Visualization of Fuel Cell Water Transport and Performance Characterization Under Freezing Conditions

DOE Hydrogen Program

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Overview

Timeline

- Start date: 03/01/2007
- End date: 02/28/2010
- 35% complete

Budget

- Total project funding
  - DOE: $ 2.68M
  - Contractor: $ 0.8M
- FY07: $ 0.915M; FY08: $ 0.9M

Barriers

- Barriers addressed:
  - C: Performance
  - D: Water transport within the stack
  - E: System thermal and water management
- Targets — MEAs

	2005	2010	2015
Unassisted start from low temperature (C)	-20	-40	-40

Partners

- Rochester Institute of Technology
- General Motors Corporation
- Michigan Technological University

Objectives

Overall: • To gain a fundamental understanding of the water transport processes in the PEMFC stack components

• To minimize fuel cell water accumulation while suppressing regions of dehumidification by an optimized combination of:

- New gas diffusion layer (GDL) material and design
- New bipolar plate (BPP) design and surface treatment
- Anode/cathode flow conditions

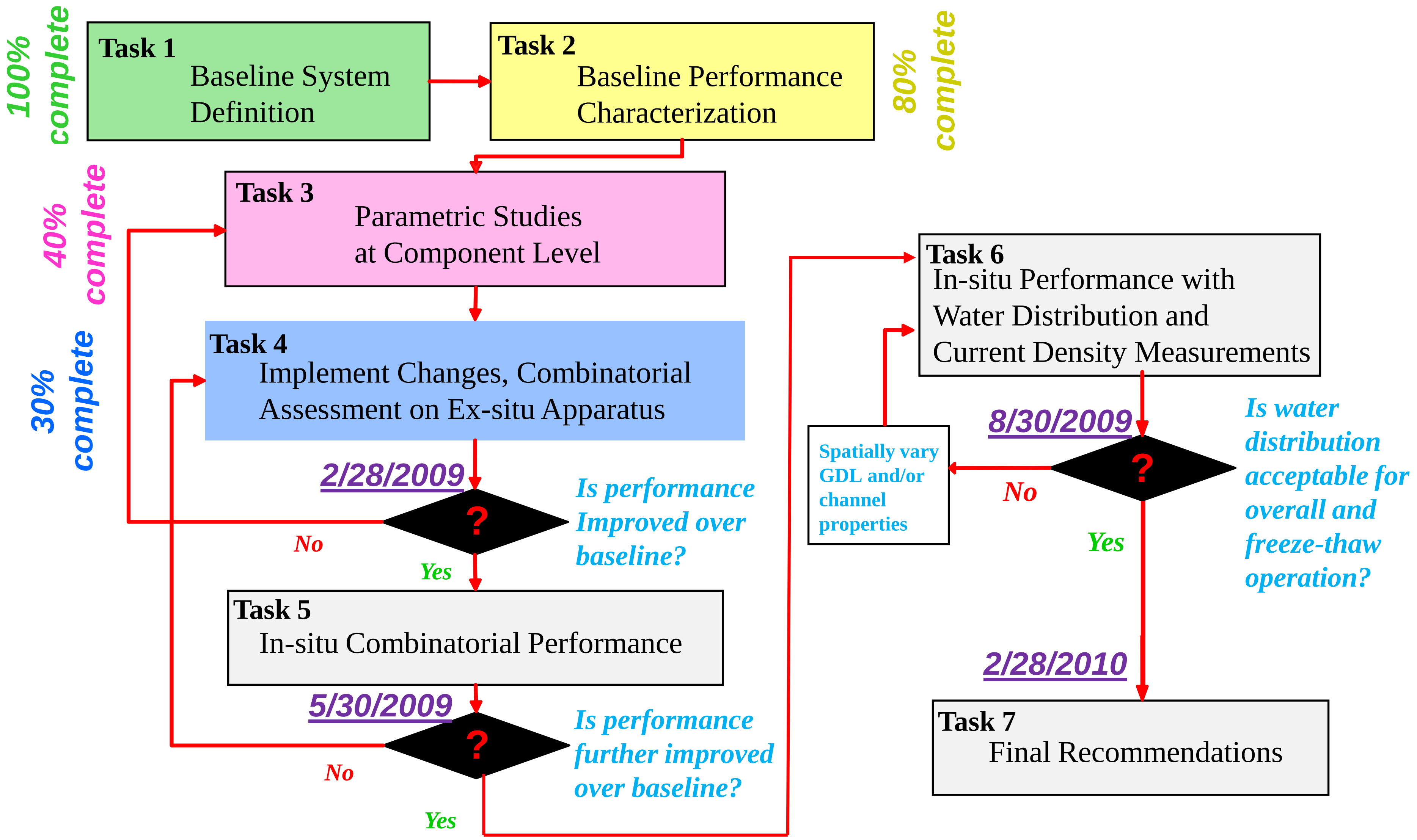
Phase I: • Establish baseline system performance:

- Performance matrix for the ex-situ multi-channel and in-situ fuel cell experiments
- Freeze effects on performance and durability
- Microscopic study and models for water transport in GDL and parallel channels

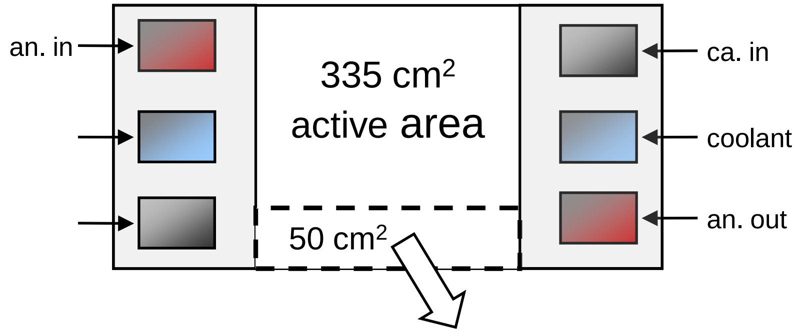
Milestones

Month/Year	Milestone or Go/No-Go Decision Point
Jun-07	Milestone: ▪ Select materials (GDL, MEA and channel surface treatment) for the ex-situ and in-situ experiments. ▪ Design flow field to simulate full fuel cell stack to meet the DOE target of power density requirement of 2 kW/L for an 80 kW stack.
May-08	Milestone: ▪ Characterize the baseline system performance through ex-situ and in-situ fuel cell experiments. ▪ Develop a Performance Matrix for characterizing GDL and channel design from the water management standpoint. ▪ Establish the water transport characteristics of the fuel cell under freezing conditions for baseline design.
Aug-08	Milestone: ▪ Characterize commercially available GDL morphology and wettability with respect to flooding. ▪ Determine the effect of wettability, channel geometry, and flow conditions on flow stability and water holdup. ▪ Complete network model for GDL.
Go-No Go Decision Point: Phase I to II	▪ Develop a Performance Matrix for quantifying GDL/channel performance from water management standpoint. ▪ Establish baseline performance in ex-situ and freeze study experiments and compare with other combinatorial GDL/Channel configurations.

Plan & Approach

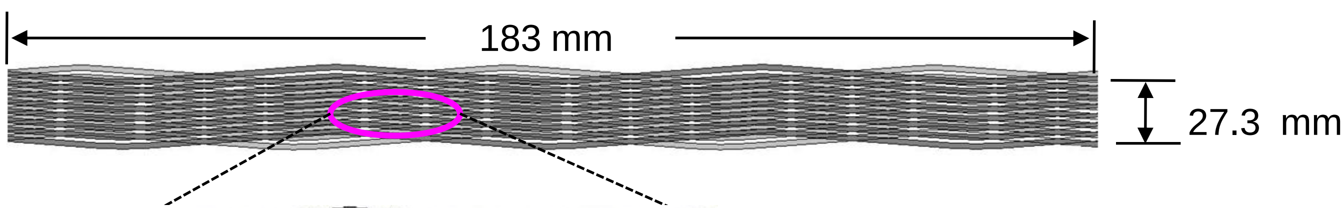


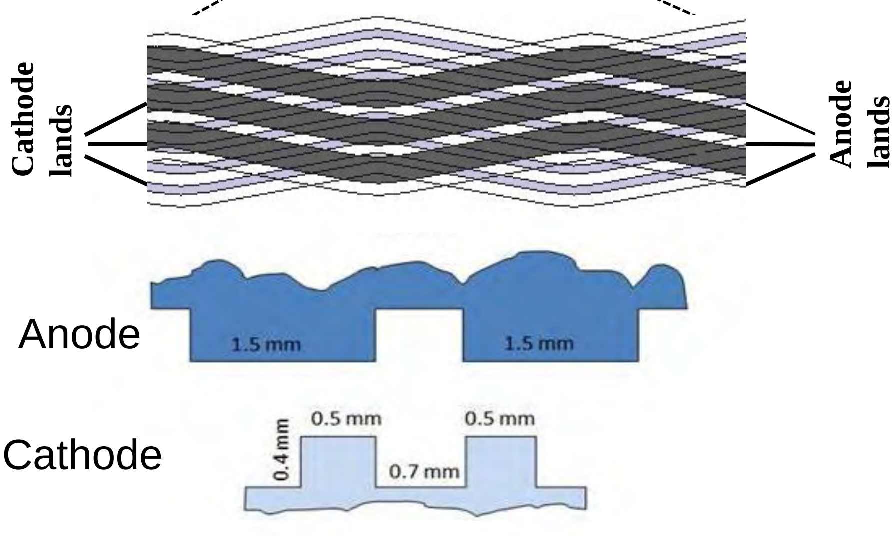
Technical Accomplishments
Task 1. Baseline System Definition



A. Flow Field

- Achieved key features of full-scale hardware in a 50 cm^2 test cell, with DOE 2010 FreedomCAR target of 2 kW/L and literature data as the design basis





B. MEA and GDL

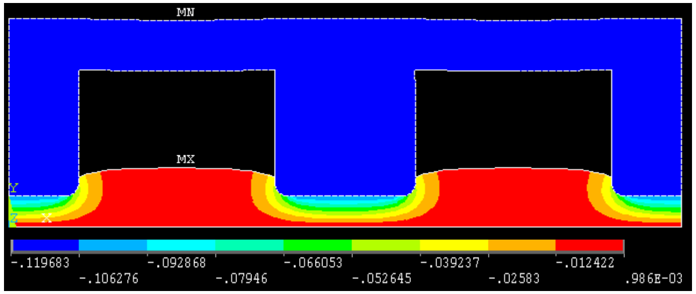
- Anode/cathode Pt loading: 0.2/0.3 mg $/cm^2$, approaching toward DOE 2010 total Pt loading target of 0.3 mg/cm^2
- GDL made in house by General Motors; demonstrated the best performance.

