Cummins PEM Fuel Cell System for Heavy Duty Applications

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Cummins

DE-EE0009247
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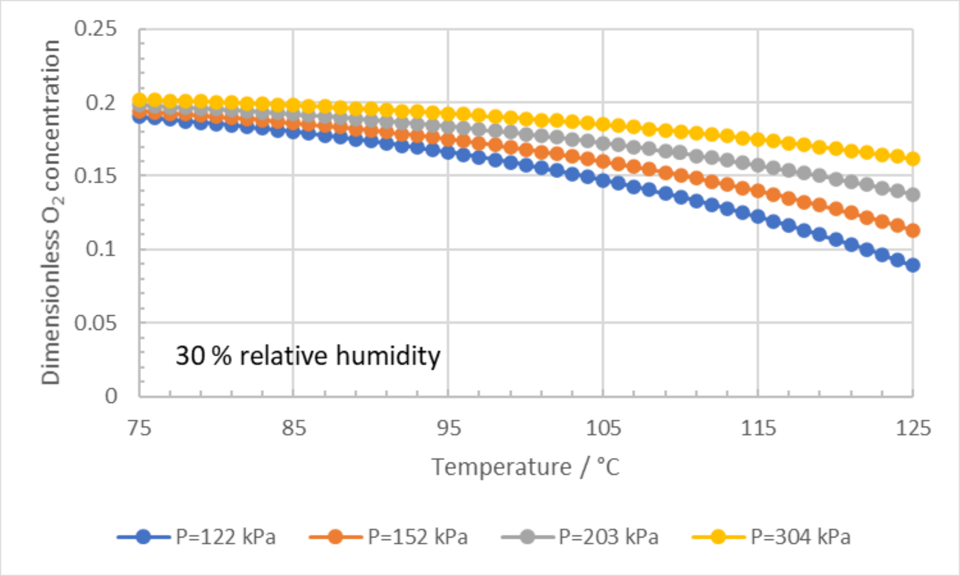
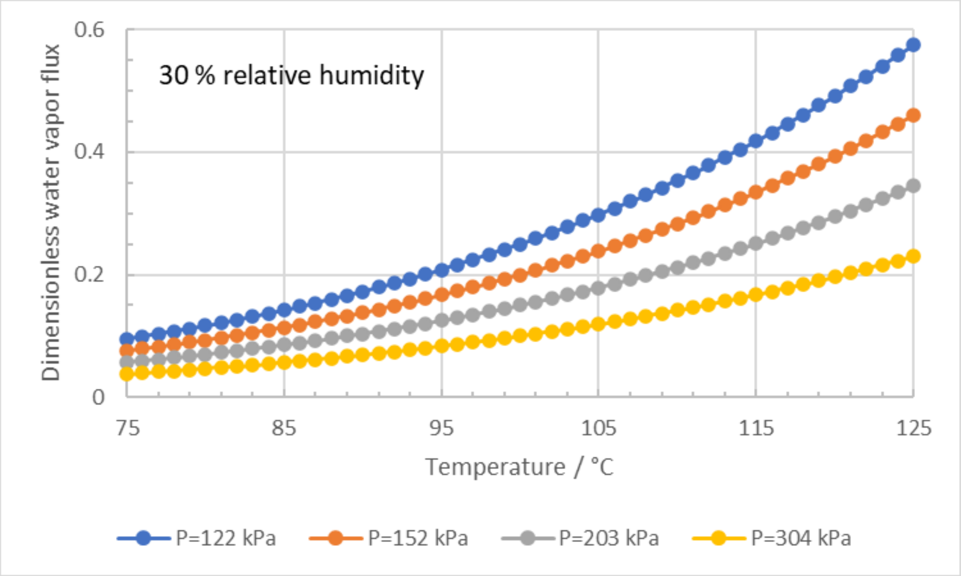
DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting
AMR Project ID FC337

Project Goal

- Develop a mass produced PEMFC stack and system for heavy duty applications able to operate at temperatures ≥100 °C to reduce the size of the radiator and lower activation losses
- Focus on key components enabling high temperature operation
  - Membrane/electrode assemblies (MEAs) based on ionomers tolerant to high temperatures
  - Electrically assisted air turbo-compressor (e-turbo) to limit oxidant dilution and ease humidification
  - Micro-channel molded bipolar plates to achieve practical pressure drops and lower cost





Kinetics and ohmic losses are reduced by higher O_2 concentrations (ORR is a 1st order reaction) and lower water requirements to achieve higher relative humidity and ionomer conductivities

Overview

- Timeline and Budget
  - Project start date: 7/28/2021
  - Project end date: 7/31/2024
  - Total project budget: $3,750,000
    - DOE share: $3,000,000
    - Cost share: $750,000
    - DOE funds spent: $895,256 (as of Mar. 31, 2023)
    - Cost share funds spent: $302,239 (as of Mar. 31, 2023)

- Barriers
  - Cost ($80→60/kW fuel fell system cost enabled by a smaller radiator, high-volume manufactured bipolar plates, and a smaller, higher efficiency system)
- Partners
  - Project lead (Jean St-Pierre, Cummins Technical Center)
  - Partner organizations
    - Cummins Accelera (MEA and stack design and testing)
    - Cummins Turbo Technologies (e-turbo prototype supplier)
    - Dana (bipolar plate supplier)
    - W. L. Gore (membrane supplier)
    - Argonne National Laboratory (data analysis)
    - M2FCT (sample analyses, AST selection support)

