MATERIALS AND MODULES FOR LOW-COST, HIGH PERFORMANCE FUEL CELL HUMIDIFIERS

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W. L. Gore & Associates, Inc.
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Project ID: FC067

Overview

TIMELINE
- ✓ Start date: 4/01/2010
- ✓ End date: 9/30/2012
- ✓ ~75% complete

BUDGET

✓ DOE share:	$ 1,492,163
✓ Cost share:	$ 373,040
✓ Funding received in FY11:	$ 200,820
✓ Planned Funding in FY12:	$ 473,642

DOE PLAN BARRIERS ADDRESSED:
- ✓ System cost, fuel cell performance and durability
- ✓ Task 7, "Develop balance of plant components"
  - B - Reliable, cost-effective fuel cell systems.
  - E - System thermal and water management.
  - A and C (indirectly) – Fuel cell durability and performance.

TEAM and PARTNERS
- ✓ Project Lead - W. L. Gore & Associates, Inc.
- ✓ Subcontractor - dPoint Technologies
- ✓ Collaborators (no funding)
  - Argonne National Laboratories
  - General Motors Company

Objectives

Demonstrate a durable, high performance water transport membrane; and a compact, low-cost, membrane-based module utilizing that membrane for use in automotive, stationary and/or portable fuel cell water transport exchangers.

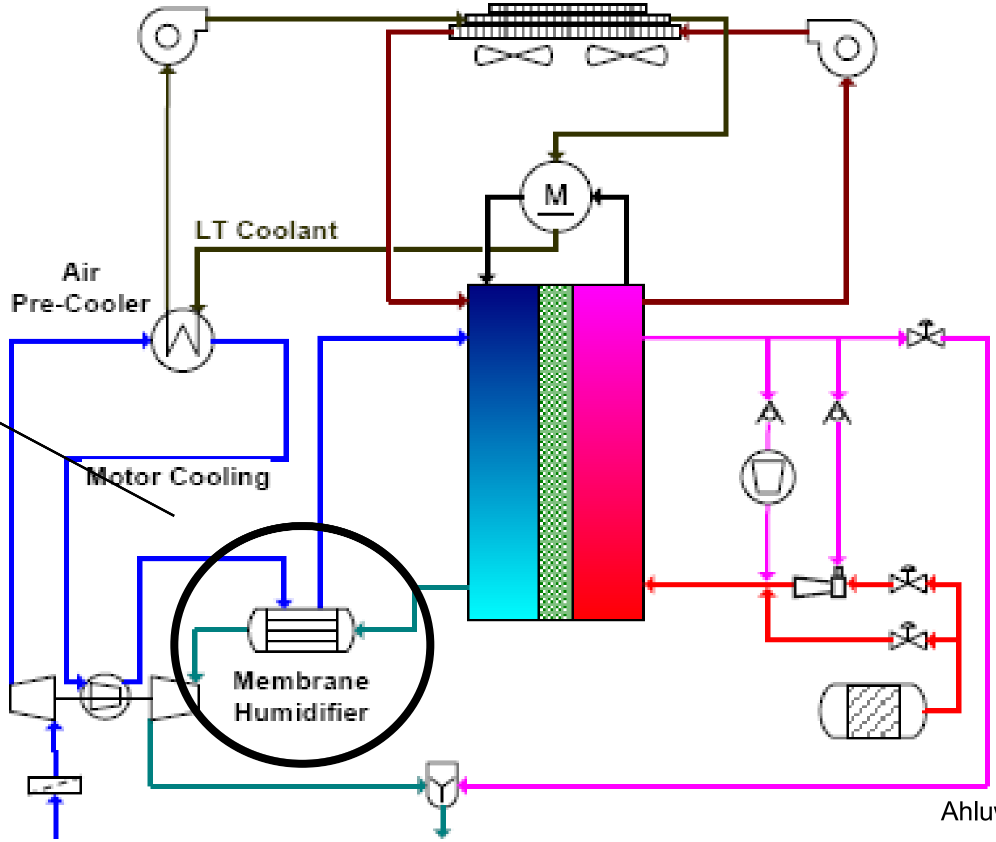
Relevance

More efficient, low-cost humidifiers can increase fuel cell inlet humidity:

- **Reduce <u>system cost</u> and <u>size</u> of balance of plant.**
- **Improve fuel cell performance.**
- **Potentially decrease size of fuel cell stack by running under wetter conditions.**
- **Improve fuel cell durability.**

Background

dPoint module



Ahluwalia, et. al, ANL.

Illustrative block diagram of fuel cell system

Approach: Plan

Task	Completion
Task 1: Materials Preparation • Initial material selection/preparation • Scale-up to m^2 sizes	80%
Task 2: Materials Testing • Identify conditions • Water transport measurements • Durability by hot soak & RH cycling • Air permeability	80%
Task 3: Cost Modeling • Membrane and module level	85%
Task 4: Module Design, Test and Build • Design exploration • FEA models • Design/build alternatives using rapid prototyping • Build/test full scale module	50%
Task 5: Project Management and Reporting	~75%

Go/No-Go
15 months
July 2011 √

- Module Volume < 8 L √
- Module cost < $150 √
- Membrane life > 5000 h hot soak √
- Membrane life>1000 h RH cycling √
- Membrane water transport > 0.030 g/cm^2-min at 80 ºC √

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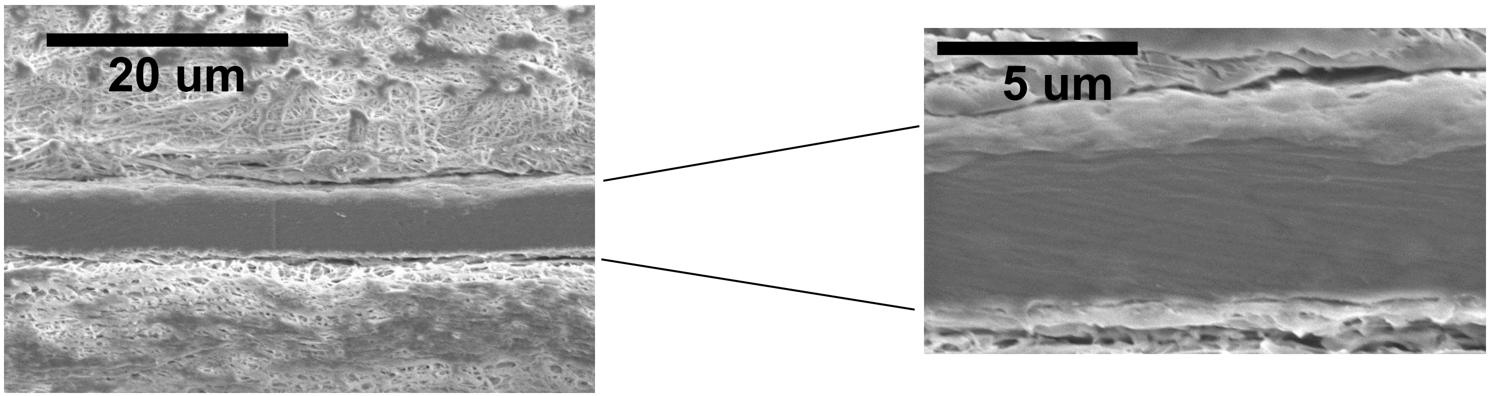
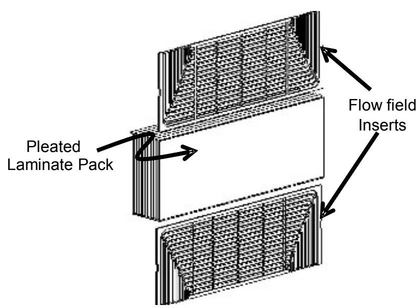
Approach: Technical