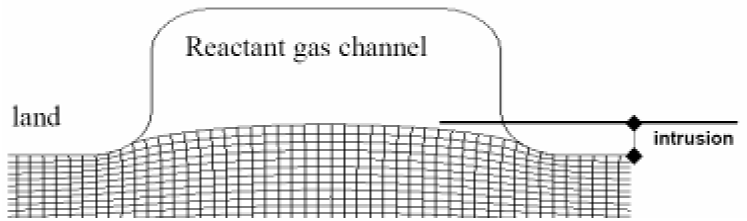
Task 2. Baseline Performance Characterization

2.1 Baseline Ex-situ Multi-channel Performance Characterization

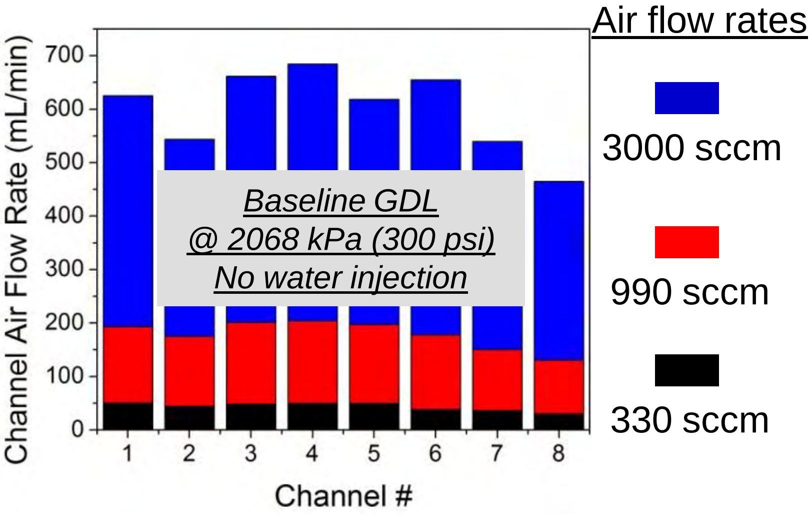
- Objectives:
  Two-phase flow stability and water distribution in parallel multi-channels

Intrusion measurement





Flow maldistribution



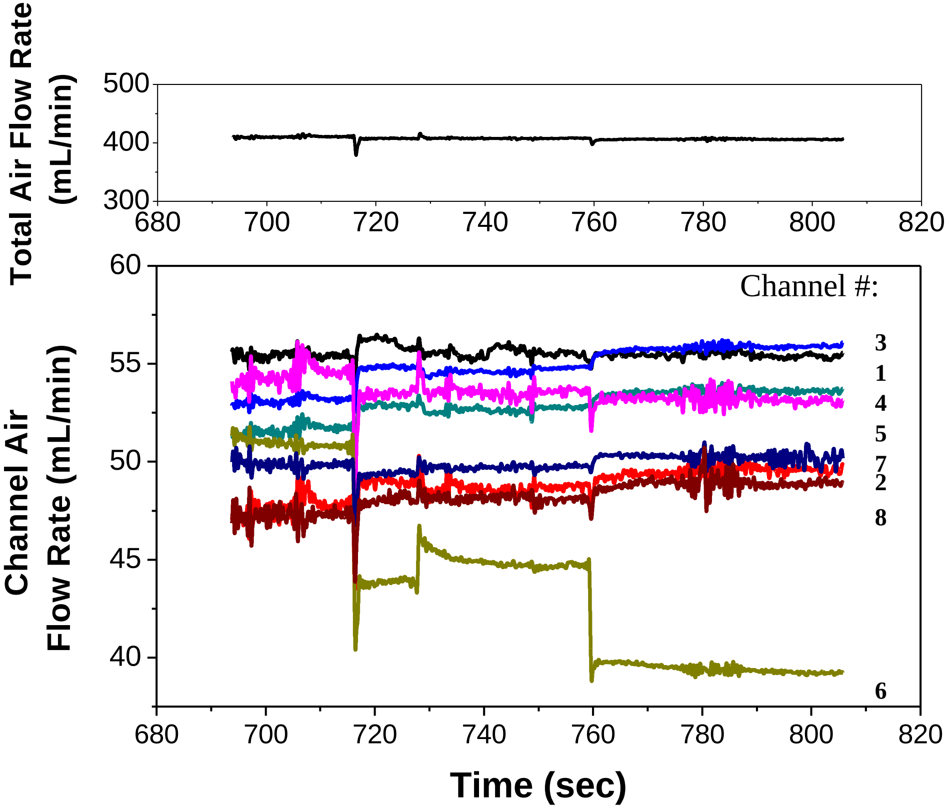
Test setup features:

- Flow maldistribution - Measure instantaneous flow in individual channels
- Measure GDL intrusion as a function of compression
- Visual access with high speed camera
- Instantaneous pressure drop measurement

2.1 Baseline Ex-situ Multi-channel Performance Characterization

A. Low Air Flow Observation — Slug Flow

Channel interactions during slug flow



Baseline GDL @ 2068 kPa (300 psi)
WFR= 0.04 mL/min, AFR= 400 sccm

1 2 3 4 5 6 7 8

VIDEO

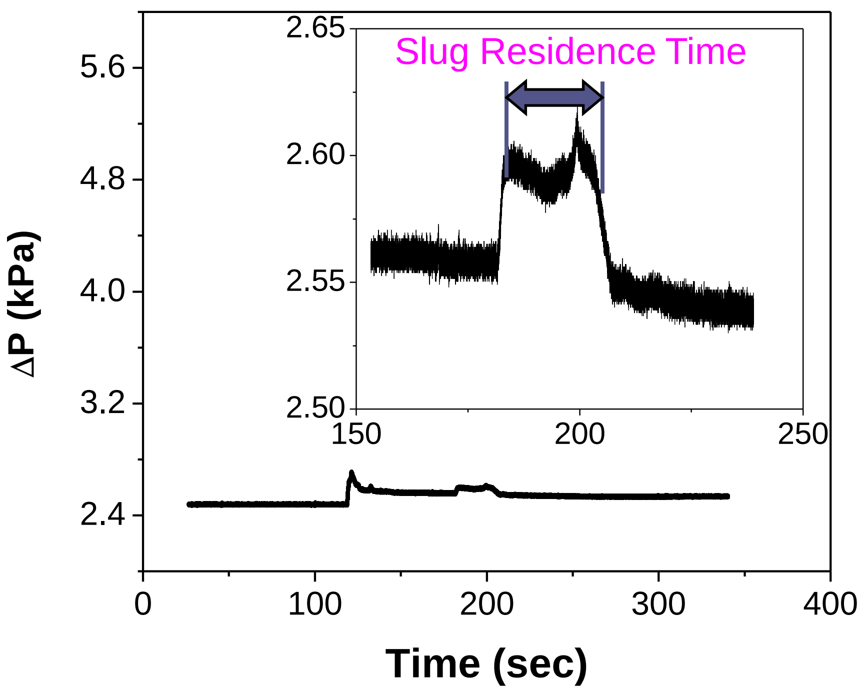
- Slug flow has significant influence on two-phase flow stability

2.1 Baseline Ex-situ Multi-channel Performance Characterization

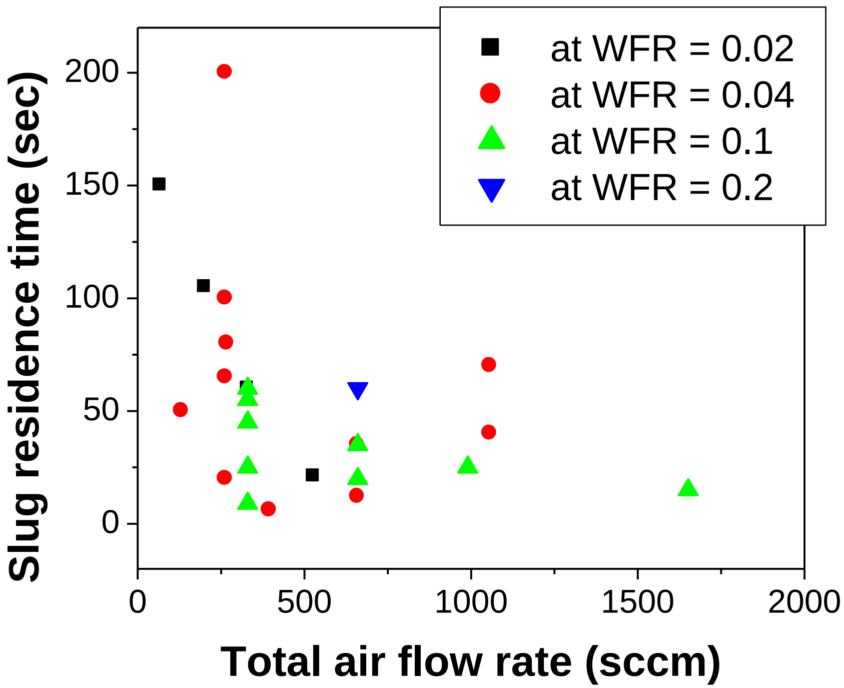
Slug Flow Features

- Slug flow signature — ΔP increases due to slug formation
- Slug residence time in a channel decreases with increasing air flow rates
- Slug flow undesirable - leads to channel blockage