Relevance/Potential Impact

- Demonstrate capabilities of recently available and high temperature compatible ionomers
- Leverage Cummins expertise in turbo-machinery for fuel cell applications
- Push the boundaries of compression molding technology with graphite/polymer composites
  - Form fine flow field channels and achieve practical pressure drops at high pressures

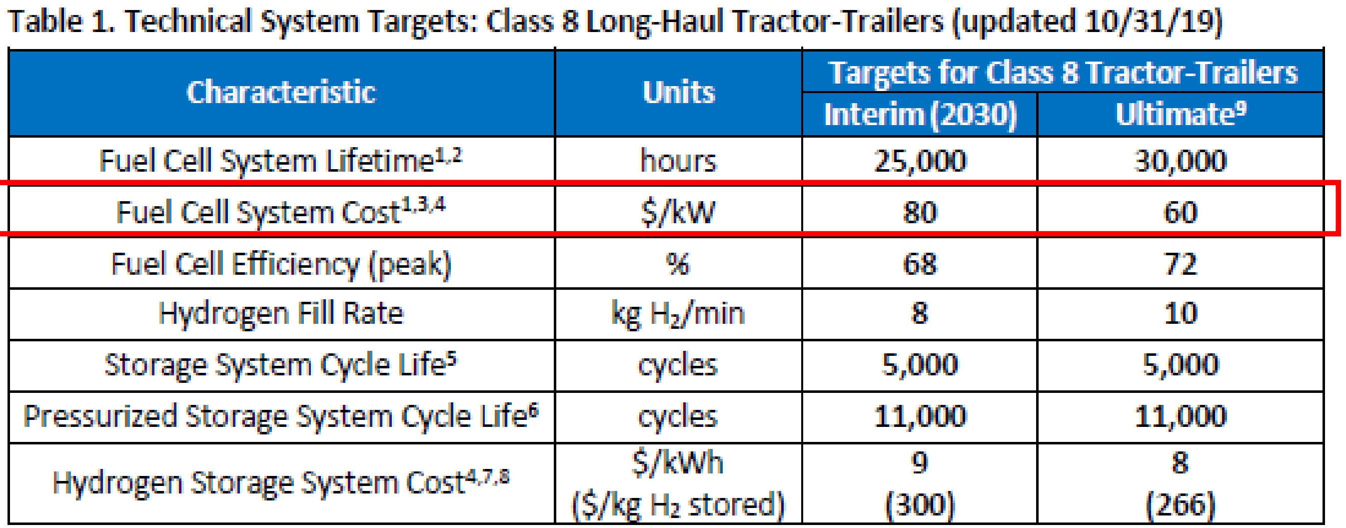


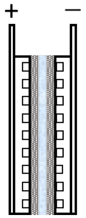
Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	25,000	30,000
Fuel Cell System Cost[1,3,4]	\$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life[5]	cycles	5,000	5,000
Pressurized Storage System Cycle Life[6]	cycles	11,000	11,000
Hydrogen Storage System Cost[4,7,8]	\$/kWh (\$/kg H_2 stored)	9 (300)	8 (266)

Hydrogen Class 8 Long Haul Truck Targets, U.S. Department of Energy, Record # 19006, October 31, 2019

DE-FOA-0002229, p. 20: "Furthermore, demonstration of stacks operating at higher temperature (≥100 °C, for heat rejection) and stack designs that would decrease the cost of BOP and power electronics components are desirable."

Approach



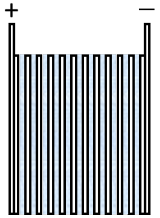
1. Cell

- Membrane/electrode assembly material selection, design, and performance verification
- Bipolar plate design and performance verification

Period 1

Jul. 2021 to Jan. 2023

- 1 kW stack build and performance verification

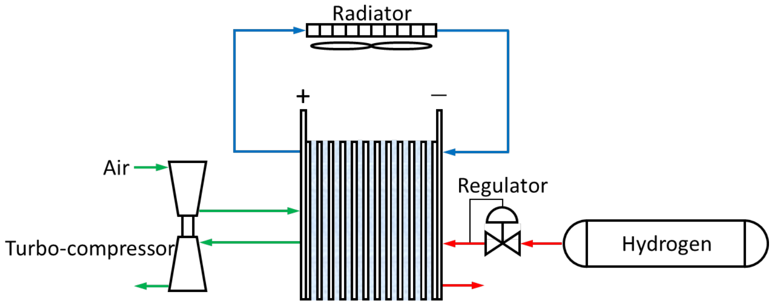


2. Stack

- 1 kW stack build and duty cycling verification (5000 h)
- 100 kW stack build and performance verification

Period 2

Feb. 2023 to Jul. 2024



3. System

- E-turbo prototype performance verification
- System model development and analysis
- Stack projection costs