- **Membranes:** **Utilize unique, high performance, GORE™ Humidification Membranes**



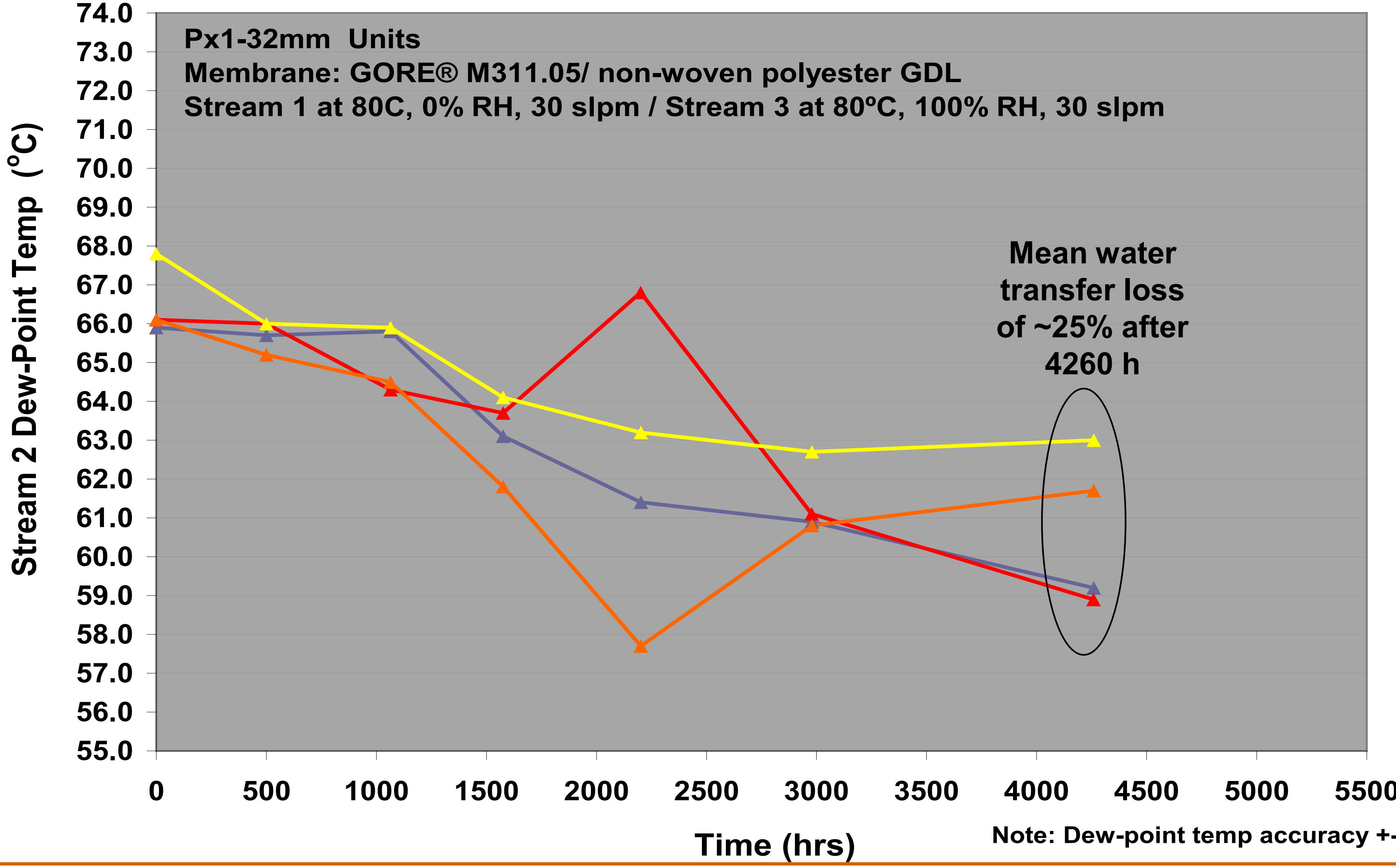
- **Modules:** **Optimize flow field, pleat geometry and module design to take advantage of very high transport rate materials, while maintaining low-cost assembly process**



Technical Accomplishments and Progress
Summary of Results to Date

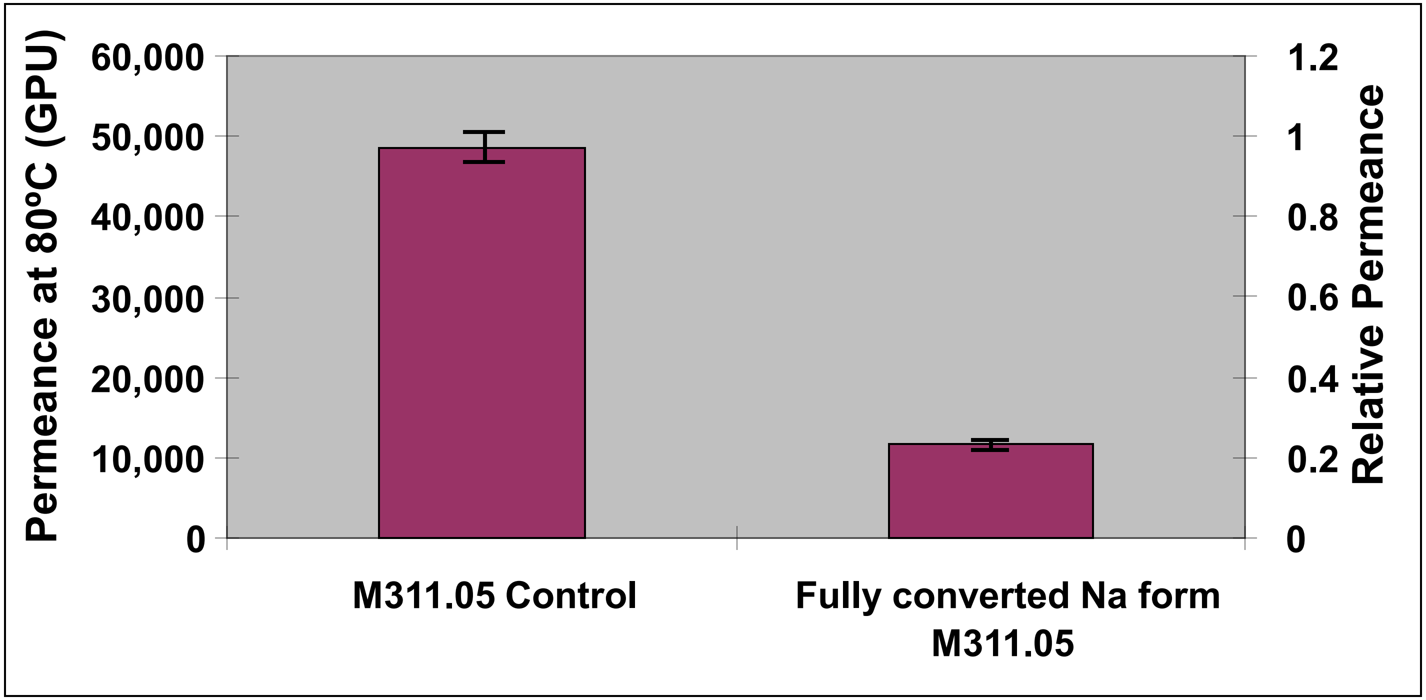
- **Testing**
  - ✓ Pseudo-static water transport test developed that increases testing throughput dramatically (Details shown last year).
    - Currently establishing viability as QC qualification test.
- **Membrane Performance**
  - ✓ Water vapor transport properties established – very high water transport rates under fuel cell humidifier conditions.
    - Product specifications under development in consultation with customers.
- **Membrane Durability**
  - ✓ Over 4000 hours of acceptable module level performance at 80ºC.
  - ✓ 20,000 cycles achieved in RH cycling in DOE membrane AST.
  - ✓ Freeze cycling shown last year – no transport issues observed.
  - ✓ Accelerated durability test is in development using a dry, high temperature soak of restrained samples.
- **Module Development**
  - ✓ High water transport, cross-flow module that meets all program criteria has been designed and tested at sub-scale.
  - ✓ Initial full-scale module in process using scalable manufacturing process.

