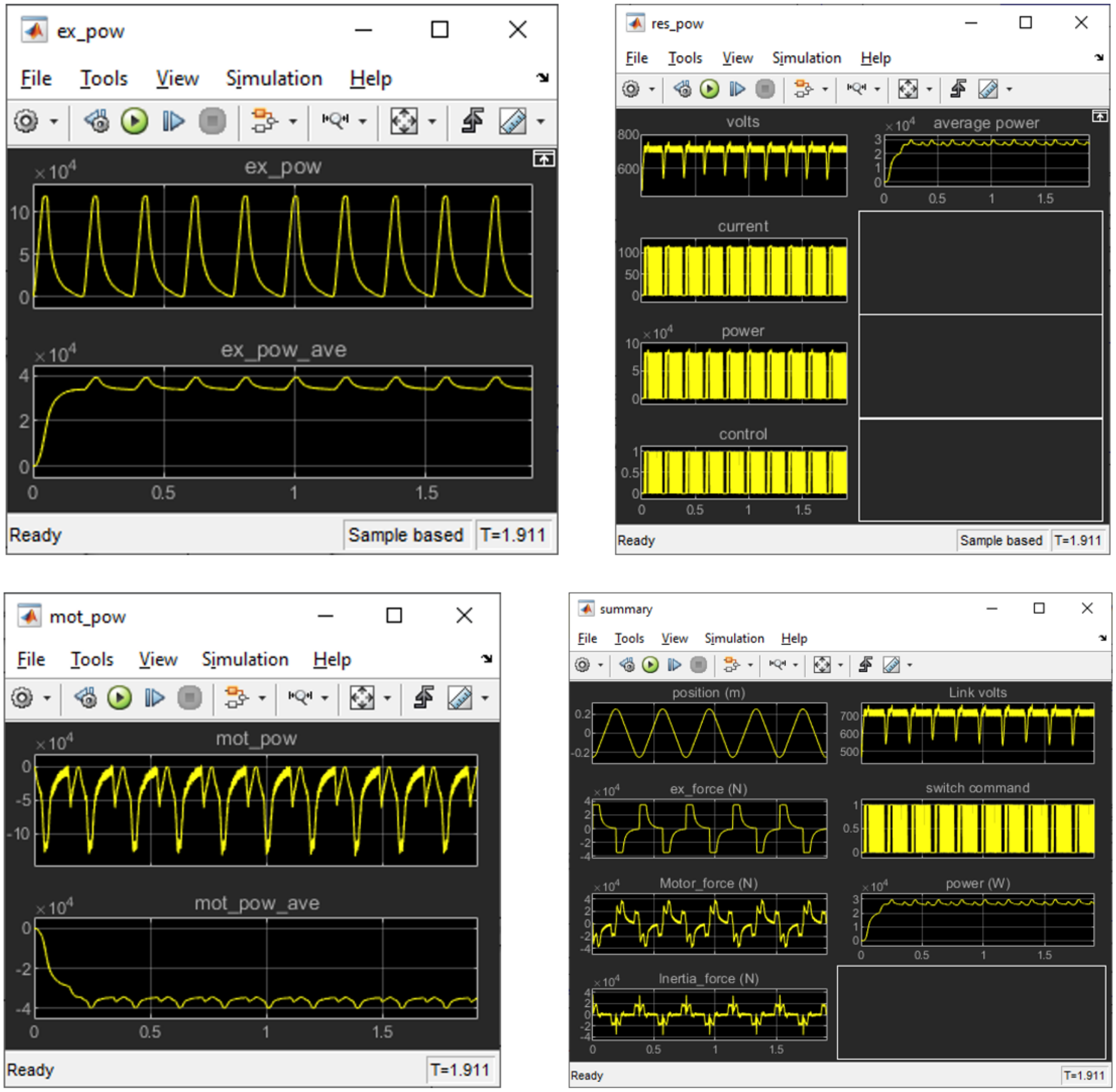
s=seconds; W=watts

Source: GTI

The team also evaluated the detailed performance of power systems, which are summarized here and pictured in Figure 5. The expander generates large power spikes as the high pressure CNG pushes on and moves the expander piston. The energy from the expander is converted to electrical energy by the movement of the motor. This energy produced by the motor is temporarily stored in a DC bus capacitor, causing the voltage to rise until the bus voltage limit is reached. At that time IGBTs are used to siphon off excess energy from the bus to the power resistors that dissipate the excess energy as heat. The system input power is very low at the beginning of the fill because the expander is producing enough excess energy to supply the motor; however, the input power isn't zero because there are brief moments when the expander is not producing energy to supply the motors, though the motors still require energy to move and control the system.

While this analysis looks very promising, and the team demonstrated during preliminary testing with nitrogen that the system can produce power, the performance and efficiency of that power generation still needs to be tested, measured, and verified in the lab.

Figure 5: Detailed Performance Plots for the First Two Seconds of Expansion



Source: GTI

The team developed a simulation that included a constant pressure supply of CNG to a simulated expander, which removed energy from the gas as it dropped in pressure before flowing through a simulated dispenser and into the vehicle. This simulation did not represent every CNG station since some stations have a 3-bank cascade to fill vehicles; however, the team believes it is a reasonable representation of larger CNG stations that directly fill vehicles from the compressor. These stations will benefit the most from an expander since compressed gas exiting a compressor is typically hotter than ambient and the vehicles being filled have larger storage volumes that will reap greater benefits from improved full fills.

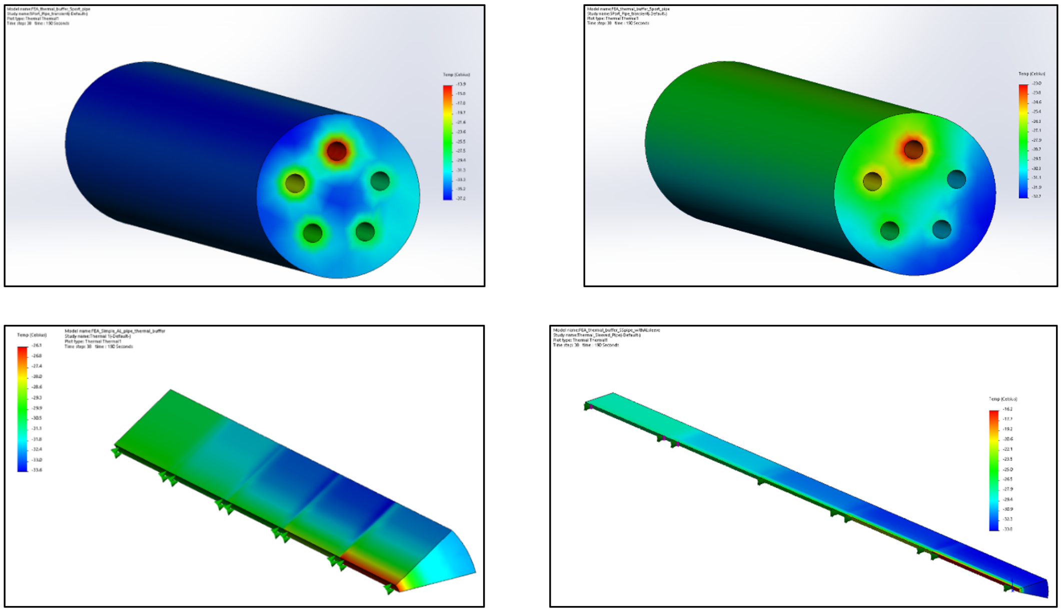
In addition to the components described above, the team focused on the integration and simulation of a thermal buffer necessary to keep the expander's discharge temperature above -40 degrees Fahrenheit (°F) (-40 degrees Celsius [°C]). At the beginning of a fill, the large expansion ratio resulting from high supply pressures (~4,500 pounds per square inch gauge [psig]) and a low vehicle pressure (~250 psig) can cause the gas exiting the expander to be extremely cold. This cold gas could potentially damage components in the dispenser or the vehicle. To address this issue, the team plans to integrate a thermal buffer to transfer heat to the gas at the beginning of the fill, keeping the gas above the -40°F (-40°C) limit for most components before removing heat from the gas at the end of the fill when the gas expansion ratio has been reduced. The thermal buffer essentially consists of a small block of steel or aluminum that adds the needed mass to maintain the gas discharge temperature above the thermal limit of the downstream components. An advanced version of this design may include a calibrated phase change material that will add additional thermal capacity to the thermal buffer.

The team worked to optimize mass, surface area, and buffer materials to ensure the gas exiting the buffer was warmer than the -40°F (-40°C) limit on many station components, while also ensuring that the expander efficiency remained high enough to improve full fills. Striking this balance between efficiency and maintaining a warm enough discharge temperature has proved difficult using a passive thermal buffer. In the perfect scenario the thermal buffer would cool off at the beginning of the fill as it keeps the coldest gas above -40°F (-40°C), then warm back up at the end of the fill as warm gas from the station is precooled before entering the vehicle. Ideally, the starting and ending temperature of the thermal buffer are equal to ensure it is not either gaining or losing energy. However, variations in filling conditions (such as the vehicle's volume or starting pressure) make it nearly impossible to ensure that the thermal buffer ends at the temperature where it started.

An alternative to a passive thermal buffer might be a buffer with some active control of the discharge gas temperature. This control might be achievable using a few different strategies. One strategy might be to lower the expansion ratio of expander to prevent overcooling the gas. This could eliminate the need for a thermal buffer altogether but would also reduce the cooling potential of the expander as it would not be utilizing the full pressure drop between the compressor discharge and the vehicle's tank. Another option might be to control the flow through the thermal buffer using control valves used to target an ideal discharge temperature from the thermal buffer. Lastly, it might also be possible to direct a portion of the station's flow past the expander completely and mix that gas with the cold gas coming from the expander to ensure it isn't too cold for either the dispenser or vehicle components.

The team developed a computation fluid dynamics (CFD) model of the thermal buffer. This model was built in Solidworks and was used to better estimate the performance of the thermal buffer mass and heat transfer area throughout the fill. The CFD model was supplied with the mass flow and discharge temperatures from the dynamic MATLAB Simulink simulation. The heat transfer to the thermal buffer was then calculated within Solidworks. Some results from the CFD analysis are shown in Figure 6. Two designs were explored. The first was a short cylindrical design with multiple gas passages drilled through the body to efficiently utilize the mass of the cylinder. The second design was a single tube with a thick wall so only one pass is required. While the preliminary results show some promise that the designs can effectively buffer the expander's discharge gas temperature, the team is continuing to work on validating the CFD to ensure that those results are accurate.

Figure 6: Sample CFD Analysis of the Thermal Buffer



Source: GTI

Preliminary Expander Compressor Design

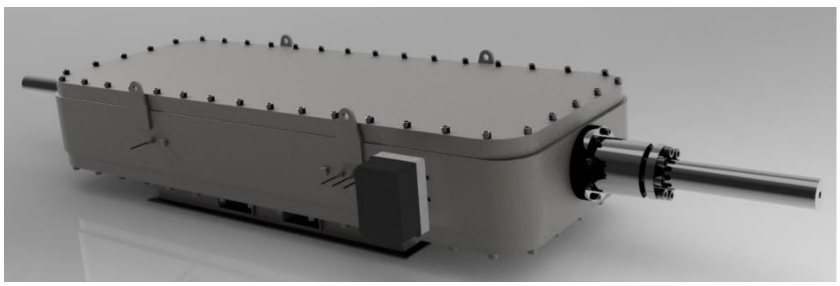
During the preliminary development and setup of the simulation, the team needed to make a few assumptions about the design and operation of the expander. For starters, the team needed to decide if the compressor and expander would be mechanically or electrically linked to each other. During the proposal phase, the team was leaning towards a physical connection between the two devices to improve efficiency; however, after some additional analysis the team decided to separate the compressor and expander so that they are only linked electrically rather than physically attached to the same motors.

This decision was made for the following reasons: (1) The complexity of a multi-stage expander/compressor integrated into a single moving shaft introduced unnecessary design complexity and risk into the project. (2) The team originally thought that the compressor force would offset the expander forces, helping to balance the load on the linear motors being used to control the system; however, preliminary simulation of the system indicated that the peak forces will not likely overlap to offset each other in a combined system, resulting in higher motor currents than if they were separated. (3) Mechanically linking the two devices forced them to operate at the same frequency that resulted in imbalanced flow rates during a vehicle fill. This was caused by the fact that an expander operating at a constant frequency will result in an increasing flow as the pressure differential across the expansion pistons decreases. However, the compressor flow at a fixed frequency remains nearly constant because it is a positive displacement device. These issues led the team to make the decision to operate the compressor and expander independently.

Following the decision to operate the expander and compressor separately, the team focused on the preliminary design and layout of the expander fluid ends. This decision to focus on the expander fluid ends was made because the expander design and operation were higher risk than the compressor, which was demonstrated by the team on earlier projects. The team considered a few expander layouts that included, single-acting pistons, double-acting pistons, and one-sided expanders with a spring return, but settled on a single-acting piston design that included one piston located at each end of the motor frame.

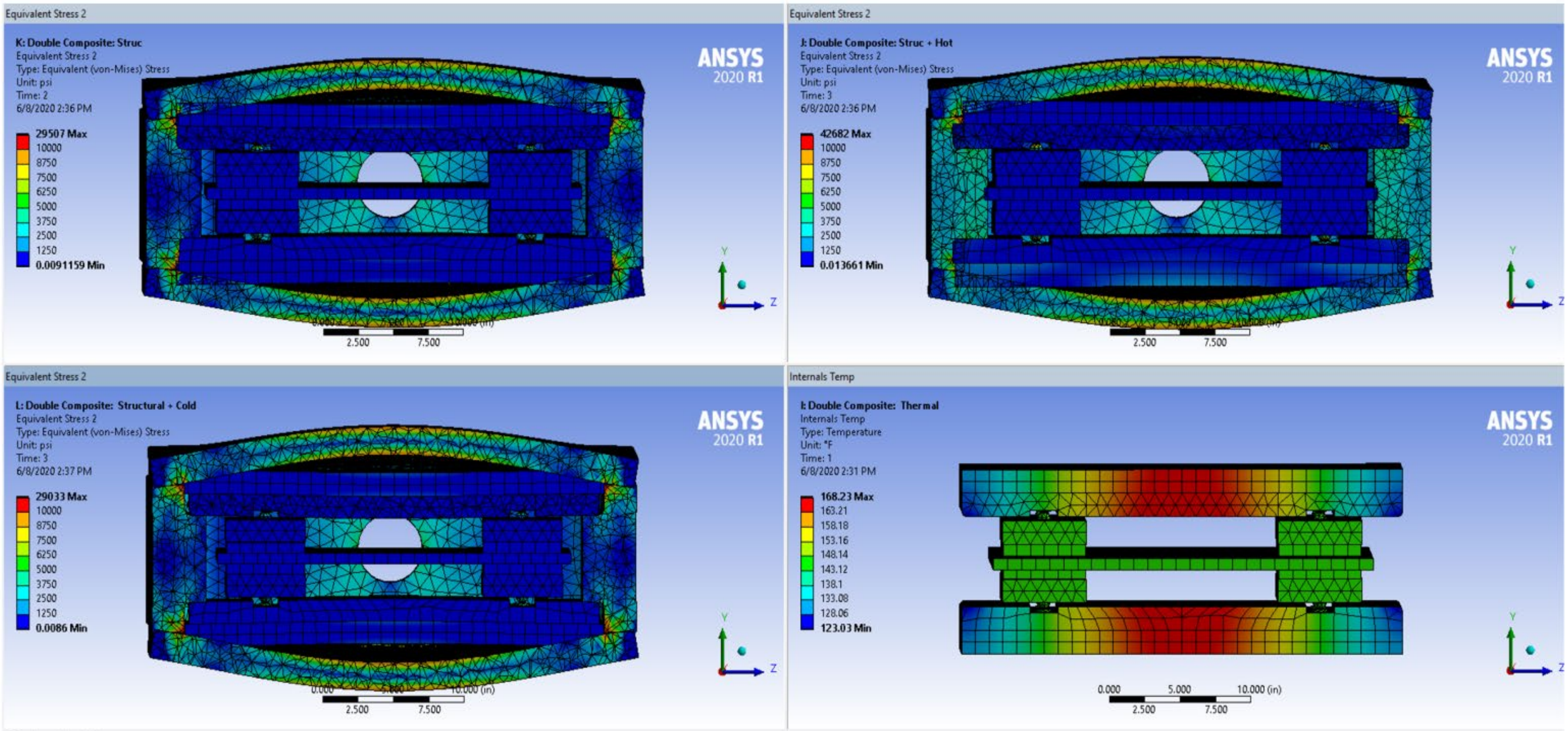
The team advanced the design and layout of the linear motor frame and expander pistons. The design included an oil-free, hermetically sealed motor housing located between the opposing CNG expansion chambers. The team conducted extensive structural and thermal analysis on the motor frame and bearings, ensuring they operated properly across a range of operating temperatures and pressures from -40°F to 140°F (-40°C to 60°C) and up to 100 psig. The design as of Q4 is shown in Figure 7. An example of the finite element analysis (FEA) results is shown in Figure 8. The team conducted a system hazard analysis, followed by a detailed mechanical design review to finalize the design of the assembly to ensure it could be operated safely.

