GTI ENERGY

solutions that transform

Free-Piston Expander for Hydrogen Cooling

AMR Project ID: IN016

DOE Project Award #DE-EE0008431

PI: Devin Halliday

GTI Energy

2024 Annual Merit Review | May 7, 2024

Project Goal

- Develop a free-piston linear motor expander to conduct required hydrogen pre-cooling for light-duty hydrogen fueling, while producing energy than can be used to offset compression energy consumption.

Overview

GTI ENERGY

Timeline

Project start date: January 2019

Project end date: March 2024

Percent complete: 100%

Budget

Total project budget: $3.39M

Total cost share budget: $0.69M

Total federal share: $2.7M

Total DOE funds spent*: $2.7M

Cost share funds spent*: $0.69M

*As of 02/29/2024

Barriers

High fuel delivery costs

High fueling station costs

Limited consecutive fills

Partners

University of Texas at Austin – Center for Electromechanics

Argonne National Laboratory

Potential Impact

GTI ENERGY

- High cost of hydrogen fueling stations is a barrier to market adoption
- Pre-cooling unit represents 10% of capital cost and significant operational cost
- Replacement with expander could eliminate power requirement and offset compression

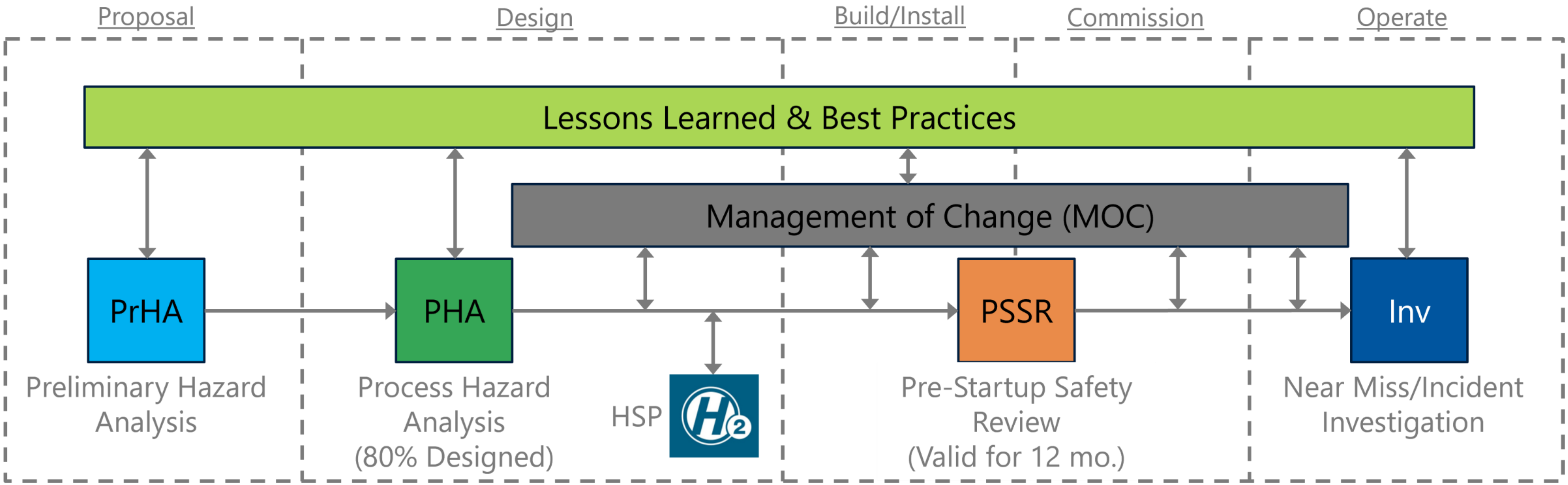
Targets	Units	2015 State of the Art	HFTO Target	Project Target
Pre-Cooling Capital Cost (Uninstalled)	$	$140,000	$70,000	$60,000
Delivery Costs	$/kg	3.35-4.35	<2.00	
Pre-Cooling Energy Consumption	kWh/kg	0.5-2.0		<0
Pre-cooling cost (capital + electricity)	$/kg	0.50-3.00		0.20

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

Approach: Safety Planning and Culture

GTI ENERGY

- This project submitted a safety plan to the HSP in 2021
- Feedback focused on clarification and improving ventilation – addressed with changes to plan
- GTI process safety management program has been improved over last few years (below)



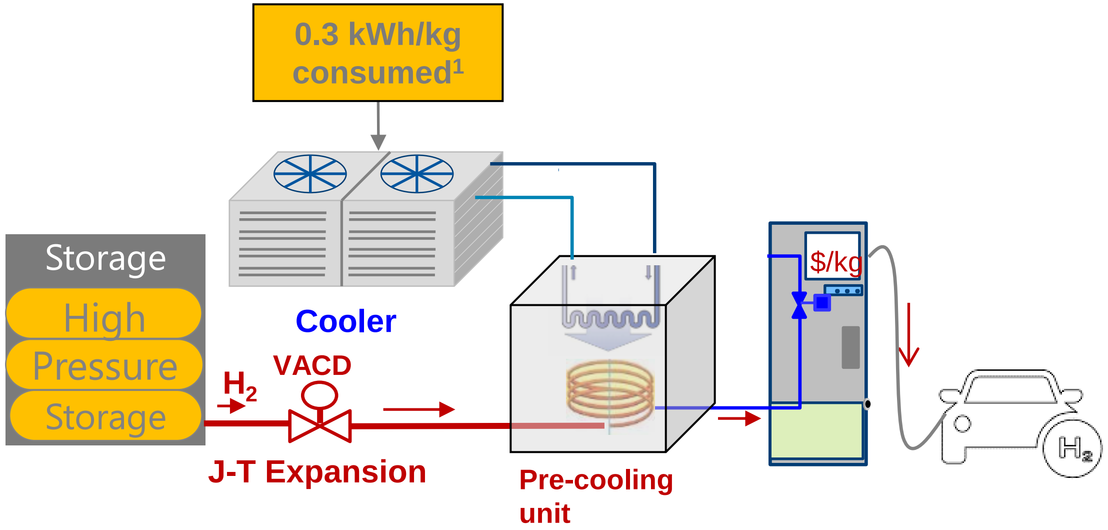
Approach: Utilize Existing Pressure Differential to Remove Energy from H2

- Current system

  $140,000 uninstalled[1]

  50 kWh/day baseload[1]