Technical Accomplishments and Progress
Task 2: Module level Membrane Durability Testing at 80ºC



Note: Dew-point temp accuracy +- 1C

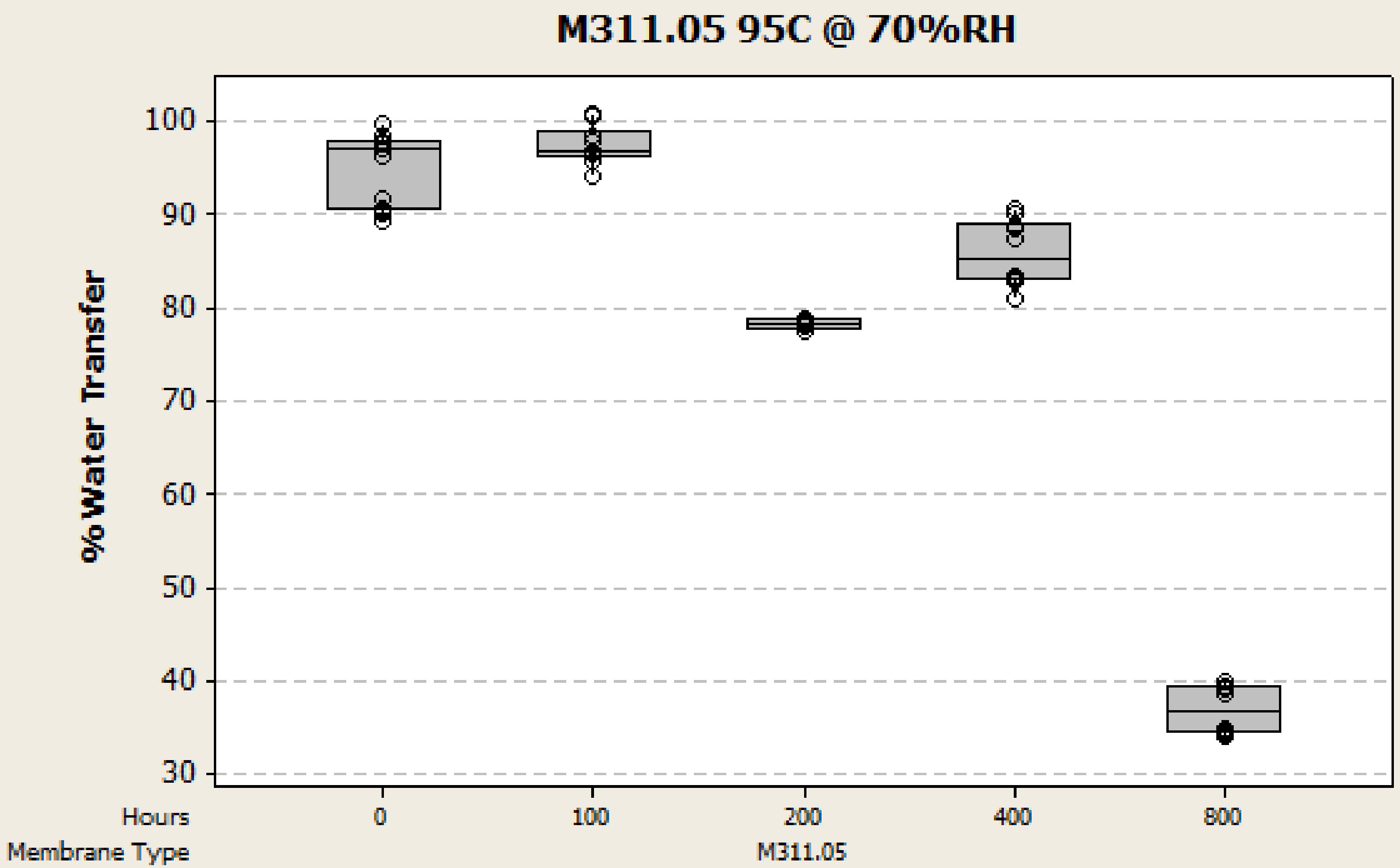
Technical Accomplishments and Progress
M311.05 Degradation Mechanism - Contamination



Permeance from pseudo-static 80ºC permeance test protocol.

