Free-Piston Expander for Hydrogen Cooling

Project ID: IN016

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Overview

Timeline

Project start date: January 2019

Project end date: December 2021

Percent complete: 50%

Budget

Total project budget: $3.125M

Total recipient budget: $0.625M

Total federal share: $2.5M

Total DOE funds spent*: $777,948

*As of 03/31/2020

Barriers

I. Other Fueling Site/Terminal Operations

Target: Delivery cost < $2.00/kg

Partners

University of Texas – Center for Electromechanics

Argonne National Laboratory

Quantum Fuel Solutions

Relevance

Objectives:

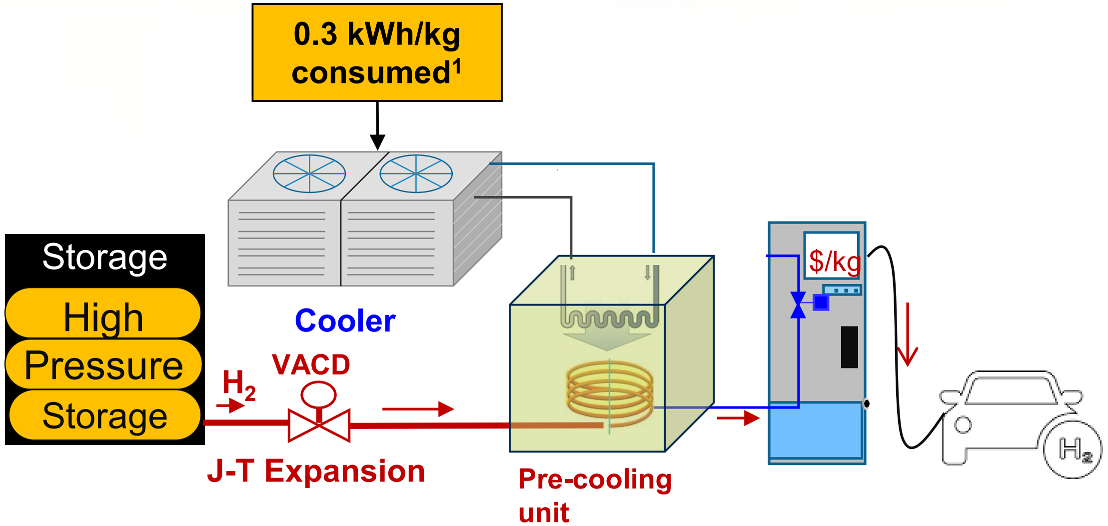
- Reduce capital cost and eliminate energy consumption of pre-cooling system.
  - Project goal: Design, build, and test free-piston expander
  - Progress since 2019 AMR: key component designs down-selected, simulation shows safe fueling attained with 100% SOC

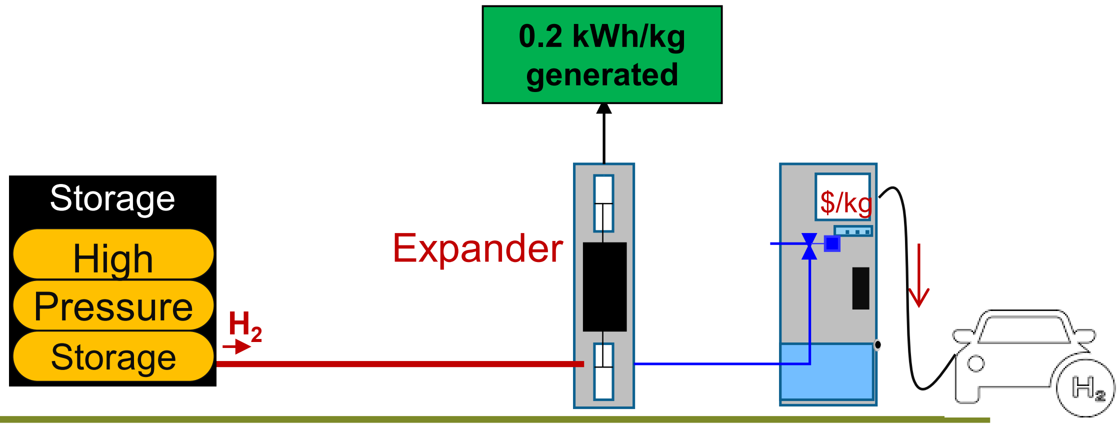
Targets	Units	Current (2015)	DOE 'Ultimate' Target	Project Target
Pre-Cooling Capital Cost (Uninstalled)	$	$140,000	$70,000	$60,000
Delivery Costs	$/kg	3.35-4.35	<2.00	
Pre-Cooling Energy Consumption	kWh/kg	0.5-2.0		<0
Pre-cooling cost (capital + electricity)	$/kg	0.50-5.00		0.20

Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, Updated Aug 2015

Approach: Utilize Existing Pressure Differential to Remove Energy from H2

- Current system
  - $140,000 uninstalled
  - 50 kWh/day baseload[1]
  - Frequent fueling interruptions due to over-temperature
- Expander system
  - Targeting $60,000 uninstalled
  - 5-10kWh/day baseload
  - Infinite back to back fills; system gets colder with fueling





[1] *Elgowainy et al, Int Journal of Hydrogen Energy 42 (2017), 29067-29079*

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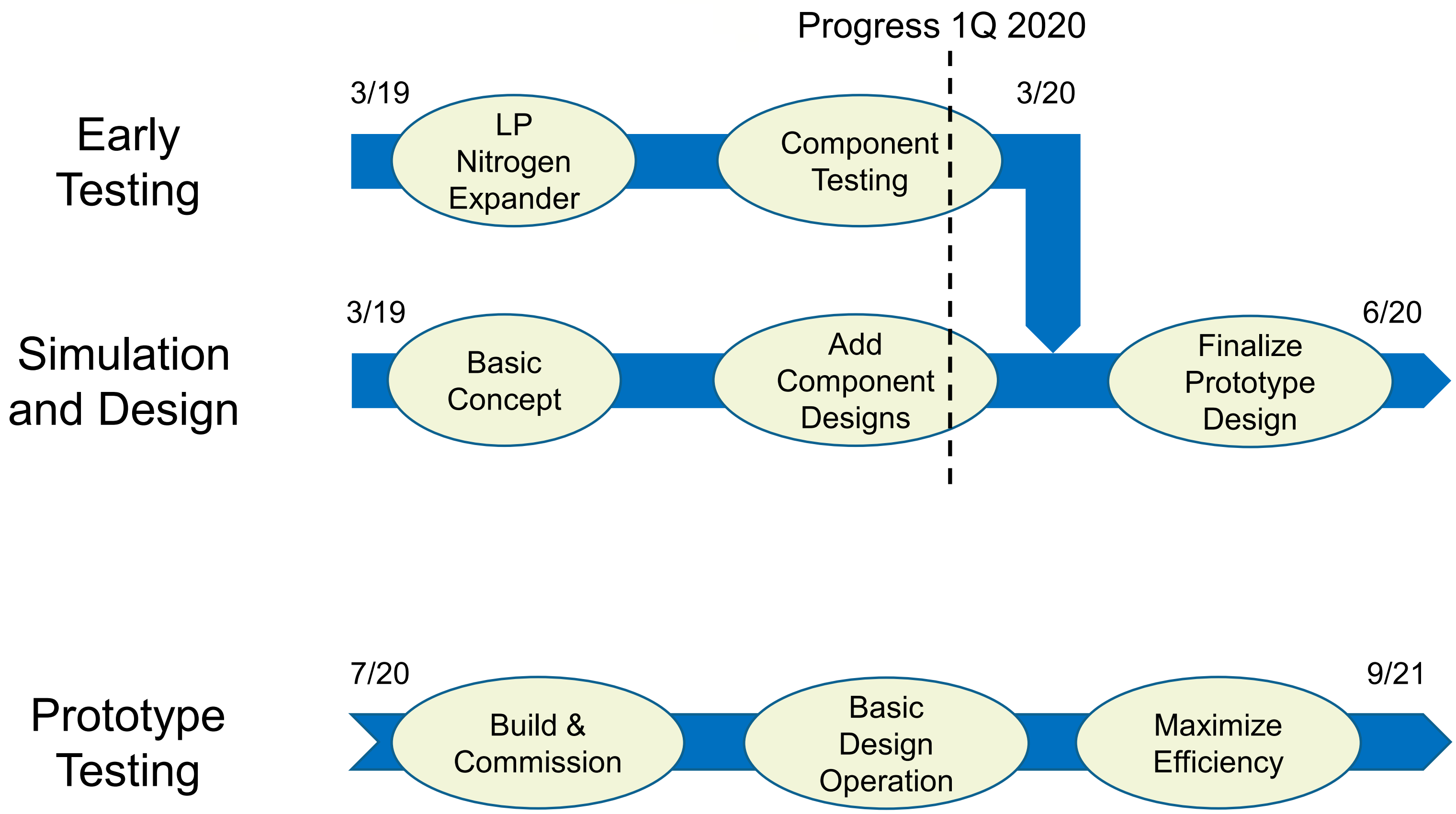
Approach: Workflow

