



GTI ENERGY

solutions that transform

Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling

AMR Project ID: IN036

DOE Project Award #DE-EE0009625

PI: Devin Halliday
GTI Energy

2023 Annual Merit Review | June 7, 2023

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Goal

- Deliver a validated high-flow chiller design ready for manufacture and installation in a heavy-duty fueling station
- Provide marketable, optimized system to accelerate construction of heavy-duty hydrogen fueling stations
- Ensure design is sustainable and withstands future refrigerant regulations

Overview

Timeline

Project start date: August 2022

Project end date: July 2025

Percent complete: 20%

Budget

Total project budget: \$2.75M

Total cost share budget: \$0.550M

Total federal share: \$2.2M

Total DOE funds spent*: \$0.15M

Cost share funds spent*: \$0.075M

*As of 03/31/2023

Barriers and Targets

Barrier – lack of commercial pre-cooling technology

Target < 200 kW peak load

Target < \$500,000 capital cost

Partners

Creative Thermal Solutions

Argonne National Laboratory

Potential Impact

DOE Goals	Project Impact
Build clean energy infrastructure	Create path to market for key component in heavy-duty fueling stations
Lower greenhouse gas emissions and criteria pollutants	Enables heavy-duty fuel cell vehicles, displacing diesel vehicles
Lower price of delivered hydrogen	Cost-effective pre-cooling will reduce cost of fueling
Provide pathways to private sector uptake	Technology transfer and commercialization at the end of the project will lead to private sector ownership of chiller design

Approach: Project Plan

Budget Period 1

Preliminary Chiller Design

- Develop detailed understanding of duty cycle and system requirements
- Consider several configurations and select best option

- Go/No-Go #1: Modeling shows system capable of 10 kg/min with power under 200kW

Budget Period 2

Detailed Design and Build

- Design for 1/5th capacity to allow for cost-effective testing
- Incorporate learnings from early heat transfer testing

- Go/No-Go #2: Economic analysis shows cost < \$500,000 per unit

Budget Period 3

Testing and Final Design

- Test results used to update design
- Technology transfer and commercialization top priority to ensure unit gets to market

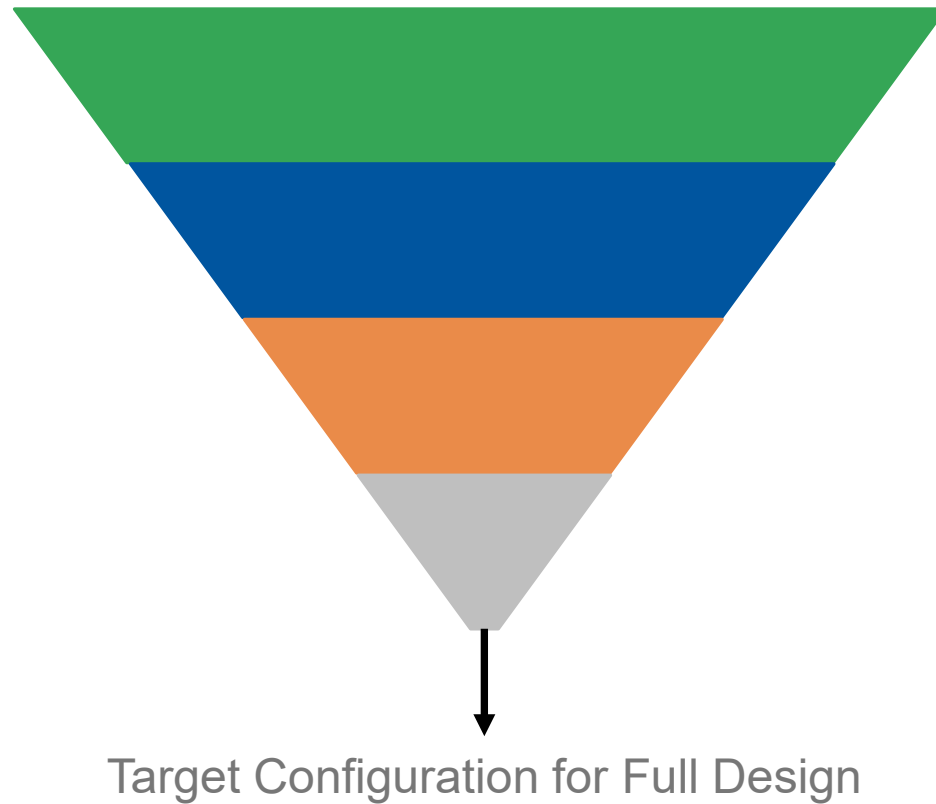
Approach: Budget Period 1 Plan

		2022					2023						
Subtask	Description	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1.1	System Modeling												
1.2	On-Demand Cooling Testing												
1.3	Preliminary Design												