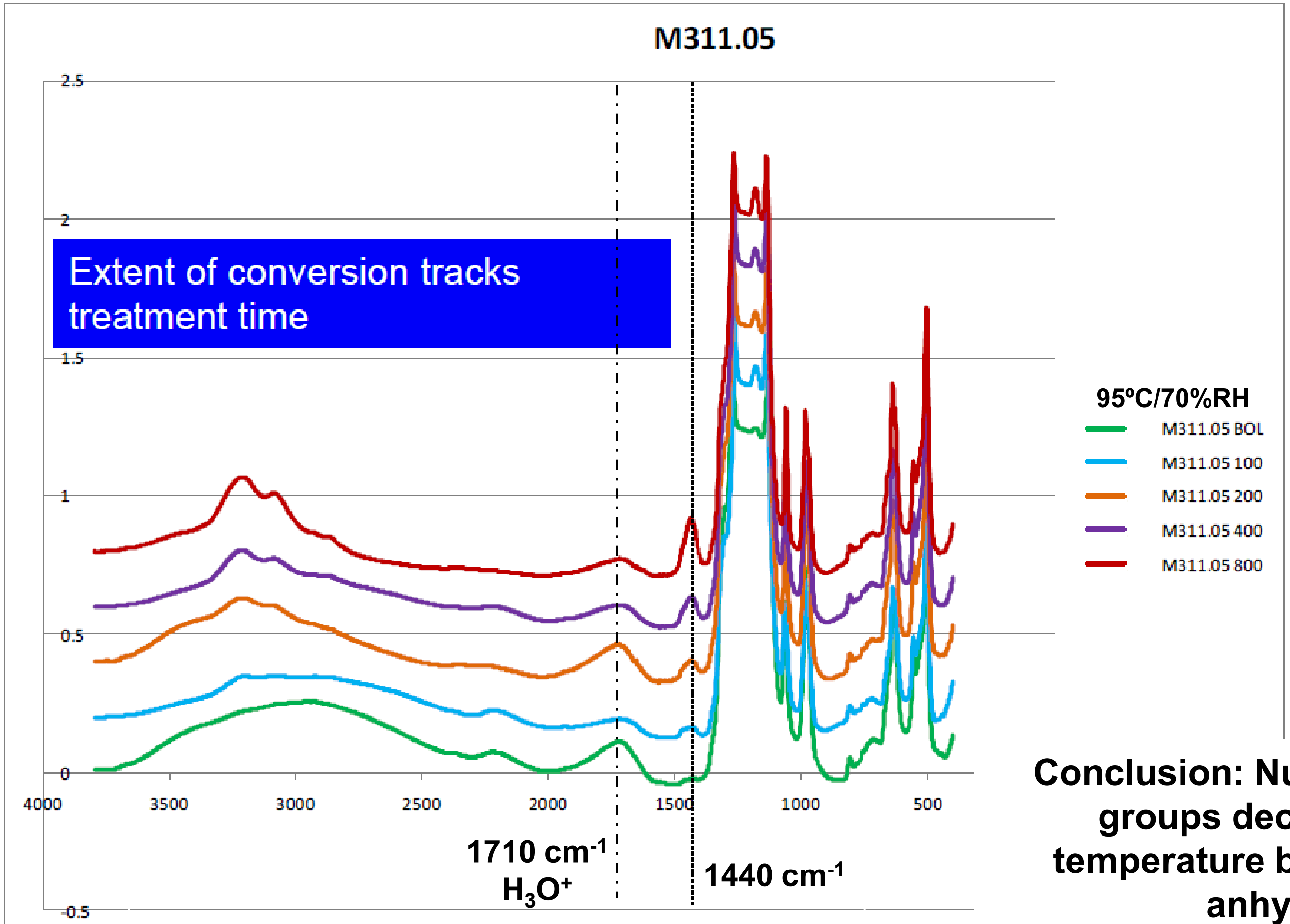
- Gore has not observed contamination related degradation in our testing, but some of our customers have.
- This degradation mechanism is controllable – minimize presence of ionic contaminants, e.g., Na, Mg, K, etc.

Technical Accomplishments and Progress
Task 2: Durability Testing at 95ºC in Wet Conditions



Data courtesy of General Motors Company

Technical Accomplishments and Progress
Degradation Mechanism - Chemical Changes in PFSA Ionomers



Data courtesy of General Motors Company

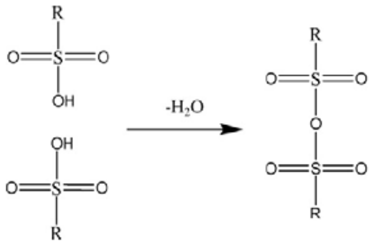


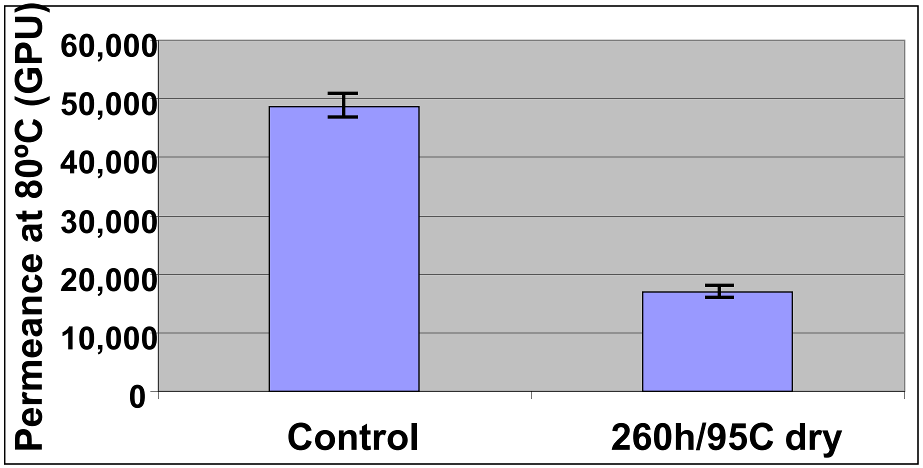
Fig. 11. Reaction of sulfonic acids condensation.

Ref: Collette, R. M. et. al., "Hygrothermal Aging of NAFION®", J. Memb. Sci. 330(2009)21-29.

Conclusion: Number of accessible SO_3 groups decreases with aging at temperature because of formation of anhydride species.

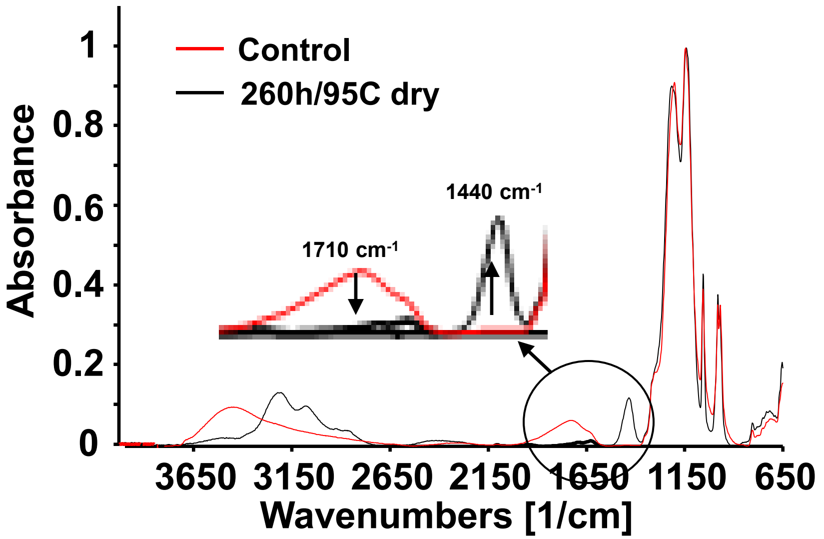
Technical Accomplishments and Progress
Ex-Situ Accelerated Durability Test: Dry Hot Soak