  Frequent fueling interruptions due to over-temperature

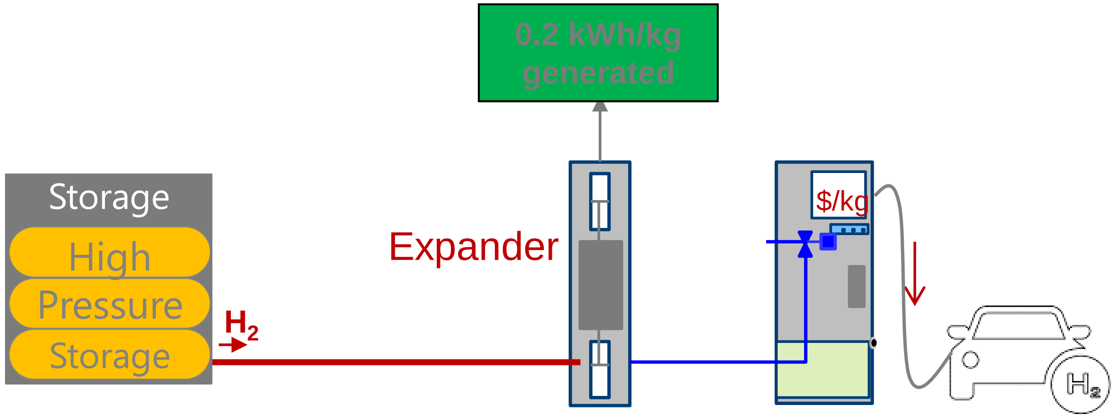


- Expander system

  Targeting $60,000 uninstalled

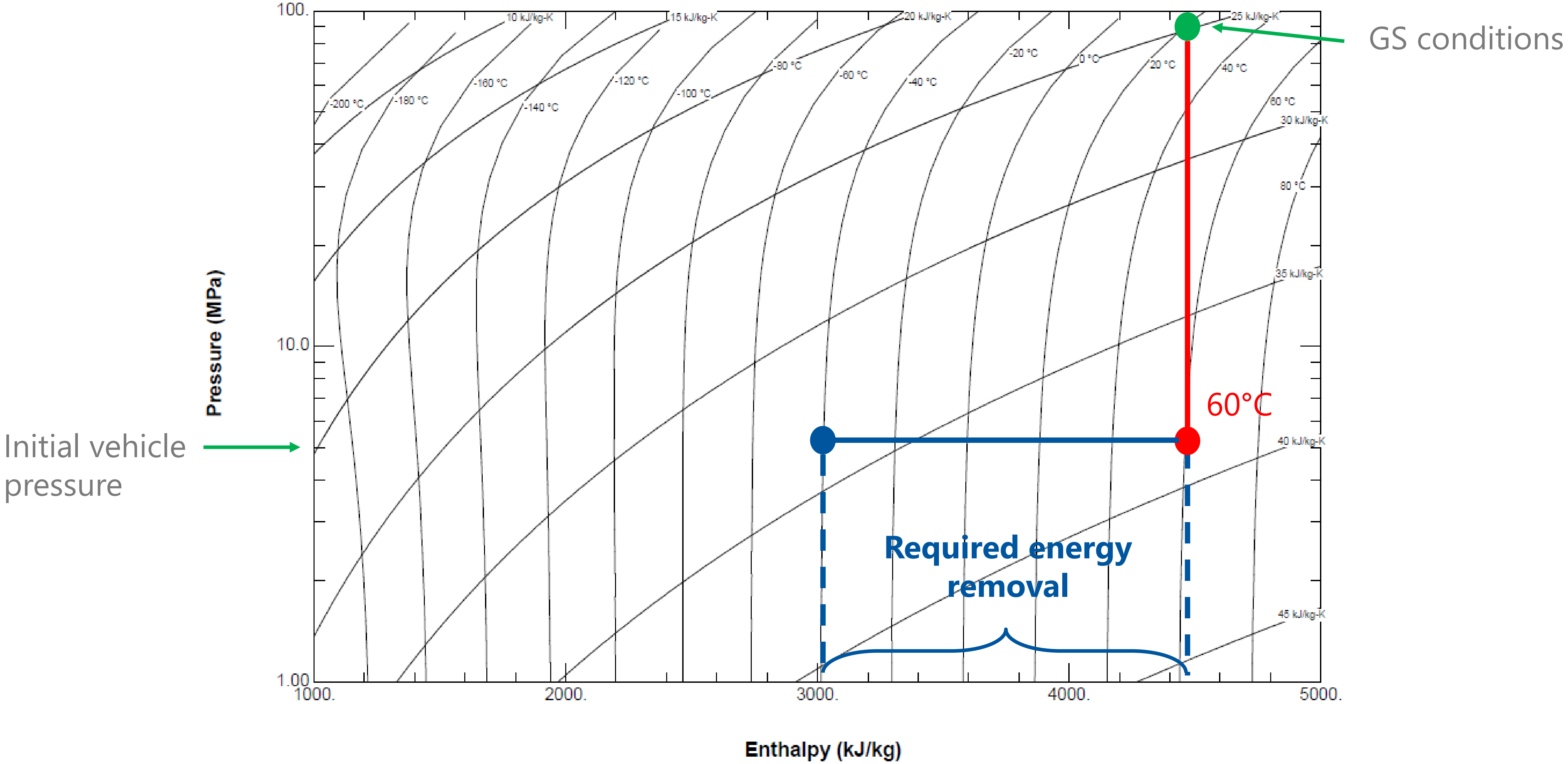
  5-10kWh/day baseload

  Infinite back to back fills; system gets colder with fueling