Limit risk by incorporating early testing of concept and components



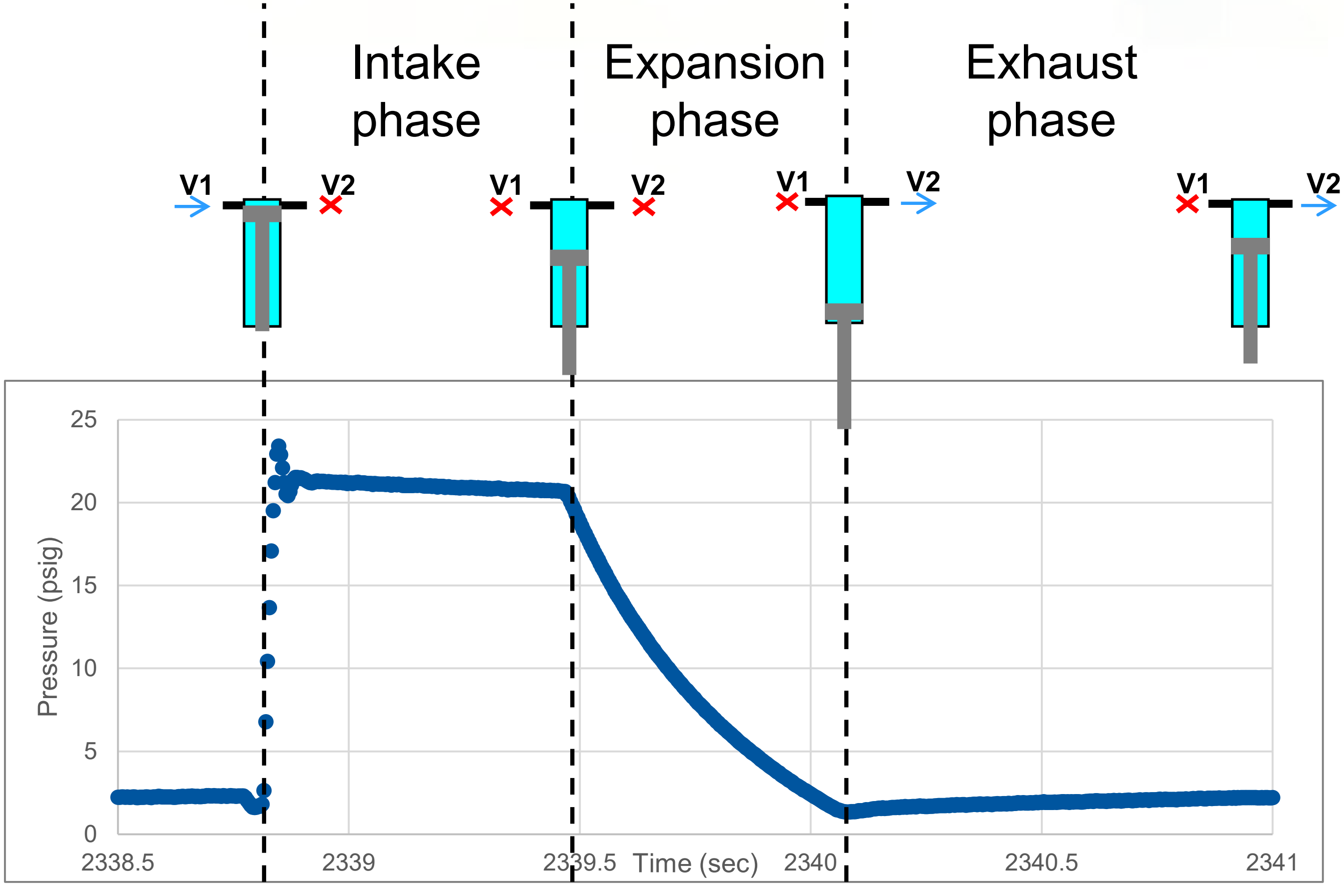
Approach: Project Task Structure

Budget Period 1 (2019): Preliminary Expander Design	**Progress**
1.1 Select expander geometry	100%
1.2 Down-select 2-3 component designs	100%
1.3 Complete preliminary expander design	100%
1.4 Complete first-round benefit analysis	100%
Go/No-Go: Modeling shows benefits in capital and operating cost	GO
Budget Period 2 (2020): Detailed Expander Design and Build	
1.1 Finalize valve and control system design	80%
1.2 Detailed design completed	50%
1.3 Procure major components	10%
1.4 Complete assembly of prototype unit	0%