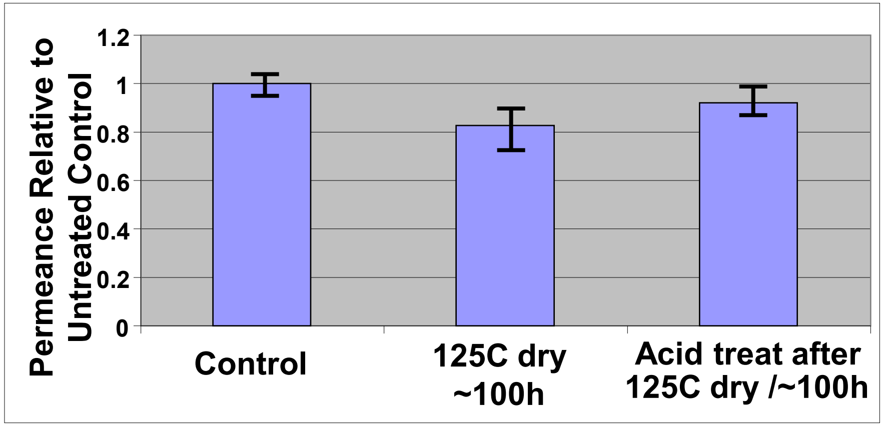
Heat treatment results



Permeance from pseudo-static 80ºC permeance test protocol.

IR results

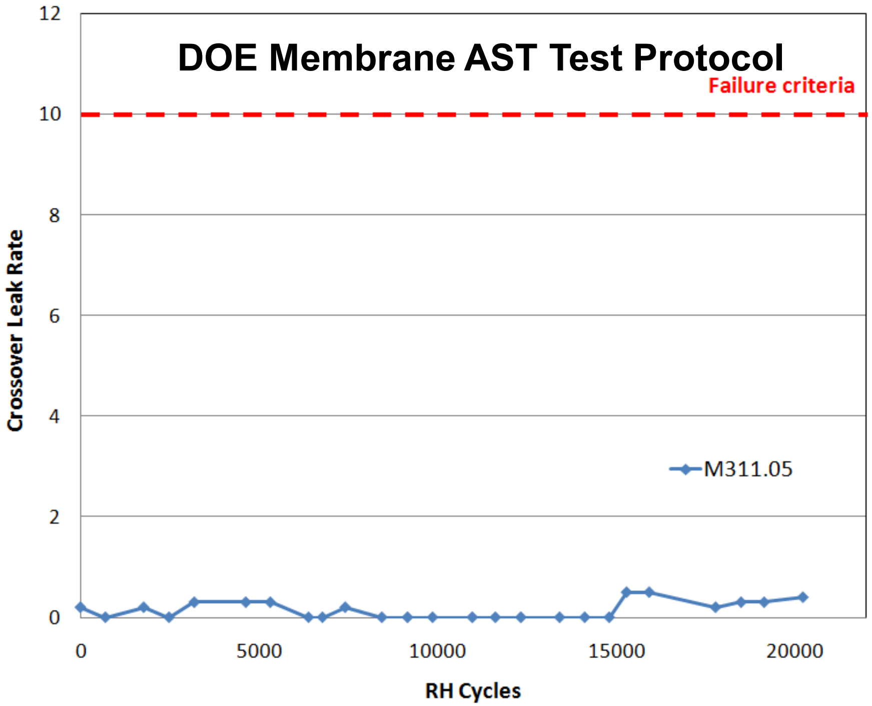




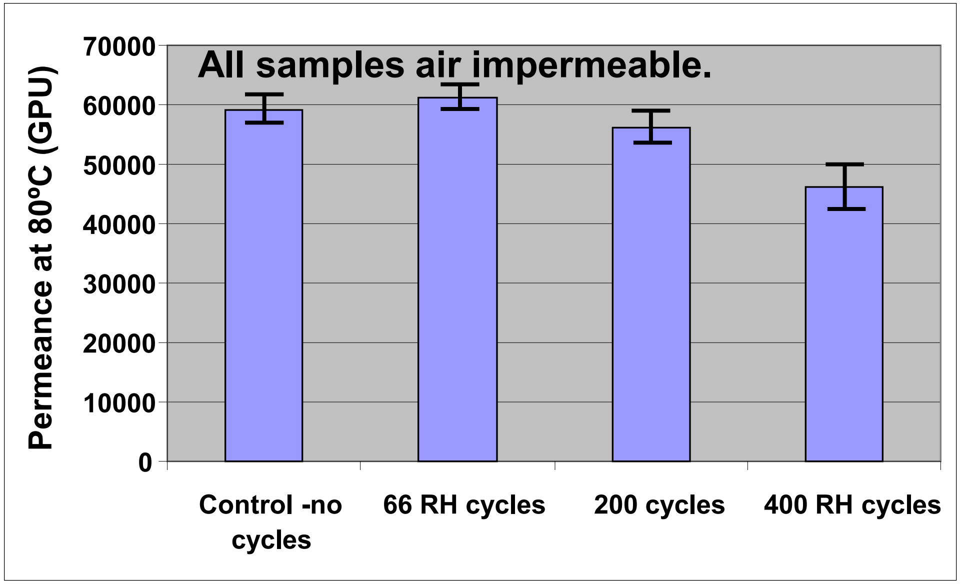
Acid heat treatment largely reverses the effect of dry, hot-soak treatment of M311 materials.

Consistent with literature results: Collette, R. M. et. al., "Fuel cell rejuvenation of hygrothermally aged Nafion®", J. Power Sources. 202(2012)126-133.

Technical Accomplishments and Progress
Task 2: RH Cycling Membrane Durability Testing at 80ºC



Data courtesy of General Motors Company from DOE membrane AST protocol.



Permeance from pseudo-static 80ºC permeance test protocol.

Gore permeance data generated on restrained M311 materials after testing in environmental chamber (80ºC/88%RH<->20%RH over ~3 hour cycle).

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Technical Accomplishments and Progress
Task 4: Module Modeling & Experimentation Approach

- Analytical
  - ✓ Module control volume calculator based on stack conditions
- CFD analysis
  - ✓ Mass transfer and pressure drop of flow field features
  - ✓ Housing flow distribution
- Experimental
  - ✓ Pressure drop and mass transfer tests of 23 flow fields
  - ✓ Multiple sub-scale cartridges tested in various housings
- Hybrid Analytical / Experimental Calculator
  - ✓ Module architecture and characteristic dimensions input
  - ✓ Pressure drop calculated using analytical methods
  - ✓ Performance estimated using results of module tests

Technical Accomplishments and Progress
Task 4: Module and Design Specifications

Typical Automotive Module Specifications	
Module Parameters	
Pressure differential across membrane	0.25 - 0.7 bar
Temperature transients	Short term, up to 110 - 125ºC
Total module volume incl. manifolds	8 L
Allowable pressure drop on either side	0.1 bar
Projected lifetime	5000 - 6000 hours
Min temperature capability	-40ºC
Process Flow Cross over	<1-3 % at rated flow & pressure
Wet Side Parameters (Stack outlet)	
Temperature	80 – 83 ºC
Flow rate	280 - 350 kg/h dry gas
Pressure	1.3-1.5 bar
IDew point	70 - 75ºC (66-80% RH at rated temperature)
Dry Side Parameters (Stack inlet)	
Temperature	80ºC
Pressure	1.8 - 2 bar
Dew point	55-56ºC (25-30% water recovery)