Figure 7: Model of the Expander Design at the End of Q4



Source: GTI

Figure 8: Structural and Thermal FEA of the Motor Frame



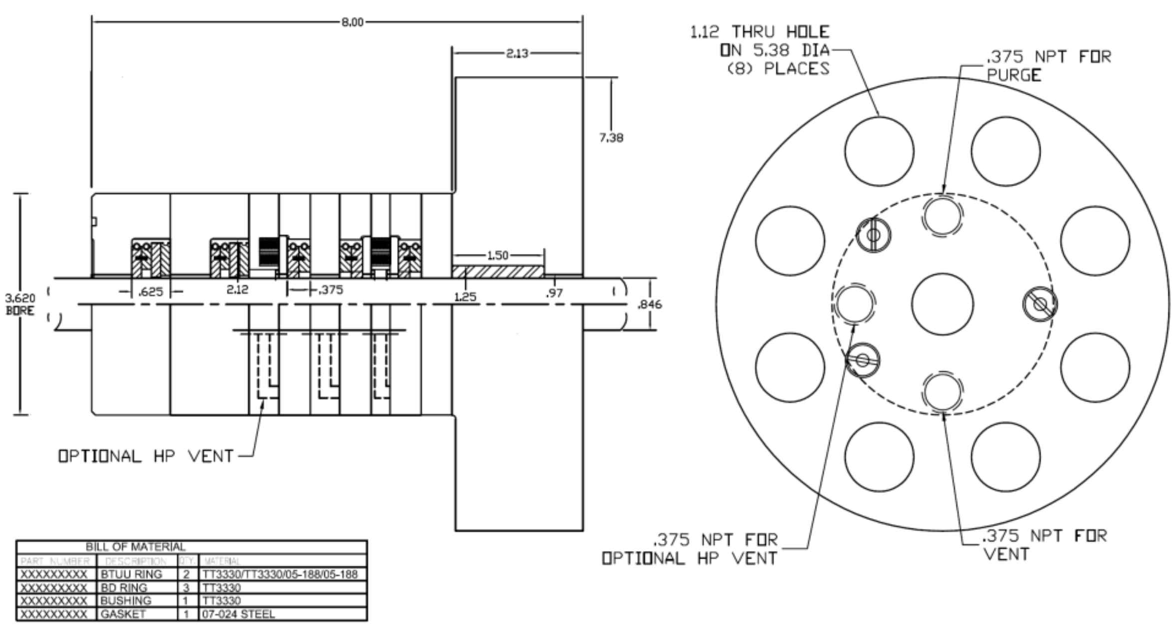
Source: GTI

Key Component Design and Analysis

At the start of the project, the team investigated commercial solutions for some of the key expander and compressor components, including seals and valves. The team believed standard compressor seals could work for the expander and worked with Dover Corporation to develop piston and rod seal designs for the 22 mm diameter piston. The team also identified some high-pressure solenoid valves from Seitz and Clark Cooper that were suitable for the operating pressure; however, the manufacturers expressed concerns about the requested opening and closing times needed to maintain high operating efficiency. In addition to the commercially available valves, GTI also designed custom valves that improve the valve timing while also eliminating one of the solenoids by actuating the discharge valve, using the piston directly.

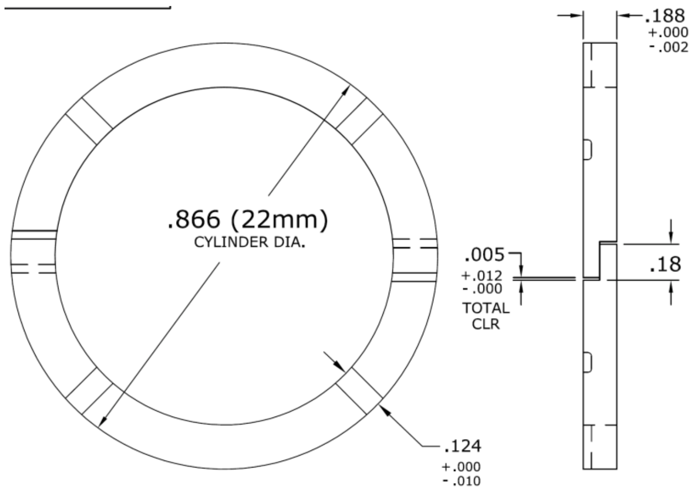
The team contacted Cook Compression, a division of Dover Corporation, which specializes in compressor seals for numerous applications (including for hydrogen and natural gas compressors) as well as polyethylene compressors that operate at pressures up to 10 times higher than at CNG stations. While expansion is slightly different from compression because the temperatures are lower and the pressure profile is reversed, the Cook Compression application engineers believed they could develop a suitable sealing solution. Using the finalized fluid-end dimensions and operating conditions (22 mm diameter piston and 500 mm stroke length), GTI discussed seal options that included piston and rod seal designs. The Cook Compression engineers concluded that either option was possible to manufacture, so the team tried both to see if either had any performance advantages for durability, friction, and efficiency. Drawings of the proposed rod seal design are shown in Figure 9, and one of the piston seal designs is shown in Figure 10. The materials used were a proprietary blend of Teflon™ (a registered trademark of Dupont), but specifically designed for non-lubricated applications.

Figure 9: Rod Seal Gland for the Expander



Source: GTI

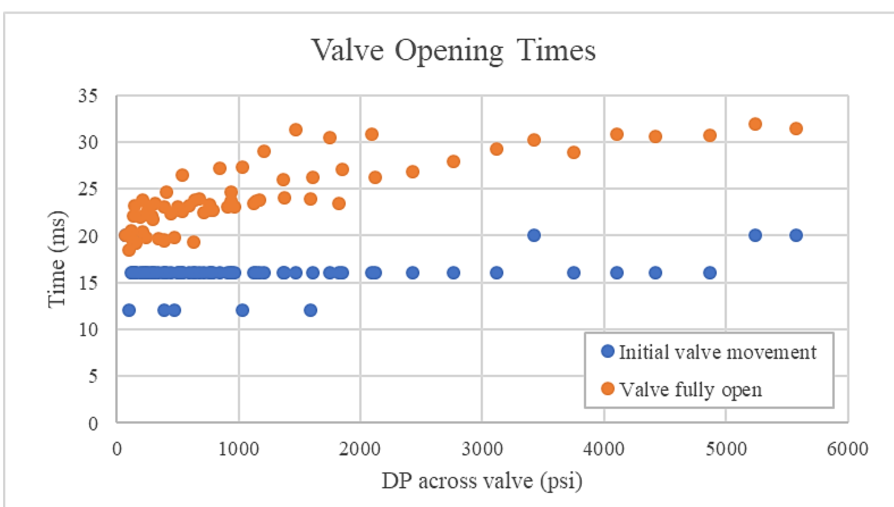
Figure 10: An Example of the Proposed Piston Seal Design



Source: GTI

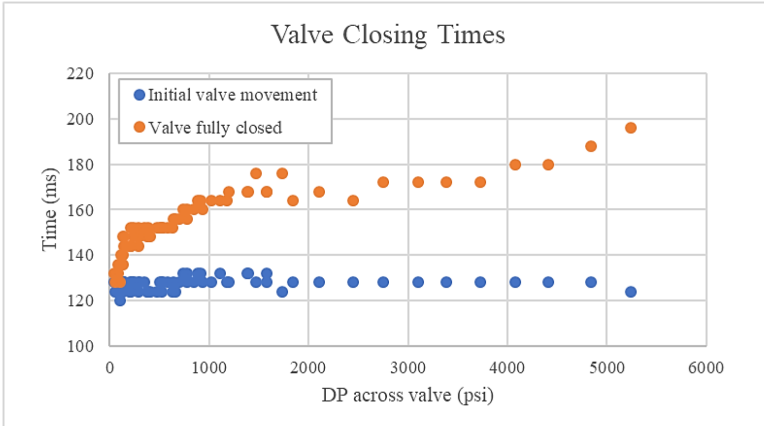
The team acquired some commercial solenoid valves from two commercial valve companies that offer hydrogen and CNG solenoid valves for dispensers. These valves were tested for both their opening and closing times and durability. The valve testing utilized a simple system that connected two fixed volumes with the valve being tested. The valves were leak tested using high-pressure gas and were also tested for durability by actuating the valve at a high frequency for 10,000 cycles. More important to the performance of the expander, the valves were tested for their opening and closing speed and consistency. One of the valves appeared to have very promising performance that was also a good fit for the expander. For starters, the valve consistently began to open in about 15 ms, as shown in Figure 11 and was usually fully open within about 50 ms. This performance was acceptable for the 500 mm stroke length design based on the analysis pictured in Figure 12. However, the valve closing time is a bit slower, requiring about 125 ms to start closing and up to 150 ms to fully close. This was about three times longer than the minimum valve speed.

Figure 11: Valve Opening Timing Plotted Across a Range of Differential Pressures



Source: GTI

Figure 12: Valve Closing Times Plotted for a Range of Differential Pressures



Source: GTI

To improve the valve speed, the team reverse engineered the valves to better understand how they operate. The valves are pilot-actuated solenoids, so the solenoid opens a tiny internal valve that allows gas behind the primary valve element to flow downstream, opening the primary valve element using the pressure gradient between the upstream and downstream pressures across the valve. When closing, the internal pilot valve closes, preventing gas behind the primary valve element from flowing downstream. The primary valve element then closes as the pressure gradient across the primary element equalizes.

After taking the valves apart and running tests, the team was confident that the solenoid was the primary cause of the slow closing time. This is because the solenoid has an internal current that continues after power has been removed from the valve. This current appears sufficient to hold the solenoid open for about 100 ms after power has been removed, preventing the primary valve element from closing. To improve the valve performance the team tested stronger springs that can overcome the solenoid force more quickly than the stock valve spring, as seen in Figure 13. In addition to the new spring, the team also investigated modifications that could be made to the solenoid circuit to speed up discharge times. This included adding a solenoid controller that reduces the solenoid's holding current after the initial opening current has been applied. This reduces the duration of the internal current in the solenoid following removal of the power supply.

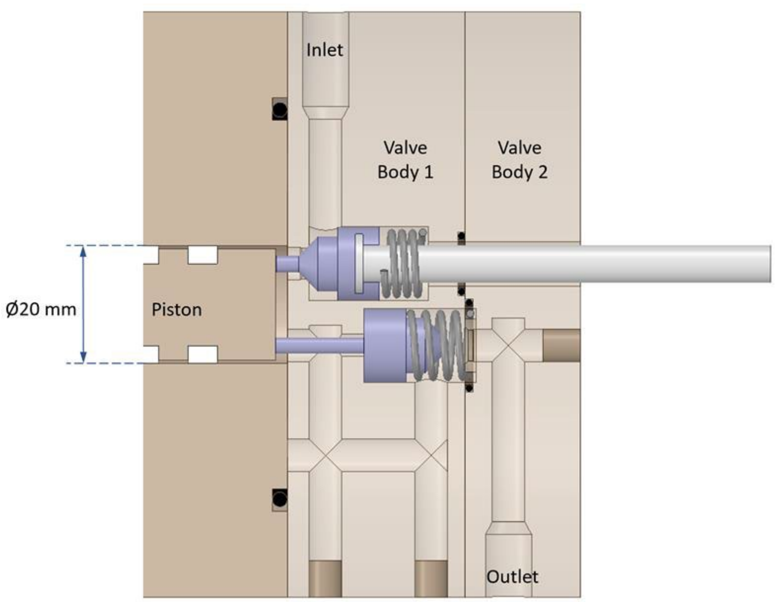
Figure 13: Valve Pilot Element Shown With Spring

Source: GTI

The project team also continued to develop custom valves that meet the fast response times necessary to maintain high operating efficiency. Preliminary solid models of the valves were developed, and the team integrated the characteristics of those solid models into a dynamic simulation of the valve movement when opening and closing. Results from the simulation were then used to improve the custom valve element designs.

The preliminary inlet and outlet valve designs are shown in Figure 14. The inlet valve is on the top of the image and the discharge valve is at the bottom. This design simplifies valve control and improves valve timing by directly controlling the valve with the piston. For example, the inlet valve is designed to be pushed open using the piston and is then held open using a direct actuating solenoid. This allows the valve to be directly opened even when there is a large pressure differential acting on the valve element. The solenoid then simply needs to hold the valve element until the proper amount of gas has been drawn into the expansion chamber. The discharge valve opens using a spring that pushes the valve open at a target pressure differential between the discharge and the expansion chamber. The discharge valve is closed using the piston to push the valve directly when it reaches the end of the expansion chamber. The discharge valve is held closed as the inlet valve is opened. The high expansion chamber pressure then holds the discharge valve closed until the gas has sufficiently expanded, allowing the discharge spring to push the discharge valve open. Using this design, the discharge valve has a passive design and does not require an active solenoid.

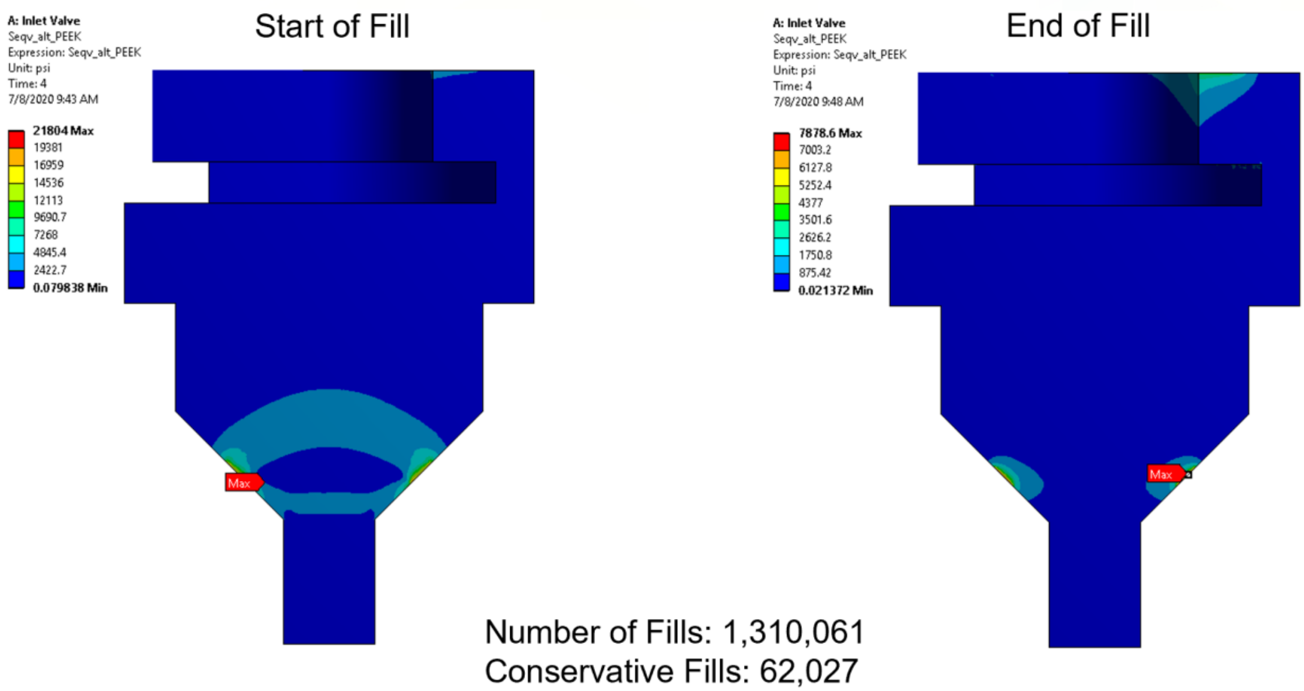
Figure 14: Free Body Diagram of a Preliminary Design of the Expander Inlet Valve



Source: GTI

The team also evaluated the strength of the valve elements using various materials including both virgin and embedded polyetheretherketone materials. Some preliminary results of the inlet valve are shown in Figure 15. These results show the valve stress at the start and end of the fill. Based on the FEA results, the team believes the valves should last for over 1 million fills making the design extremely durable. These results will be tested during the operation of the prototype expander.