Go/No-Go: Component testing with modeling still shows benefits in capital and operating cost	TBD
Budget Period 3 (2021): Operation	
3.1 First controlled pressure reduction completed	0%
3.2 Operation with nitrogen completed	0%
3.3 Operation with hydrogen - above break-even efficiency	0%
3.4 Benefits analysis repeated with operational data	0%
EOP Goal: 5-year levelized cost of pre-cooling under $0.20/kg	

Progress: Low Pressure Expander Operation

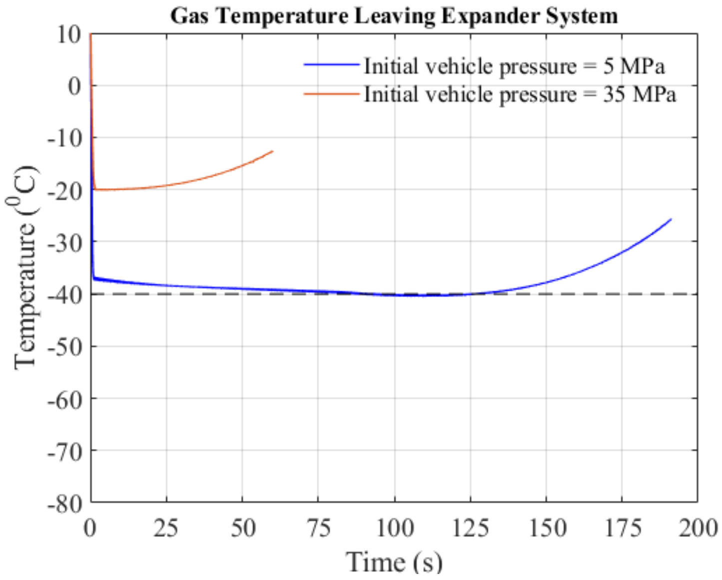
- Repurposed existing linear motor assembly and purchased off-the-shelf expansion cylinder
- Goals achieved
  - Proved motors can be operated as generators
  - Proved dynamic control of expansion ratio
  - Understand efficiency losses and mitigation options