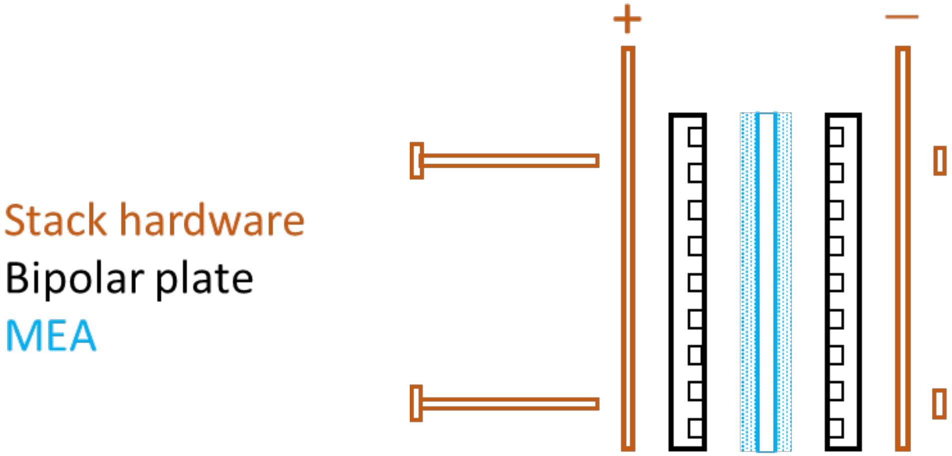
Approach

Detailed in Accomplishments and Progress

Milestone/deliverable (as of Apr. 14, 2023)	Due date	Completion extent
1.101. Fuel cell stack cell active area defined based on analysis of expected product requirements	Q1	100%
1.102. HD fuel cell system product requirements defined for use in setting 100 kW modular PEMFC stack design and requirements	Q2	100%
1.212. Bipolar plate design released for 100 kW HD stack based on validation of design specifics via non-electrochemical coupon tests	Q3	100%
1.215. Stack model report released which meets stack requirements as laid out in the product requirements document	Q4	50%
1.224. Bipolar plate delivered for short stack test which meets design requirements related to dimensional tolerance (+/- 0.3 mm of general dimension and +/- 0.05 mm of thickness), through plane electrical conductivity (<0.08 ohm cm^2), and permeation rates of gas (<0.001 ccm/cm^2 at 40 psi N_2) and coolant (target and test method to be developed) as well as passes pneumatic pressure testing at 250 kPa and successful CFD prediction of pressure drop across the plate	Q5	In progress
1.235. MEA prototype for short stack test delivered which meets design requirements related to dimensional tolerance as well as passes functional inspection compared to specifications in the product requirements document including catalyst loading (<0.3 mg PGM/cm^2) and performance (0.75 V at 0.3 A/cm^2, peak power 0.80 W/cm^2)	Q5	In progress
Go/No-Go. Successful demonstration of a 1 kW HD PEMFC short stack as indicated by meeting the following metrics: 1) Performance (0.75 V at 0.3 A/cm^2, peak power 0.80 W/cm^2) 2) Successful testing at high temperature (>100 °C) and pressure (>250 kPa) 3) Short term degradation (<10 mV/1000 h at 0.4 A/cm^2) 4) Cost review	Q6	
4.101. Fuel cell system specifications, including compressor, humidifier and cooling system requirements, defined for heavy duty applications in the range of 200-300 kW	Q7	
4.301. Air compressor validated as demonstrated by meeting pressure, flow rate, and power requirements specified in the HD fuel cell system model	Q8	
5.401. Fuel cell stack manufacturing cost targets, including at high-volumes of 100,000 units/year, identified based on results of studies on roll-to-roll MEA production, BPP production line, stack hardware & endplates, and automated stacking process	Q9	
6.101. 5,000 hours MEA demonstrated on a short stack using a relevant drive cycle intended to test peak performance at 100 °C, achieving a degradation rate of <15 mV/1000 h	Q10	
6.601. Validation of 100 kW stack prototype complete meeting performance target (0.73 V at 0.3 A/cm^2 and peak power of 0.75 W/cm^2) at rated and peak power conditions of current densities, temperature, pressure, humidity conditions, stoichiometries, and cooling requirements	Q11	
7.101. Final report completed and delivered to DOE	Q12	

Accomplishments and Progress

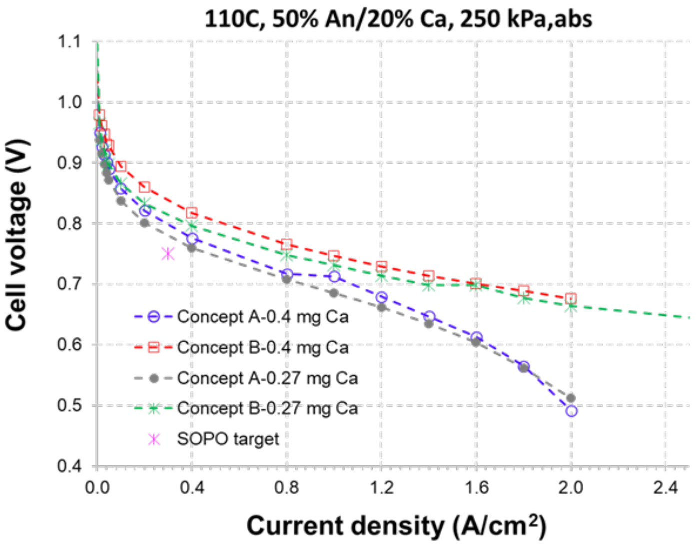
- Bipolar plate design was largely completed before the 2022 AMR (no new results shown, milestone 1.212)
  - Minor changes subsequently introduced
- MEA selection completed with subscale single cells after 2022 AMR (new results shown on slides 8-12)
  - MEA and membrane beginning of life and degradation data (tasks 1.231, 1.232, 1.31, and 1.32)
  - Mathematical model development to rationalize stack data (task 1.214)
- Stack hardware design completed (new results shown on slide 13, tasks 1.213 and 1.216)