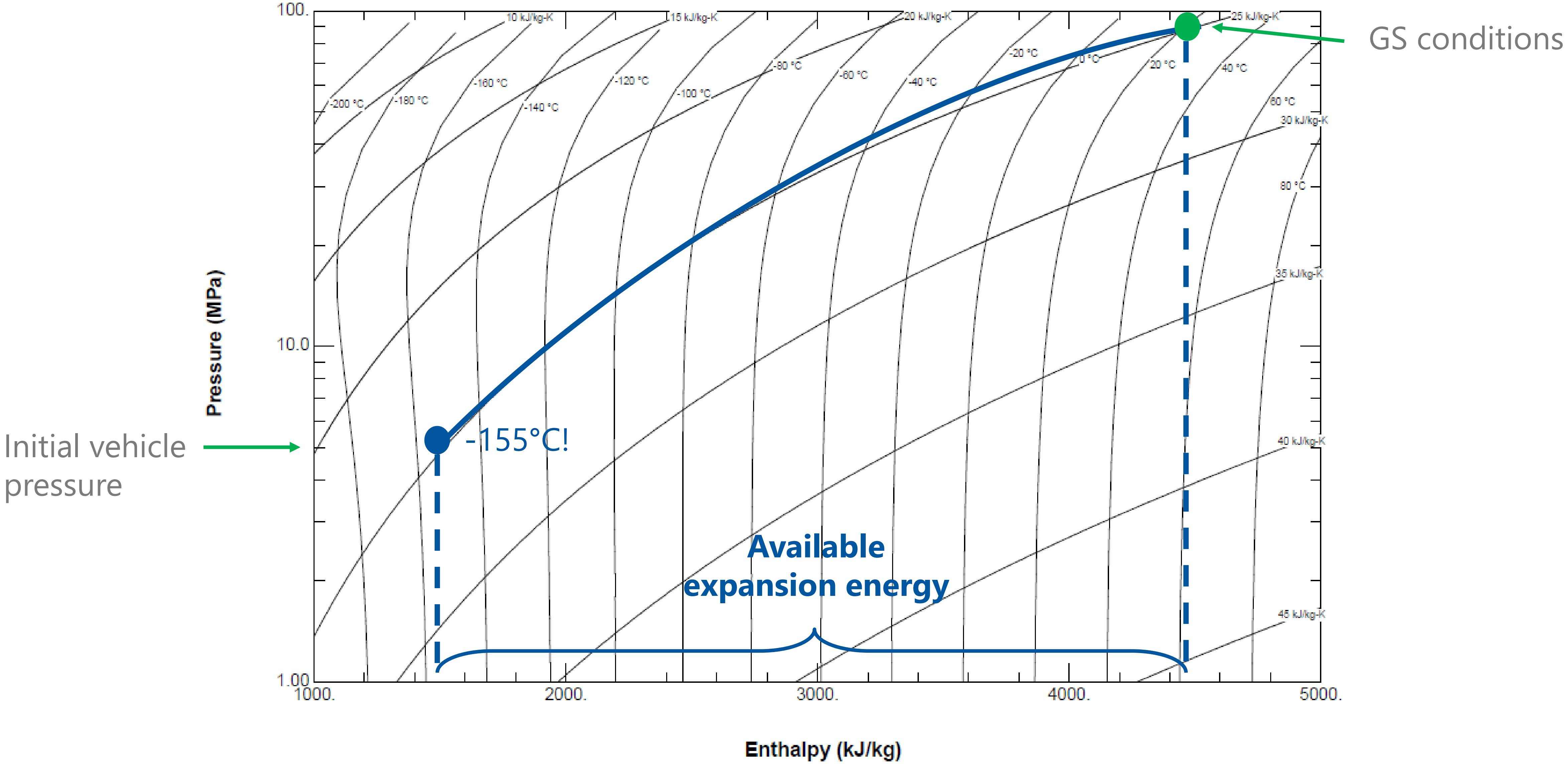


[1] *Elgowainy et al, Int Journal of Hydrogen Energy 42 (2017), 29067-29079*

Approach: Isenthalpic Pressure Reduction (current technology)



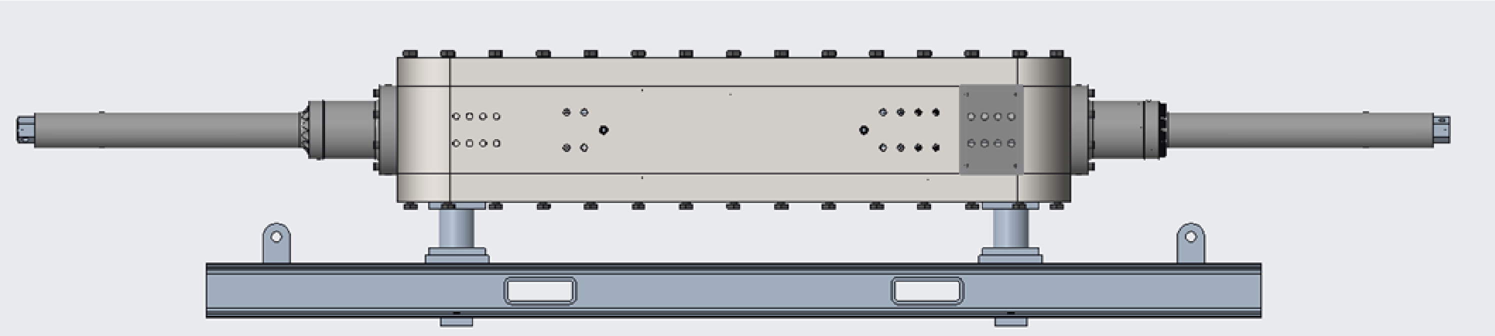
Approach: Isentropic Pressure Reduction (expander)