Figure 15: FEA of the Inlet Valve



Source: GTI

Design and Build Test Apparatus

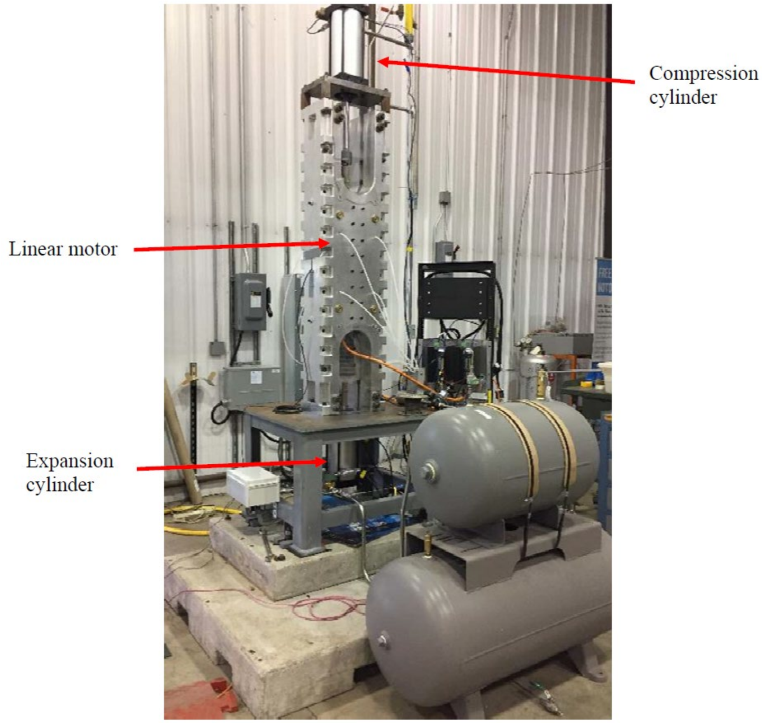
The preliminary testing of the linear motors and controls was completed using an existing test rig that was repurposed before the start of this project. Those test results demonstrated that linear motors can be used to control the linear expander efficiently and accurately. The repurposed test rig is shown in Figure 16. Rather than developing another intermediate test rig, the team developed the full-scale frame design.

The project team developed a full-scale, hermetically sealed linear motor housing, as shown in Figure 16. This design was used to test the operation of the full-scale expander and compressor fluid ends. This testing included the final designs of the valves, seals, and expander/compressor.

The compressor and expander were integrated into an environmentally controlled test loop that enabled the team to test the operation of the system across a wide range of temperatures. In addition, GTI used a variety of target CNG vessels to simulate fills. These vessels were used to test the ability of the expander to increase full fills under a variety of simulated ambient conditions.

The team developed and built the full-scale test apparatus. In late 2019, GTI started construction of a new testing area that built on existing testing capabilities. The new test area has space for several environmental test chambers designed to be suitable for testing, using high-pressure CNG and hydrogen. Cooling and heating of the environmental chambers and supply gas is done using a centralized chiller and heater. The first chamber has a footprint of 12 feet by 20 feet, which enables GTI to test full-scale compressors, dispensers, and other prototype equipment such as expanders.

Figure 16: The Nitrogen Expander Test Rig



Source: GTI

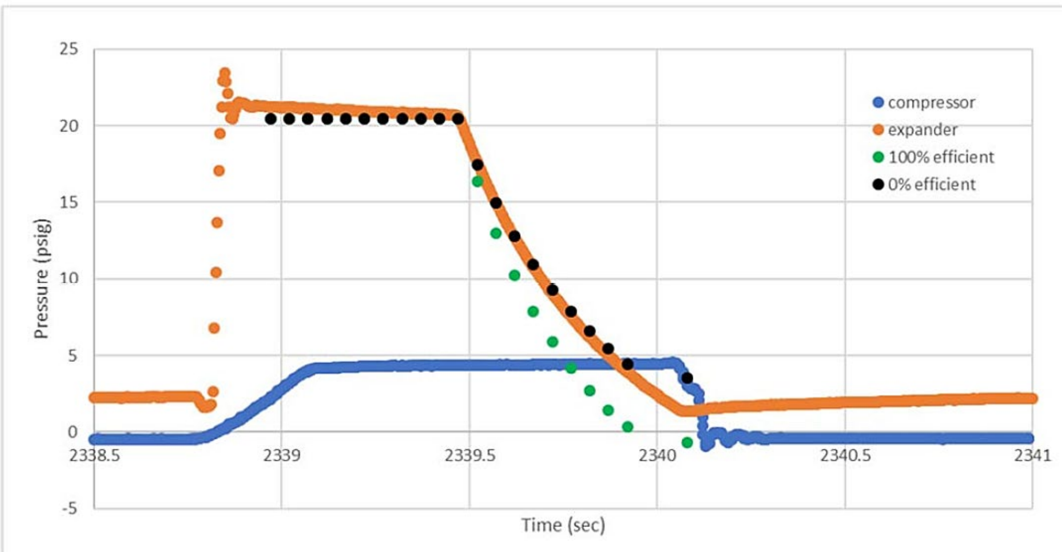
In addition to the full-scale testing, the team was able to use an existing linear motor rig to test the control and performance of a simple expander, using low-pressure nitrogen. The expander was built using a 6-inch diameter pneumatic cylinder and ASCO solenoid valves to control gas moving in and out of the cylinder. The piston was attached to an existing linear motor rig GTI built for a previous project. The team supplied the expander with a regulated nitrogen supply and controlled the motion of the expander using the linear motors.

This testing resulted in several accomplishments.

1. The team was unsure if the linear motor controls would be able to maintain control of the piston during expansion. The primary concern was the impulse of pressure on the piston as the supply valve was opened. This was tested and the motor controls maintained their target position, with little error.
2. The nitrogen expander was operated at steady state to measure the efficiency under various operating conditions. The highest measured efficiency using low pressure nitrogen reached nearly 60 percent. This is significantly better than preliminary results. The team also determined that the losses were related to the pneumatic cylinder friction and ambient heat transfer. An example of the nitrogen expander testing is shown in Figure 17. This test reached an efficiency of about 40.5 percent and had an expander discharge temperature of 14°F (-10°C). Higher efficiencies were achieved at higher pressures and flow rates with some additional valve timing optimization.

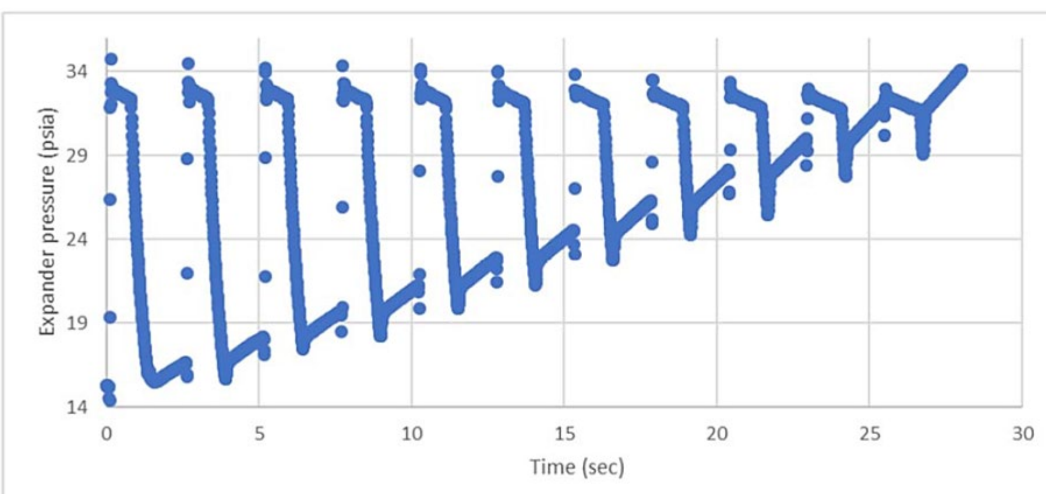
3. The team filled a compressed air tank using the low-pressure nitrogen expander. This is noteworthy because the expander must adjust the supply and discharge valve timing to account for the changing pressure ratio as a vehicle cylinder is filled. The team was able to program the nitrogen expander with a valve control loop that adjusted the valve timing based on the measured pressure ratio. This worked as intended and the valve timing was adjusted as a small, compressed air cylinder was filled to the nitrogen supply pressure. The expander pressure during this test is shown in Figure 18. The supply pressure was constant with each stroke, but the discharge pressure rose as the cylinder filled. The time the supply valve remained open to the ~34 pounds per square inch (psi) supply also increased as the cylinder filled.

Figure 17: Early Test Results of the Nitrogen Expander



Source: GTI

Figure 18: Expander Pressure While Filling a Tank With Nitrogen



psia=pounds per square inch absolute

Source: GTI

Determine Economic Benefits

A detailed economic analysis of a linear-motor-driven CNG compressor was conducted. That economic analysis included a detailed breakdown of both the compressor components and their costs. Many of the compressor components are also shared by the expander, making the compressor economic model a good starting point for estimating expander costs. In fact, many of the components such as the motors, bearings, housing, and control hardware, were identical between the compressor and expander. The biggest difference between the two designs is the valves. The compressor uses passive check valves to control the flow of gas and the expander uses solenoid or similar control valves to control the flow through the system. As the design of the expander was finalized and the team received quotes for those components the team updated the compressor model to better reflect unique attributes of the expander.

Figure 19 summarizes the estimated costs to build the linear motor compressor. These costs are similar to the costs of the expander. The goal for the expander was to have a cost of $25 to $50 per standard cubic feet per minute (SCFM) of capacity. This target was selected to lower the cost of conventional chillers, which cost over $100 per SCFM (according to industry contacts). These chillers are not consistently used across the industry but have been used at virtual pipeline filling stations. Unfortunately, when the team set the cost target for the expander, the team did not realize that the expander flow would increase as a vehicle was filled. This increasing flow is the blue line shown in Figure 20. As the discharge pressure of the expander increases, more gas must be delivered to the expansion chamber with each stroke. This results in an increasing flow over time if the frequency of the expander is held constant. To estimate the cost of the expander per SCFM, the total mass dispensed can be divided by the fill time to estimate an average flow rate of 9.23 kilograms (kg) per minute. Natural gas has a standard density of about 0.02 kg per cubic foot, resulting in an average flow of about 462 SCFM.

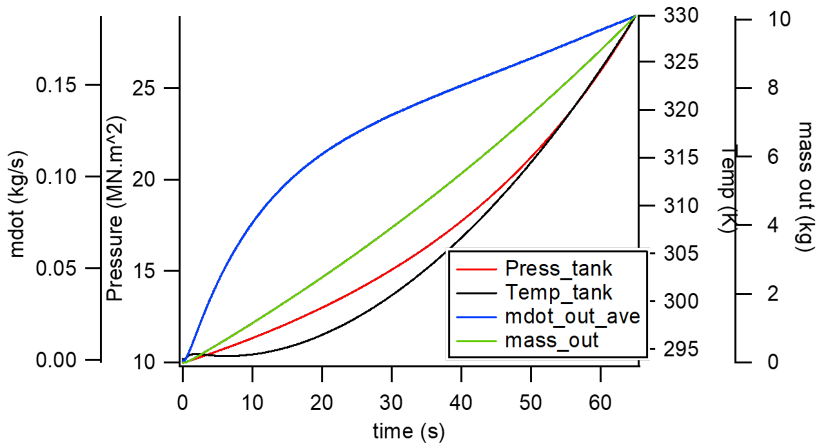
Using the unit costs shown, the team estimates that the capital cost of the current expander might be between $60 to $115 per SCFM. This is higher than the target cost that was originally proposed but is comparable to or lower than the quotes GTI previously received for chillers. While at first glance it appears the expander might only result in a nominal improvement over traditional chillers, these numbers need closer analysis in the future. For starters, the expander being designed is conservative, only partially utilizing the motor frame to ensure that the expander could be fully tested. Once the performance of the expander is better understood it may be possible to significantly increase the power and flow of the expander simply by increasing the piston diameter. This small change to the design would have a minor impact on the total cost while potentially doubling the flow. This would lower the capital cost of the system to $30 to $60 per SCFM, much closer to the original target. The team will continue to refine this economic analysis throughout the project to more accurately reflect the true cost of building and operating a CNG expander within a smart CNG station.

Figure 19: Summary Costs of Building a Linear Motor-Driven Natural Gas Compressor

Description	Total cost for components at scale			
	Unit Quantity			
	1	10	100	1000
Linear Motor Components	$15,741	$15,741	$11,019	$10,344
Bearing Ribs	$10,238	$10,238	$5,200	$3,005
Forcer Frame	$6,812	$6,812	$4,285	$3,745
Flotor	$502	$502	$502	$502
Compressor Ends	$12,101	$12,101	$8,527	$6,009
Balance of Skid	$7,500	$7,500	$5,285	$3,724
Cumulative Unit Costs	$52,894	$52,894	$34,818	$27,330

Source: GTI

Figure 20: Simulated Pressure, Temperature, and Flow Data of a CNG Tank Being Filled Using the CNG Expander



K=kelvins; kg=kilograms; kg/s=kilograms per second; MN/m^2=meganewtons per square meter; s=seconds

Source: GTI

Component Testing, Detailed Design, and Fabrication

Key Component Testing

The preliminary testing of the controls and the operation of the expander were performed using an existing linear motor test rig repurposed from a prior project. That test rig allowed the team to gather testing and performance data much faster than originally anticipated, which in turn allowed the team to focus on development of a full-scale test rig designed for high-pressure natural gas. The full-scale test apparatus design was based on solid models, after which the team completed a hazard analysis and mechanical design review. Following the design review, the team created drawings for fabrication and assembly. Drawings were sent to a fabrication shop to get a quote, and an order was subsequently placed for the linear motor frame.

In addition to the expander fabrication, GTI built a new test facility that enables full scale hydrogen and natural gas testing within a temperature conditioned space. The enclosure is 12 feet by 20 feet, is completely insulated, and all electrical and utilities are suitable for hazardous environments. This enclosure allowed the smart station components to be fully tested in a variety of environmental conditions to ensure their safety and effectiveness. With the enclosure in place, GTI built structures to run power and other utilities to the enclosure.

Fabrication of the full-scale expander components occurred in parallel with the enclosure construction. All of the motor frame components were machined and sent to GTI for final assembly. The design of the seals and fluid ends were finalized, quoted, and ordered. The test enclosure included most of the required utilities and data collection equipment. The last major step was installation of the heater and chiller system for environmental conditioning.

The flotor, a term for the moving portion of the motor the team coined in place of a traditional rotor on a rotary motor, was a bit out of tolerance and the fabrication shop corrected its manufacturing defects. Following the completion of the flotor, it was lapped to smooth the surface and the entire assembly was then delivered to GTI for assembly. In parallel with the motor frame, the expander fluid ends and seals were ordered and fabricated.

The commercial valves that were tested in the first year met the minimum flow and speed requirements of the expander; however, the team decided further improvements to the valve's speed could help reduce the size and cost of the expander design in the future. The barrier preventing faster actuation of the valve was determined to be the valve's solenoid. The primary challenge was that the current in the solenoid continued to flow for about 125 ms after the power supply was removed. That current continued to hold the valve open, slowing down the closing time. The team previously tested stronger springs to overcome the solenoid current and close the valve faster. While the stronger springs cut the closing time in half, they still barely met the minimum closing time of the valve: ~50 ms.