Baseline GDL @ 2068 kPa (300 psi)
WFR = 0.02 mL/min, AFR= 530 sccm



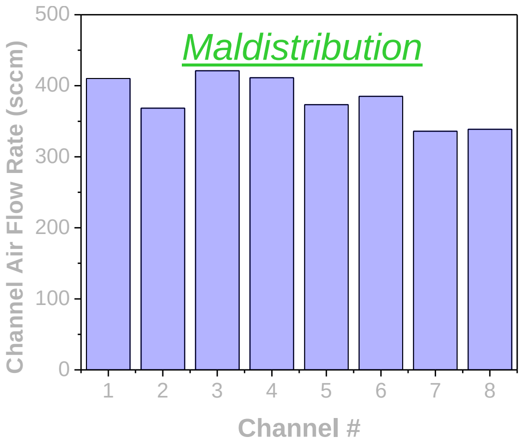
Slug residence time

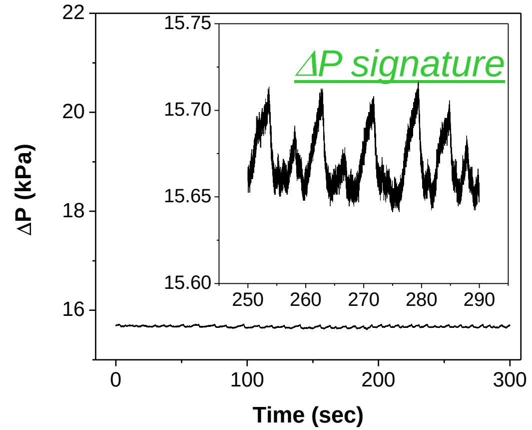


2.1 Baseline Ex-situ Multi-channel Performance Characterization

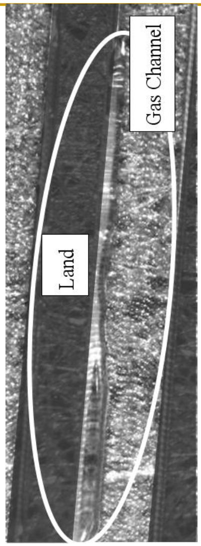
B. Intermediate Air Flow Observation — Film Flow

Baseline GDL @ 2068 kPa (300 psi)
WFR= 0.1 mL/min, AFR= 3000 sccm



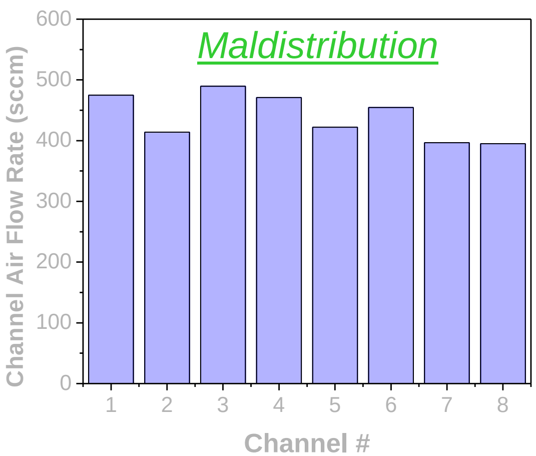


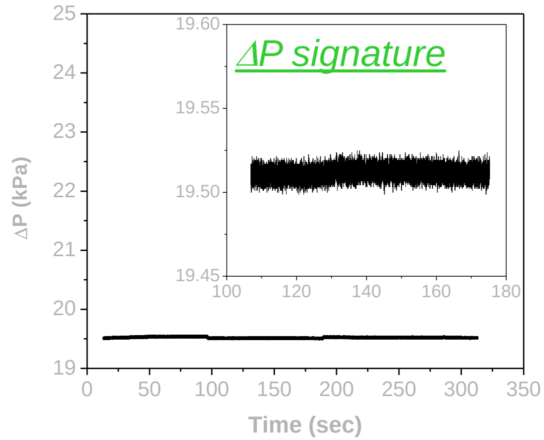
Film flow pattern

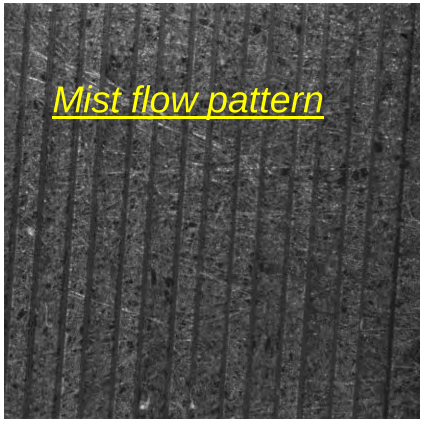


C. High Air Flow Observation — Mist Flow

Baseline GDL @ 2068 kPa (300 psi)
WFR= 0.02 mL/min, AFR= 3500 sccm

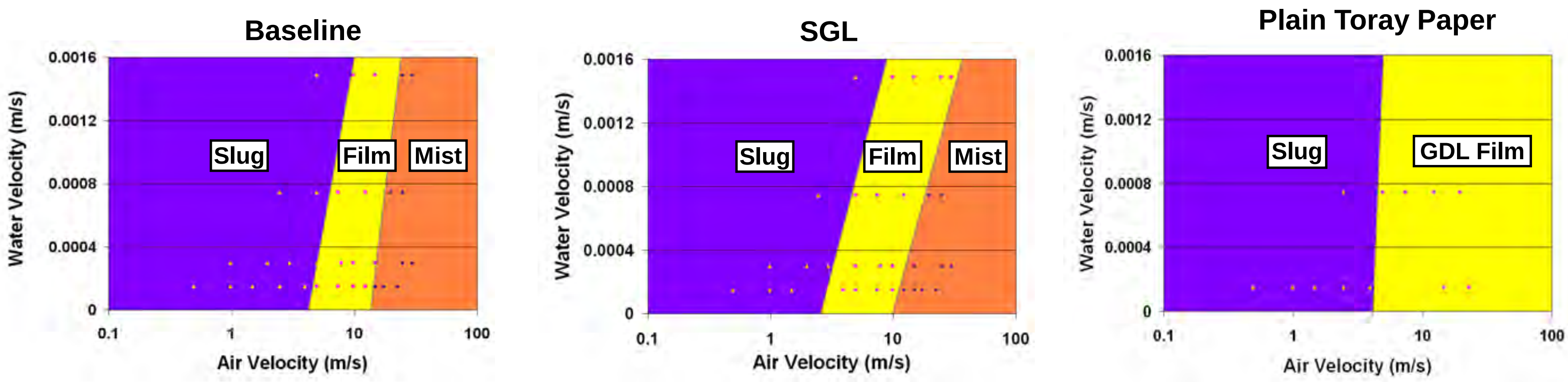






- Film and mist flow have different pressure drop signatures

Performance Characterization: Two-Phase Flow Pattern Maps



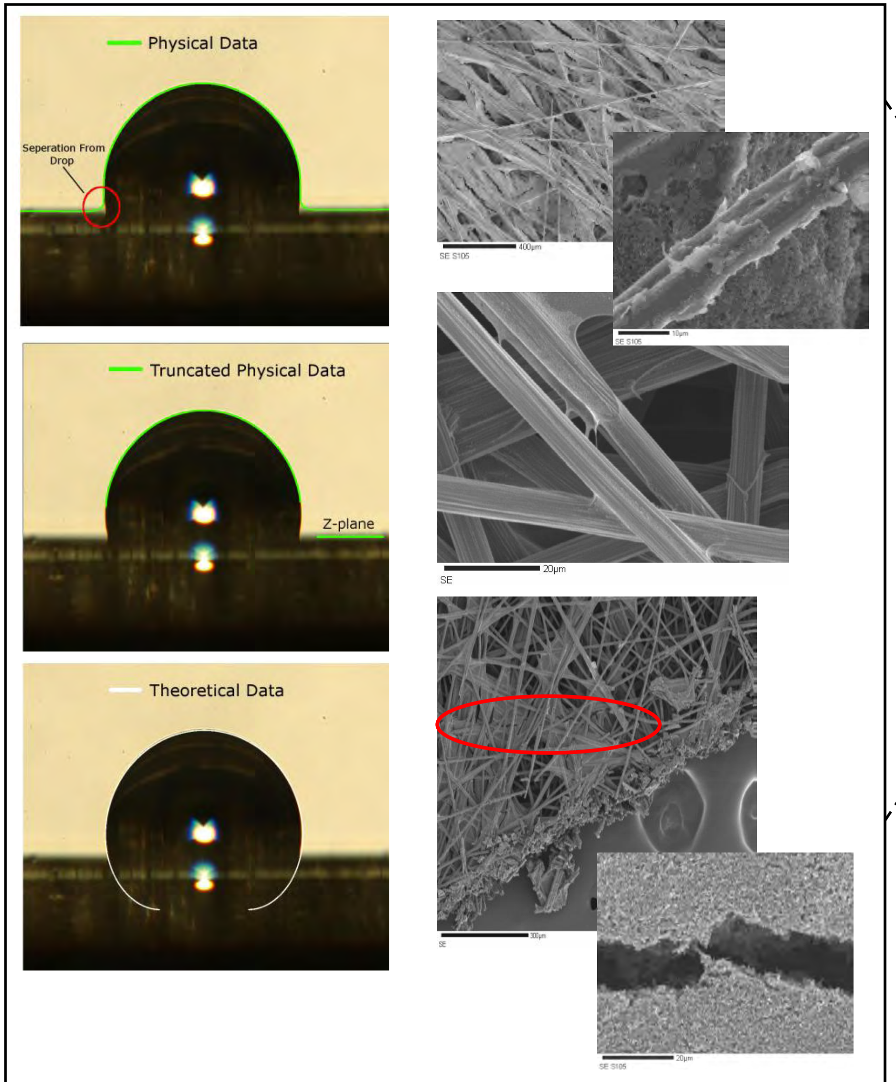
•Baseline and SGL have similar flow patterns whereas the Plain Toray is different