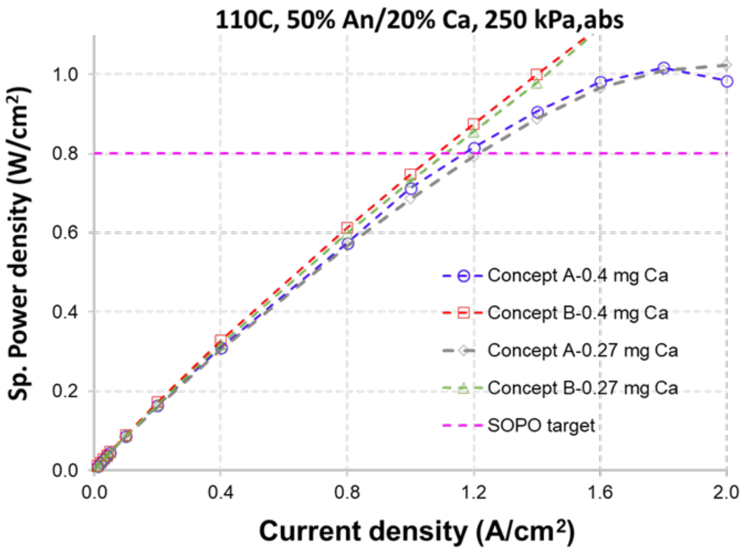


Accomplishments and Progress

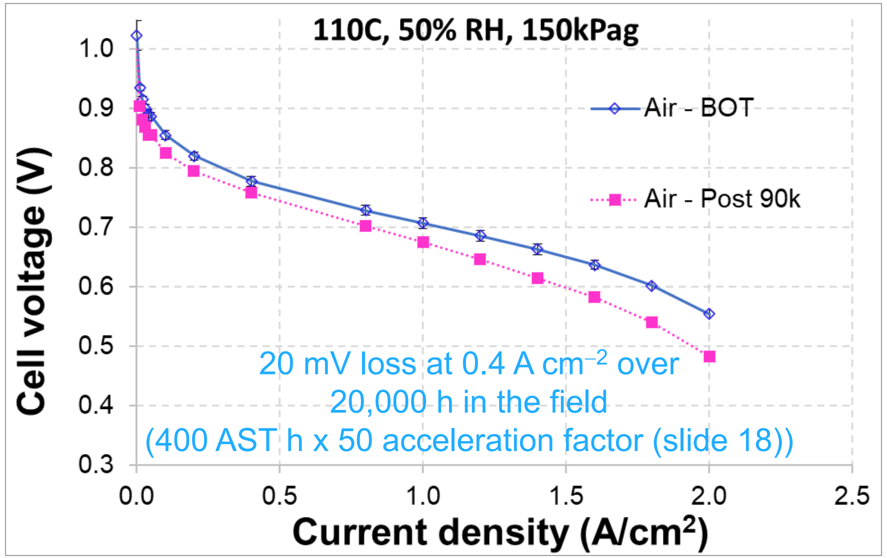
- Concept A MEA embedding a Gore-1 membrane and a 0.27/0.1 mg Pt cm^{-2} loading was selected for the 10 kW short stack* demonstration
  - ~0.77 V at 0.3 A cm^{-2} exceeds project target of 0.75
  - >1 W cm^{-2} peak power exceeds project target of 0.8
  - Membrane AST (slide 12) and MEA AST degradation deemed acceptable
    - Constant current density target (10 μV h^{-1} at 0.4 A cm^{-2}) is higher than the observed MEA degradation (1 μV h^{-1})

* At 2 A cm^{-2}, a 900 cm^2 cell would generate >0.5 V and >900 W. A 1 kW stack would only have 1 cell. Therefore, a 10-cell stack was planned to ensure that the stack contains a reasonable number of cells.





40 cm^2 active area

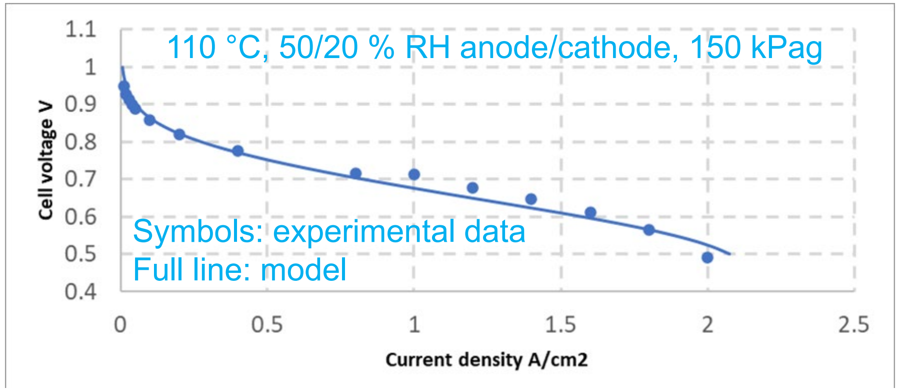


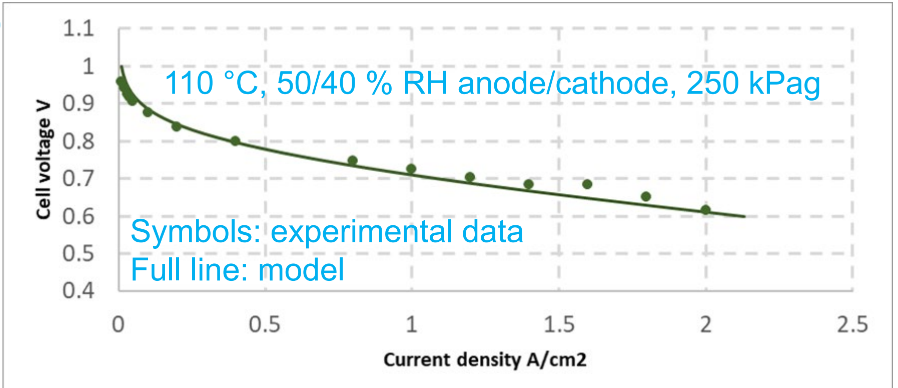
20 mV loss at 0.4 A cm^{-2} over 20,000 h in the field (400 AST h x 50 acceleration factor (slide 18))