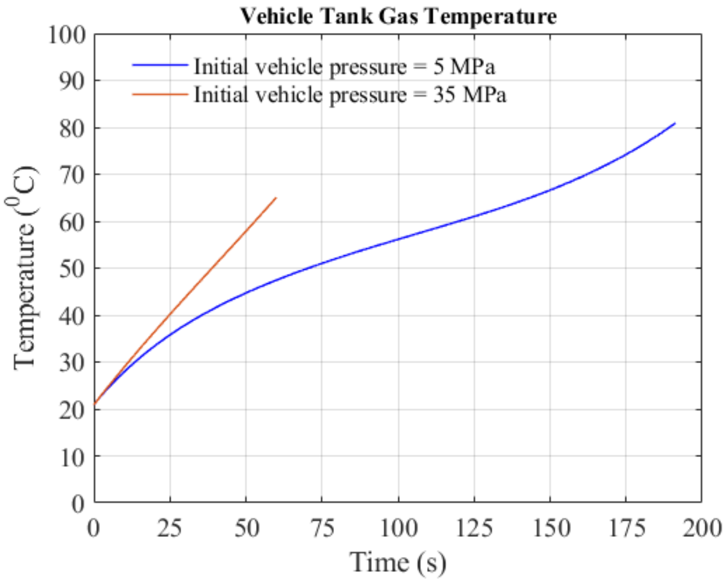
Progress: Linear Piston Expansion Cycle



Progress: Simulation Shows Safe Full Fill

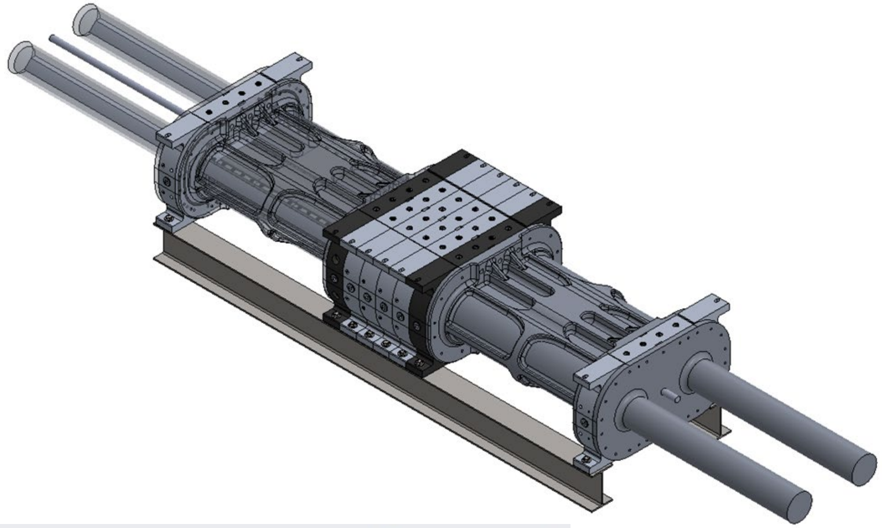
- Simulation includes:
  - Ground storage (87.5 MPa)
  - 129L vehicle tank – currently no heat transfer to tank wall
  - REFPROP fluid properties
- Major efficiency losses included
  - Valve pressure drop
  - Seal friction
  - Heat transfer from expander body
- Further modeling planned with H2SCOPE aimed at quantifying heat absorbed by tank wall during fill