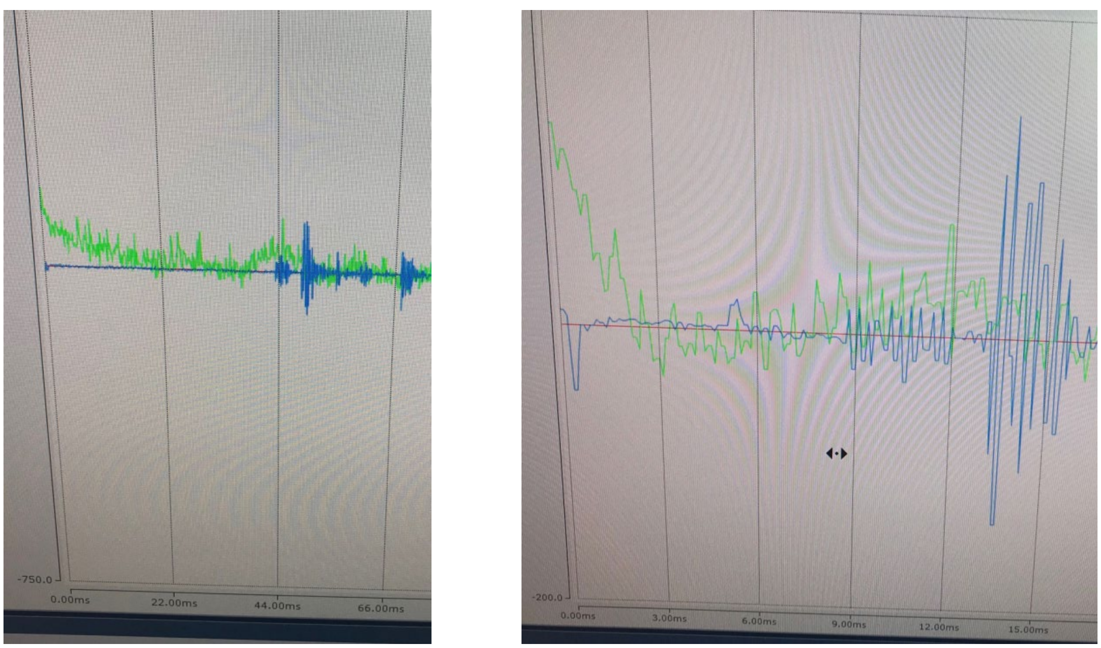
To further improve the valve speed, the team searched for advanced valve controllers to replace the simple switched voltage supply used previously. Instead of supplying a constant voltage, the controllers improved the valve actuation speed using a few additional steps. First, the controller can briefly boost the supply current used to open the valve. The higher current produces a stronger solenoid force, opening the valve faster. Once the valve is open, the controller immediately reduces the holding current to the minimum value required to keep the valve open. This is accomplished using a current control loop within the controller. Lastly, the controller significantly improves the closing time by reversing the polarity of the supply voltage. By reversing the polarity, the current in the solenoid decays much faster than it would by simply turning the power off, in turn allowing the valve to close much faster. The team purchased and tested several different controllers.

The advanced valve controllers were assembled and bench tested. Using the controller's capability to control the valve current amplitude and direction, the team was able to significantly speed up the valve's opening and closing times. Images of the valve control before and after enabling the advanced control features are shown in Figure 21. In the images, the green trace is measured current used to determine how it decays over time. The blue trace is a contact microphone used to measure when the valve strikes the valve seat during closing. The valves were first tested (left image) without any of the advanced control features enabled, so the valve controller acted like a simple switch that was turned on and off to open and close the valve. The time to close the valve without the advanced features was about 50 ms, which agrees with previously reported data from Q5. However, once some of the advanced control features were enabled (such as current control and reversal), the valve closing time was reduced to about 15 ms, as shown in the right image in Figure 21.

Achieving these fast-closing times helped improve expander performance since the valves more ideally opened and closed to optimize the thermodynamics of the CNG expansion. The impact of the valve speed is shown in Figure 20. From those early simulation results the new valve times enabled the team to maximize system performance.

The images in Figure 21 are from the programmable logic controller (PLC). The green trace is current, and the blue trace is a contact microphone used to detect when the valve closes and strikes the valve seat. In each image time, zero is set when the valve opening signal is removed to start the closing action. The green trace is a unitless measure of current and the blue trace is a contact microphone that indicates when the valve element strikes the valve seat. The left image is shown without any advanced control features, and the valve takes about 50 ms to close. The right image is with valve current control features enabled and the closing time is reduced to about 15 ms.

Figure 21: Valve Opening and Closing Signals



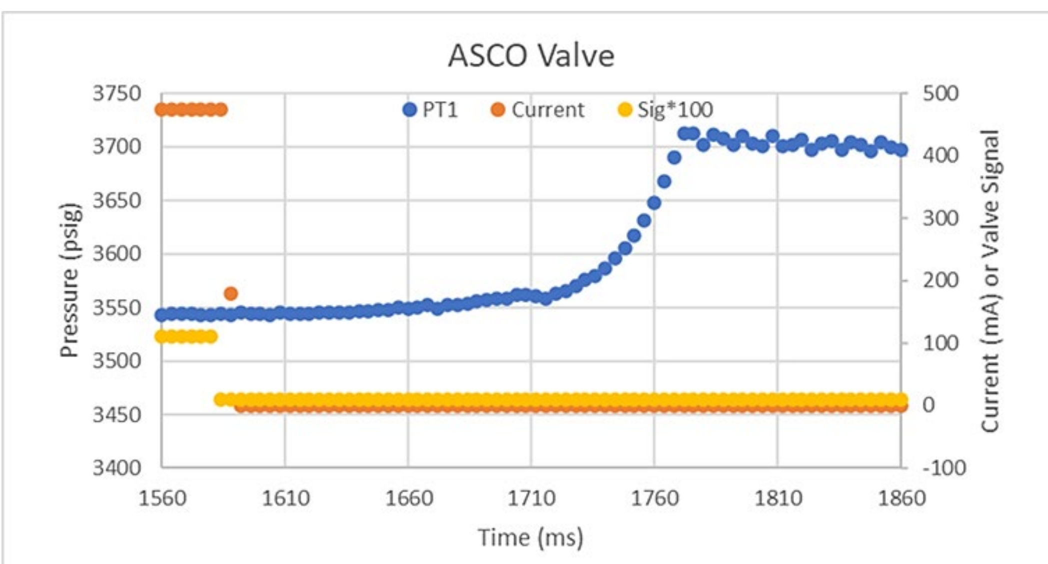
Source: GTI

Preliminary valve testing was conducted with a 3/8 in valve designed for hydrogen. The team believed that any improvements made to the hydrogen valve opening and closing times would also work for CNG. While it might be partially true that stronger springs and valve controllers will increase the speed of the valve, the team did not anticipate that the higher molecular weight of methane would also have a significant impact on the valve's speed. Three different sizes of CNG solenoid valves (designed by the same company that makes the hydrogen solenoid valve) were purchased and the first of the three was tested in Q7. Unsurprisingly, the stock valve was slower than the team would have liked, but what was surprising was the shape of the data. Figure 22 shows the CNG valve closing. When testing the hydrogen valves, the blue pressure trace was flat, then quickly increased when the valve closed. That was because it was the solenoid that was holding the valve open and as soon as the solenoid holding force dropped below the spring force the valve closed quickly. However, the CNG valve pressure slowly increased over time, indicating that the valve, slowly closing, restricted the flow that caused the pressure to rise.

GTI ran tests and concluded that the valve was closing slowly because of methane's proportionally high molecular weight when compared with hydrogen. These valves operate by opening a pilot valve that creates a pressure imbalance that forces open the primary valve. When the pilot closes, gas leaks through a small orifice to rebalance the pressure acting on the primary valve element, allowing a spring to close the valve. Unfortunately, the orifice used in the CNG valves is the same size as the hydrogen valve, and because of methane's higher molecular weight it takes longer for the pressure to equalize and fully close the valve. Therefore, a larger orifice is required to speed up valve closures.

GTI measured and then enlarged the orifice used to rebalance the pressure after the pilot valve is closed. After testing the valve, the closing time was cut in half compared to the unmodified valve. The unmodified performance is seen in Figure 22, and the improved performance is seen in Figure 23. Unfortunately, the closing time was still too slow and needed further improvement. GTI tried to enlarge the orifice further but saw little additional improvement in terms of valve speed. This indicated that another attribute had become the performance choke point.

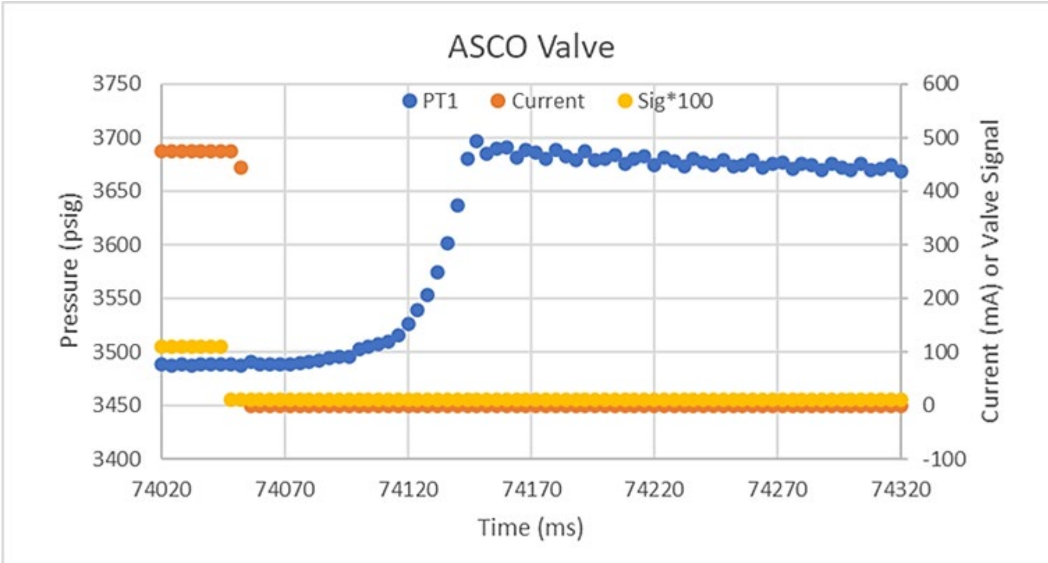
Figure 22: Unmodified CNG Valve Closing Times (Valve Control Signals Shown in Orange, Pressures Upstream in Blue)



mA=milliampere

Source: GTI

Figure 23: Modified CNG Valve Closing Times (Valve Control Signals Shown in Orange, Pressures Upstream in Blue)



Source: GTI

The first year of the project heavily focused on the development of a natural gas expander to pre-cool gas delivered to CNG vehicles to help overcome the heat of compression. However, other major issues preventing full fills are a lack of information about the state of the vehicle's tank and a dispenser algorithm able to utilize that information. To overcome these issues, GTI identified hardware that could be deployed onboard vehicles to measure the real-time pressure and temperature on the vehicle, both when driving and fueling. Initially, these data acquisition systems were used to capture data from existing vehicles and dispensers; however, they were also designed to eventually communicate with smart dispensers during fueling to improve full fills. GTI developed two systems for possible vehicle deployment.

The first system utilized equipment from the HEM Data Corporation (HEM). The HEM equipment is shown in Figure 24. The HEM equipment measures the pressure and temperature onboard the vehicle, broadcasts the data onto the vehicle's control area network (CAN) bus, then streams the entire CAN bus to the cloud, using a cell modem. This system was extensively tested at GTI, and the first prototype was deployed onboard a truck at the end of Q5 to demonstrate that the equipment's communication and operation capabilities were robust. Following the initial testing, the pressure and temperature sensors were integrated into the vehicle's tanks and the HEM system recorded every driving and fueling event to provide GTI with a complete picture of the vehicle fuel system's operation.

Figure 24: HEM Data Equipment for Capturing Vehicle Fuel System Data

Source: GTI

The second system tested is manufactured by Campbell Scientific, Inc. (Campbell) (Figure 25). Instead of broadcasting all the vehicle’s data to the CAN bus, the Campbell system records the CAN bus data and combines it internally with measured pressure and temperature signals from the vehicle’s fuel system. The data is then broadcast to the cloud using a cell modem. Development of this system lagged behind the HEM unit. Like the HEM system, the Campbell system allows GTI to capture all the driving and fueling events for a vehicle to form a complete understanding of the tank’s thermodynamics and allow GTI to develop the best fueling algorithm possible.

Figure 25: Campbell Scientific Hardware Testing on the Bench

Source: GTI

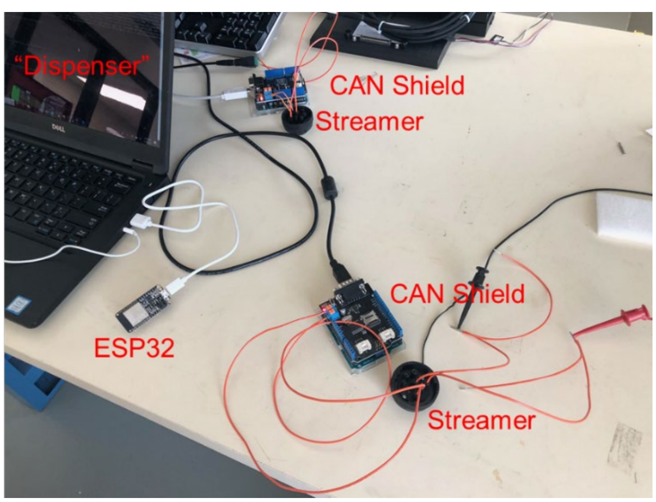
In addition to capturing data onboard several vehicles, GTI devised communications protocols for the vehicle to communicate with the dispenser. The two primary communications protocols considered were Bluetooth and Wi-Fi. Both have benefits and drawbacks. Both the HEM and Campbell systems have Wi-Fi capabilities to directly test vehicle-to-dispenser Wi-Fi communication in the future. However, neither will ultimately be used in a commercial design and Bluetooth has unique communications protocols that might make it significantly easier to use with CNG fueling stations.

The team ultimately made the decision to stop work on the Campbell data acquisition unit and move forward with the HEM data design. The decision was made so that the team could move forward with data acquisition fabrication and assembly. Components for the HEM systems were purchased and packaged into protective waterproof cases for installation onboard vehicles. The team also halted work on the Campbell units so that work could start on the smart dispenser components.

The team selected a prototyping board built around an ESP32 microcontroller to operate as the smart dispenser receiver. The ESP32 microcontroller is commonly used for Wi-Fi and Bluetooth communications since it is capable of both. It is also the microcontroller used in the HEM streamers selected to transmit data from the vehicle to the dispenser. The dispenser ESP32 microcontrollers are designed so that they can be integrated into any existing dispenser and communicate to that dispenser over a universal asynchronous receiver transmitter (standard two-way hardware communication protocol for exchanging serial data). The role of the dispenser's ESP32 device is to monitor Wi-Fi and/or Bluetooth frequencies for local vehicles that are broadcasting their CNG fuel system data. The ESP32 then uses a proprietary algorithm to track those vehicles and securely connect to the vehicle that connects to the dispenser for fueling. If the vehicle that connects to the dispenser is identified as a smart vehicle, then the ESP32 takes control of the fueling algorithm from the dispenser and controls it throughout the fill. Once the vehicle is full, or a safety limit has been reached, the ESP32 ends the fill and tells the dispenser to shut off.

GTI connected several streamers to Arduino CAN shields. These were used to represent the broadcast from multiple vehicles at a CNG station. The ESP32 '"pings" these streamers and determines which is "connected" to a test dispenser represented by a computer connected to the ESP32. This simple setup allowed the team to test various connectivity issues and debug the vehicle selection and connectivity code. Eventually the streamers were installed on actual vehicles and the computer connected to the ESP32 was replaced by the dispenser's control system. The bench testing setup is pictured in Figure 26.