Accomplishments and Progress

- An existing Cummins single cell model was modified by adding physical phenomena relevant to operation at high pressures and temperatures to rationalize stack data
  - 1D, non-isothermal, 2 phase
- Parameters and properties were either revised or updated
- An initial validation was conducted using 1 dataset for calibration and 3 more for validation, which resulted in a good fit

Concept A MEA
(40 cm^2 active area)





Description	Variable	Flux	Continuity	Domain
Electron transport	ϕ_e	$j_e = -\kappa_e \nabla \phi_e$	$\nabla . j_e = S_e$	AGDL, ACL, CCL, CGDL
Proton transport	ϕ_p	$j_p = -\kappa_p \nabla \phi_p$	$\nabla . j_p = S_p$	ACL, MEM, CCL
Cathode gas phase transport	w_{O_2} w_{N_2} w_{H_2O}	$j_i = -(\rho_{mix} D_{i,mix}) \nabla w_i$ $i = O_2, N_2, H_2O$	$\nabla . j_i = S_i$	CGDL, CCL
Anode gas phase transport	w_{H_2} w_{H_2O}	$j_i = -(\rho_{mix} D_{i,mix}) \nabla w_i$ $i = H_2, H_2O$	$\nabla . j_i = S_i$	AGDL, ACL
Water transport ionomer	λ	$j_\lambda = -(D_\lambda / V_m) \nabla \lambda + (\xi / F) j_p$	$\nabla . j_\lambda = S_\lambda$	ACL, MEM, CCL
Liquid water transport (pores)	s	$j_\lambda = -\left(\frac{\kappa}{\mu V_w}\right)(\partial p_c / \partial s) \nabla s$	$\nabla . j_s = S_s$	CCL, CGDL
Heat transfer	T	$j_T = -\sigma_T \nabla T$	$\nabla . j_T = S_T$	AGDL, ACL, MEM, CCL, CGDL

Accomplishments and Progress

- Potentiostatic hold (VAST) tests were completed with both W. L. Gore membranes including duplicate tests to assess durability and variability for mostly high temperatures
  - 15-21 cm^2 active area single cells

Operating conditions set reference number[1]	Membrane	Cell voltage (V)	Cell temperature (°C)	Relative humidity (%)	Pressure (kPa absolute)
1	🟩 Gore-1, 🟩 Gore-2	OCV [2]	110	30	300
2	🟨 Gore-1, 🟥 Gore-2	0.85	110	50	300
3	🟥 Gore-1, 🟥 Gore-2	0.85	95	30	300
4	🟨 Gore-1	0.85	110	30	200
5	🟨 Gore-1	0.85	90	30	300
6	🟩 Gore-1	0.85	110	75	300
7	🟨 Gore-1	0.8	110	30	300
8	🟩 Gore-1	0.85	80	30	300
9	🟩 Gore-1	0.85	110	30	150
10	🟥 Gore-1, 🟨 Gore-2	0.85	110	100	300
11	🟨 Gore-1	0.7	110	30	300
12	🟨 Gore-1	0.85	60	30	300
13	🟩 Gore-1, 🟩 Gore-2	0.6	110	30	300
14	🟨 Gore-1, 🟩 Gore-2	0.6	60	30	300
15 (baseline)	🟩 Gore-1, 🟨 Gore-2	0.85	110	30	300

[1] Color code: green - membrane tests and duplicate tests are completed; yellow - tests initiated/in-progress; red - tests not yet initiated.

[2] OCV: open circuit voltage.

Membrane ID	Thickness (µm)	Reinforcement	Stabilizer
Gore-1	15	ePTFE reinforced	Enhanced chemical stabilizer
Gore-2	8		Chemical stabilizer

Accomplishments and Progress

- Potentiostatic hold (VAST) tests were completed with both W. L. Gore membranes including duplicate tests to assess durability and variability for mostly high temperatures
  - 15-21 cm^2 active area single cells
- VAST FRR (not shown) and H_2 crossover results indicate that
  - Conditions differentially affected membranes
  - Results are acceptably reproducible