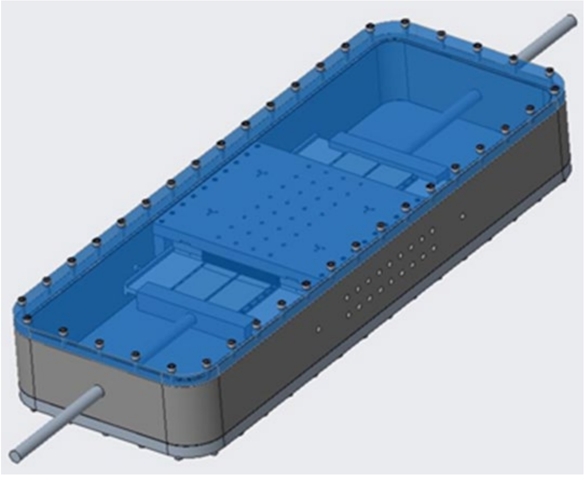




Progress: 2 Linear Motor System Designs

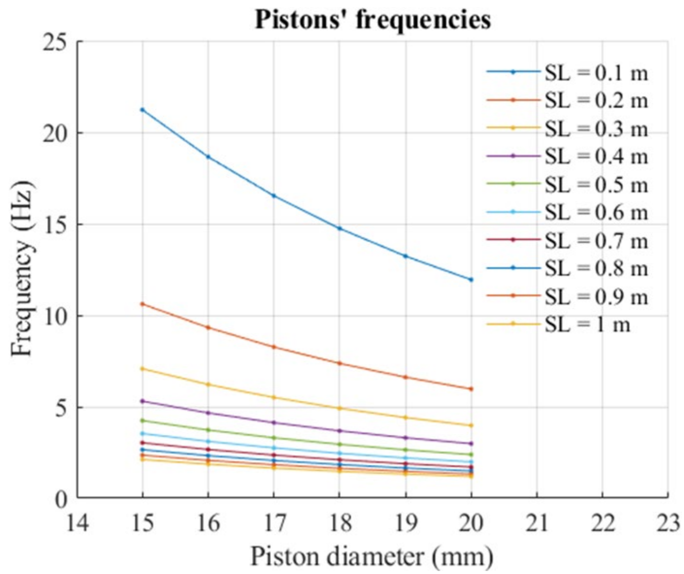
- Initial motor system design is more compact, but is more complicated and therefore carries more risk
- While the bearing system for the first design is awaiting testing, a second, simplified design was created
- Second design (lower image) has fewer moving parts, but is larger (3 feet wide vs 2 feet wide in the first design)
- Testing of bearing system (expected in June 2020) will guide decision between two designs

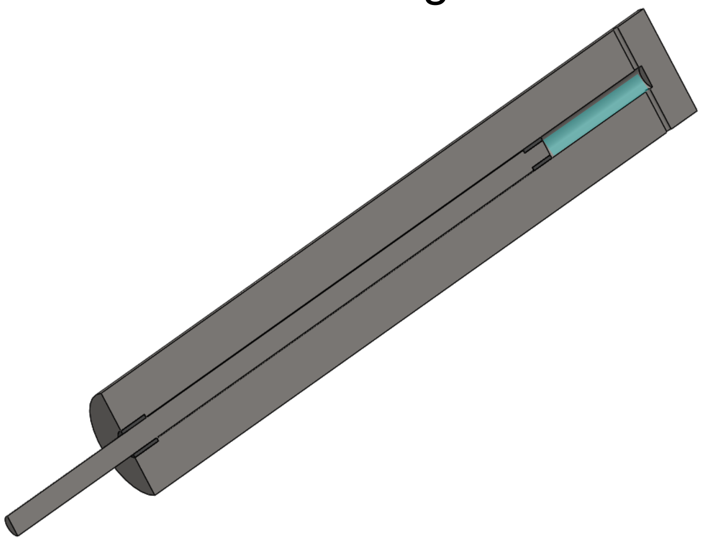




Progress: Fluid End Geometry Finalized

- One of two identical fluid ends pictured below without valves
- Efficiency increases with diameter, but diameter limited by max motor force
- Shorter stroke length (SL) allows smaller size, but requires higher frequency
  - 0.5 m stroke length for initial testing – allows 50ms valve actuation
  - Stroke length can be shortened easily if valves are fast enough





Progress: Valve Designs Down-Selected

- Valve speed is key to operation; no commercial valves meet requirements
- Team developed 3 steps of valve implementation to reduce risk during startup
  - The second step may be omitted if only marginal improvement expected

Valve Option	Description	Purpose	Risk	Performance
Commercial	Standard fitting connections Standard pilot-operated solenoid valves	Prove expander concept with minimal technical risk	Low	Very confident in operation, but speed will likely be limited
Limited Customization	Standard valve components integrated into expander body Possibly custom solenoid actuator	Show performance improvement	Medium	Speed will likely still be limited
Fully Custom Design	Custom valve components integrated into expander body 3 of 4 actuations are passive	Maximize efficiency	High	Maximum speed and efficiency

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Progress: Economic Analysis

Preliminary capital cost

- Expander slightly lower cost
- Assuming quantity of ~100
- Built using mostly real quotes for prototype components