Progress: Prior to 2023 AMR

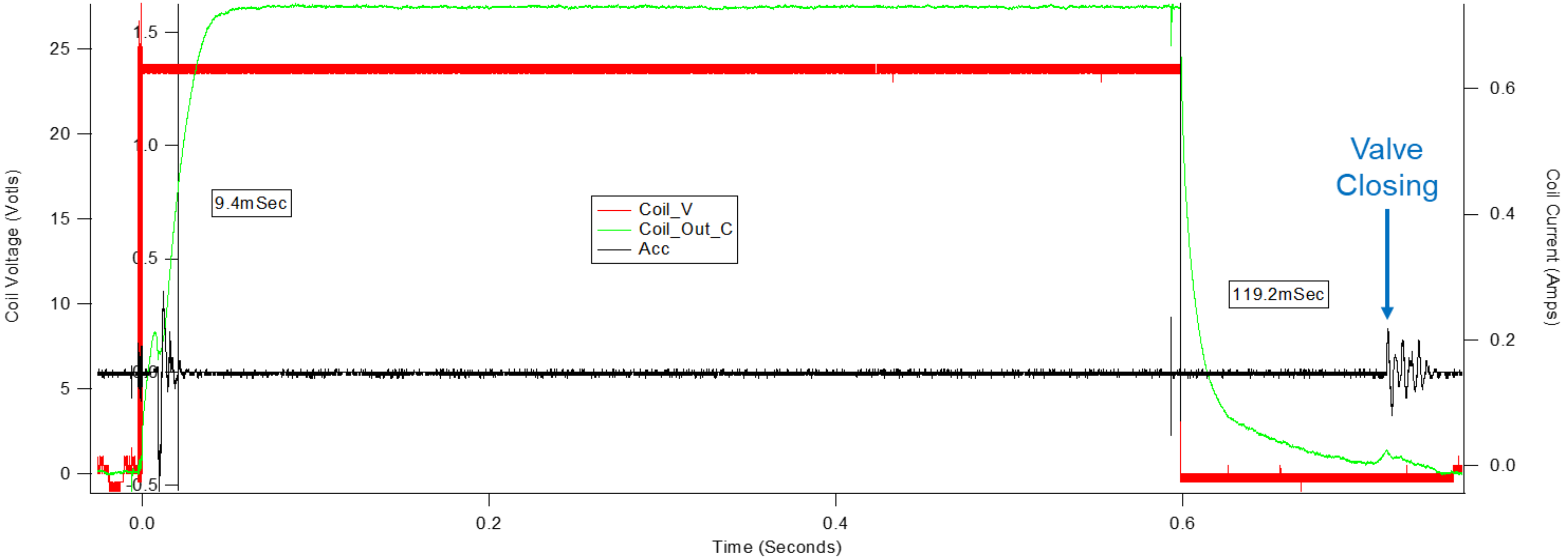
GTI ENERGY

- Linear geometry selected for high efficiency and control over wide range of conditions
- Linear motor fabrication and assembly completed in summer 2022
- Safety tests and verification completed by end of 2022
- Testing with nitrogen completed
  - Proved out system with safer gas
  - 30% isentropic efficiency



Progress: Transition to Hydrogen

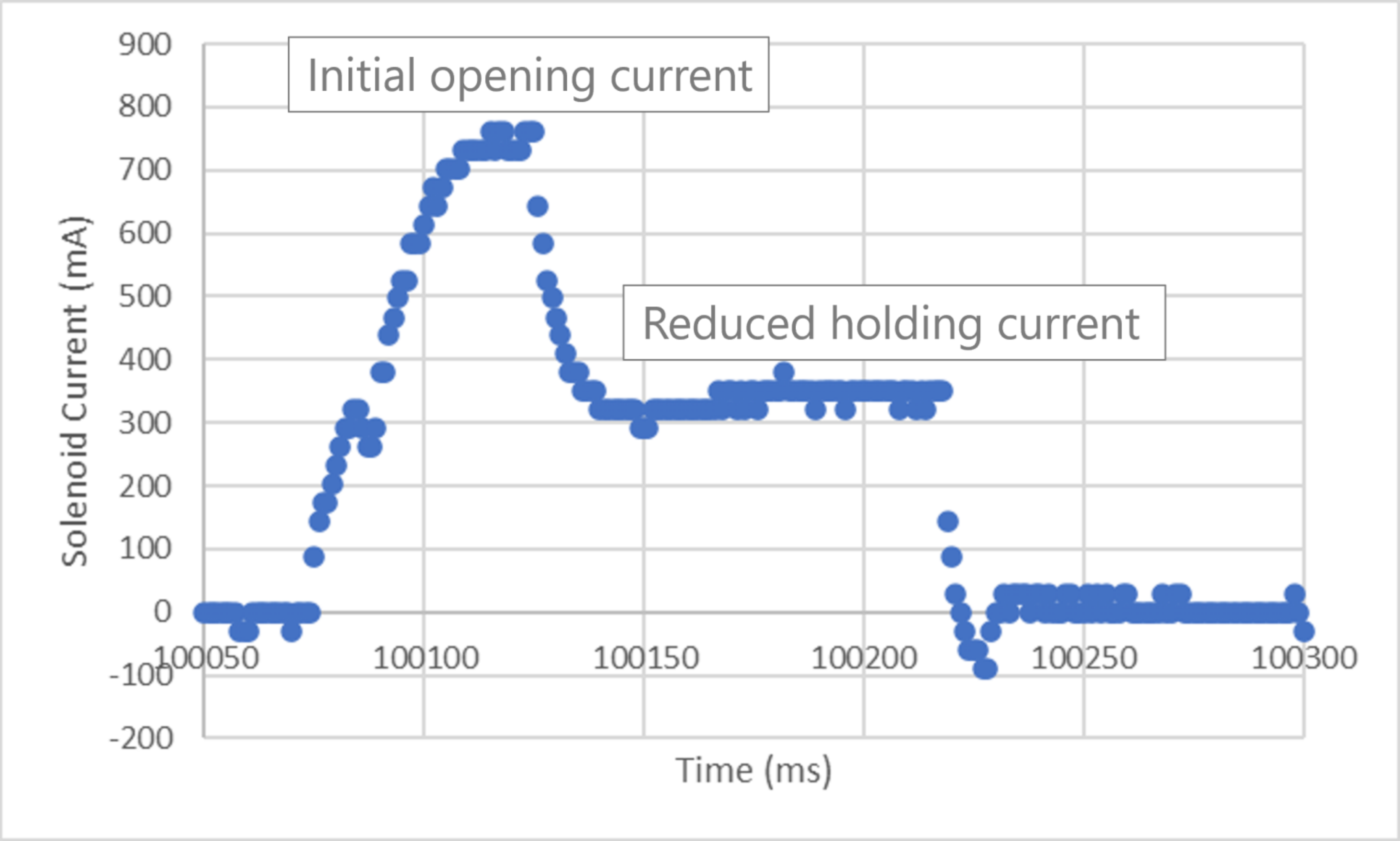
- Completed safety checks and Pre-Startup Safety Review for transition to H2 – August '23
- Started at 15MPa inlet pressure and slowly increased to 80MPa
- Velocity initially limited to 500mm/s due to long solenoid inlet valve closing time
- Tests from 2021:



Progress: Valve Control Improvements

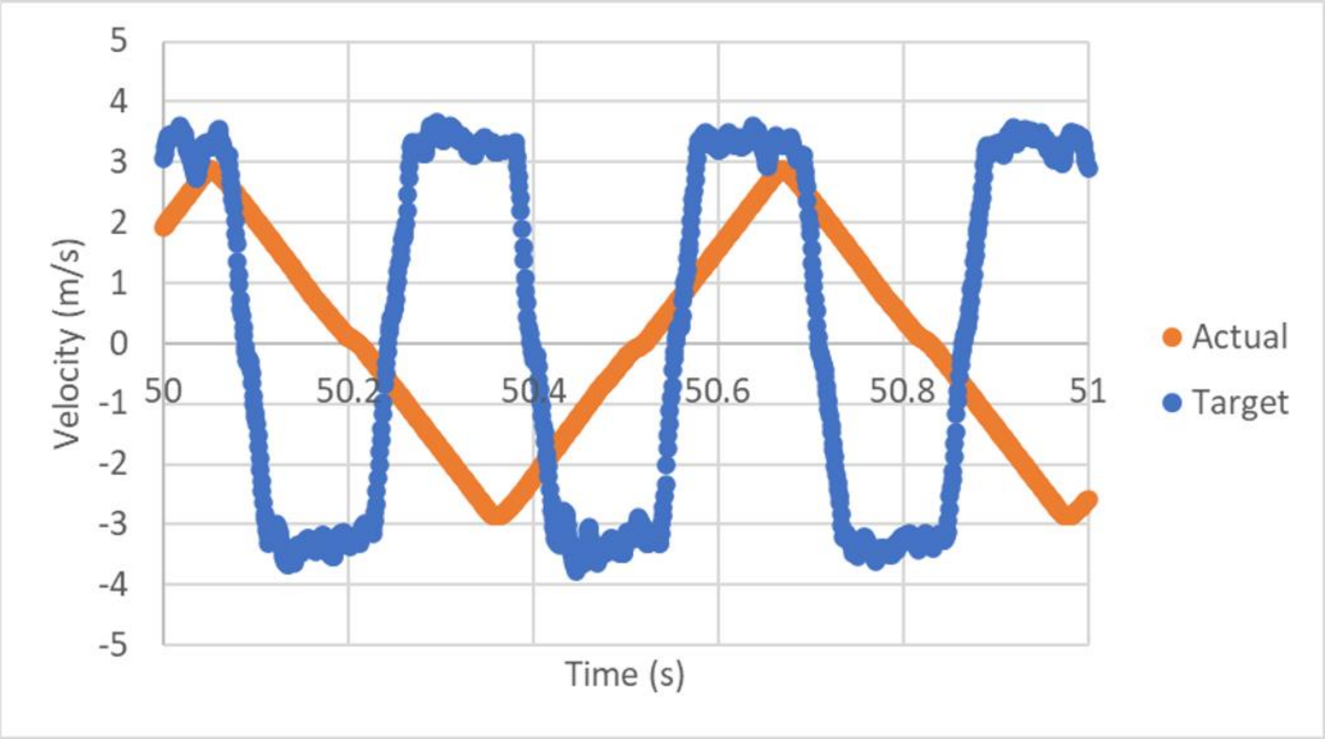
GTI ENERGY

- Replaced with DC solenoids with no diode bridge
- New solenoids controlled with new modules with pole-switching and current control
- Result is fast closing – each data point is 1ms
- Pilot element closes in a few milliseconds, primary valve element takes a further 20-30ms to close



Progress: Velocity Maximization

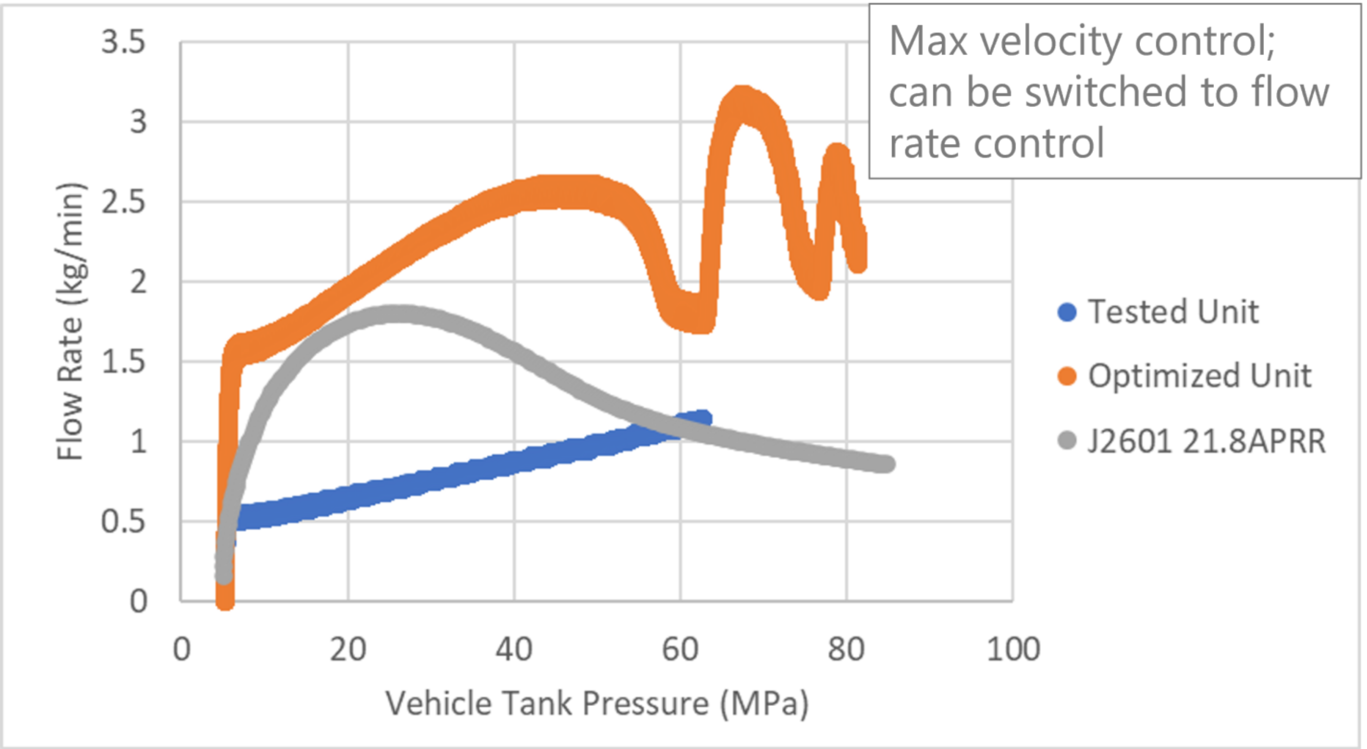
- Able to increase velocity to 3m/s, but only as a peak
- Acceleration limited to 20m/s^2 due to vibration, target was 100m/s^2
- As a result, flow rate was approximately half of target