- Milestones:

- M1.1.1: Modifications to H2SCOPE model for high-flow operation – due 10/31/22 **Completed**
- M1.2.1: Mathematical model of heat exchanger performance – due 5/31/23 **Delayed**
- M1.3.1: Down-selection to 2 or 3 refrigerant systems – due 1/31/23 **Completed**
- M1.3.2: Preliminary design – due 7/31/23 **On Track**

Approach: Refrigerant System Selection



Select refrigerants that meet project criteria

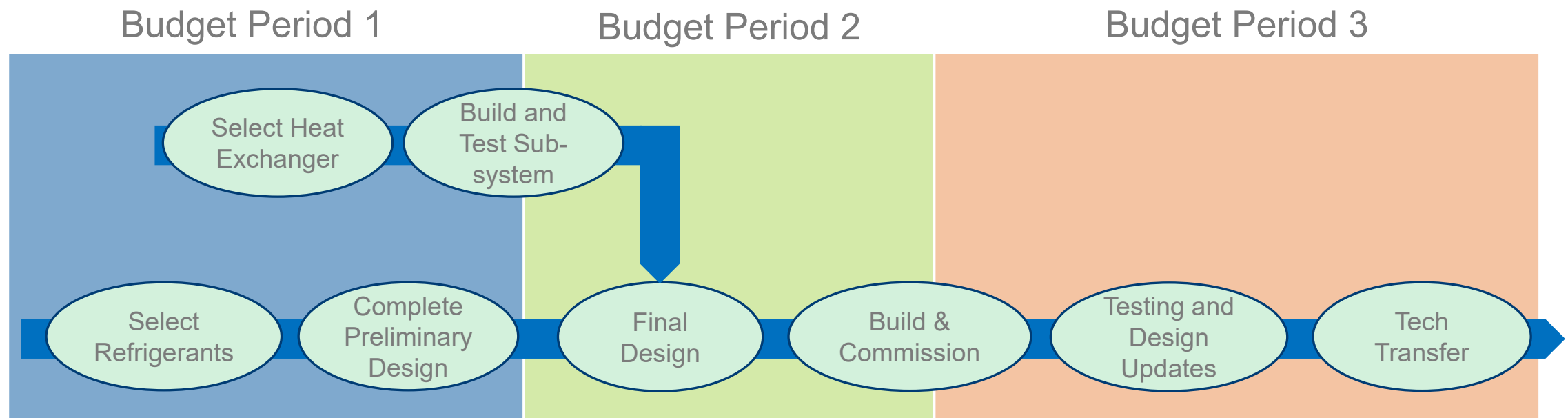
Select 2-3 refrigerant systems capable of achieving project goals

Consider refrigeration cycle configurations and their costs and benefits

Complete high-level cost analysis on several configurations

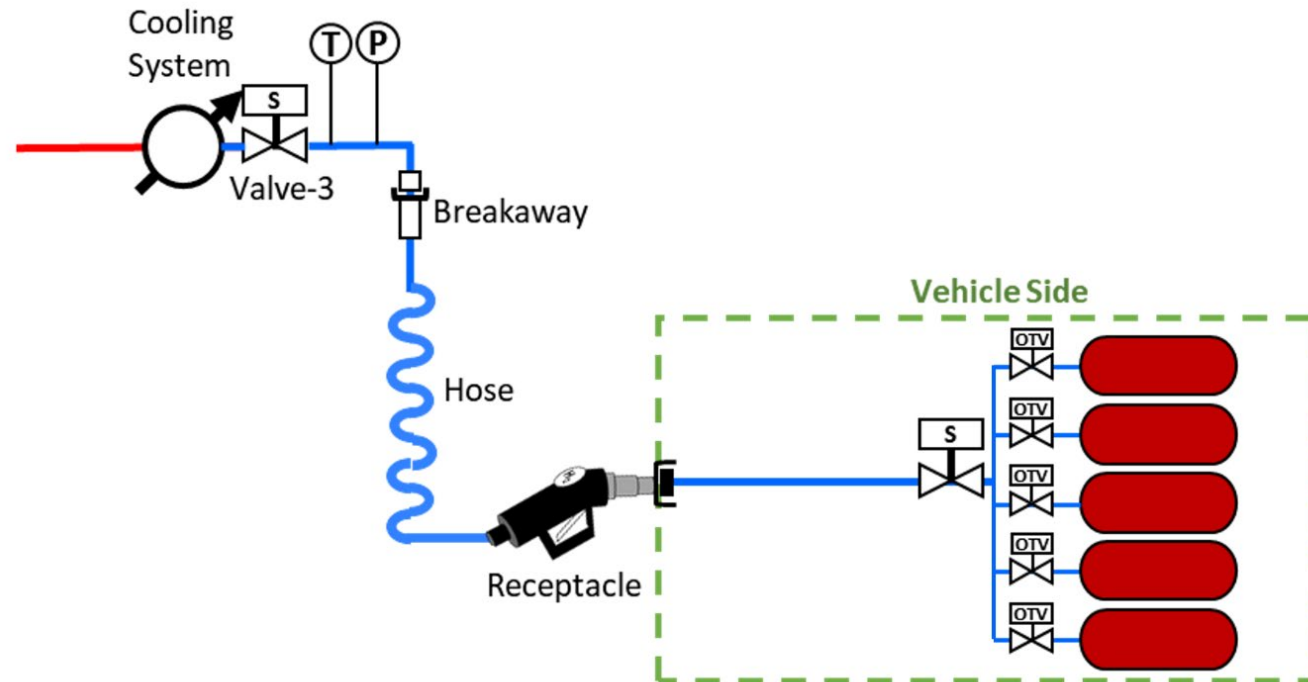
Approach: Integrating Early Testing Results