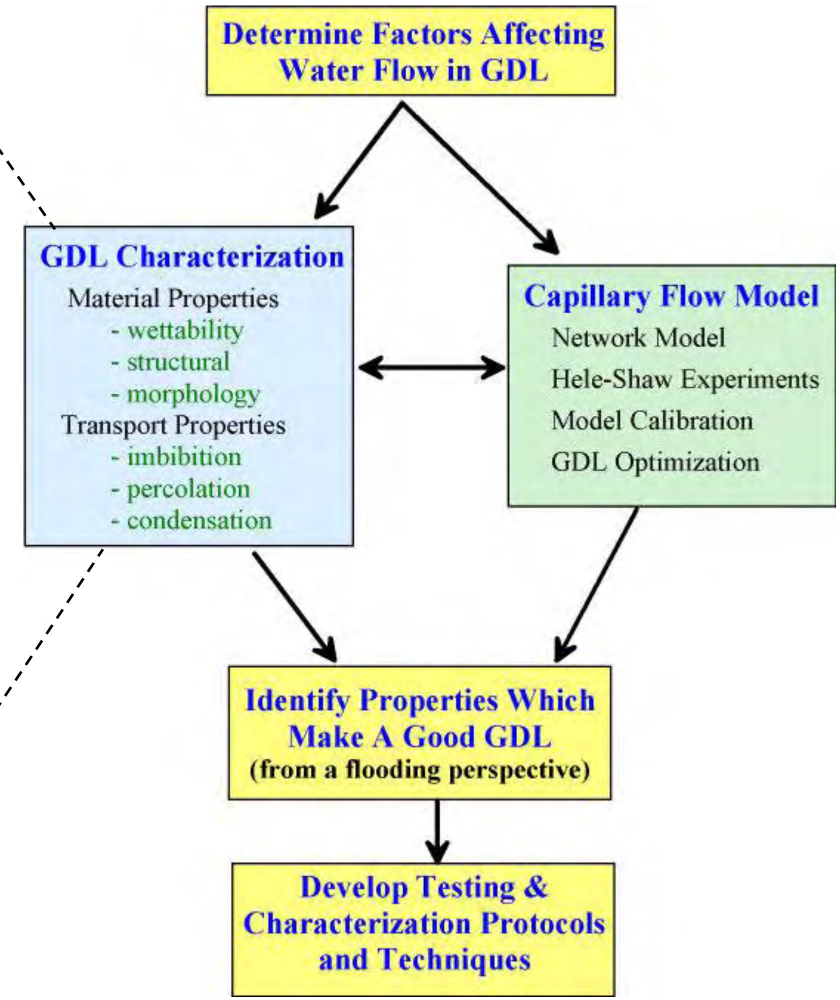
Highlights of Ex-Situ Work:

- For the first time, flow maldistribution has been measured in individual parallel channels.
- GDL intrusion measured as a function of compression
- Parallel channel interactions and two-phase flow patterns
- Flow pattern, total pressure drop and pressure drop signature – important parameters in the performance matrix for GDL/channel characterization

Task 3. Parametric Studies at Component Level

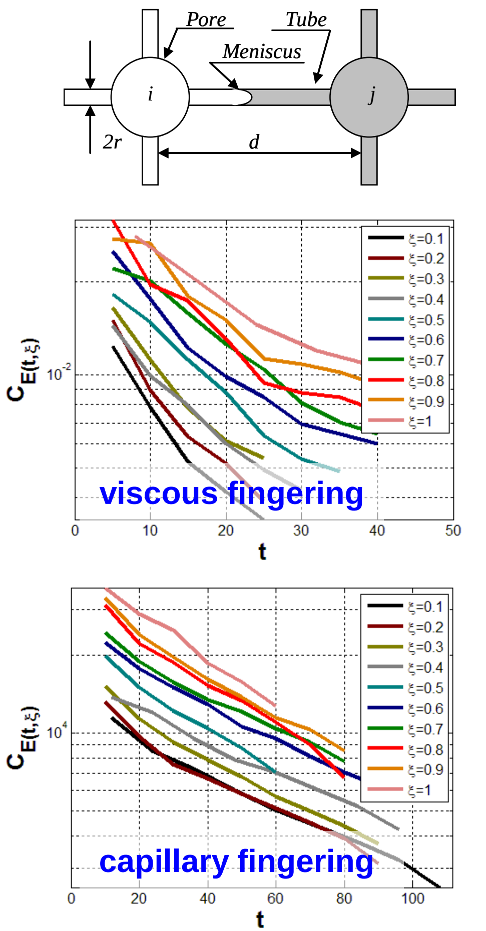
3.1 GDL Component Studies – Material Property Characterization

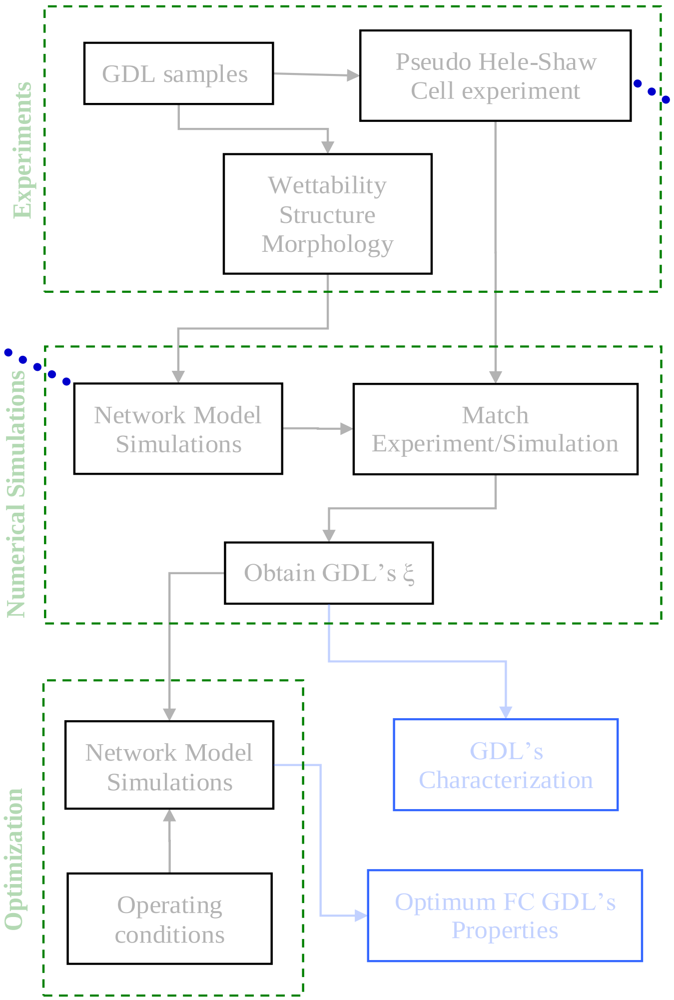


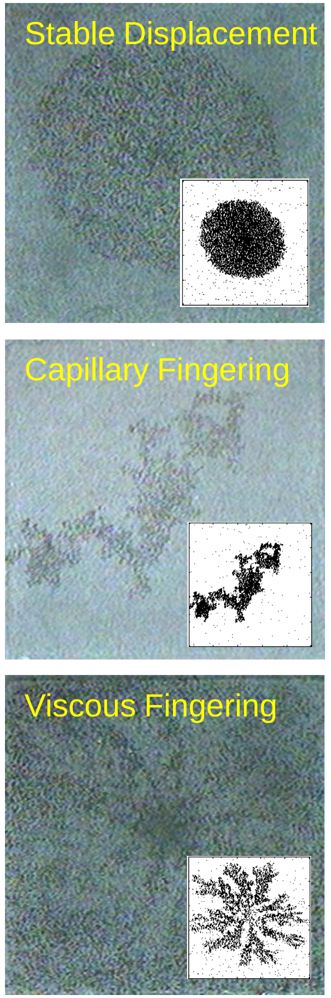


3.1 GDL Component Studies – Capillary Flow Model

$$r \rightarrow r_m(1 \pm \xi) \qquad \xi = [0,1]$$

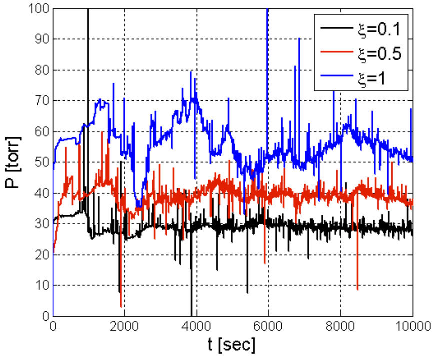




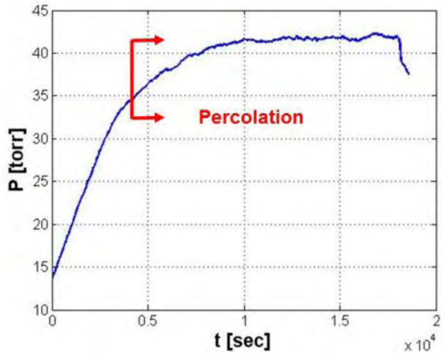


3.1 GDL Component Studies – Capillary Flow Model

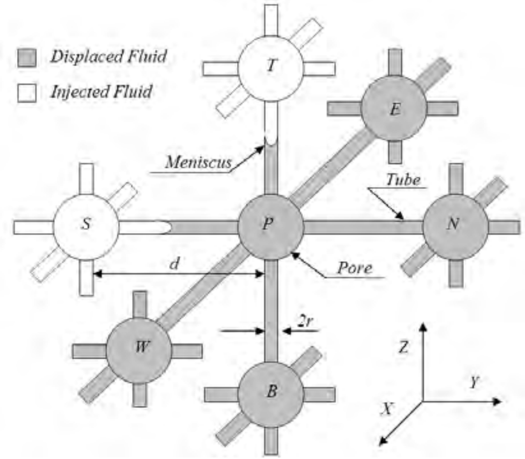
Numerical pressure drop
Ca = 1.1 x 10^{-7} & *M* = 64