Progress: Flow Rate Target

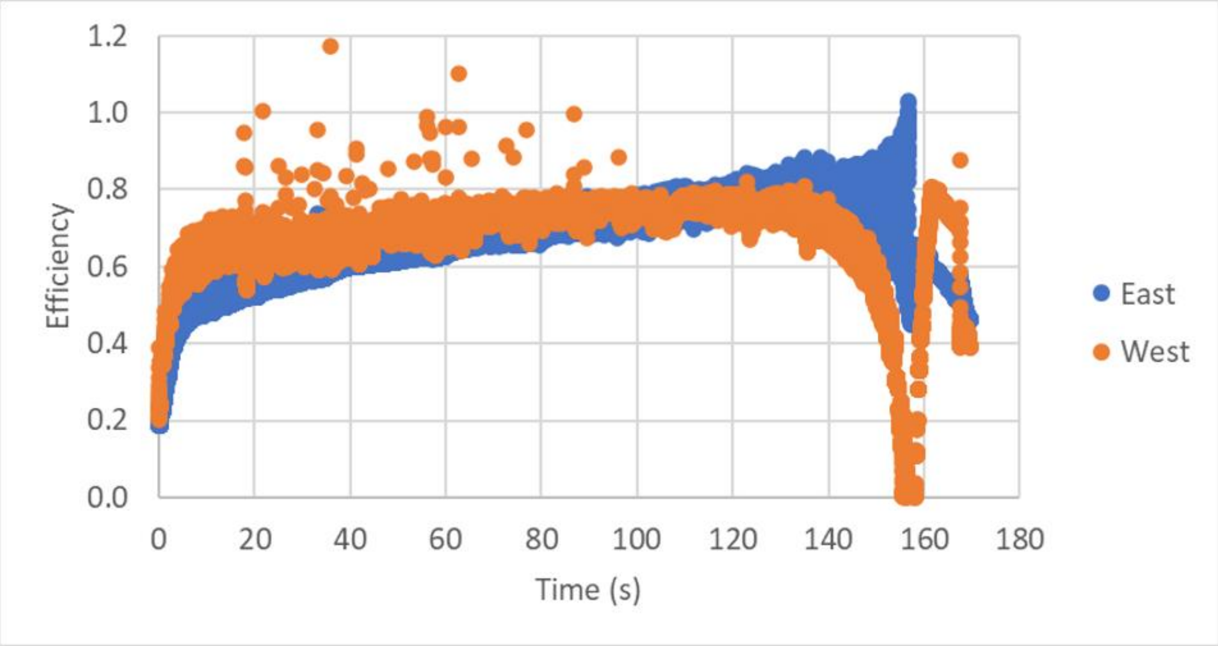
GTI ENERGY

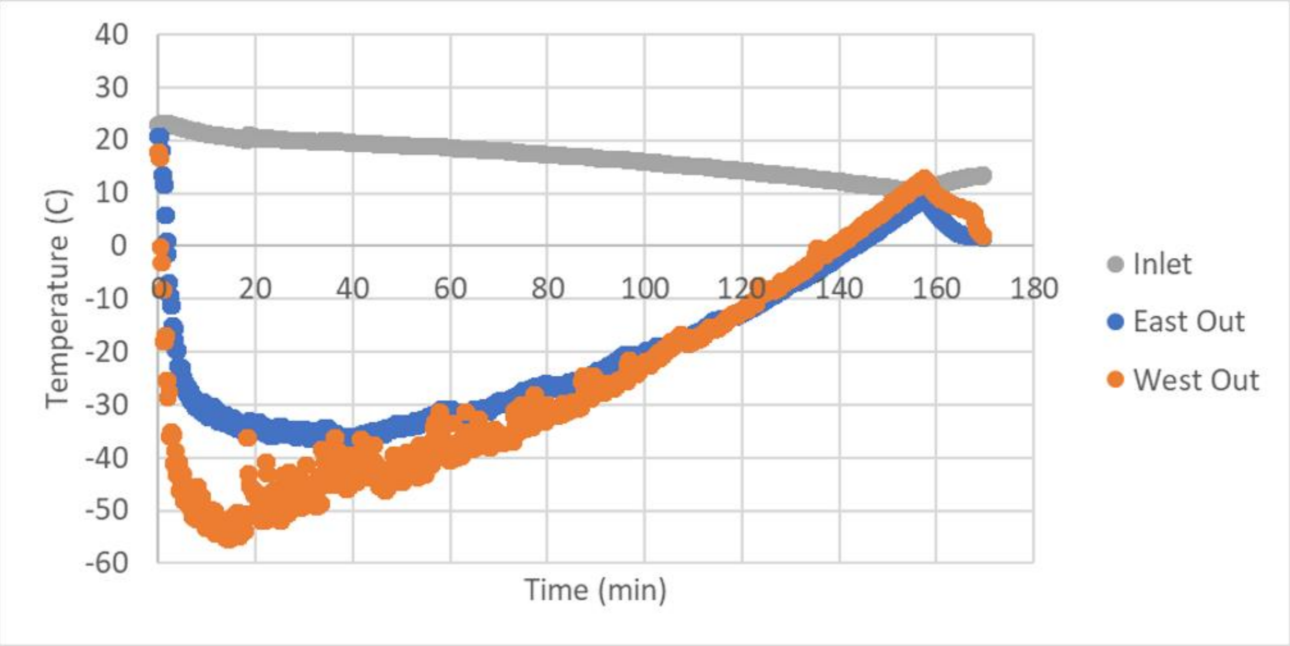
- Flow rate limited to 0.5-1.1 kg/min (average 0.8 kg/min)
- Tests showed motors were only 65% utilized - conservative design
- In simulation, increased piston area
  - Also returned to full velocity profile
- Showed target flow could be achieved
- How to address vibration?
  - Couple two opposing units