- Risk: Heat exchanger performance carries many unknowns
 - Direct expansion heat exchanger, with high pressure H₂, in a highly transient duty cycle
- Mitigation: Test sub-system early and apply learnings to design
 - Goal is modeling of heat exchanger performance



Progress: Duty Cycle Modeling

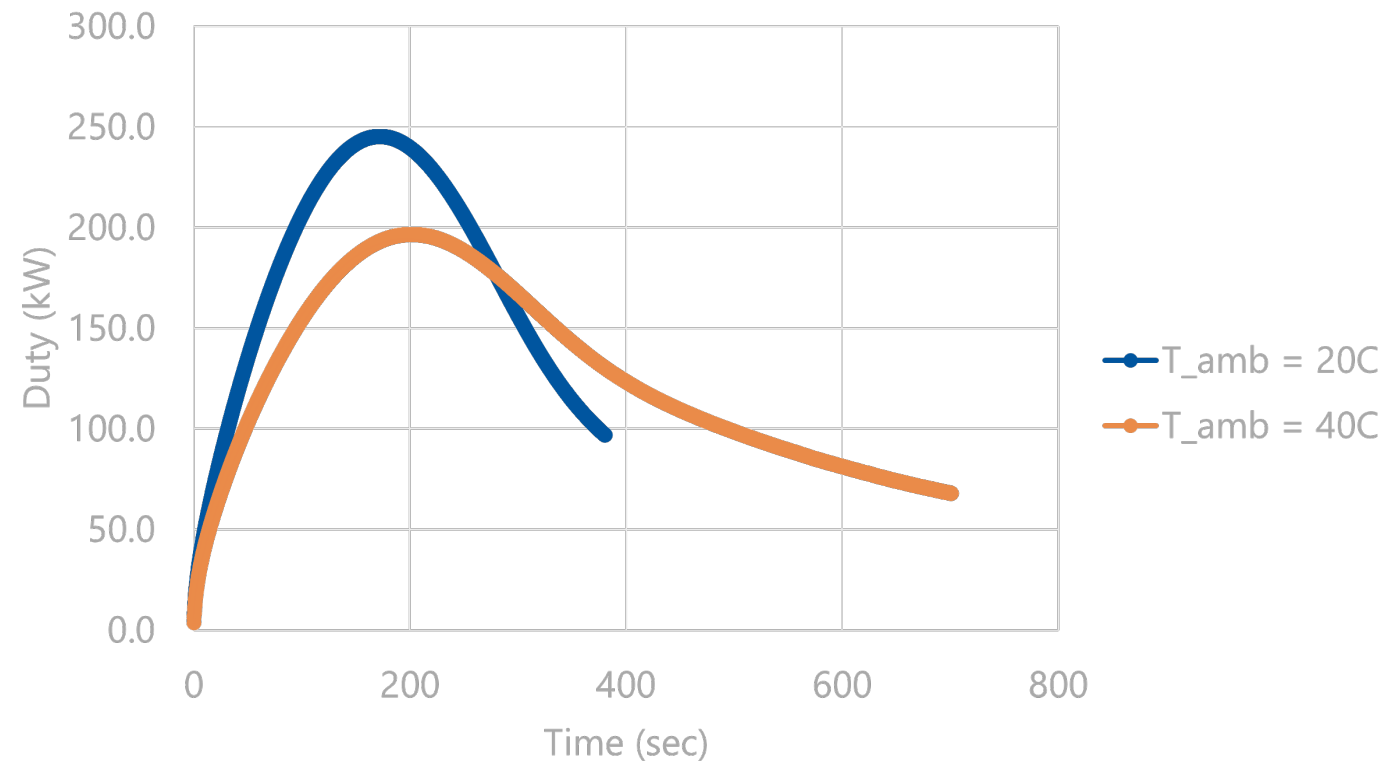
- Goal: define pre-cooling temperature and flow profile for heavy-duty fill
- Tank system: 5 tanks filled in parallel, all the same size (large diameter vessels)