Figure 26: Smart Station Bench Testing
(The CAN Shields and Streamers Represent Vehicles at a CNG Station)

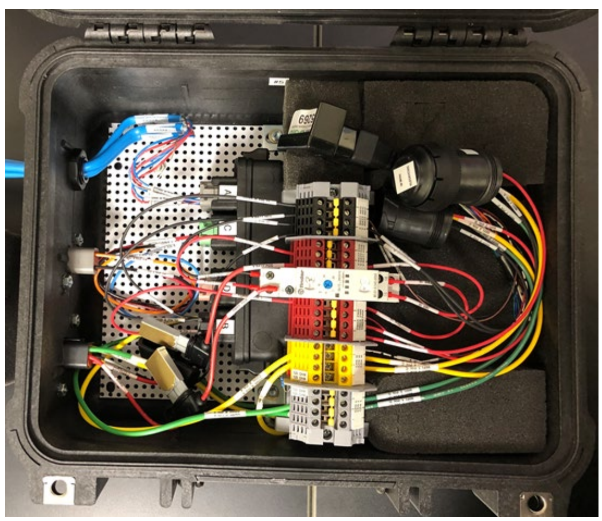


Source: GTI

The team built additional data acquisition systems for deployment onboard multiple CNG trucks while also working to improve the performance of the smart dispenser components. The data acquisition system pictured in Figure 24 was an early prototype created for initial deployment and testing. After proving the performance of the hardware, the design was refined, and additional units were fabricated and prepared for deployment. Figure 27 shows the refined design for the on-vehicle data acquisition units. This box contains connections to the truck's power, connections to pressure and temperature sensors, and wireless communications hardware to enable transmission of the data to the cloud or other wireless devices. Figure 28 shows multiple units that were fabricated and are ready for deployment on heavy-duty CNG trucks.

In addition to the data acquisition systems, GTI worked on the smart dispenser software using the bench setup in Figure 26. To advance this design, GTI reached out to several dispenser manufacturers to gather information about communications wiring and protocols. Responses indicated that most dispensers utilize the Modbus protocol (Modbus), so the smart dispenser prototype was programmed as a Modbus server that can be pinged by the dispenser as frequently as necessary to obtain data about the connected vehicle. Modbus was implemented and worked with a low error rate. GTI developed a protocol for selecting which vehicle is connected to the dispenser but had some issues managing multiple connections. They appeared to lock up when the dispenser tried to connect too frequently. However, additional testing identified a workaround.

Figure 27: Final On-Vehicle Data Acquisition System



Source: GTI

Figure 28: Multiple Data Acquisition Systems Ready for Deployment

Source: GTI

The team delivered and began installation of the remaining data acquisition units shown in Figure 28. In total, 18 units were delivered to a local fleet and installed onboard their vehicles to monitor CNG fills and fuel consumption. Four additional units were fabricated for lab testing of the smart dispenser components. These units were installed in a test cell and used to monitor test fills of CNG cylinders.

The team made design modifications to an existing test cell being used for the CNG solenoid valve testing. The modifications allowed the team to fill two small CNG tanks while simulating the operation of a commercial dispenser using LabVIEW. LabVIEW operates similar logic as a commercial dispenser, except that it is also programmed to communicate to the ESP32 communications board that monitors the area for smart vehicles. This communication uses a Modbus protocol, similar to how it is designed to operate in a commercial dispenser. If the ESP32 detects a HEM data acquisition unit, it utilizes its internal logic to verify whether that HEM system is attached to the LabVIEW dispenser before providing LabVIEW with a more accurate filling algorithm that can be used to fill the tank. The goal of the lab testing is to ensure the ESP32 logic is working when filling a single vehicle, followed by testing to ensure it is not confused when multiple vehicles are filling, or when other rare scenarios occur. Ideally, the testing approved the operation of the ESP32 so that it could be installed in a commercial dispenser.

GTI also developed a more comprehensive data management plan. A large amount of data was sent to cloud-based servers by the HEM data acquisition units on vehicles, and that data needed to be converted to a usable format, saved in a secure location, and accessed for data analysis. The team set up a virtual machine that runs a conversion tool. That machine converts the data files one at a time as they are uploaded to the cloud. The converted files were then stored in a secure location where they could be downloaded or accessed for data analysis.

Expander Compressor Controls Testing and Verification

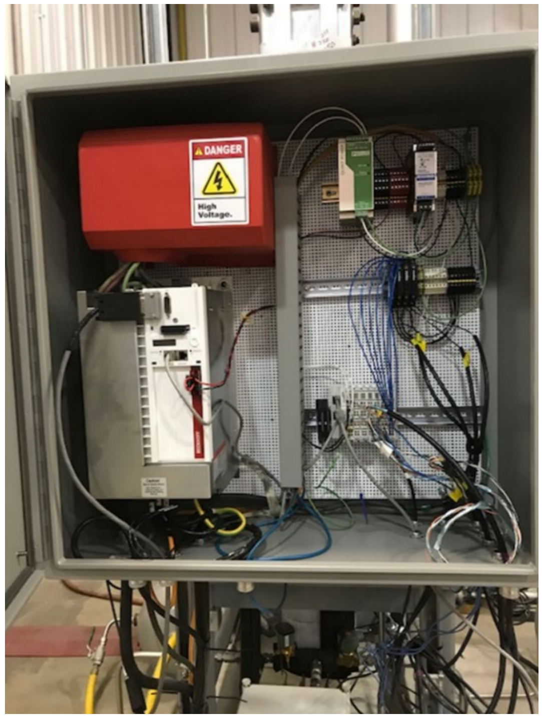
The expander motor control system was fully tested in the first year of the project. That testing demonstrated that the motor could not only be used to control the linear motors and the expander pistons but could also produce power that could offset the cost of compression. However, that system was built from existing equipment, so the motors, valves, and sensors were controlled by different hardware manufacturers and required two persons to operate the system.

To prepare for full-scale testing, the team integrated all the expander control hardware into one package. This used a real-time programmable logic controller (PLC). The PLC not only directly interfaced with the motor drives but measured the CNG pressure and temperatures and controlled the valve timing to efficiently expand the CNG. In addition, the PLC also handled all the safety and shutdown procedures for the test rig.

The team purchased one of the new motor drives used to integrate with the PLC and control the motors used to operate the expander. Testing started by integrating the drive into the prototype pictured in Figure 16. Motor files were programmed into the PLC. This included the motors used on the nitrogen test stand (Figure 16) and the motors used during full scale testing. These motor files included detailed motor characteristics so that the drive accurately controlled them during operation. The drive was hooked up to the existing encoder on the nitrogen rig and could detect its movements. The drive was mounted in an electrical cabinet and wired so that testing the actual controls and operation could begin.

The team fully integrated the PLC system into the nitrogen test expander used early in the project. Figure 29 shows the motor drive and data acquisition system wired to the expander, pressure and temperature sensors, and the control valves. This demonstration was critical because it showed that the new motor drives could control the selected motors during expansion. This was also the first time all the hardware was integrated into a single PLC that monitored and controlled the complete expander operation. After learning the PLC language and tuning the motors, the team ran the nitrogen expander and reached similar efficiencies achieved during preliminary testing. This rig was used to test and demonstrate key safety and shutdown features critical for the full-scale expander to operate safely. New power resistors were ordered, which enabled GTI to test the energy rejection performance on the nitrogen rig prior to CNG testing.

Figure 29: The Complete PLC Control System for the Low Pressure Nitrogen Test Expander



Source: GTI

Detailed Design and Simulation

After completion of the detailed design and analysis of the CNG expander, the project team created a complete drawing package to send to manufacturers for price quotations. GTI received three quotes from United States-based fabrication shops and worked with the lowest bidder on making some minor changes to the design before placing an order for the fabricated components. The full-scale expander prototype was then fabricated, and assembly and commissioning began.

The motor frame was completed except for the flotor, which was slightly out of tolerance; the fabrication shop worked to salvage the part.

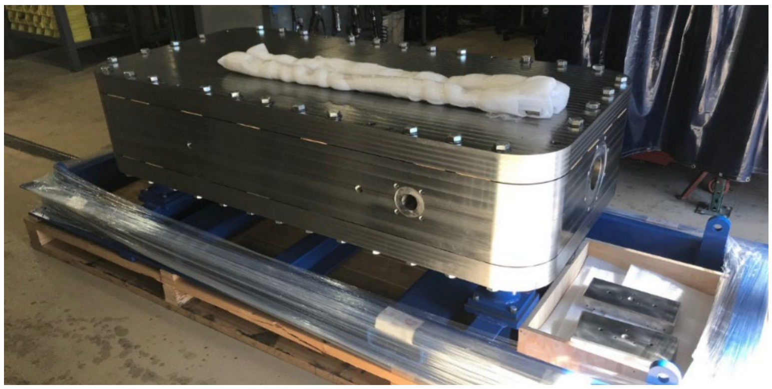
The fabrication of the expander fluid ends and seals was completed shortly after the motor frame. While the team was waiting on the fabrication, progress was made toward the completion of the smart station communications devices. Eighteen HEM data collection units were completed and delivered to a local fleet for installation on CNG vehicles. In addition, four HEM units were built to enable the lab testing of the smart dispenser ESP32 microprocessor. These were connected to CNG vessels and communicated with the ESP32 during fills to ensure the functioning of the smart dispenser logic.

Commission, Testing, and Demonstration

Commission Expander and Compressor

Figure 30 shows the expander frame in GTI's fabrication shop, including some of the bearing components pictured to the right of the frame. The flotor was sent back to be machined so that additional mounting holes for a conventional linear bearing could be added. The flotor was delivered later than expected, but upon arrival GTI began the assembly and commissioning of the expander.

Figure 30: The Expander Motor Frame



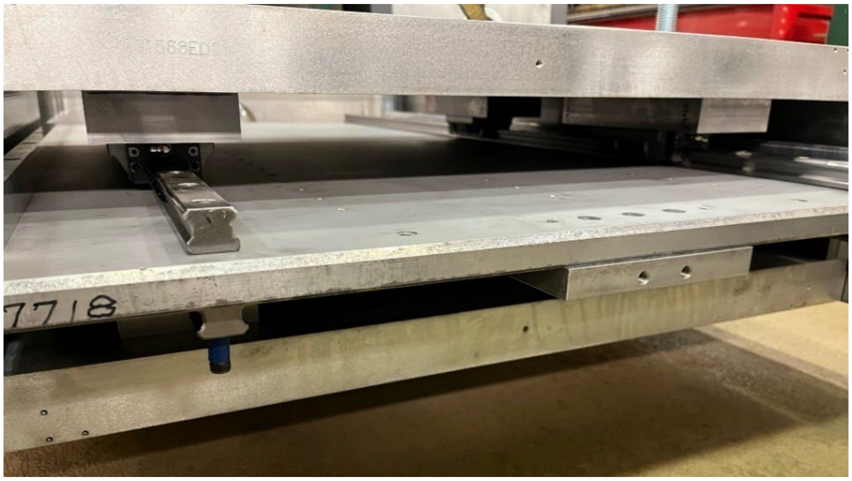
Source: GTI

The first step was to machine several bearing adapters to size so that the bearings on either side of the expander fit properly into the frame without overloading any of the components. This machining was done at GTI. Following that process, GTI assembled the bearings and frame components without installing the magnets. Figure 31 and Figure 32 show the dry fit of the frame components without the motors. The flotor moved easily without the motors in place.

Figure 31: The Linear Motor Frame Assembled without Motors to Test the Fit of the Bearings

Source: GTI

Figure 32: The Linear Motor Frame With Both Sets of Bearings Assembled



Source: GTI

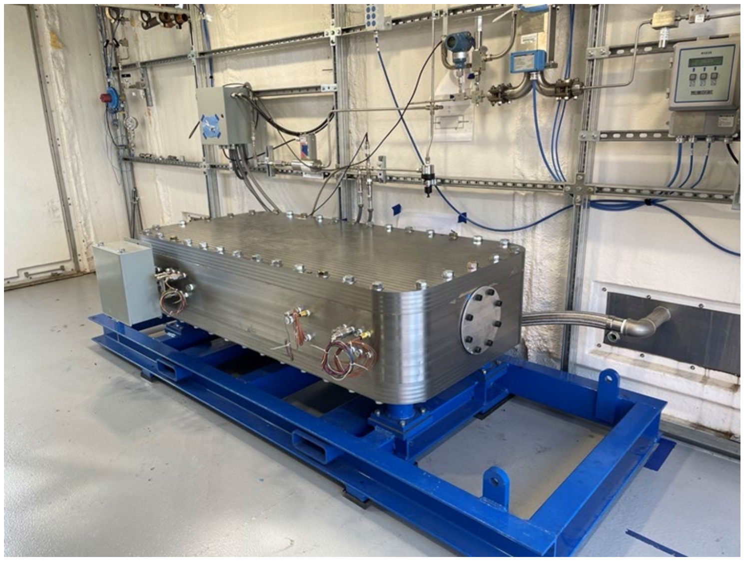
Following the dry fit, GTI assembled the motors in the frame. This started with the magnets, which required a special jig to hold them safely during installation. GTI fabricated the jig using plastic and added 10 holes where steel bolts could be inserted to hold the magnets to the jig. The jig is pictured in Figure 33. One set of magnets was installed, and the forcer was installed on top of them. Then the frame was flipped, and the second set of magnets and forcer were installed to complete the assembly.

Figure 33: The Magnet Assembly Jig

Source: GTI

Following installation of the motors, the frame was turned on its side to adjust the alignment of the internal components. This resulted in some binding of the bearings that made it difficult to move the flotor plate. This issue was eventually resolved so that both motors and the flotor could be easily moved by hand. With the motors installed, GTI worked on installing the other internal components such as the piston couplings, encoder, power, and signal passthroughs so that the motor frame could be connected to the motor drives and tested. After the expander was fully assembled and moved into the final test cell, the fluid ends were mounted, and the final tubing was completed (Figure 34). The expander was fully commissioned and tested using nitrogen.

Figure 34: The Fully Assembled Expander Installed In the Final Test Cell (but before adding the Fluid Ends)



Source: GTI

The expander was fully tested using the final PLC hardware, demonstrating that the hardware was capable of fully controlling and operating the system. However, there were still a few aspects of the controls that required verification. These included energy rejection, safety shutdowns, and parallel motor-drive performance.

Energy rejection commissioning required GTI to run the expander with enough speed and pressure so that excess power, beyond the capacity of the drive capacitors, was produced but rejected to a load bank. GTI received and wired a load cell to the low-pressure expander to conduct this testing.

Safety shutdowns also needed to be tested and finalized to fully commission the expander. Some shutdowns had already been verified such as position error and motor thermal limit shutdowns, which were tested and verified during preliminary expander testing. The team also completed a detailed hazard analysis that included other scenarios (such as a loss of power) that required verification.

Lastly, the high-pressure expander required parallel motor drives to fully power and control the unit. The low-pressure unit was originally controlled using two smaller drives with one feedback system; however, this control scheme was not tested and verified using the new, larger drives until the full-scale expander was available, so it took place following complete assembly of that unit.

The operating pressure and speed of the nitrogen expander were increased to produce more power and force the controls to reject that energy to the load bank. In practice, this higher-pressure operation caused the DC bus voltage to increase until it reached the drive’s specified limit. At the voltage limit, IGBTs were used to connect the bus voltage to the external load bank. The load bank acted like a giant resistor, with heat sinks that rejected the excess power as heat. The drive's bus voltage and cumulative power through the load bank were measured to quantify the total amount of energy rejected. On the full-scale system, GTI also installed inlet power measurements to verify both net power consumption by the expander and the energy produced by the high-pressure gas.

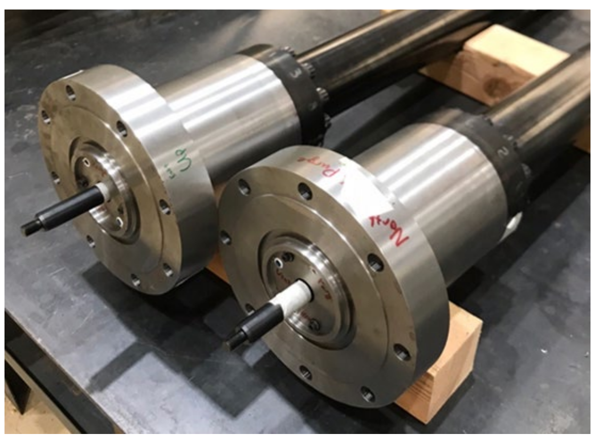
While the expander was being assembled, GTI also worked on assembly of the test cell and power electronics. GTI ran the variable frequency drive and other signal cables from the drives to the preliminary test area. Once the motors were running smoothly and reliably, the expander was moved into the final test cell and rewired at that location.