Progress: Thermodynamic Performance

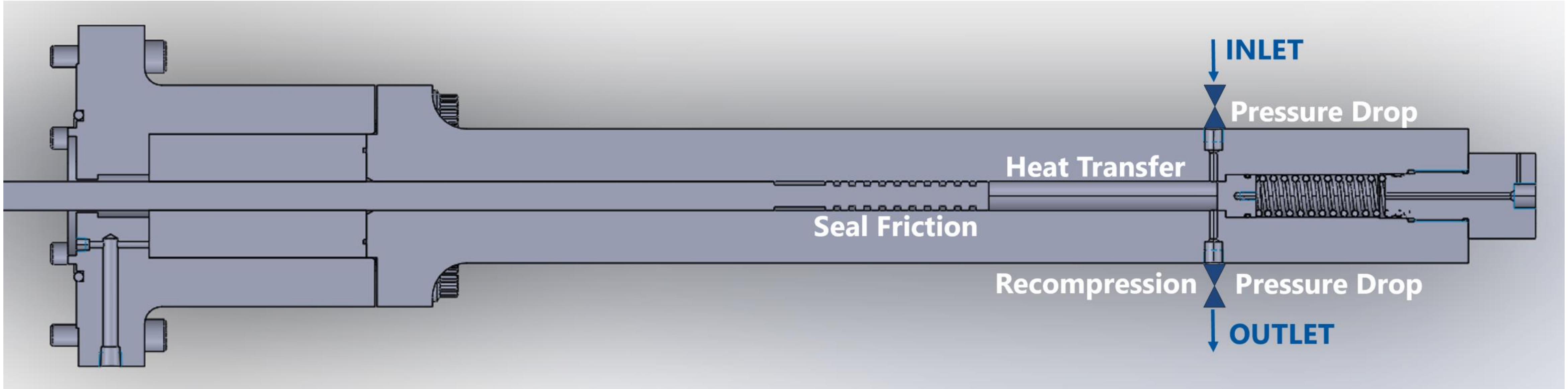
- Isentropic efficiency varies from ~65% to 75% over course of fill
- Differences in performance of east and west sides largely attributed to outlet valves
- Expander body starts at ambient, cools down by 1-2°C during fill





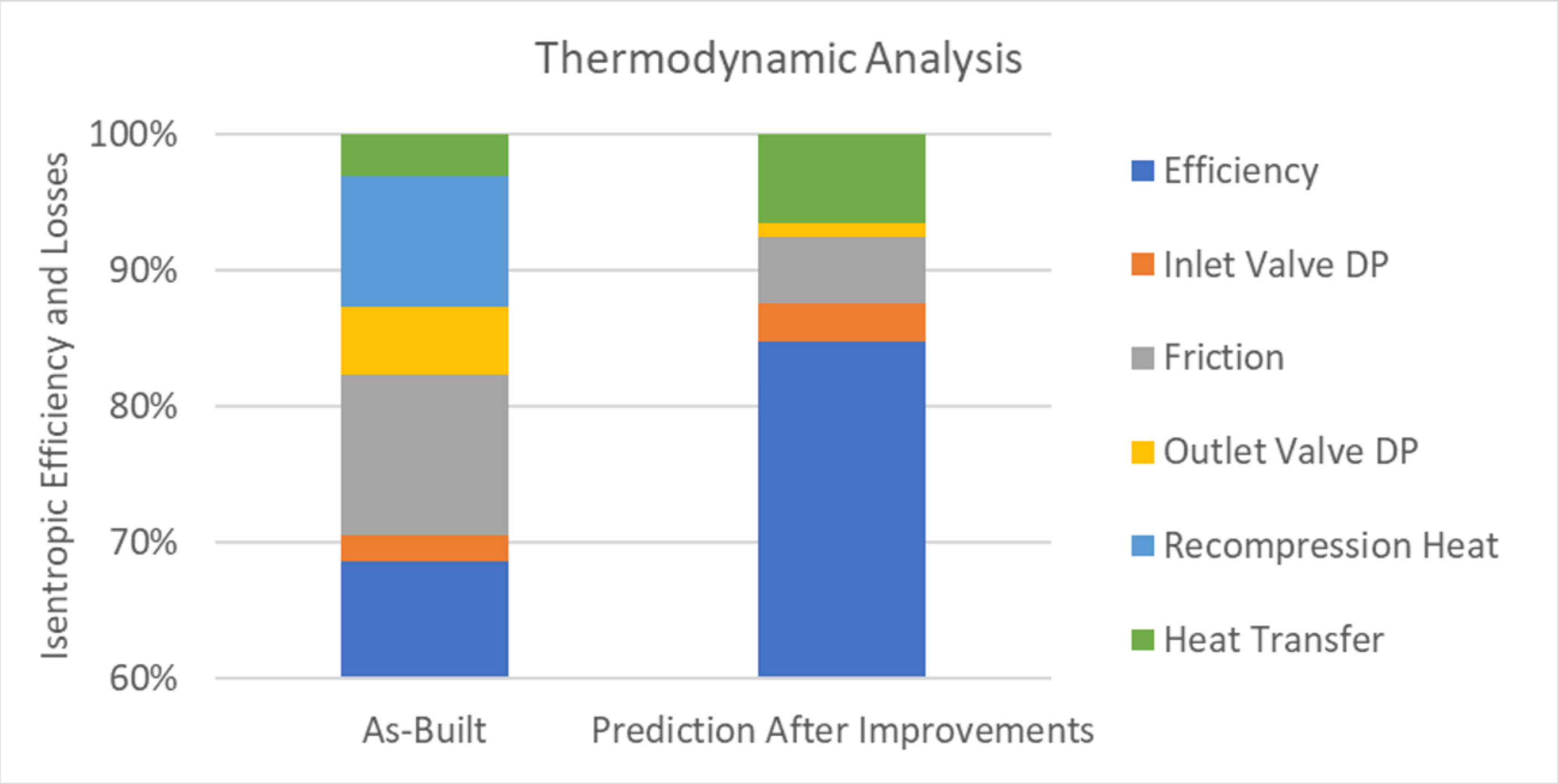
Progress: Inefficiencies and Improvements

- Operational data was used to identify main losses (below and next slide)
- Recompression was necessary due to poor function of pilot-actuated solenoid valve (outlet)
  - Rapid increase in inlet pressure caused valve to open, causing ‘blow through’
  - Outlet valve redesign would have big benefits
- Seal friction another leading contributor – plan for redesign to shift heat away from gas