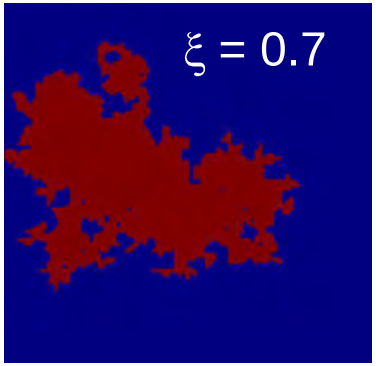


Experimental pressure drop
Ca = 1.1 x 10^{-7} & *M* = 64

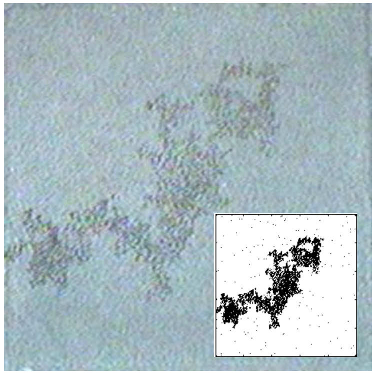


$$q_{ij}^{t} = \frac{\pi r_{ij}^{4}}{8\mu_{\mathrm{eff}_{ij}}^{t} d}\left(P_i^t - P_j^t - P_{c_{ij}}^{t}\right)$$

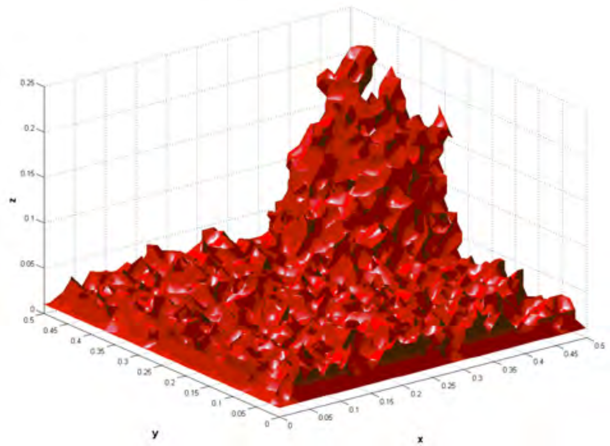




Numerical water distribution
Ca = 1.1 x 10^{-7} & *M* = 64

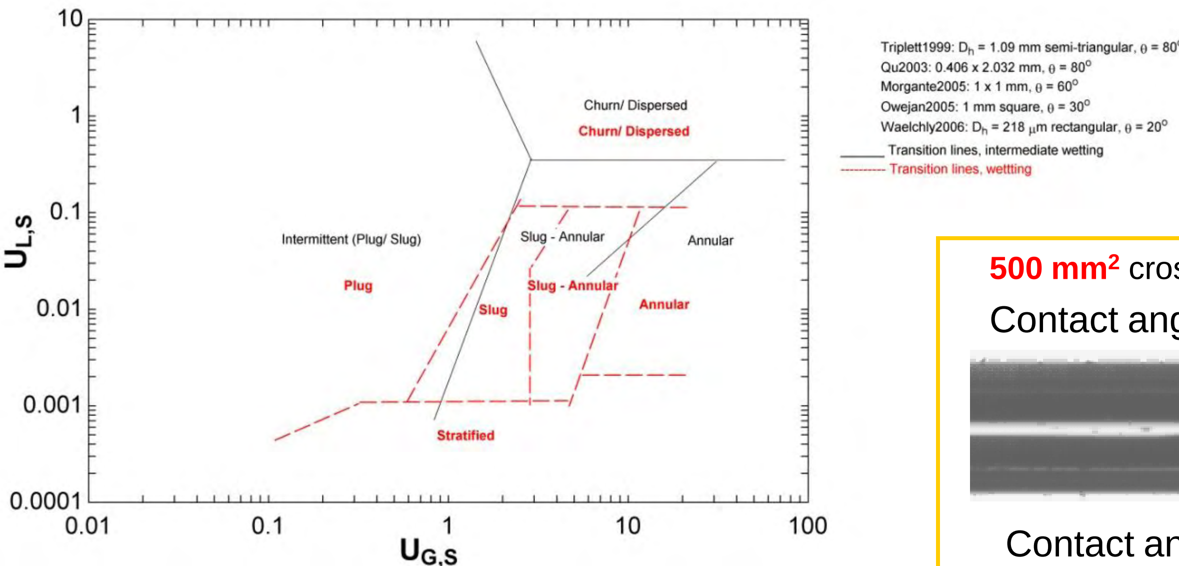


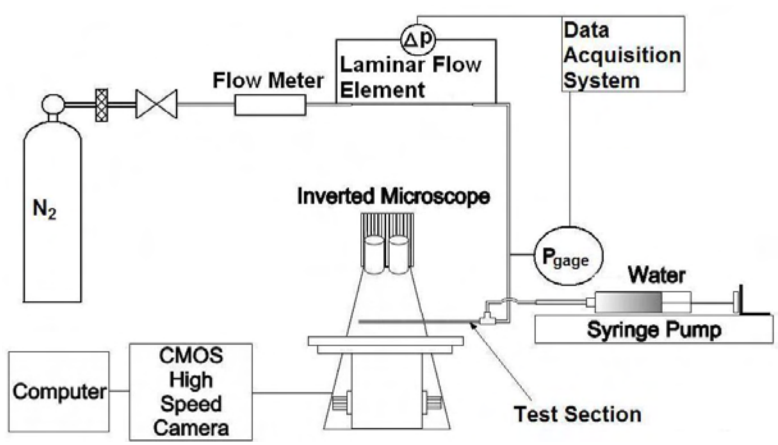
Experimental water distribution
Ca = 1.1 x 10^{-7} & *M* = 64