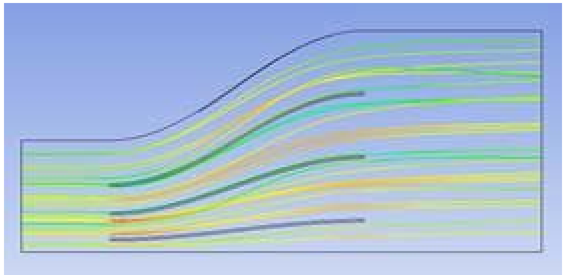
Technical Accomplishments and Progress
Task 4: Cartridge Concept Selection

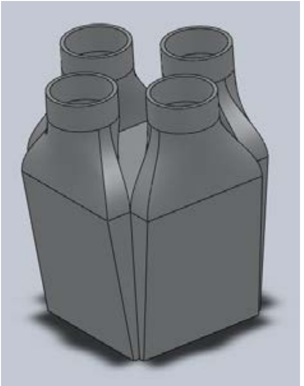
- **Single cell testing and CFD reveals pitch is paramount**
  - Small linear channels have excellent transfer per pressure drop versus featured channels
  - Small pitches are advantageous for volume and cost
  - Above considerations to current configuration: membrane pocket over plate assembly concept.

  - Adhesive choice to form membrane pocket is critical issue.
    - Testing protocol to evaluate pockets developed – led to leading candidate, silicone adhesive.
- **Cross flow Cartridges**
  - Theoretically have 96% Log Mean Vapor Pressure Drop (LMVPD) of counter flow at 25% Water Recovery Ratio (WRR)
  - Ability to have very short channels
  - Easy to Manufacture

Technical Accomplishments and Progress
Task 4: Module Housing Design

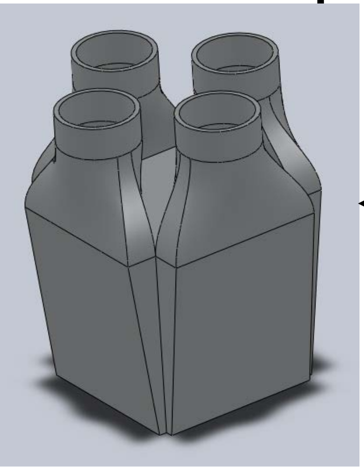
- **Validated compact housing with vanes to distribute flow**
  - ✓ Was able to match performance of normal flow distribution housing within volume constraints of project
- **Found vanes themselves had insignificant effect on performance relative to their manufacturing difficulty**
  - ✓ Vertical flow distribution within cartridge is more important than lateral
  - ✓ Redesigned housing to be die cast-able which is economical. Maintains vertical flow distribution with small change in lateral flow distribution
  - ✓ Expected performance difference is small subject to validation
  - ✓ FEA used to calculate required wall thicknesses

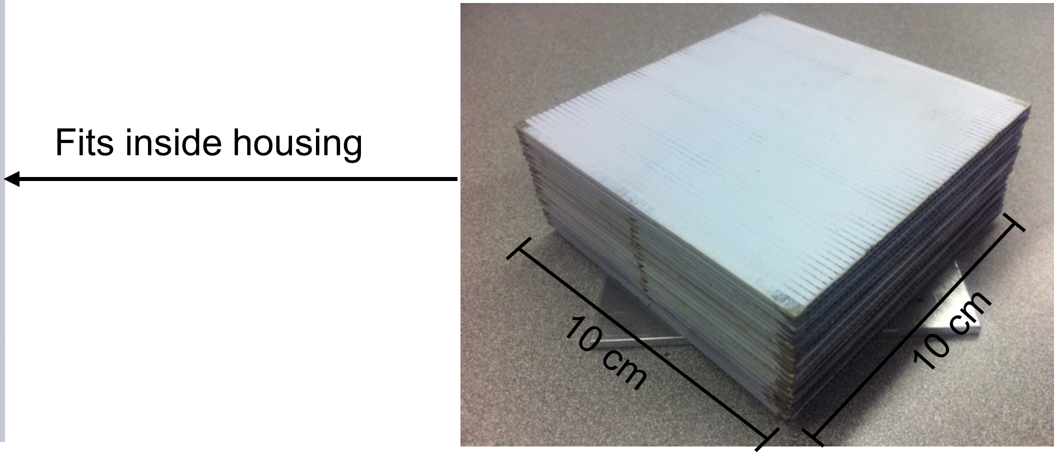




Technical Accomplishments and Progress
Task 4: Sub-scale Longevity Testing

- Completed a sub scale cartridge for longevity testing
- Utilizes latest assembly techniques
  - ✓ Welded pocket with silicone primary seal
  - ✓ H-profile plates
- Performance and leak rate evaluated periodically
  - ✓ Leak rate low (< 0.5%) through initial 150 hours of testing.
  - ✓ Performance acceptable and as expected from previous work.





Accomplishments and Progress
Task 3: Humidifier Module Cost Model

Category	*Est. Cost**
Housing	$ 15
Inserts/Flow fields/membrane	$ 32
Miscellaneous assembly components	$ 1
Overhead/Labor	$ 23
	$ 71
40% Contingency to reflect early stage design	**$ 28**
TOTAL COST	**$ 99**

*** 500, 000 units, 3 year equipment amortization, on DOE-funded dPoint automotive module design that has been validated by CFD and ¼ scale module builds. Equipment amortization as needed is included in each cost category.**

Future Work

- Membranes
  - ✓ Complete accelerated dry, hot soak testing, and establish correlation with actual humidifier testing.
  - ✓ Validate pseudo-static water transport test for QC.
  - ✓ Complete process validation for final manufacture of membranes for final module build.
- Module Design/Build
  - ✓ Complete exploration of alternative pocket forming methods and longevity testing.
  - ✓ Validate ability to die cast housing geometry.
  - ✓ Assemble sub-scale prototypes for external (customer) testing.
  - ✓ Establish final design parameters for full scale humidifier based upon validated sub-scale performance.
  - ✓ Build full scale prototypes for external testing.
  - ✓ Finalize module cost model using final design parameters and process.

Collaborations

- **<u>Subcontractor</u>**
  - ✓ dPoint Technologies
    - Design and build low-cost module using new membrane
- **<u>Partners providing Input at no cost</u>**
  - ✓ Automotive OEMs have provided data on conditions
    - GM, Ford, Daimler, Volkswagen, etc. under NDA
  - ✓ Argonne National Laboratory modeling of Gore membranes in humidifier modules.
  - ✓ General Motors Corporation – support in testing and analysis of humidifier membranes.