Current Pre-cooler Technology

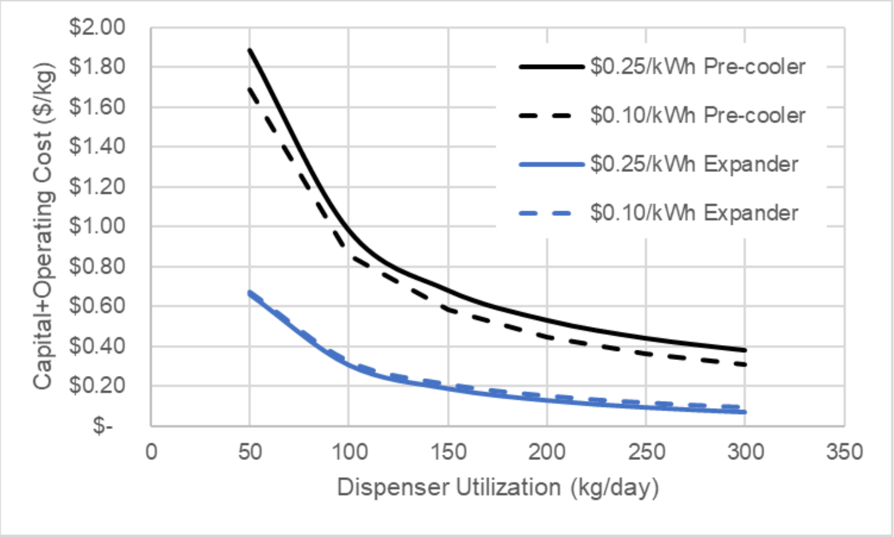
Pre-cooler	$140,000
Ramp Regulator	$2,500
Total	**$142,500**

Expander

Linear motors	$ 14,619
Frame	$ 8,959
Fluid ends	$ 10,156
Miscellaneous	$ 3,373
Assembly (40%)	$ 14,843
Profit (20%)	$ 10,390
Total	**$ 62,339**

Total pre-cooling cost

- Includes operating cost
  - Pre-cooler ***consumes*** 0.3kWh/kg
  - Expander ***produces*** 0.2kWh/kg



Response to Reviewer's Comments

Project was not reviewed last year.

Collaboration and Coordination

Organization	Project Roles	Importance to Project
GTI	Project lead, management and coordination; prototype mechanical design and build; prototype testing and reporting	Integral to the organization and direction of the project
University of Texas at Austin – Center for Electromechanics	Electrical system design; lead for system simulations; assist mechanical component design and selection	Integral to the technical success of the project. Invaluable electromechanical experience
Argonne National Lab	Techno-economic modeling; environmental benefit assessment	Vast hydrogen fueling knowledge and experience with current pre-cooling systems and J2601 standard
Quantum Fuel Solutions	Source of H2 fueling dispenser operational data and experience; assist in component design and selection	Connection with industry; potential commercialization partner; source of real-world experience

Remaining Challenges and Barriers

- Demonstrate full fill possible with simulated expander performance
  - Many different conditions to consider
- Build and operate prototype, demonstrating:
  - Safe operation
  - Functionality of custom valves and other key components
  - Capable of achieving full fill within tank limits
- Minimizing capital cost
  - Shorter stroke would allow more compact size, fewer components
  - Integrating with compressor electronics

Proposed Future Work

Remainder of 2020

- Complete detailed design of expander system
  - Includes valve and control system testing that was delayed due to COVID-19 shutdown
  - Includes at least 2 options for valve designs to be tested
  - Conduct full hazard assessment of system
- Complete fabrication of expander system in test facility at GTI

First Half of 2021

- Complete commissioning and safety checks
- Conduct tank fills with nitrogen before moving to hydrogen in Q3 2021

Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

- Investigation of other applications key to maturing technology and reducing system cost. Promising applications include:
  - Compressed natural gas (CNG) fueling
  - Small-scale cryogenic cooling and liquefaction (Brayton cycle)
  - Small-scale power generation (e.g. Organic Rankine Cycle)
- Potential future funding
  - Current NREL-funded project developing CNG fueling application
  - Potential deployment project at H2 or CNG fueling site
- Patents and licensing
  - Investigating IP around novel component designs

Summary

Objective:	Demonstrate free-piston expander technology which can reduce the pre-cooling cost to less than $0.20/kg (5-yr levelized)
Relevance:	Pre-cooling cost represent 10% of station capital costs
	Pre-cooling energy consumption of 0.5-5 kWh/kg would be completely eliminated with expander system
Approach:	Free-piston expander technology selected due to high efficiency operation, which can completely eliminate pre-cooling need.
	Design approach focused on eliminating risks early in project by testing low-pressure system and designing several valve systems with increasing technical risk potential.
Progress:	Simulation shows full fill possible within tank limits
	Design options created; testing will allow down-selection
Nest Steps:	Complete testing which was delayed due to COVID-19
	Complete detailed design, build, and commissioning of prototype