3.2 Channel Component Studies

Effect of Wettability on Flow Regime Transition in Non-Circular Channels





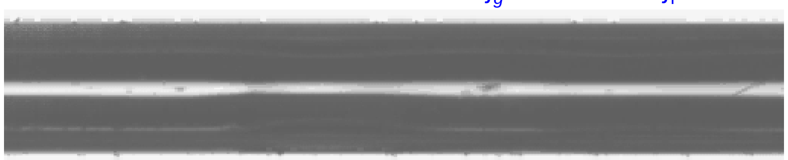
500 mm² cross section

air: 1.2 x 10^{-6} kg/s

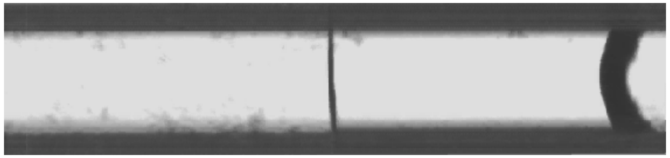
water: 10 x 10^{-6} kg/s

j_g = 0.04 m/s j_l = 4.1 m/s

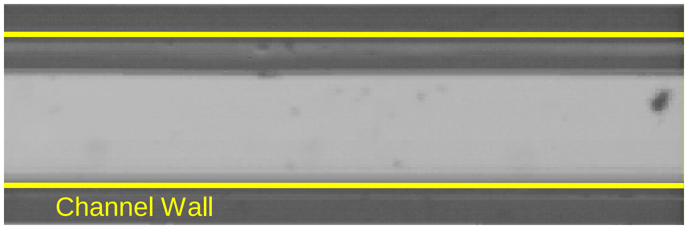
Contact angle: 20°



Contact angle: 80°

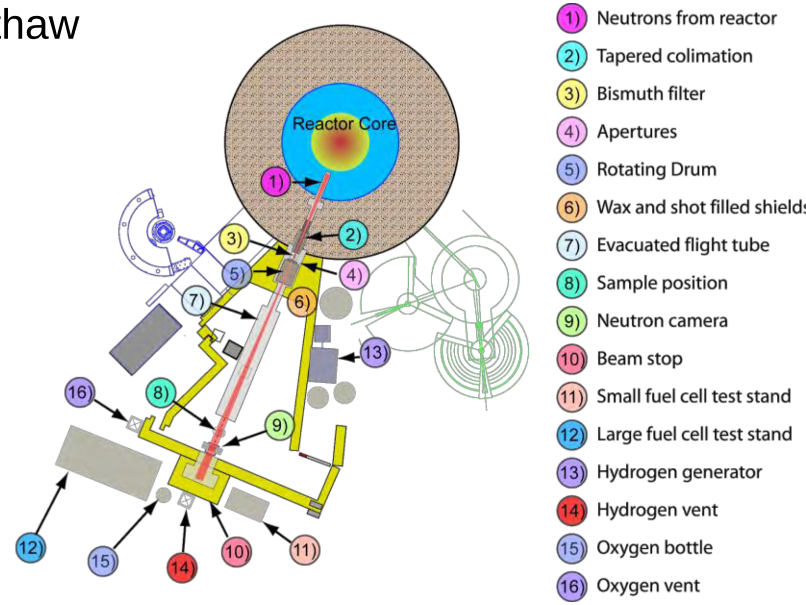


Contact angle: 105°

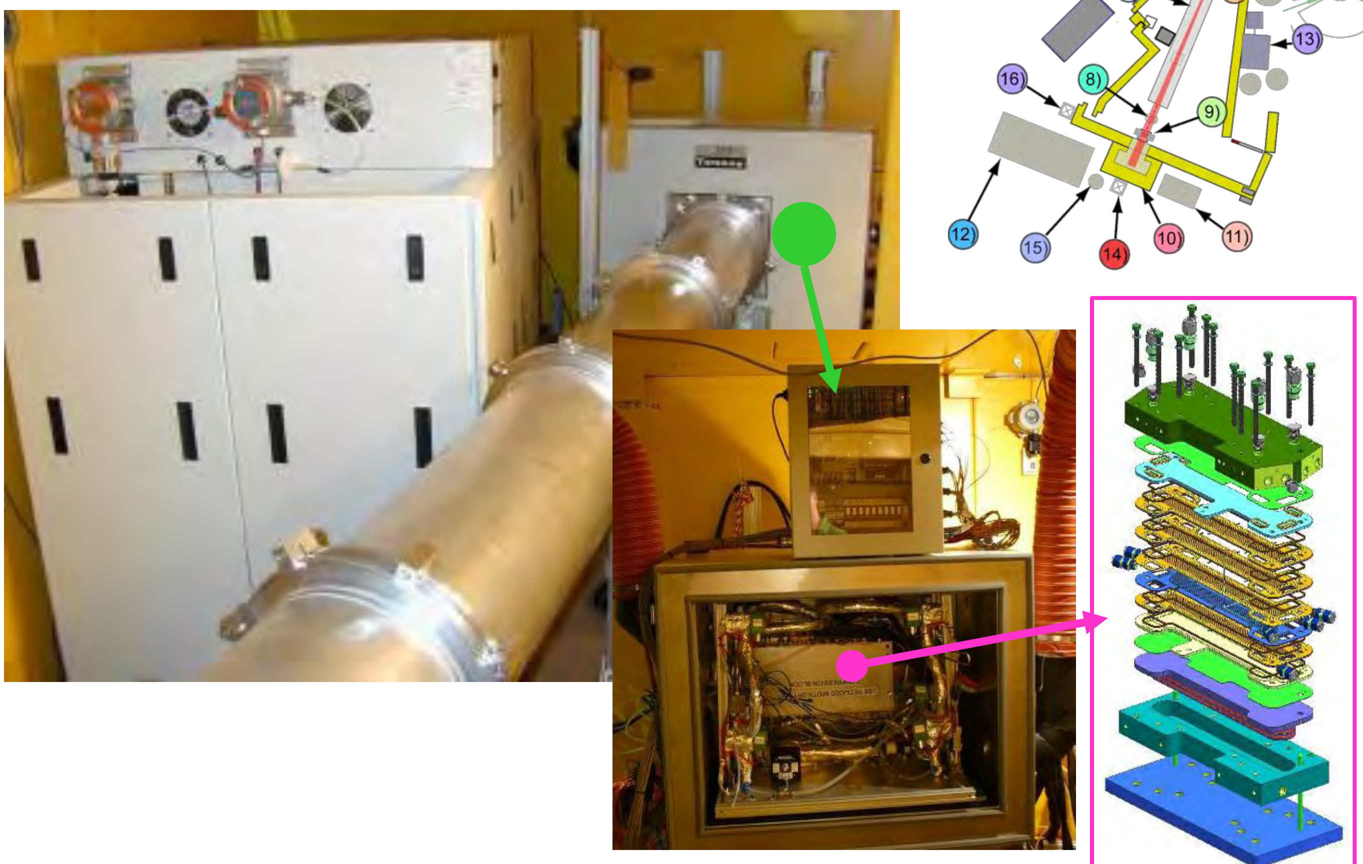


2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

- Developed apparatus and methods for freeze-thaw experiments at NIST.
- Capability to freeze to - 40 C



<u>Freeze system – Neutron compatibility</u>



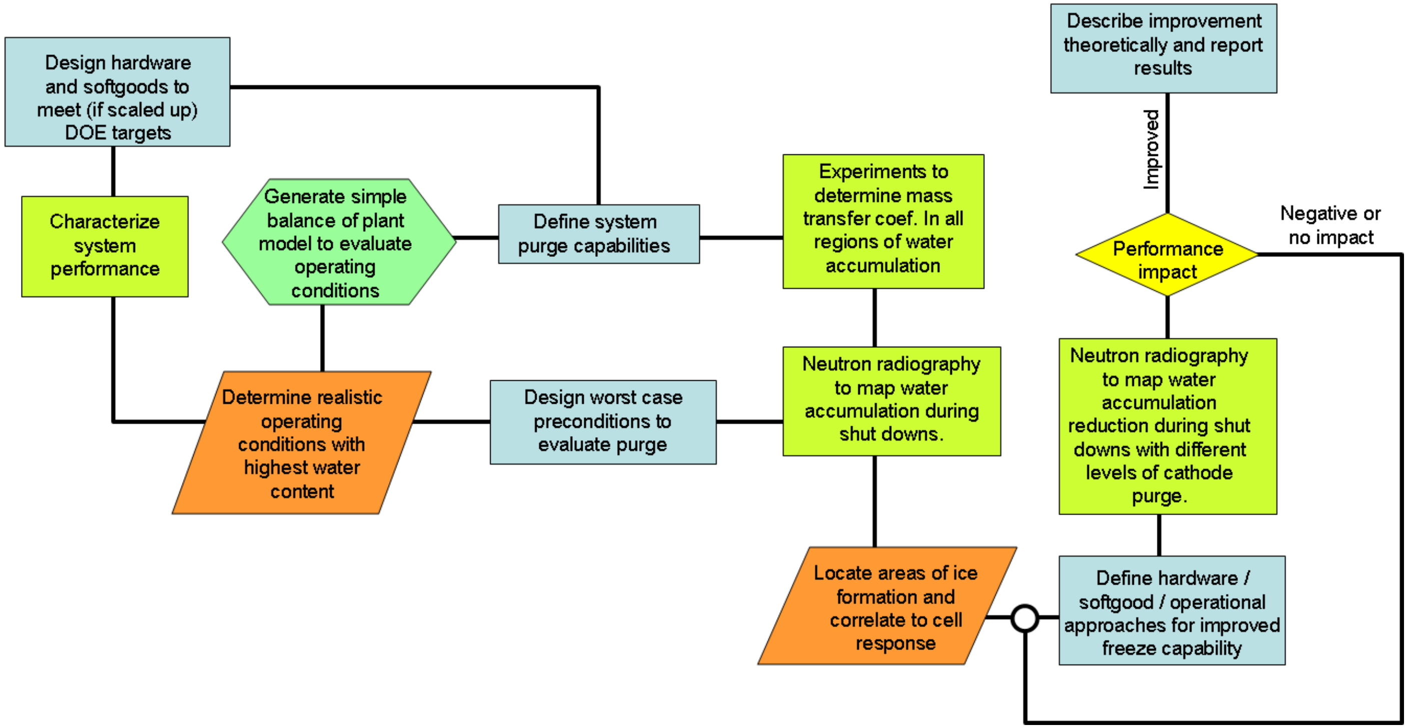
<u>Chamber Features:</u>

- Dew point control
  - Eliminate frost
- Gas recirculation
  - Isolate vibration in refrigeration system
- Nitrogen working fluid
  - Hydrogen safety
- Neutron transparent window
  - Al windows with frost control

2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

A. Characterization Protocol – General Plan

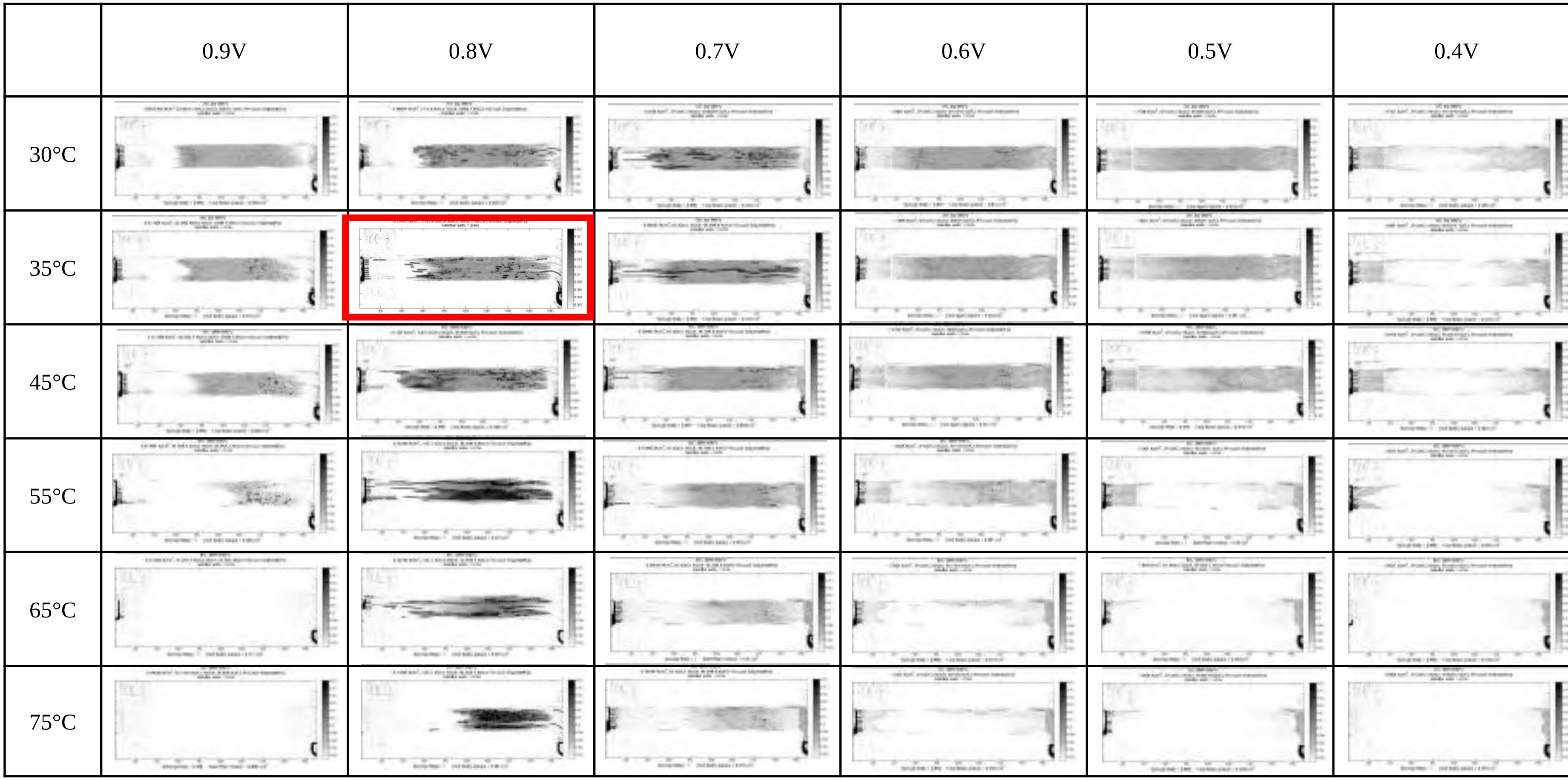
1. Define “worst case" shutdown conditions for automotive PEMFCs
2. Define individual mass transfer coefficient for all areas of accumulation
3. Determine required purge to dry individual areas of accumulation
4. Determine purge requirement for successful freeze start
5. Correlate known areas water accumulation, water removal rates, and pressure/voltage response during freeze start
6. Use these parameters to evaluate next generation material set