Membrane ID	Thickness (µm)	Reinforcement	Stabilizer
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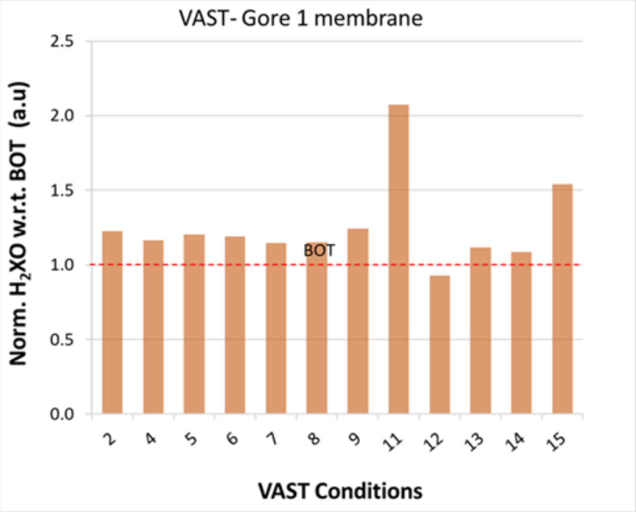
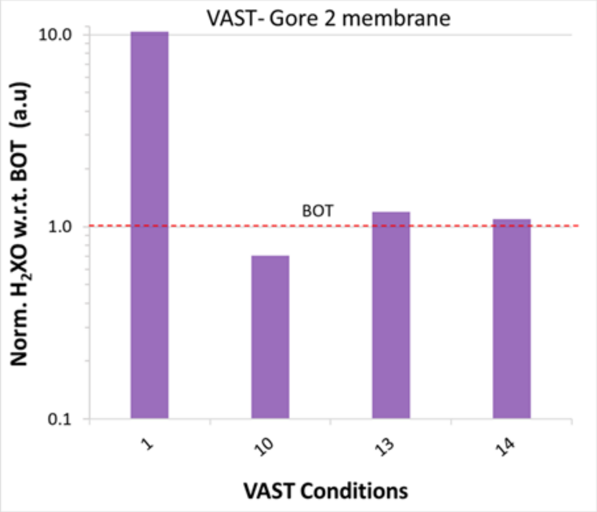
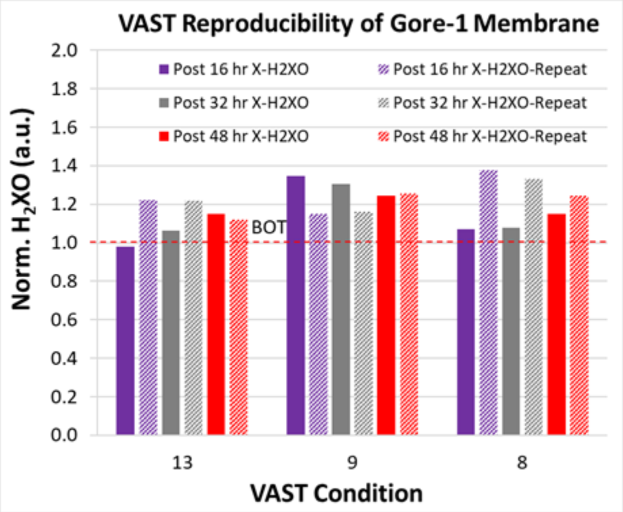
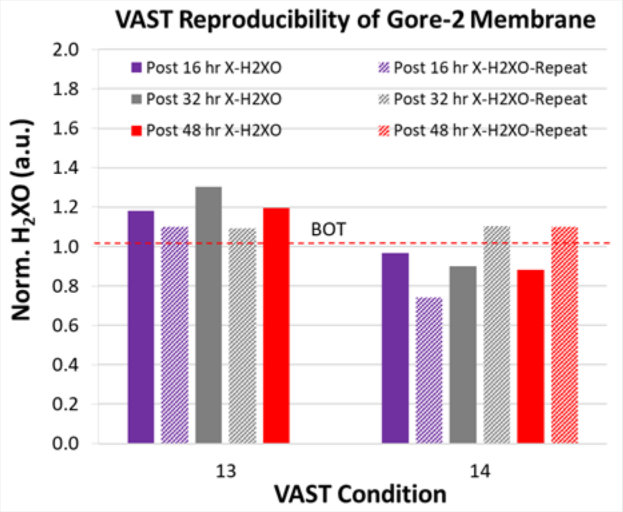
Gore-2	8		Chemical stabilizer