The expander controls and programming were then tested as much as possible, without the final gas supply and discharge valves installed. The motors and control logic worked as intended, including the safety shutdown controls. The team operated the expander with nitrogen at about 2,500 psig and filled a target cylinder to 2,500 psi.

Test Using Nitrogen

The fluid ends were hydro-tested, assembled, and leak-tested using nitrogen. Installation included finalizing the tubing, valve installation, and sensor installation (Figure 35).

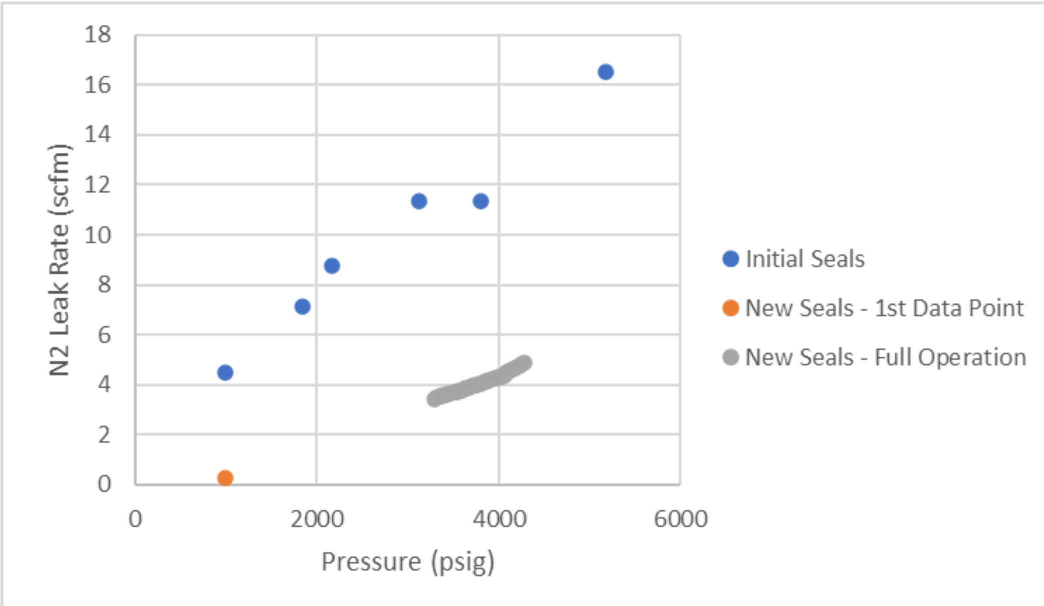
Figure 35: Fully Assembled and Leak-Checked Fluid Ends Before Assembly on the Motor Housing



Source: GTI

Once the expander test loop was fully assembled, the expander and test loop were leak-checked, using nitrogen. The test loop held the pressure. However, the expander piston seals leaked more than anticipated. The seal leaks were quantified at various pressures to determine if higher pressure might force the seals to operate better; however, the leaks increased nearly linearly with the increase in pressure. The manufacturer was contacted about the leaks, and they offered an alternative design that they believed would reduce the leak rate significantly. This new design took several weeks to arrive, but once it did the seals were installed and tested again. Immediately, the leak rates under static pressure were reduced by between 90 percent and 95 percent. This allowed the team to move forward with higher pressure testing. During operation, the seals leaked slightly more than during static testing, but the leaks were still far below previously recorded leak rates. The new seals appeared to leak well below 10 percent of the throughput of the system, which was sufficient for preliminary testing. Figure 36 shows the leak test data.

Figure 36: Test Data Taken During Nitrogen Leak Testing of the Expander Piston Seals



Source: GTI

The team slowly built pressure and tested the expander with nitrogen up to 2,500 psi, which is when seal leak issues were identified. After the seal leaks were reduced, GTI intended to test the expander operation using the new seals; however, some glitches in the control code and feedback systems forced the team to delay the test plan. Fortunately, these issues were eventually resolved by rewiring some sensors and GTI was able to get about 3 days of test data, which led to expander testing up to 7,000 psig. During this test, the target cylinder was filled from about 700 psi to about 4,500 psi. The fill pressure was limited by the volume of the supply cylinders, not by operation of the expander.

The expander efficiency varied throughout the fill; however, it was lower than expected. Issues that caused the lower-than-expected efficiency during nitrogen testing were:

- The valve pressure drop was higher than expected with nitrogen.
    - The pressure drop improved with hydrogen and CNG.
- Discharge valve blowby.
    - Opening the supply valve and letting high pressure gas rush into the expansion chamber caused the discharge valve to briefly open unexpectedly. This caused warm, unexpanded gas to flow directly into the target vessel, reducing the efficiency of the expander.

    - GTI closed the discharge valve early, which recompressed the gas in the expander before opening the supply valve. This helped to keep the discharge valve shut, but also caused the recompressed gas to heat up, reducing efficiency.
- Thermal mass of the expander.
    - There is a lot of mass in the expander fluid ends that must be cooled down before the expander can operate efficiently. The fluid ends cool down during a fill; however, multiple fills are necessary to reach a steady temperature that will result in an efficient fill. This should not be an issue at large CNG stations or virtual pipeline facilities where back-to-back fills are common.
- Seal friction.
    - The seal friction coefficient was challenging to quantify. During simulation of the expander the team assumed that it was about 0.05; however, during preliminary testing it was measured between 0.1 and 0.2 while under static gas pressure. This was later quantified using a force balance, and the estimated friction was reduced back to 0.04. Part of the uncertainty and variability in the measured friction had to do with how the seals operate and the tests that were performed. The seals are designed with multiple rings in series that act as pressure breaks for the gas being sealed. When testing these seals under static pressure, the team assumed that the pressure would leak past the seals and that the pressure drop would be distributed across all 10 seals. This would cause a force on every seal that would result in increased apparent friction. However, when actually expanding the gas, the pressure would have less time to equalize across the seals as the pressure in the expansion chamber was rising and falling. This dynamic operation forces the first 1 to 2 seals to take most of the pressure drop and therefore have the highest normal force. However, as normal forces increase on seal materials, the friction coefficient can actually drop. The team assumed this was because there is probably a stiction or shear limit that can be generated by the seal; above that force additional normal load has no effect. So, with a very high load on the first seal, the friction coefficient appears low.

Following the first tests with nitrogen, the team ran into more frequent operational issues. These issues forced GTI to disassemble the expander motor, which led the team to identify a broken encoder wire. The encoder connections were redesigned and routed outside of the motor housing to make future repairs easier. Following the repairs, the team was able to reliably run the expander up to 12,000 psi using nitrogen without further issues. The expander speed was also increased to test control of the system. GTI continued testing with nitrogen until the expander reached full pressure, and all control and design attributes were tested and verified. The expander was then switched to hydrogen and tested before testing with CNG.

The first step to switching to hydrogen was to leak-check the motor housing and ensure that no hydrogen from the fluid ends could migrate into the motor housing. This was done using helium. The fluid ends were operated with high-pressure helium, with all nitrogen purges in place. The team took gas samples from the motor housing, then tested those using a gas chromatograph. This testing verified that no helium was leaking from the fluid ends into the motor housing. With this test complete, the team officially transitioned to hydrogen testing.

Test Using CNG

A hazard assessment was completed for the hydrogen expander design. All identified risks were mitigated with engineering and procedural controls. Safety shutdowns were also programmed and tested prior to operation with nitrogen. Following hydrogen testing, the team performed a "management of change" procedure before switching to CNG. The switch to CNG involved changing some of the tubing, sensors, and safety shutdown setpoints. These were all reviewed and tested prior to testing with CNG. Further, the team identified that sulfur in pipeline natural gas could contaminate the system and prevent the team from using or testing with hydrogen in the future, so the decision was made to purchase ultra-high purity methane for testing. The methane was also tested to make sure there was no trace sulfur, and then 12-packs of bottles were ordered and used to fill the test system.

The expander and test loop had already been leak-checked with nitrogen and hydrogen; however, modifications were required to test with methane. This was done as the system was charged from the 12-packs of methane. This testing verified that all the fittings were sealing, and that nitrogen purges were still working as intended.

The expander was extensively tested using hydrogen and CNG to fully quantify and optimize the performance while also determining how to further improve the performance and efficiency of the system. Ultimately, the team reached efficiencies as high as 73 percent with hydrogen and between 40 percent and 45 percent with natural gas. The team concluded that efficiencies in the high 80 percent to low 90 percent range are achievable with some minor modifications to the valves, seals, and expander geometry.

While testing with both gases, the team started at low pressures and speeds, slowly ramping up both until the maximum limits determined prior to testing were reached. The pressure limit was determined by the supply cylinders, and was limited to 12,000 psi, while the speed was limited due to vibration and was limited to about 1.5 meters per second (m/s). Once the expander reached the full pressure and speed, the team focused on optimizing the control and efficiency of the system.

Demonstrate CNG Full Fill Using Expander/Compressor

The expander was tested, and the performance was quantified at full pressure using three separate gases. The team started testing using nitrogen to verify the control and operability of the expander at pressures up to 12,000 psi without the added risk of operating with a flammable gas. Once the basic operation was demonstrated and components such as valves, seals, and controls were optimized, the team switched to hydrogen to test and quantify the performance in a hydrogen fueling station.

The expander was tested up to 12,000 psi using hydrogen, which was the pressure limit of the hydrogen storage cylinders GTI purchased. However, the expander should be able to operate at the higher pressures seen at commercial hydrogen fueling stations. The expander results were very promising. The expander removed up to 73 percent of the available energy from the hydrogen, significantly reducing the cooling load required from a traditional vapor compression chiller, while also producing power from the energy removed. The real-time efficiency results can be seen in Figure 37. While these results were promising, the team concluded that the performance could be further improved by making a few minor modifications to the design.

The first change would be to redesign the expander discharge valve. The valves that were used for the inlet and outlet were designed for commercial hydrogen dispensers and used as a solenoid-controlled pilot to open the primary valve element. This design worked surprisingly well for the inlet and discharge valves (given that it was never specifically designed for this application); however, issues remained, especially on the discharge side of the expander. The main issue was that the pilot actuation did not perform well with fluctuations in upstream pressure. It was common for the valve to briefly open when hit with a sudden rise in the upstream pressure, which could happen when opening the inlet valve as gas would rush into the expansion chamber and force open the discharge valve. This would cause gas to briefly flow straight through the expander without any energy being removed. These blow-through events would significantly lower the operating efficiency because the gas flowing past the valves was essentially expanding with an efficiency of 0 percent. To counteract this issue, the team started closing the discharge valve early so that the gas in the expander chamber was more gradually recompressed by the piston back up to the inlet pressure so that opening the inlet valve would not cause the blow through event. However, this recompression is also a loss because the gas being recompressed would heat up and add energy to the system. The estimated losses from these issues were as high as 10 percent.

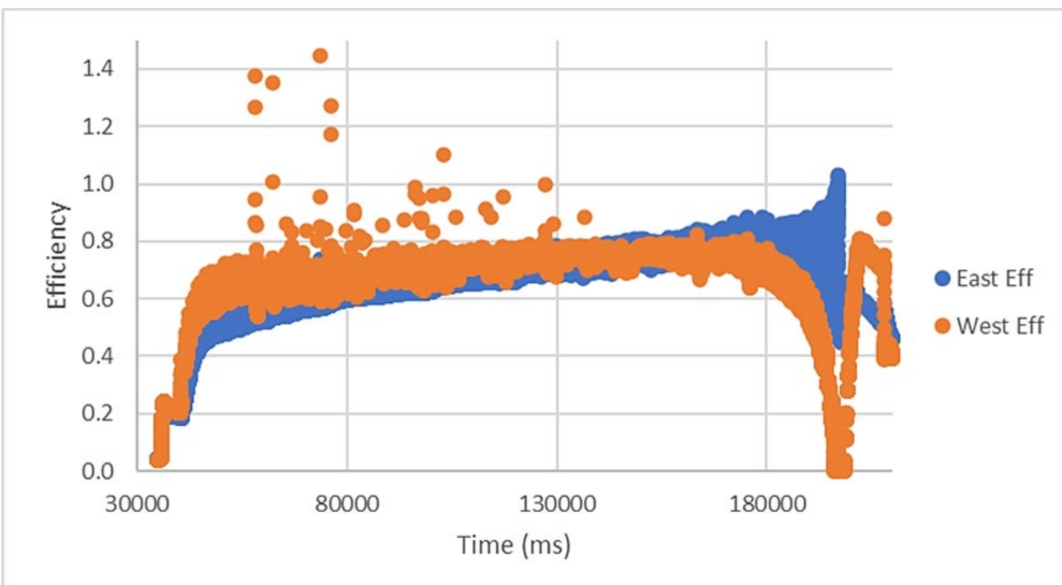
To counter these issues, the team developed some early concepts for a valve that can be actuated using the piston. This new design would help to eliminate the blow-through, reduce dead volume in the system, and reduce pressure drops across the discharge valve. These changes could help bump the efficiency from between 68 percent and 73 percent to between 80 percent and 85 percent.

In addition to the valves, the next biggest loss was related to seal friction. The current design uses piston seals to seal the 12,000 psi gas. The seal friction coefficient was measured at about 0.04; however, the force that the gas exerts on the seals is still significant, and that heat is transferred directly into the expander wall and then into the gas. The team believes that the seal design can be modified so that more of the sealing work is done by rod seals positioned behind the piston seals. This would reduce the load by the piston seals and the heat transfer to the gas. The heat would instead go into the piston rod, but that is expected to have a much smaller impact on the expander performance. The overall losses from seal friction in the current system were estimated at between 10 percent and 12 percent, though changes to the seals would probably improve that performance by between 5 percent and 6 percent.

The final improvement to the system would be increasing the capacity of the expander by increasing the diameter of the piston. By increasing the diameter, the volume of the cylinder increases relative to the circumference. This means that losses associated with heat transfer to the cylinder wall or seal friction are reduced in proportion to the volume of gas being expanded. This would help further reduce losses as long as the increased capacity does not significantly increase the valve pressure drop. The team investigated how much the piston diameter could be increased using the motor capacity. The motor is currently only used at about 65 percent of its peak capacity, so the area of the piston could be increased by almost 50 percent. In addition, the team worked on a higher-power motor with about 50 percent more power than the current unit, so the total capacity (using the full capability of the larger motor frame) would allow the team to more than double the piston area and flow while further improving system efficiency.

Overall, the team concluded that by optimizing the design, the expander could consistently reach efficiencies of between 85 percent and 90 percent. In addition, the capacity could be even further improved by operating the expander faster. The team ran the current unit at about 1.5 m/s before system vibrations became excessive. However, if the vibration issues can be reduced, the system should be capable of reaching an average operating speed close to 3 m/s. This would double the capacity again, resulting in 4 times the flow compared with the current system. Increasing the flow by 4 times and making the system modular would make the design useful for heavy-duty fills in addition to the light-duty fills tested.