2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

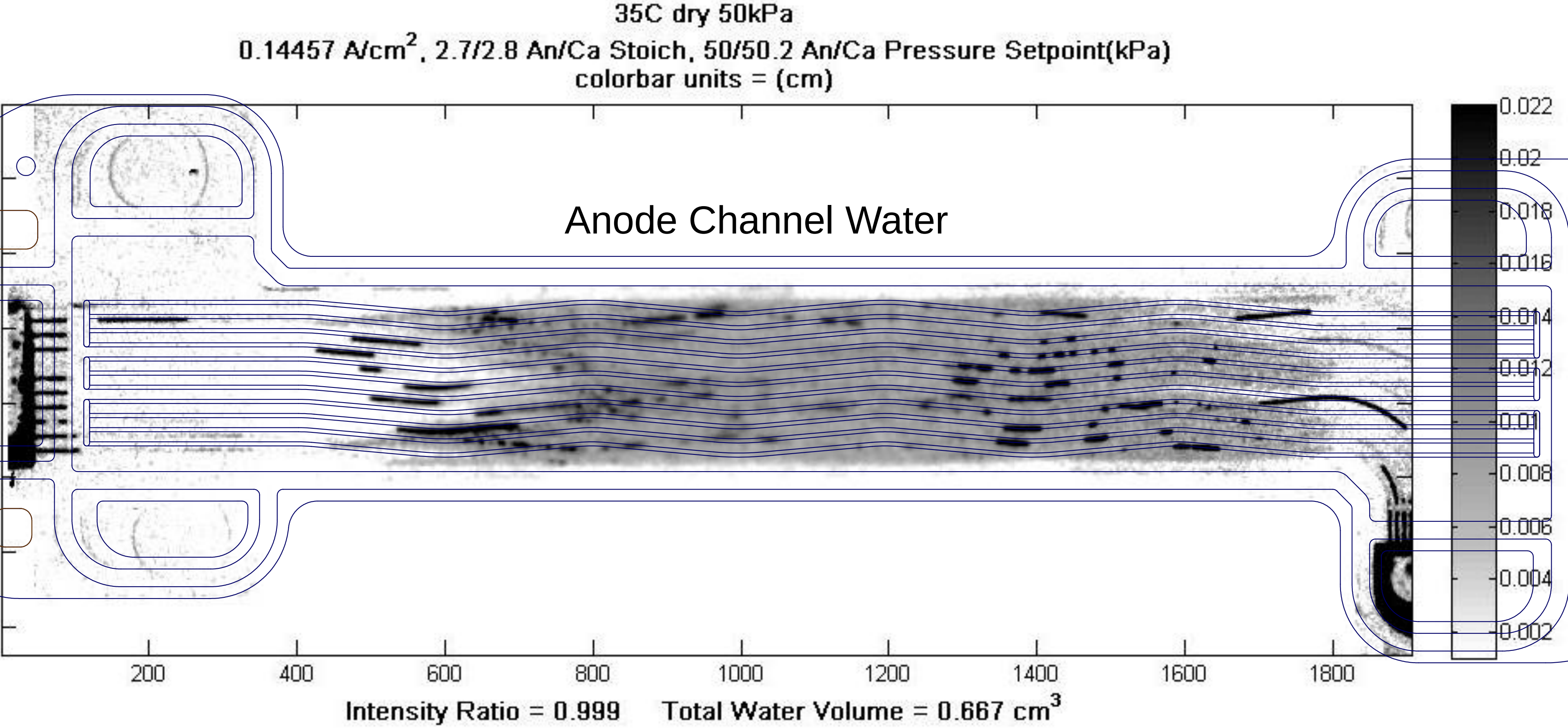
B. Characterization Protocol – Operating Space

Water Distribution Through Start-up Temperature and Current Density Range



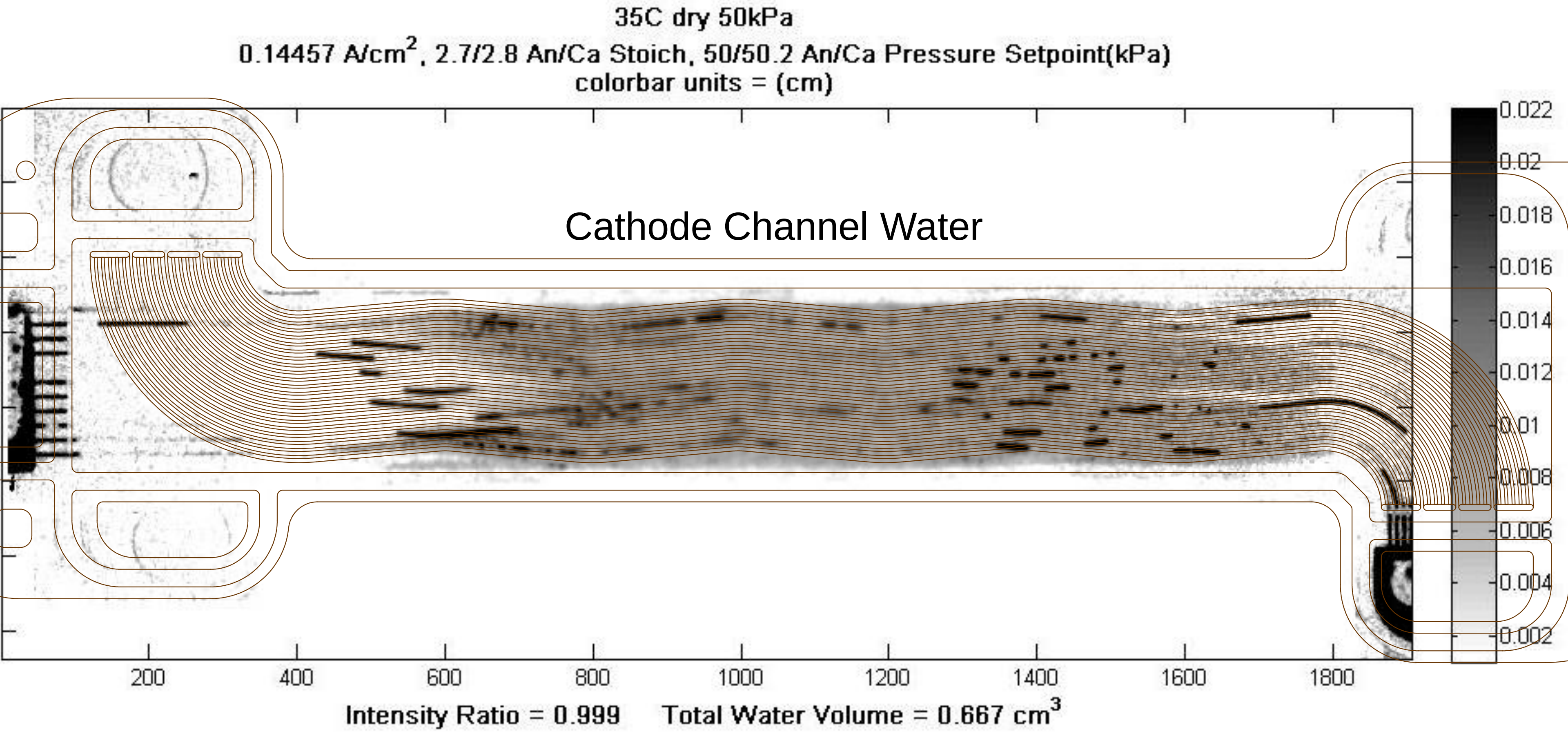
2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

C. Anode Channel Overlay of "Worst Case" Condition



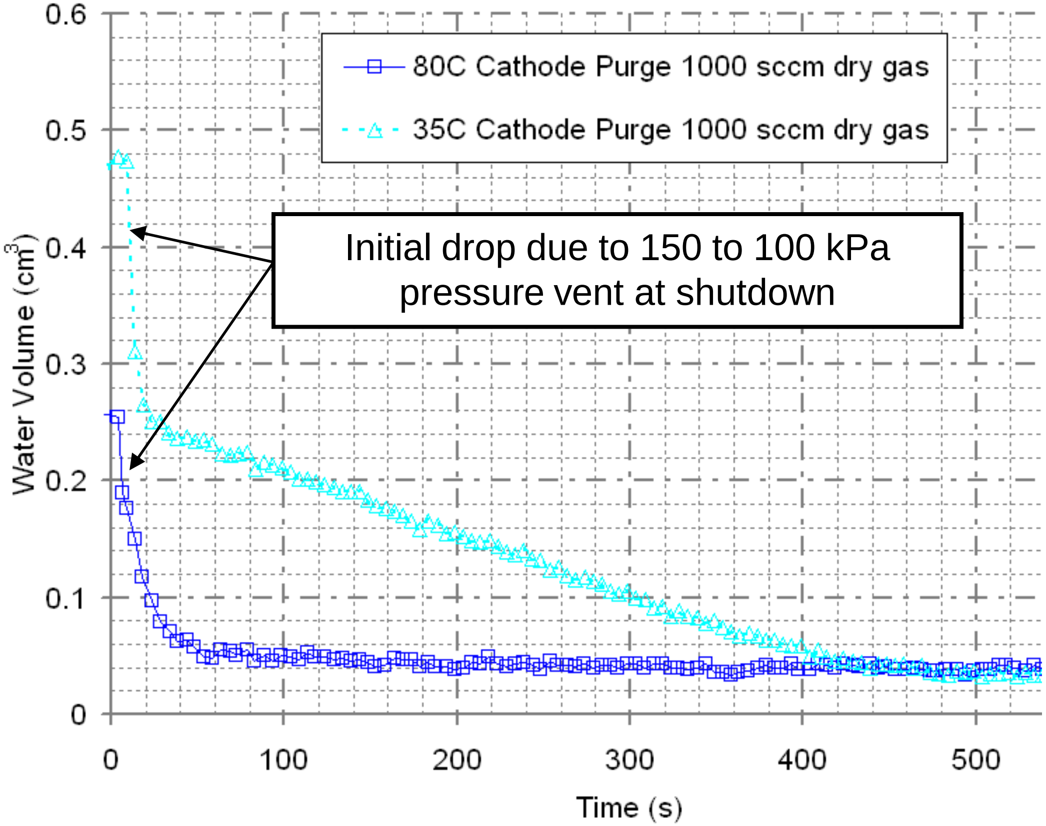
2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