Project Summary

Objective:	Durable, high performance water transport membrane; and a compact, low-cost, membrane-based module
Relevance:	Reduce system cost and size of balance of plant, AND improve fuel cell performance.
Approach:	Utilize unique new Gore membranes in modules optimized for high performance and low cost.
Technical Progress:	➢Membrane development nearing completion, with high performance cost-effective material identified. Scale-up of this material underway. ➢Performance and durability testing of identified membrane nearly complete. Module performance consistent with single cell and ex-situ testing shows loss of performance of 20-30 % over 5500 hours. ➢Developed understanding of source of durability loss – chemical changes in PFSA. ➢Sub-scale module design complete, and sub-scale prototypes built and under test. ➢Module cost estimated to be ~$100 at high volumes.
Collaborators:	➢dPoint (partner in testing and module design and build). ➢Argonne National Laboratory (No cost collaborator in system modeling). ➢General Motors Company (No cost collaborator).
Future Work:	➢Complete membrane durability testing. ➢Scale-up membrane manufacturing for final module build. ➢Finish sub-scale validation testing. ➢Build final full scale module.

Technical Back Up Slides

Proposed Final Project Targets

Specific Target	Value*	Rationale
Beginning of life membrane performance (flux):	> 0.030 g/cm2-min at 80 ºC and gas impermeable (Gurley > 10,000 s)	Small humidifier footprint; Improved stack performance
Projected membrane durability	1. Projected < 25% performance loss after 5000 h hot soak at 80 ºC 2. Projected < 25% performance loss after 1000 h RH cycling 3. Gas impermeable (Gurley > 10,000 s) after above tests.	Automotive lifetime

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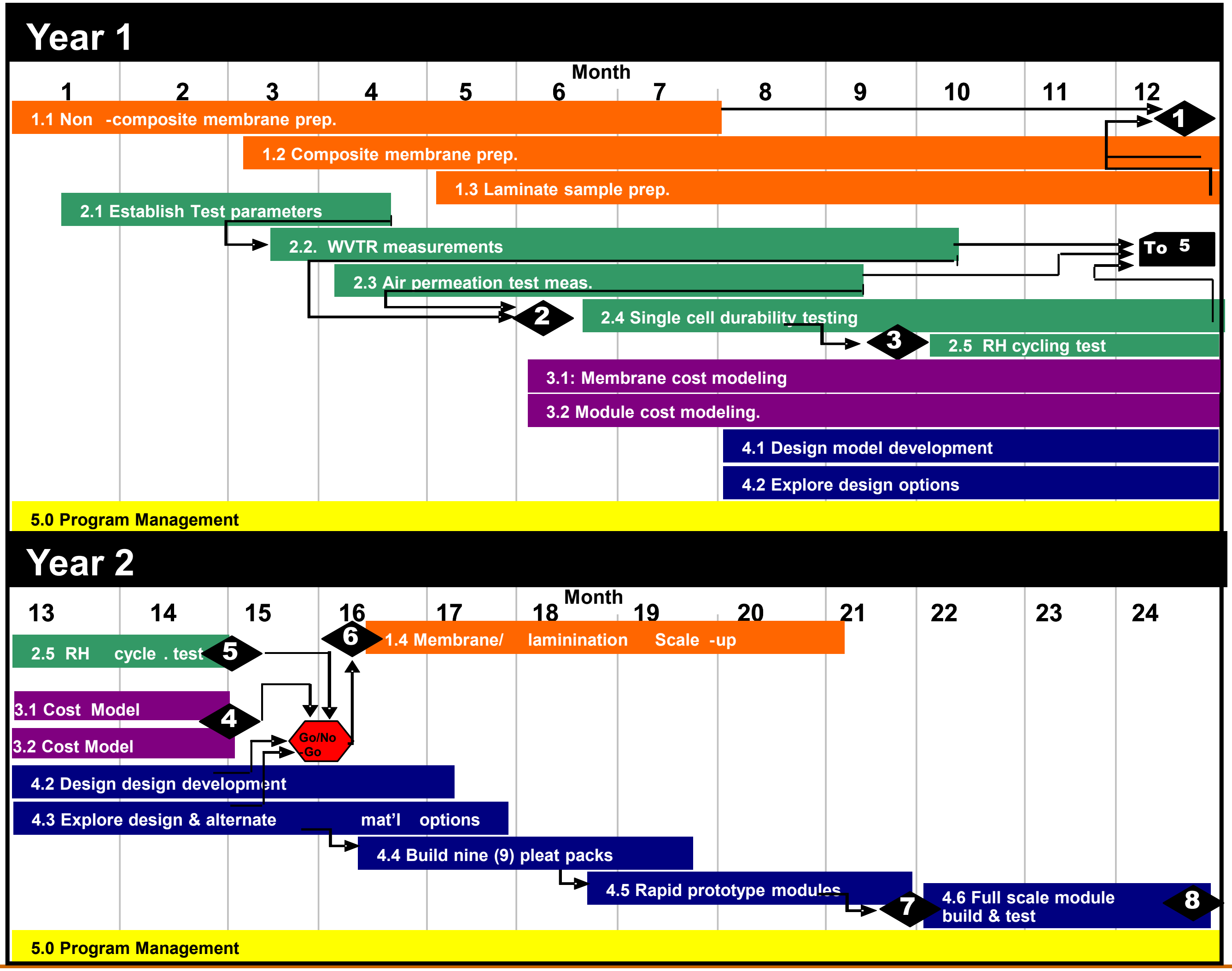
Approach: Timeline and Milestones