Figure 37: Real-Time Efficiency of the Hydrogen Expander when Filling a 3-kg Hydrogen Cylinder

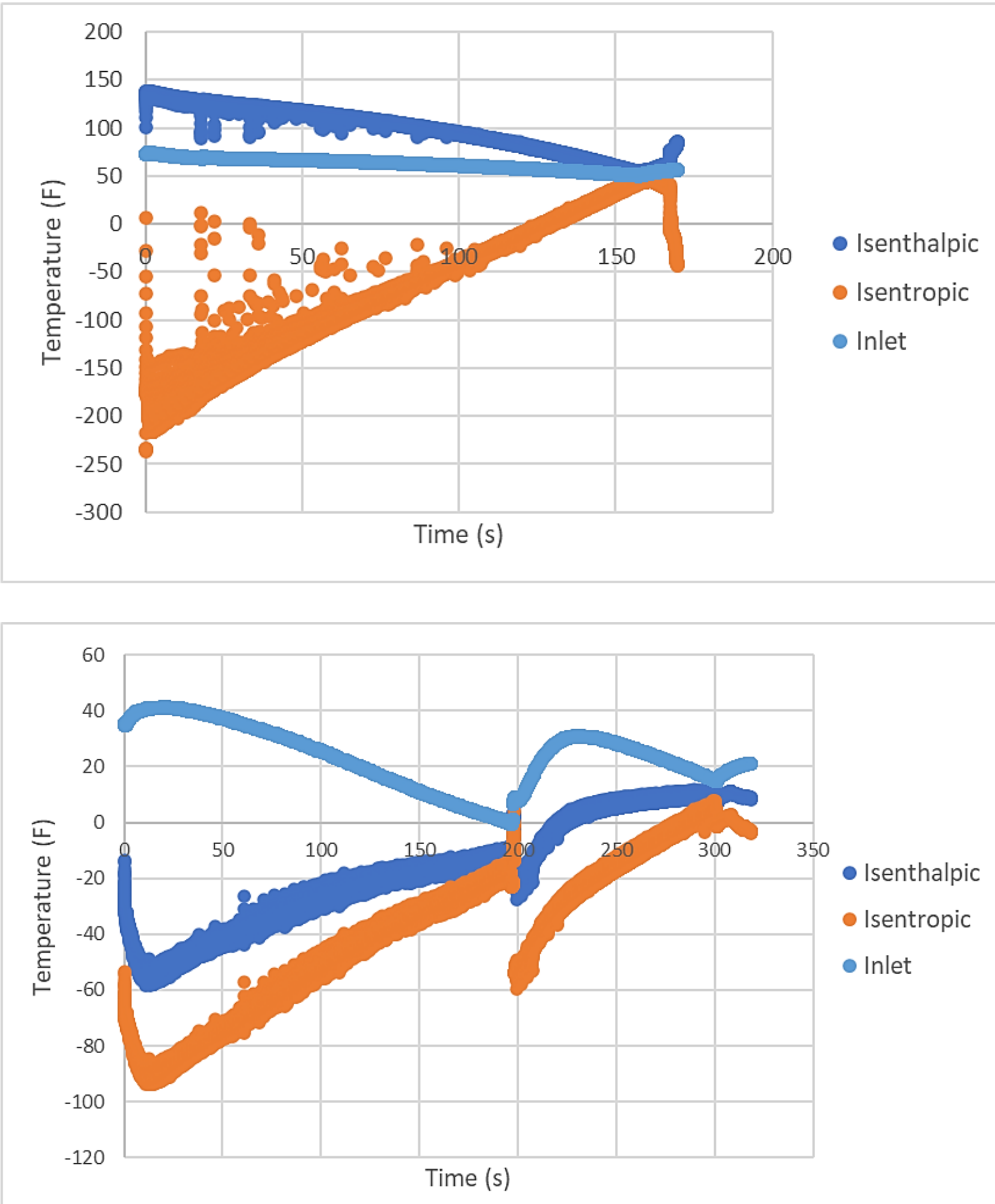


Source: GTI

Following extensive testing with hydrogen, the team converted the design to methane. The original plan was to use pipeline natural gas, but the team wanted the option of testing some of the valve and seal improvements with hydrogen for the future, so pure methane was used in place of natural gas. GTI purchased cylinders of methane and tested them to ensure there were no contaminants, particularly sulfur, which could contaminate the entire expander. Once the team verified that the methane was pure, it was used to fill the hydrogen cylinders used during the prior tests. The main difference was that the cylinders were only charged to 5,000 to 6,000 psi so that the results would be more applicable to CNG.

Testing with methane was similar to testing with hydrogen, except that methane does not have as much energy that can be removed; it was therefore harder to control the valves, so the efficiency was lower. Further, both methane and natural gas cool when they drop in pressure isenthalpically, so the difference between isentropic and isenthalpic pressure drops were not as dramatic as with hydrogen, which heats up during an isenthalpic pressure drop. Figure 38 compares the temperatures and impacts of isentropic versus isenthalpic pressure drops for both hydrogen and methane.

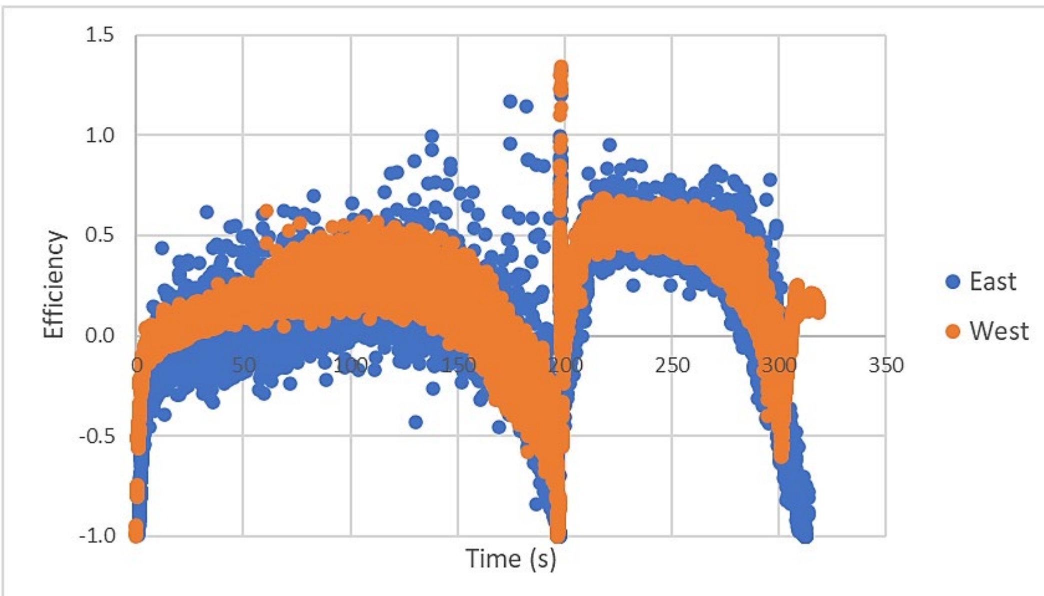
Figure 38: Hydrogen (Top) and Methane (Bottom) Pressure Drops, Compared Both Isnetropically and Isenthalpically



Source: GTI

Despite the additional challenges, the team successfully tested the expander using methane at pressures as high as 6,000 psi, then used two banks to fill the target cylinder as fully as the supply volume would allow. Unfortunately, the efficiency with methane, shown in Figure 39, was significantly lower than with hydrogen, Figure 37. But this lower efficiency was not entirely unexpected given the losses already discussed with hydrogen. The losses for methane were the same as with hydrogen but were more impactful because methane has less energy to remove and more pressure drop, which exacerbated the discharge valve issues even more than with hydrogen. Furthermore, the expander was designed as a compromise between hydrogen and methane, which meant that it needed to be designed for high hydrogen pressures. This meant that the piston was even more undersized for methane than it was for hydrogen.

Figure 39: The Real-Time Efficiency of the Methane Expander, Using Two Banks to Fill the Target Cylinder



Source: GTI

The net efficiency of the methane expander was about 40 percent. An estimated 45 percent of the lost energy was related to the valves, and the remaining 15 percent was related to friction.

Around 10 percent of the total energy was lost due to pressure drop through the valves, which was higher than hydrogen because of the high molecular weight of methane. Another 15 percent was leakage through the discharge valves as they were closing. Lastly, 20 percent was related to recompression that was necessary to keep the discharge valves closed during the inlet stroke. These compounding issues consumed 45 percent of the available energy and could be almost entirely solved with the development of a custom discharge valve that does not open during the inlet stroke and therefore will not leak when either closed or require recompression. Further, a custom design could minimize the dead volume and increase the orifice size to further improve the efficiency over the existing valves. There will always be some pressure drop and associated losses; however, this can be kept to a minimum to keep the expander efficiency high.

The remaining 15 percent of the lost energy was related to friction. The friction coefficient for methane was still measured at around 0.04, but the losses were more significant because of the lower energy content of the methane versus hydrogen. With a properly sized methane expander piston and corresponding valves, the losses associated with the seal friction could be reduced to less than 10 percent. Like hydrogen, the seals could also be redesigned to move some of the sealing load to the rod seals, which would further reduce the losses.

Overall, the performance of the methane expander was not ideal, but the concept was nevertheless proved and demonstrated. The team believes strongly that both hydrogen and methane can reach efficiencies in the 85 percent to 90 percent range, making them both strong candidates as cooling agents at fueling stations.

The commercial ANGI Energy (ANGI) dispenser, Figure 40, used for testing the smart station, was installed in GTI's environmental chamber along with two target cylinders connected to HEM data loggers capable of monitoring the real-time pressure and temperature in the cylinders. The HEM loggers wrote the cylinder data into the vehicle's CAN bus (which was then converted), added to other relevant vehicle information, and then transmitted wirelessly using a custom streamer (Figure 41). The streamer sent the data via Wi-Fi to the station router that was connected to the GTI smart controller. The smart controller received the CNG cylinder information in real time while wired to the ANGI dispenser through a Modbus connection. The smart controller monitored data from both the cylinders and the dispenser, verifying which cylinder was connected to the dispenser and then adjusting the filling target within the dispenser.

Figure 40: ANGI Dispenser With Target CNG Cylinders in GTI's Environmental Chamber

Source: GTI

Figure 41: The HEM Data Logger (Left), Wireless Router (Center), and Smart Controller (Right) Used To Communicate Between the Vehicle Cylinder and Dispenser

Source: GTI

Initially the smart station components and the expander were tested independently to ensure they were working as reliably as possible; the team could make only a few attempts given the limited amount of the pure methane used in the expander to fill the CNG cylinders connected to the dispenser. The expander was tested in a closed loop that recycled the pure methane while the dispenser was tested separately using GTI's CNG station as the supply.

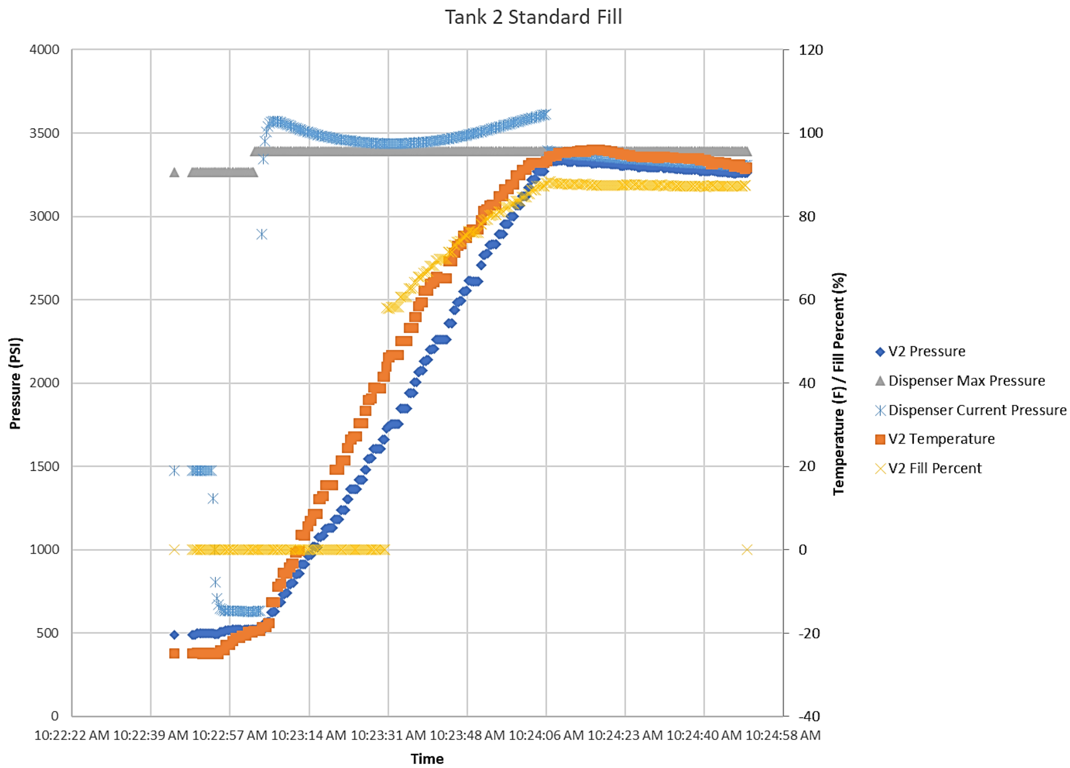
When the separate components were finally working reliably, the team integrated them by connecting the discharge of the expander to the dispenser inlet. This required a review of the system hazard analysis because the expander discharge tubing, relief valves, filters, and other components needed to be increased in size, which lowered their pressure ratings from 12,000 psi to about 4,500 psi. Once these changes were reviewed and implemented, the systems were ready to be tested together.

The team completed several successful tests of the combined smart CNG station, using the expander to precool the gas. The procedure for testing the system was as similar as possible to a commercial station. The target cylinders were emptied to similar starting pressures and temperatures. Cylinder 2 was filled without precooling (using GTI's CNG supply) until the dispenser terminated the fill. The CNG supply was then closed and a valve connecting the dispenser to the expander was opened. Cylinder 1 was connected to the dispenser using the same hose and procedure as Cylinder 2, except that, as the pressure in the hose equalized with the target cylinder it caused the discharge of the expander to drop in pressure, which automatically triggered the expander to start operating so that cold gas was supplied to the dispenser and target cylinder. The fill progressed until the cylinders supplying the expander were fully utilized and the expander turned off. The dispenser then terminated the fill on low flow.

The smart controller data from the standard fill is shown in Figure 42. The smart controller monitored the dispenser hose and target fill pressures over Modbus while monitoring the vehicle pressure, temperature and "percent full" values. At the beginning of the fill, the hose pressure (Dispenser Current Pressure) drops and allows the dispenser to estimate the vehicle starting pressure. The dispenser then sets the target filling pressure (Dispenser Max Pressure). This value is then set for the duration of the fill and the fill is stopped when the hose pressure and flow are used to calculate the real-time pressure in the cylinder. This last step is performed very accurately as the fill stops exactly when the internal tank pressure, which the dispenser cannot see, is equal to the dispenser target. However, it was also apparent that the vehicle could have received more gas since the vehicle was only about 85 percent full when the fill stopped and neither the vehicle's pressure nor temperature were near safety limits. So the vehicle could have received a better fill. GTI's best guess about this conservative approach was that the dispenser simply could not determine the true state of the vehicle fill, so conservative assumptions about the starting conditions or filling conditions were critical for ensuring that the vehicle was not overfilled.