D. Cathode Channel Overlay of "Worst Case" Condition

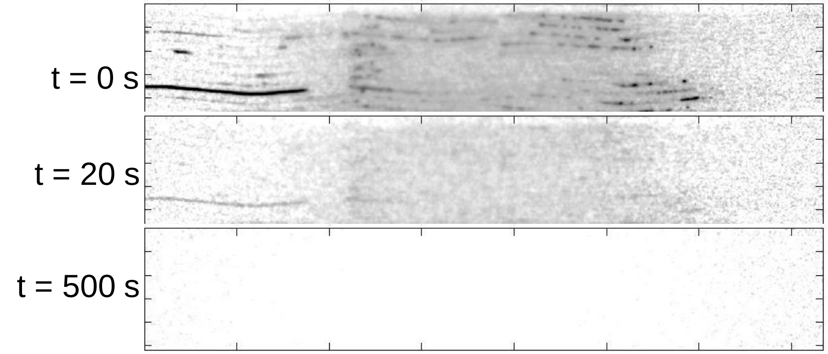


2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

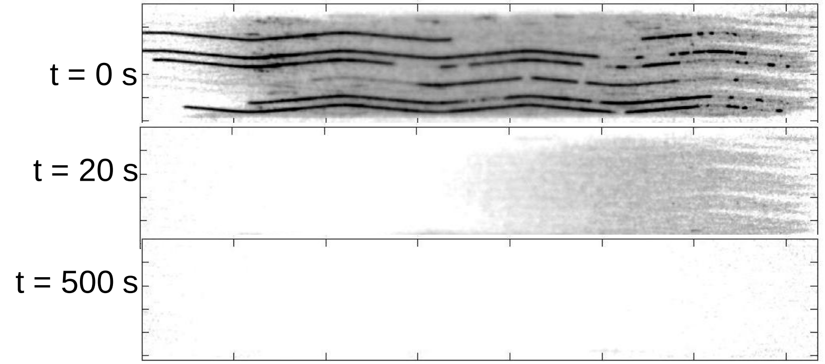
E. Determination of water transfer rates at anode GDL / MEA / cathode GDL from purge at various temperatures



80 °C Cathode Purge (1000 sccm dry N_2)

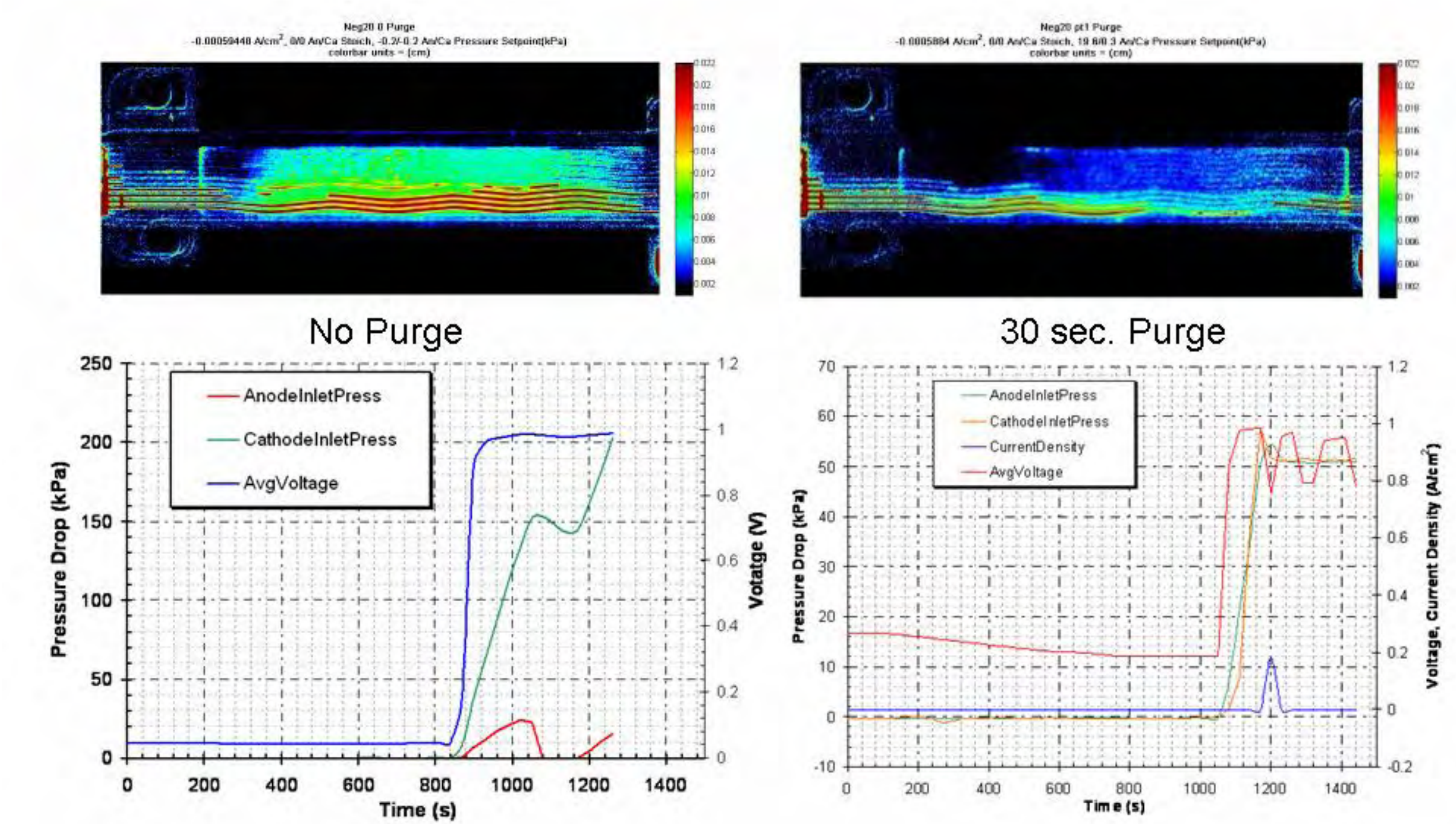


35 °C Cathode Purge (1000 sccm dry N_2)



2.3 Baseline Freeze-Thaw Experiments with Neutron Radiography

F. Start-up Response, with and without Purge



Applying a 30 second purge reduces the cathode pressure drop at start-up from ~200 to 50 kPa

Future Work

FY08

- Complete the baseline system characterization (ex-situ, in-situ and freeze-thaw experiments)
- Establish the full baseline Performance Matrix
- Determine the most effective GDL properties (wettability, structure and morphology) and the effective channel surface treatment to avoid flooding
- Microscopic study and models for water transport in GDL and parallel channels
- Implement changes and evaluate GDL/channel combinations on ex-situ apparatus (Decision Point #1)

FY09

- Evaluate the improved GDL and channel properties with combinatorial in-situ multi-channel and freeze-thaw experiments (Decision Point #2)
- Map and quantify liquid water transport in the GDL and the channels in real time under normal and freezing conditions with spatially resolved neutron radiography and current distribution measurements (Decision Point #3)
- Implement and test the variations in material properties over the active area

The following decision points will be addressed in the course of the project. In-situ testing is in progress and additional freeze-thaw experiments and model development are progressing well at this time.

- **Decision Point #1: Is ex-situ combinatorial performance improved over baseline?**
- **Decision Point #2: Is in-situ combinatorial performance improved over baseline?**
- **Decision Point #3: Is water distribution acceptable for overall fuel cell operation and freeze-thaw performance?**

Summary — Baseline Performance Matrix

	Parameters	Baseline performance
Ex-situ multi-channel experiments	Total pressure drop (ΔP)	▪ Total ΔP in the range of 0-20 kPa ▪ ΔP fluctuations of ca. 0.05 kPa due to the presence of water droplets and slugs
	Slug residence time	▪ Slugs reside in the channel over ~10 seconds may adversely affect the performance. ▪ Slug residence time is a strong function of air flow rate, but not water flow rate
	Flow map	▪ Three basic flow patterns (slug, film and mist flow) identified and flow pattern maps developed.
GDL component studies	Contact angle	▪ θs > 160 ; Δθ < 10 (new, uncompressed); ▪ θ(T), θ(H_2) not yet completed ▪ (contact angle greater than 125 seen as beneficial from water management standpoint)
	Capillary number	▪ Maximize Ca ▪ Large disorder parameter ▪ Stable in-plane displacement.
Channel component studies	Pressure drop	▪ Strong function of θ
	Range of pressure excursions	▪ Strong function of θ and cross section ▪ high speed gas flow generates shock-like events
	Liquid phase morphology	▪ Separated flow observed for specific θ/geometry ▪ Strong capillary-driven corner flow

Summary — Baseline Performance Matrix

	Parameters	Baseline performance
Freeze-thaw experiment with Neutron Radiography	Water accumulation locations	▪ Anode and cathode channels, within GDL over the entire active area, channel-to-exit header transitions
	Purge to dry individual water accumulation area	▪ Water volume from neutron images combined with high-frequency resistance data. For a 1000 sccm cathode purge, 100+ seconds at 80 ºC vs. 400+ seconds at 35 ºC required to thoroughly dry cell. Testing at other purge flows, T & RH in progress.
	Minimum cathode purge time for successful freeze start	▪ Testing in progress.
	Pressure drop / voltage response during freeze start	▪ Testing in progress.

Additional Results:

1. Quantified gas flow maldistribution in parallel channels as a random phenomenon. Variations of 70 to 130 percent from mean flow observed in individual channels.
2. Intrusion of GDL into flow channel of up to 30 percent observed.