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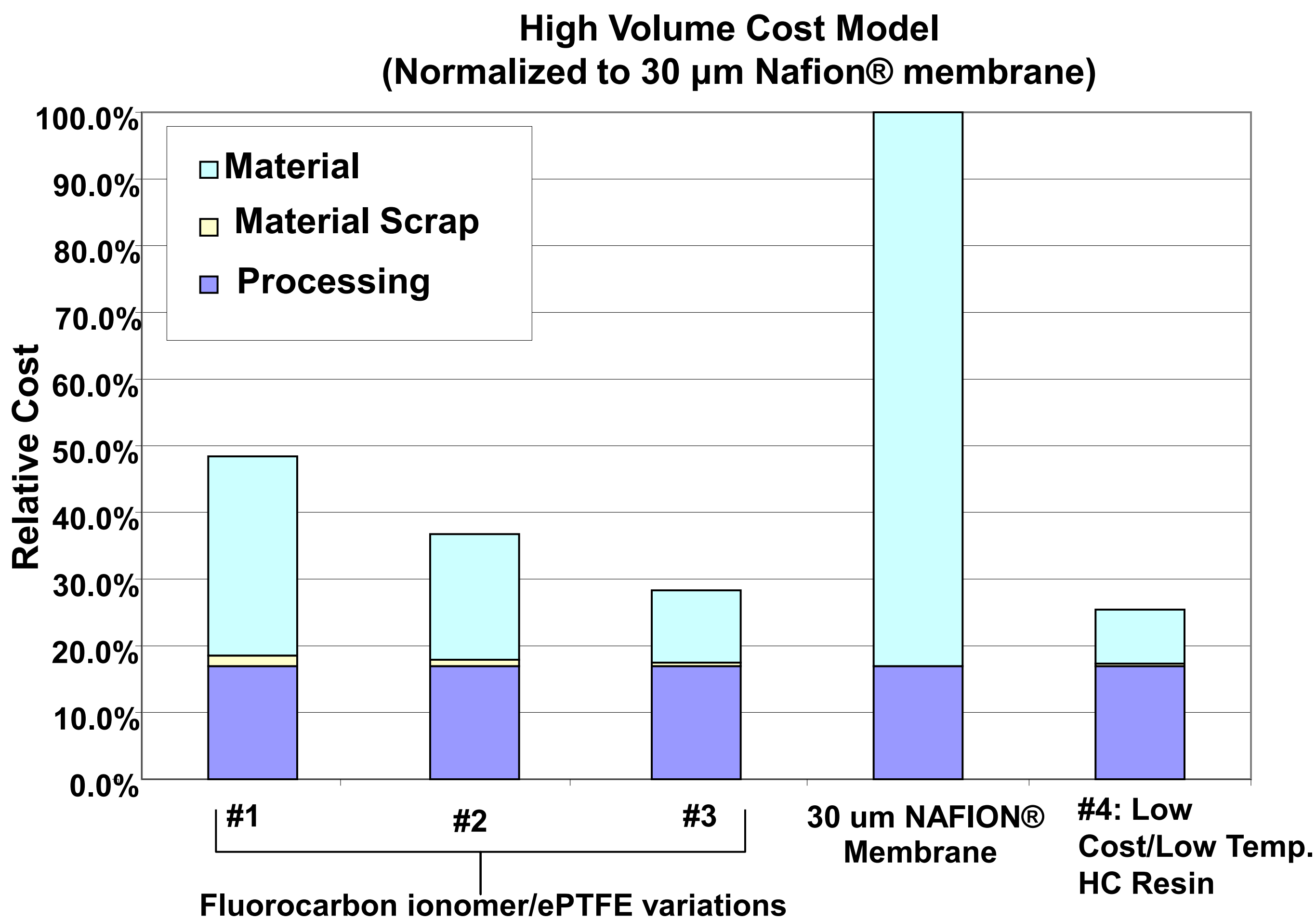
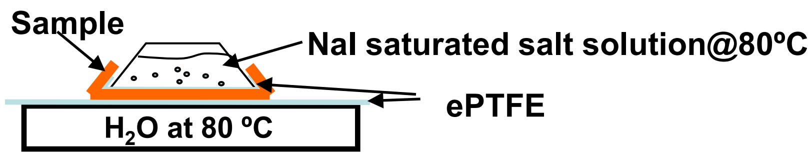
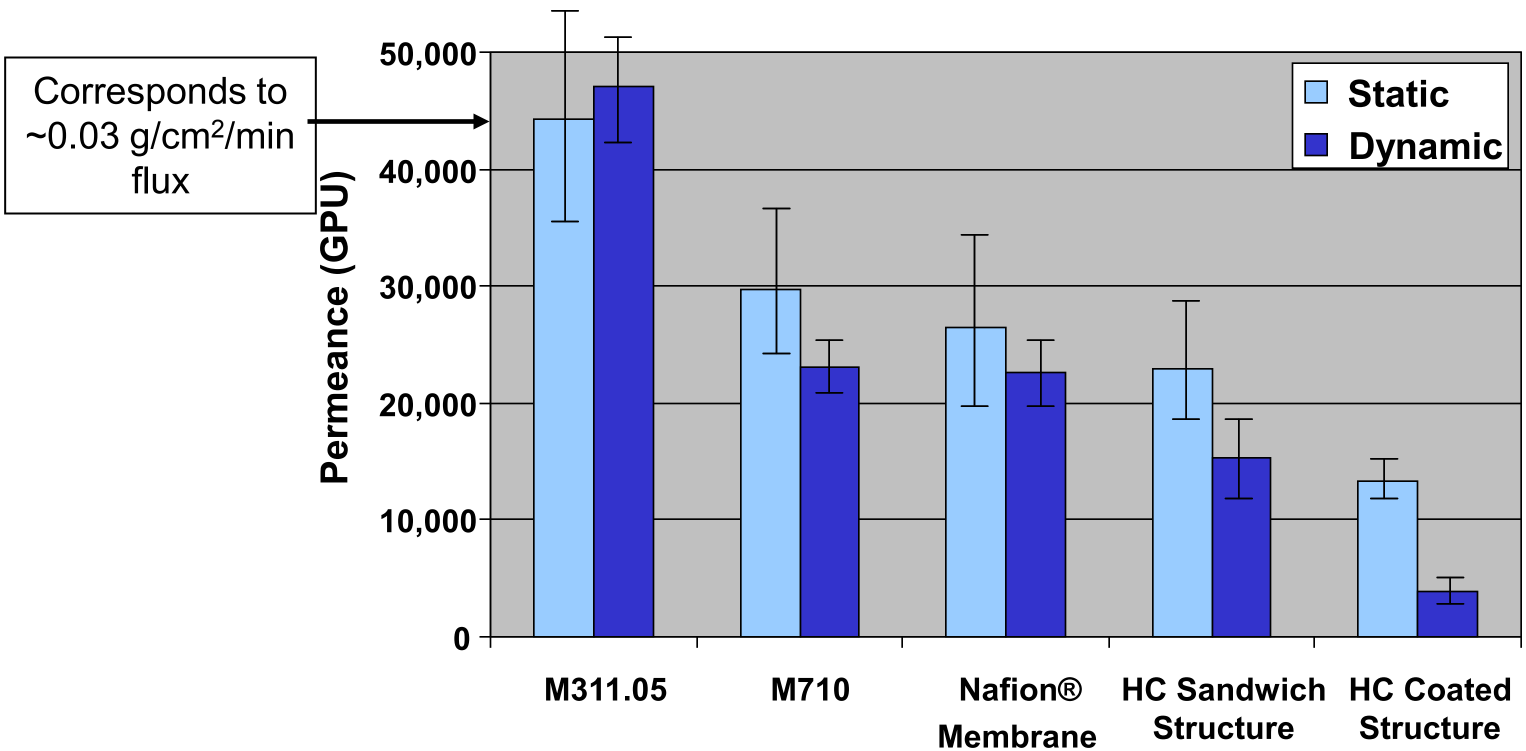
Technical Accomplishments from Previous Period
Task 3: High Volume Membrane Cost Estimates



Technical Accomplishments from Previous Period
Performance Testing: Modified Static Testing

Permeance: Static





Technical Accomplishments from Previous Period
Task 4: Projected Cartridge Specifications

- **Based on flow field and earlier sub scale testing, concluded:**
  - **~ 2 m^2 membrane required, with volume of < 8 L.**
  - **To compensate for loss of permeation with time, the cartridge is over sized, so system may require feedback control to ensure over humidification does not occur at beginning of life.**
  - **Size increase for unexpected losses in scale-up also included as contingency.**
- **Pressure drop: ~0.08 bar secondary, ~0.03 bar primary**
  - **Pressure drop competes with volume and unit cost**