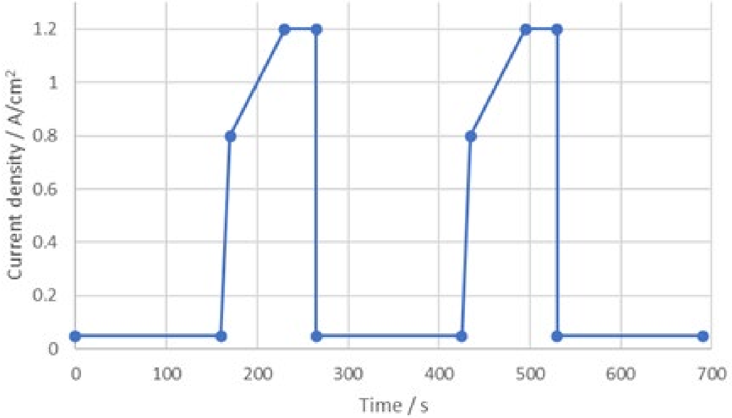




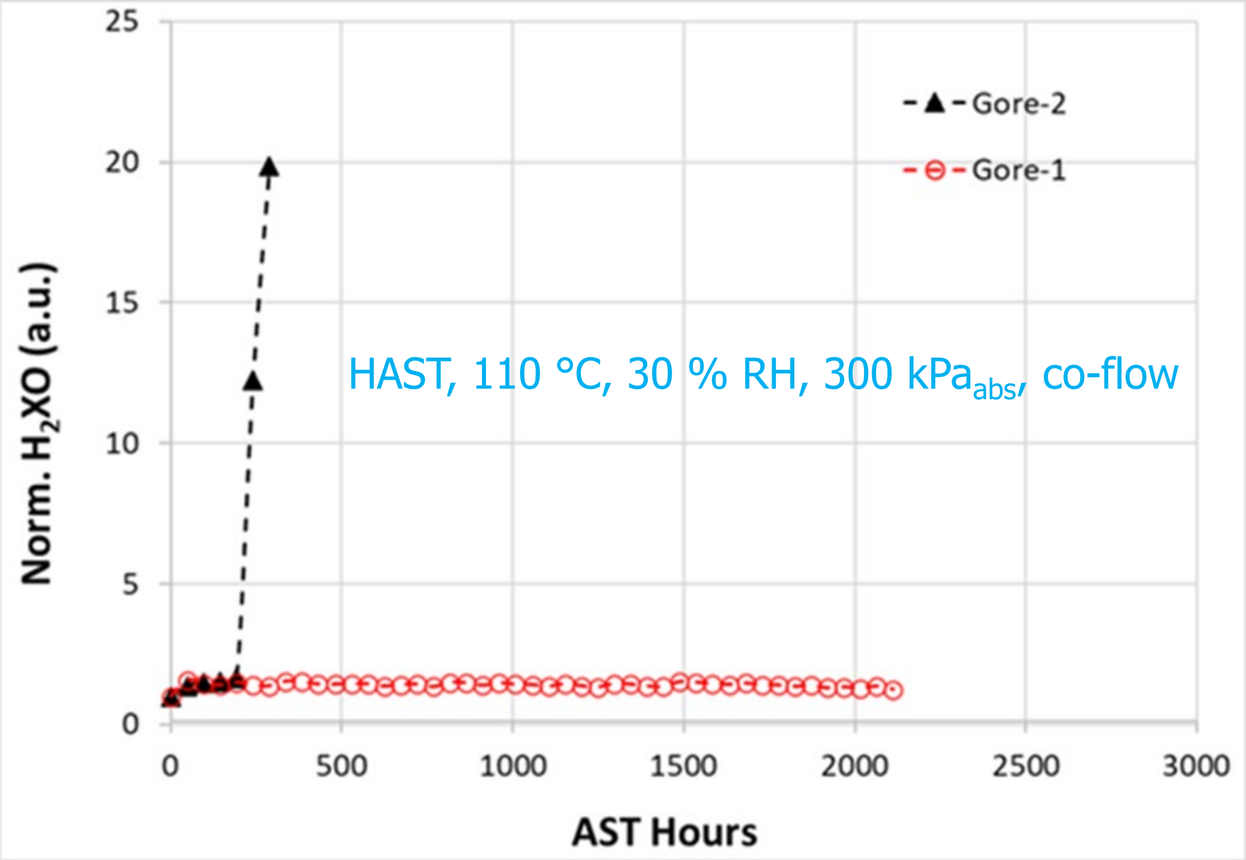


Accomplishments and Progress

- Current density cycling AST (HAST) tests were also completed with both W. L. Gore membranes to assess durability and variability for high temperatures
  - 21-25 cm^2 active area single cells
  - Duplicate tests are ongoing
- HAST FRR (not shown) and H_2 crossover results indicate that
  - Gore-1 is significantly more durable



Membrane ID	Thickness (µm)	Reinforcement	Stabilizer
Gore-1	15	ePTFE reinforced	Enhanced chemical stabilizer
Gore-2	8		Chemical stabilizer



HAST, 110 °C, 30 % RH, 300 kPa$_{abs}$, co-flow

Accomplishments and Progress

- Stack hardware design completed
  - Traditional end plate assembly design selected
  - Bill of materials breakdown structure established
  - Two designs reviews conducted

	Design Option 1 **End plate assembly also acting as a busbar**	**Design Option 2** **Traditional design with separate end plate assembly and busbar separated by an insulator**
Pros	• Simpler end plate assembly without busbar and insulator	• Traditional legacy design concept provides high level of design confidence • Thread rods do not require electrical insulation from end plate assemblies • Manifold may not need insulation from end plate assembly • Less constraints for manifold design
Cons	• Lower design confidence due to its novelty • Thread rods require electrical insulation from end plate assemblies • Manifold may need insulation from end plate assembly	• Complicated design with more parts

Item	Area	Sub Item	Part Description	P/N	Qty
1A	Dry End Option 1	1.0	Dry End Plate Side-Out Assembly	5731932-00	1
		1.1	Dry End Plate Side-Out	5731931-00	1
		1.2	Dry End Insulator Side-Out Assembly	5731933-00	1
		1.3	Dry End Insulator Side-Out	5731934-00	1
		1.4	Dry End Busbar Side-Out	5731935-00	1
		1.5	Dry End Separator Side-out	5731936-00	1
1B	Dry End Option 2	1.0	Dry End Plate Center-Out Assembly	5731819-00	1
		1.1	Dry End Plate Center-Out	5731815-00	1
		1.2	Dry End Insulator Center-Out Assembly	5731818-00	
		1.3	Dry End Insulator Center-Out	5731816-00	1
		1.4	Dry End Busbar Center-Out	5731817-00	1
		1.5	Dry End Separator Center-out	5731820-00	1
2A	Wet End Option 1	2.0	Wet End Plate As Busbar	5730521	1
2B	Wet End Option 2	2.0	Wet End Plate Center-Out Assembly	5731823	1
		2.1	Wet End Plate Center-Out	5731824	
		2.2	Wet End Insulator Center-Out Assembly	5731826	1
		2.3	Wet End Insulator Center-Out	5731829	
		2.4	Wet End Busbar Center-Out	5731828	1
3	Tie Rod	3.0	Insulator Tube	5730115	TBD
		3.1	Spring/Disc Washers	TBD	TBD
		3.2	Thread Rod	5730114	TBD
		3.3	Nuts	TBD	TBD
4	Manifolds Precheck Test	4.0	Manifold Assembly Left Side	5730129	1
		4.1	Manifold Left Side	5730127	1
		4.2	Manifold Assembly Right Side	5730130	1
		4.2	Manifold Right Side	5730128	1
		4.3	Accessories		TBD
5	Alignment Bars	5.0	Assembly	TBD	1
		5.1	Corner	TBD	TBD
		5.2	Front	TBD	TBD
		5.3	Left And Right	5731810	TBD
		5.4	Cross Bars	TBD	TBD
6	Manifolds For Short Stack Post Leak Check	6.0	Manifold Leak Test Left Side	5730131	1
		6.1	Manifold Leak Test Right Side	5730132	1
7	Final Assembly	7.0	Final Assembly	TBD	1
8	FEA	8.0	Dry End Plate, Insulator, And Busbar	N/A	
		8.1	Wet End Plate, Insulator, And Busbar	N/A	