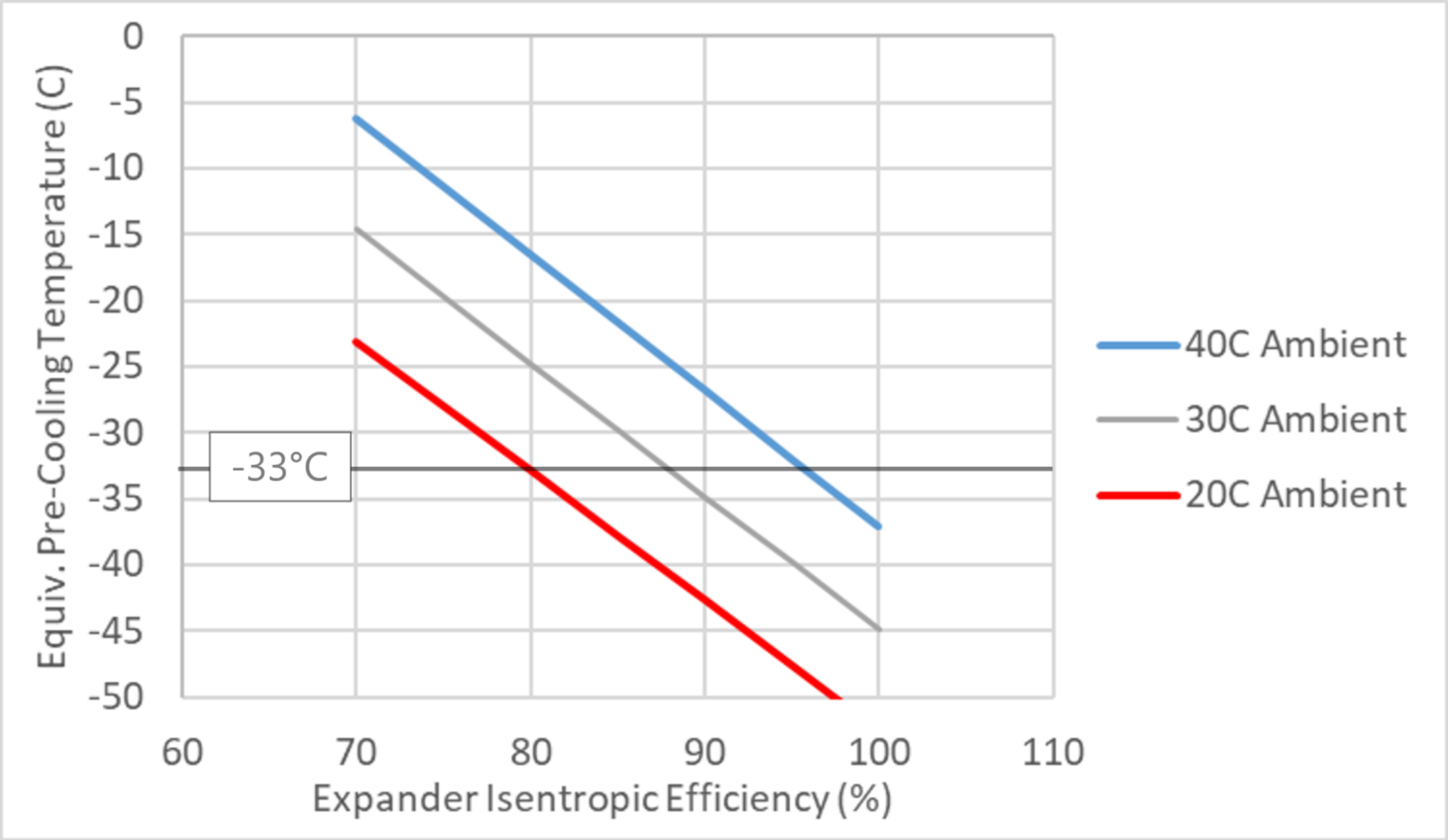
Progress: Inefficiencies and Improvements

- Operation yielded ~68-73% efficient consistently
- Path to 85% seems reasonable with changes to seals, outlet valves, larger bore



Target Level of Performance

- Light-duty T40 fueling required >95% efficiency at 40°C ambient
- Heavy-duty fueling is slightly less challenging, with -30°C fueling required to achieve DOE targets



Progress: Economic Analysis

GTI ENERGY

- Cost of unit at 100/yr achieves target capital cost

HRSAM analysis conducted by ANL

- Assumed $80k/expander
- 4-hose station (favors conventional technology)
- 20% utilization
- Expander meets "On-Demand" capability with "Thermal Buffering" capital cost
- 50% station utilization would approach target of $0.20/kg

Production Volume			1	10	100	1000
Cumulative Unit Costs			**$112,019**	**$73,832**	**$46,249**	**$35,323**
Misc. Consumables	10%		$ 11,202	$ 7,383	$ 4,625	$ 3,532
Fabrication and Assembly	10%		$ 12,322	$ 8,121	$ 5,087	$ 3,886
Profit	20%		$ 27,109	$ 17,867	$ 11,192	$ 8,548
Price			**$162,652**	**$107,204**	**$67,154**	**$51,289**

HRSAM Analysis

	Thermal Buffering Pre-Cooler	On-Demand Pre-Cooler	Expander
Total Cost per kg H2 (5 yr levelized)	$0.57	$0.76	$0.47
Capital Cost Installed	$0.34	$0.47	$0.35
Electricity Costs	$0.08	$0.08	($0.03)
Other (Maintenance, Permitting, Etc.)	$0.15	$0.20	$0.16

Maintenance assumption needs to be investigated

Response to 2023 AMR Reviewer Comments

GTI ENERGY

Reviewer Comment	Project Team Response
The team should find a manufacturing pater to help with commercialization and determining price.	We have been in contact with several manufacturing partners. While they are very interested in the system, they believe further development is necessary prior to their full involvement.
It's not clear if the system can achieve -40°C precooling for the entire fill.	The system requires a thermal mass to buffer the large swings in outlet temperature. During testing, the mass was too large due to underestimating heat transfer inside the expansion chamber. Therefore, reported results are for expander chamber outlet. Theoretically, the expansion energy can achieve T40 precooling (-33°C maximum).
Future challenges include seal durability testing.	The testing of seals and valves for long-term durability is key to determining maintenance costs of the system. This was not included in the scope of this project but needs to be done prior to commercialization.

Collaboration and Coordination

GTI ENERGY

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
Commercialization Partner	Interest from several commercial companies – most want to see further development first	Path to market for linear expander technology

Remaining Challenges and Barriers & Future Work

GTI ENERGY

- Reducing capital cost:
  - Investigating simplification of power electronics
  - Maximizing motor utilization
  - Shrinking footprint and reducing size and complexity of custom components
- Improve performance of system
  - Couple with opposing unit to maximize acceleration/throughput – HD refueling
  - Improve power factor with modified power electronics
- Understand maintenance cost of system
  - Requires longer-term testing

Summary

GTI ENERGY

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 0.5-3 kWh/kg would be completely eliminated with expander system
Approach:	Free-piston expander technology selected due to high efficiency operation over a wide range of operating conditions
	Process safety management framework followed during project
Progress:	Expander achieved 70% isentropic efficiency with average flow of 0.8kg/min
	Economic analysis showed viable product if flow & efficiency can be improved
Nest Steps:	Improve cost and performance – proposed funding for HD application