Description	Value
Total Volume	1.75 m ³
Number of Tanks	5
H ₂ Storage Capacity	70 kg
Length	1.24 m
Internal Radius	0.30 m

Progress: Duty Profiles

- Modeling determined -30C pre-cooling likely necessary
- Duty profiles needed for 2 cases: 20°C ambient (maximum cooling duty) and 40°C ambient (maximum chiller power)



Progress: On-Demand Cooling Testing

- Goal: De-risk later testing by understanding transient effects of heat exchanger utilized for pre-cooling.
 - Heat exchanger specified and ordered in early January
 - Expected delivery: mid-May
 - Other components are longer lead as well
- ➔ Testing will be completed later than originally scheduled (end of May)

Progress: Refrigerant Selection

- Requirements:
 - Capable of achieving -35°C evaporator temperature
 - Minimal risk of future regulations (zero ozone depletion potential (ODP), low global warming potential (GWP))
 - Consider flammability and toxicity as added risks
 - Cost

Refrigerant	GWP	ODP	Safety group	Evaporating pressure [kPa(a)] @ - 40 °C	\$/lb
R-744	1	0	A1	1004.5	1.36
R-717	0	0	B2L	71.6	3.06
R-290	3	0	A3	111.1	13
R-448A	1387	0	A1	101	14.6
R-449A	1397	0	A1	120.7	19
R-1234ze	7		A2L	36.8	

} Consider these 3

Progress: Refrigerant System Down-Selection

- Step 3: Refrigerant *system* selection (Milestone 1.3.1: Down-select to 2-3 systems)
- We have 3 refrigerants, but there could be multiple combinations

	Option A	Option B	Option C	Option D	Option E	Option F	Option G	Option H	Option I
Type	NH ₃ (DX) CO ₂ pumped	DX cascade	DX cascade	DX cascade	DX cascade	DX cascade	R-290 (DX) CO ₂ pumped	Booster with flash gas removal	DX cascade
Fluid HS	R-717	R-717	R-290	R-290	R717	R-290	R-290	R-744	R-717
Fluid LS	R-744	R-717	R-290	R717	R-290	R-744	R-744	R-744	R-744
COP (estim.)		1.05	1.03	1.23	1.41	1.01	1.23	1.14	1.21

3 Down-selected systems:

↑
Top COP Option

↑
Low-hazard Option

↑
'Middle' Option

Response to Reviewer Comments

- As this is a new project, there were no reviewer comments from last year.

Collaboration and Coordination

Organization	Project Roles	Importance to Project
GTI	Project lead, management and coordination. Lead for commissioning and testing of units. Responsible for ensuring the chiller design meets fueling requirements.	Extensive experience with hydrogen fueling protocols and building, commissioning, and testing hydrogen fueling systems.
Creative Thermal Solutions	Chiller design lead. CTS will also source components and assemble the chiller test unit.	Decades of experience with natural refrigeration systems, refrigerant heat transfer behavior, and test unit assembly and commissioning.
Argonne National Lab	Duty cycle modeling, integration into heavy duty fueling stations.	Vast hydrogen fueling knowledge and experience with current pre-cooling systems and J2601 standard

Remaining Challenges and Barriers

- Complete preliminary design on system
 - Ensure all options are considered to maximize probability of system success
- Complete testing on heat exchanger sub-system
 - Procurement of needed components presents challenge to schedule
 - May delay testing until 3Q or 4Q 2023
 - Many components can be re-used for full system design
- Design must be compliant with heavy-duty fueling protocol, which is still in development
 - Team will stay up to date on protocol development

Proposed Future Work

- Complete preliminary design of the chiller system
 - Select configuration that provides best total cost of ownership
 - Ensure design complies with possible future refrigerant regulations
- Complete testing of heat exchanger sub-system
 - Create performance model for heat exchanger to feed full-system design
- Stay informed on progress of heavy-duty fueling protocol to ensure compatibility

Summary

Objective:	Develop and validate chiller design for high-flow heavy-duty hydrogen fueling
Potential Impact:	Accelerate adoption of heavy-duty hydrogen vehicles, leading to emissions and other benefits
Approach:	<ul style="list-style-type: none">- Target lowest total cost of ownership of system- Ensure compliance with fueling protocol and potential future refrigerant regulations
Progress:	<ul style="list-style-type: none">- Duty cycle modeling complete, in agreement with early guidance from fueling protocol development- Down-selected to 3 refrigerant systems
Next Steps:	<ul style="list-style-type: none">- Complete preliminary design of chiller system- Build and test heat exchanger sub-system to de-risk detailed chiller design