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

2022 AMR

- The project was not reviewed

2021 AMR

- "The project seems to lack any fundamental aspect related to understanding performance and material degradation. The team should work with the national laboratory M2FCT consortium to fill that void."
  - *The M2FCT NDA was executed after the 2022 AMR. A list of samples and associated measurements are currently being finalized following the recent MEA design selection.*
- "It might be beneficial to add a collaboration with some of the catalyst durability projects or groups to ensure success."
  - *Three relevant catalyst projects were identified (FC323, FC326, FC327). However, only one catalyst was deemed promising. The Pajarito Powder catalyst was acquired in early 2023 (30 wt % Pt/ECS-003701, FC323) and will be tested for a comparative analysis.*

Collaboration and Coordination

Collaborator	Organization type	Relationship	Role
Cummins Technical Center	Industry	Prime	Project management Stack testing Modeling and CAD support E-turbo testing Techno-economic analysis
Cummins Accelera	Industry	Sub-contractor	MEA and stack design MEA and stack testing CFD, performance, and system modeling
Cummins Turbo Technologies	Industry	Supplier	E-turbo prototype supplier
Dana	Industry	Supplier	Bipolar plate supplier
W. L. Gore	Industry	Supplier	Membrane supplier Membrane characterization data
Argonne National Laboratory	National Laboratory	FFRDC	Data analysis
M2FCT	National Laboratory	FFRDC	Sample analyses AST selection support

Name change

Addition

Remaining Challenges and Barriers

- Bipolar plate fabrication issues were identified
  - Manufactured compression molding parts quality may not meet requirements due to a larger size for the prototype plates than current commercial products (from ~500 to ~900 cm^2 in active area)
  - If these quality issues are resolved and the bipolar plate design is validated, it is believed that the compression molding process will be cost competitive at high volumes and will meet cost targets
- A mitigation strategy was implemented
  - Plate machining from blank plates of a similar material and thickness was selected as an alternative, which is anticipated to have a minimal impact on fuel cell performance and degradation
  - A 9 months no cost extension was requested for supplier identification, plate fabrication lead time, and buffer because graphite composites are difficult to machine due to abrasion requiring specialty equipment

Proposed Future Work

FY 2023

- 10 kW stack build and testing
  - Complete MEA fixtures required for full size assembly and manufacture MEAs (tasks 1.233 and 1.234)
  - Receive and inspect machined bipolar plates (task 1.223)
  - Complete the last stack hardware design review and procure all necessary components (task 1.213)
  - Assemble and characterize the stack under different operating conditions (tasks 2.1, 2.21, and 2.22)
- Membrane and catalyst characterization
  - Complete conductivity, VAST, and HAST tests with Gore-1 and Gore-2 membranes (tasks 1.31 and 1.32)
  - Complete 30 wt % Pt/ECS-003701 tests for a comparative analysis
- Model
  - Conduct additional validation and modifications using short stack data under different operating conditions (task 1.217)
- National laboratory interactions
  - Transfer membrane and 10 kW stack characterization data to ANL for analysis (task 2.23)
  - Complete test plan and ship material samples to M2FCT
- Go/no go decision review (task 3)

Summary

Category	Characteristic	Units	Period 1 SOPO targets	2022 AMR status	2023 AMR status
1 kW stack	Cell voltage at 0.3 A cm^{-2}	V	0.75	~0.67	~0.77
	Power	W cm^{-2}	0.8	>0.8	>1
	Temperature	°C	>100	110	110
	Pressure	kPa	>250	250	250
	Short term degradation rate at 0.4 A cm^{-2}	μV h^{-1}	10	?	1[d]
	System cost at 100,000 units/year	\$ kW^{-1}	[a]	?	?
Bipolar plate	Areal tolerance	mm	±0.3	?	?
	Thickness tolerance	mm	±0.05	<0.05	<0.05
	Through-plane electrical conductivity	ohm cm^{2}	<0.08	<0.08	<0.08
	Gas permeation rate at 40 psi N_2	standard cm^{3} min^{-1} cm^{-2}	<0.001	<0.001	<0.001
	Coolant permeation rate	TBD[b]	TBD[b]	?	?
	Successful pressurization test	kPa	250	?	?
	Pressure drop prediction accuracy	kPa	[c]	?	?
MEA	Total PGM loading	mg cm^{-2}	<0.3	0.5	0.37[e]

[a] for review purposes only

[b] method and target to be developed

[c] target not defined

[d] AST (cycling between 0.04 (6 s) and 2 (6 s) A cm^{-2} with 2 s ramps) led to a 34 % ECSA loss after 90,000 cycles (400 h). The DOE M2FCT AST is completed with similar operating conditions and has an implied acceleration factor of 50 (25,000 h durability/500 AST h, https://millionmilefuelcelltruck.org/ast-protocols)

[e] 0.27/0.1 mg Pt cm^{-2} for cathode/anode