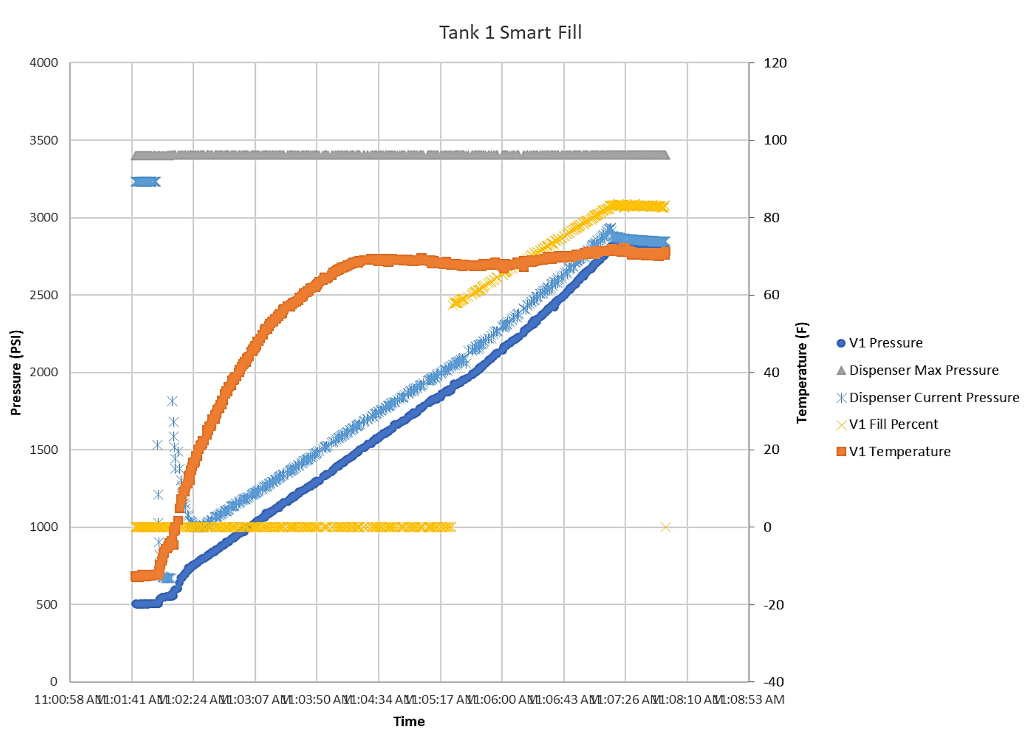
The smart controller data from the expander precooled fill is shown in Figure 43. The dispenser operation was similar because the vehicle pressure was measured, and the dispenser did not change the pressure target since both cylinders started at the same pressure. From there, the fill was different. The fill took a bit longer because the flow was limited by the expander, but more interestingly the temperature in the target cylinder behaved differently from a standard fill. The temperature rose initially, but then flattened out for the duration of the fill. The team believes that the expander was supplying cold gas to the dispenser, but that cold gas was cooling all the tubing, filters and valves between the expander and the cylinder. Once those components cooled off, the temperature in the tank leveled off because the gas was colder coming out of the expander than it would have been from a traditional CNG station. The fill never reached the dispenser's target pressure because it was limited by the volume of the cylinders supplying the expander; however, the vehicle reached a similar fill percent as the standard fill at just under 85 percent. The biggest difference was that at 85 percent full, the precooled vehicle is about 2,800 psi at 70°F (21°C) versus 3,400 psi at 90°F to 95°F (32°C to 35°C) during the standard fill. The expander fill had a lot more room to add gas before the vehicle reached the dispenser shutoff at 3,400 psi or the pressure limit at 4,200 psi. This would have resulted in a fuller fill if the expander had adequate storage to supply that fill.

Figure 42: The Smart Controller Recording a Standard CNG Fill Without Pre-Cooling



Source: GTI

Figure 43: The Smart Controller Recorded a Pre-Cooled Fill Supplied by the Methane Expander



Source: GTI

Complete Full Economic Analysis of Expander/Compressor

The intended benefit of the smart CNG station and pre-cooling expander was to improve or guarantee CNG full fills across a wide range of operating conditions. There are several benefits of guaranteed full fills. These include improved range, driver productivity, and reduced vehicle costs.

Range, particularly for fleet vehicles, is often critical to fleet operation and insufficient range can limit the operating area of the fleet, force fleet vehicles to return to base between deliveries, or stop at a public station to refuel. This can reduce productivity as additional stops during shifts can cost the business money in driver time that should be spent driving. "Range anxiety" is also an issue caused by inconsistent fills. Drivers learn that they will not get a consistent amount of gas during each fill, and as a result don't fully utilize the vehicle's range, causing more frequent fueling stops. The result of these issues is that the fuel systems on CNG vehicles is often oversized, increasing costs to the fleet, which then must purchase larger or additional CNG cylinders for each vehicle to compensate for insufficient range and range anxiety.

Throughout this project the team witnessed both underfilling and overfilling fleet vehicles. Vehicles were underfilled by as much as 20 percent to 25 percent simply because a dispenser was unable to accurately determine the starting and ending conditions of the vehicle. Possibly more concerning was that fleet vehicles overfilled by between 5 percent and 10 percent could cause over-pressurization and damage to vehicle cylinders if the gas warms up and causes the cylinder to exceed the 4,500 psi pressure limit. By improving station operation using smart station components and pre-cooling equipment it would be possible to properly size CNG storage systems and eliminate overfilling safety concerns.

The advantage of eliminating underfilling is that fuel-system volumes and costs can be reduced by up to 25 percent because there are fewer cylinders, valves, fittings, and other equipment required to protect and operate the CNG fuel system. It is difficult to determine the exact financial benefits as every fleet is different and uses different CNG tank configurations and vehicles. However, as a point of reference, GTI purchased a 4-cylinder, 160 DGE fuel system for about $55,000. These are common on heavy-duty, long-haul trucks, and removing one of these cylinders could reduce the cost by about $13,000 or 25 percent of the fuel system cost per vehicle.

In place of the storage cylinder volume, the vehicles would need some additional communications equipment, as well as some form of pre-cooling to guarantee full fills on warmer days when the heat of compression limits an achievable fill.

The communications equipment developed is very inexpensive and expected to have very little impact on station equipment. For starters, the dispenser used to demonstrate the smart station operation was not modified. The team simply connected the smart controller to the existing Modbus connection on the dispenser. Further, the smart controller itself was developed using a Raspberry Pi, which can be purchased for about $55 online and is sufficient to handle communication between multiple vehicles and dispensers at a CNG station. GTI developed this controller; however, CNG station operators could likely use controllers that are often already in place at many existing CNG stations, and simply add the GTI software to existing hardware. So the cost to the station, depending on existing hardware, could be close to zero.

The vehicles, however, would require some true modifications. The most significant is the addition of customized cylinder plugs or valves to provide easier access to the cylinders that capture the real-time temperature of the CNG in the fuel system. These plugs have an estimated cost of several hundred dollars, which is based on other cylinder plugs that GTI has purchased in the past. The vehicles would also need a thermocouple or other temperature measuring device for each cylinder. The costs of these sensors are about $100 to $200 each but could also be offset by removing other temperature sensors often in CNG fuel systems that may become redundant with in-cylinder measurements. The vehicles would then need a device that can measure the temperatures and pressures of the CNG fuel system. GTI used a HEM data logger, but a vehicle integrator would likely develop something in-house with additional functionalities. The cost of this device is only expected to be between $200 and $300 at most and again may be much less expensive since many CNG fuel systems already have integrated sensing and computing that may only require slight modifications. An example is the fuel system purchased by GTI, which already has integrated temperature and pressure sensing, just not in the cylinders. It may be possible to slightly modify that existing system or even use it as is with in-cylinder temperature measurements. Lastly, the data needs to be transmitted from the vehicle to the station. This is the one device in the communications chain that doesn’t really have an existing counterpart on CNG vehicles. This device was developed by GTI using an ESP32 microcontroller, with an integrated CAN bus reader. The hardware itself costs between $100 and $200. All in, the smart station components, when paired with existing station and vehicle hardware, could potentially cost well under $1,000 per vehicle, making them well worth the expense if they also reduce fuel-system costs by as much as $13,000 per vehicle while also reducing range anxiety and the frequency of fueling stops.

The other component needed for the complete smart CNG station is the pre-cooling unit. As described in Subtask 2.5, the goal was to develop a CNG precooling unit with a capital cost of between $25 and $50 per SCFM of capacity. The expander developed dispensed 19.8 kilograms of CNG in about 6 minutes, which is the equivalent of about 990 cubic feet or 165 SCFM, on average. However, this comes with some caveats just described. For starters, the unit tested was designed with a piston that was too small for CNG operation since it also had to operate with hydrogen. Based on the testing, the piston area could have been increased between 2.5 and 3 times over the piston that was used, which would have increased the flow by that amount at the same operating speed. Further, the unit was operated at just under 1 hertz or about 0.9 m/s. The expander is technically capable of operating at up to 3 m/s, resulting in 3 times the flow with the given piston area. Combining these two improvements, the existing expander could have filled vehicles at a rate about 9 times faster than the measured flow, or nearly 1,500 SCFM. At that flow rate the expander would cost as much as $75,000 (or less) to fall within the project’s estimated capital costs. Unfortunately, that was not the case for the prototype unit, which cost between $250 k and $500 k to build, assemble, and commission. However, the team continued to work on and refine the design to make it more cost effective, while also evaluating its cost at higher volumes to determine how much it can be reduced at both 100 units per year and 1,000 units per year. The analysis indicates that at 100 units it is likely that the cost can be brought down close to the $75,000 target for the given capacity, and that at 1,000 units the cost could likely drop to as low as $50,000.

These cost estimates were estimated using a financial model developed by GTI. The financial model includes a bill of materials for the expander that includes everything from the power electronics to the fluid ends. The financial model then uses quotes as much as possible to estimate the reduced cost of purchased or manufactured components, in larger quantities. Where quotes were not available, GTI used an experience curve to estimate the cost reduction. Not surprisingly, the biggest savings were related to the fabrication of the expander and fluid ends. These components were one-off designs made for the prototype so were expensive to fabricate. However, the team was able to get quotes for many of these components at higher volumes, indicating that the price could be reduced by between 80 percent and 90 percent at 1,000 units per year. Other components including the motors and drives had nominal savings of between 15 percent and 25 percent at higher volumes.

CHAPTER 4: Conclusion

The goal of the project was to improve CNG full fills by developing a smart CNG vehicle and dispenser, using an advanced filling algorithm to leverage smart component information to develop an innovative CNG expander that can be used to precool CNG during fueling.

The team successfully developed a smart vehicle and dispenser system (integrated into vehicles) and a commercial dispenser. These components were able to reliably identify which vehicle at a CNG station was connected to the dispenser, establish a secure connection with that vehicle, and accurately calculate how full the vehicle was when fueling. Using this hardware, the team was able to monitor consistent underfilling by the dispenser and add more gas to the vehicle by controlling the dispenser's filling target. Unfortunately, data could not be written to the dispenser to change that target. In the future, the team will continue to work with ANGI to modify the dispenser hardware or software to enable the smart station controller to maximize vehicle fills.

The team was also able to design, build, and test a first-of-its-kind gaseous vehicle expander tested with nitrogen, hydrogen, and CNG. The expander was designed to maximize the energy removed from the gas flowing from the station into the vehicle by monitoring pressures in real time and adjusting the expansion ratio in the expander. The expander reached peak efficiencies of 73 percent with hydrogen and about 40 percent with CNG; however, the team also explored improvements to the valves, piston, and seals, which could increase efficiency to between 85 percent and 90 percent for most gases, including CNG and hydrogen. Furthermore, the expander produced power at an efficiency of between 50 percent and 60 percent, demonstrating that the expander is a net positive energy producer and could lower the energy cost of the CNG or hydrogen fueling station by offsetting some of the power consumed by the compressor. The team believes this efficiency can be improved by speeding up operation of the expander.

Lastly, the team fully demonstrated the operation of smart CNG station components, working with the expander to provide greater fill rates when compared with conventional cascade station designs.

The team continues to improve these devices and is working toward field testing both the dispenser and vehicle equipment. The team also proposed improvements to the expander that would improve efficiencies. Finally, the team is talking to commercial partners to try and get this equipment out into the market so it can make a meaningful impact on CNG and hydrogen vehicle adoption, which would lead to reduced consumption of diesel and other higher-carbon-intensity fuels.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ANGI	ANGI Energy
Campbell	Campbell Scientific, Inc
CAN	control area network
CFD	computation fluid dynamics
CNG	compressed natural gas
DC	direct current
FEA	finite element analysis
flotor	a term for the moving portion of the motor the team coined in place of a traditional rotor on a rotary motor
GTI	GTI Energy
HEM	HEM Data Corporation
IGBT	insulated-gate bipolar transistor
K	kelvin
kg	kilogram
kg/s	kilograms per second
kN	kilonewton
mA	milliampere
MATLAB Simulink	a graphical programming environment for modeling, simulating, and analyzing multidomain dynamical systems
MD	medium duty
mm	millimeter
MN/m^2	meganewtons per square meter
Modbus	Modbus protocol
ms	millisecond
m/s	meters per second
N	newton
NGV	natural gas vehicle
NOx	nitrogen oxides
PLC	programmable logic controller
PM	particulate matter
psi	pounds per square inch

Term	Definition
psia	pounds per square inch absolute
psig	pounds per square inch gauge
Q#	quarter of the project
s	second
SCFM	standard cubic feet per minute
VFD	variable frequency drive
W	watts

References

SoCalGas, PG&E, SDGE, Southwest Gas, SCE, and the City of Long Beach ERD (Southern California Gas Company, Pacific Gas and Electric Company, San Diego Gas and Electric Company, Southwest Gas Corporation, Southern California Edison Company, and the City of Long Beach Energy Resources Department). 2022. *2022 California Gas Report*. Available at https://www.socalgas.com/regulatory/cgr.

Project Deliverables

This project generated the following deliverables, which are available upon request by emailing pubs@energy.ca.gov.

Milestone/ Deliverable Number	Deliverable Description	Deliverable Date
1.1	Kickoff Meeting	8/1/2019
1.2	Quarter 1 Webinar and Progress Report	10/11/2019
1.3	Quarter 2 Webinar and Progress Report	1/10/2020
1.4	Quarter 3 Webinar and Progress Report	4/10/2020
1.5	Quarter 4 Webinar and Progress Report	7/10/2020
1.6	Quarter 5 Webinar and Progress Report	10/9/2020
1.7	Quarter 6 Webinar and Progress Report	1/15/2021
1.8	Quarter 7 Webinar and Progress Report	4/16/2021
1.9	Quarter 8 Webinar and Progress Report	7/16/2021
1.1	Quarter 9 Webinar and Progress Report	10/15/2021
1.11	Quarter 10 Webinar and Progress Report	1/14/2022
1.12	Quarter 11 Webinar and Progress Report	4/15/2022
1.13	Mid-Project Presentation	4/10/2020
1.14	Final Project Presentation	6/30/2022
1.15	Draft Project Report	6/15/2022
1.16	Final Project Wrap-Up Meeting	7/15/2022
1.17	Final Project Report	7/15/2022
2.1a	Report results from operational expander/compressor simulation during Q1 webinar and progress report	10/11/2019
2.1b	Report results from operational simulation of smart station during Q3 webinar and progress report	4/10/2020
2.2a	Report status of preliminary design and layout of expander/ compressor during Q2 webinar and progress report	1/10/2020
2.3a	Report status of preliminary design of key components during Q3 webinar and progress report	4/10/2020
2.4a	Report status of test apparatus design during Q3 webinar and progress report	4/10/2020

Milestone/ Deliverable Number	Deliverable Description	Deliverable Date
2.4b	Report status of test apparatus fabrication during Q4 webinar and progress report	7/10/2020
2.5a	Review draft economic analysis during Q4 webinar and progress report	7/10/2020
3.1a	Report on test apparatus operation during Q5 webinar and progress report	10/9/2020
3.1b	Report key component test results during Q5 webinar and progress report	10/9/2020
3.1c	Report about communications components that were selected during Q5 webinar and progress report	10/9/2020
3.2a	Report on expander/compressor controls testing during Q5 webinar and progress report	10/9/2020
3.3a	Report on the status of detailed design during Q6 webinar and progress report	1/15/2021
3.4a	Evidence of major components purchased reported during Q7 webinar and progress report	4/16/2021
3.5a	Report status of fabrication and assembly during Q8 webinar and progress report	7/16/2021
4.1a	Report on expander/compressor commissioning during Q9 webinar and progress report	10/15/2021
4.1b	Report on expander/compressor controls and power electronics commissioning during Q9 webinar and progress report	10/15/2021
4.2a	Report on expander/compressor leak test results during Q10 webinar and progress report	1/14/2022
4.2b	Report on expander/compressor operation using nitrogen during Q10 webinar and progress report	1/14/2022
4.3a	Report results from expander/Compressor hazard assessment during Q11 webinar and progress report	4/15/2022
4.3b	Report results from expander/compressor leak test during Q11 webinar and progress report	4/15/2022
4.3c	Report results from expander/compressor operation using natural gas during Q11 webinar and progress report	4/15/2022
4.4a	Report results from expander/compressor operation at full pressure in final report	7/15/2022

Milestone/ Deliverable Number	Deliverable Description	Deliverable Date
4.4b	Report results from integration of expander/compressor into smart CNG station in final report	7/15/2022
4.4c	Report on CNG fill demonstration using smart CNG station and compressor/expander in final report	7/15/2022
4.5a	Report results from economic analysis in final report	7/15/2022