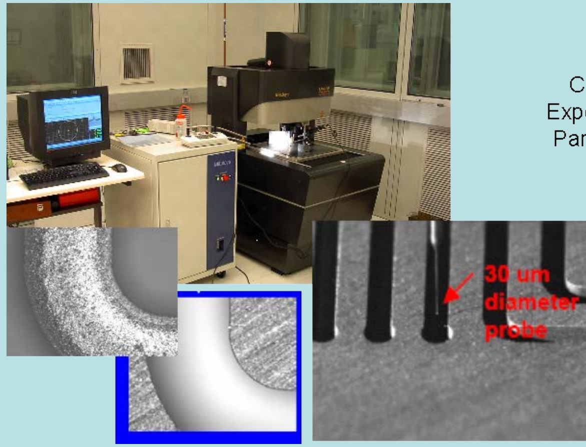
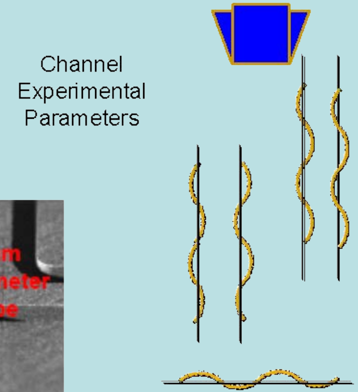
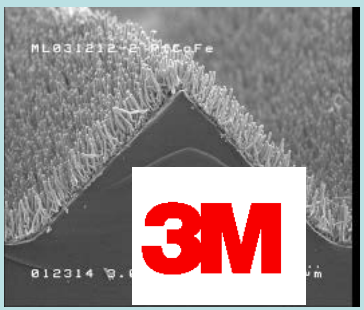
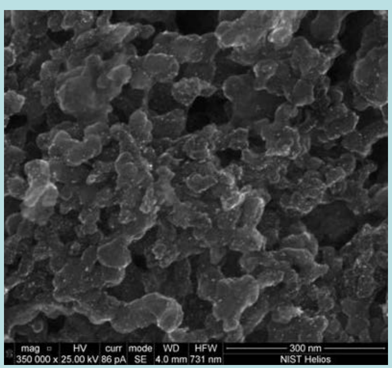




Cause and Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance



2012 DOE Hydrogen and Fuel Cells Program Review



Eric Stanfield (NIST)

Mike Stocker (NIST)

May 16, 2012

Project ID# MN011

Overview

Timeline

October 1, 2009
September 30, 2012
80% Completed

Barriers

B. Lack of High-Speed Bipolar Plate Manufacturing Processes
F. Low Levels of Quality Control and Inflexible Processes

Partners

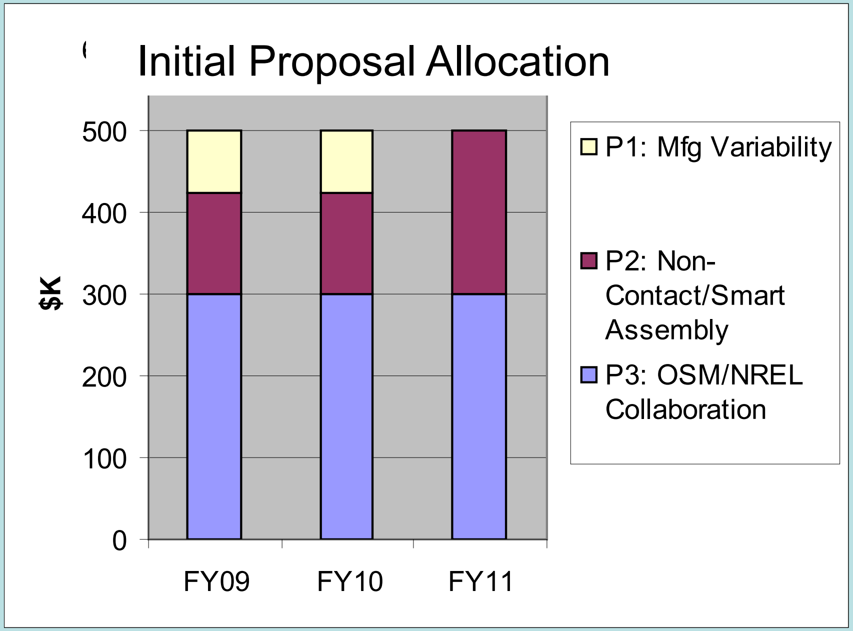
Subproject #1 Only: LANL – Tommy Rockward (Funded $75K)

Other Interactions & Collaborations addressed in each subproject section.

Overall Budget

Total Project Funding $1.5 M
Funding Received FY11 - $200 K
Funding for FY12 - $175 K [FY11 deferred]

[Cost share not required but NIST contribution to effort estimated at ~ 40% to 50% matching, Subproject P1 Manufacturing Variability Study – 100% NIST funding in FY11 & FY12]



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Subproject Overview

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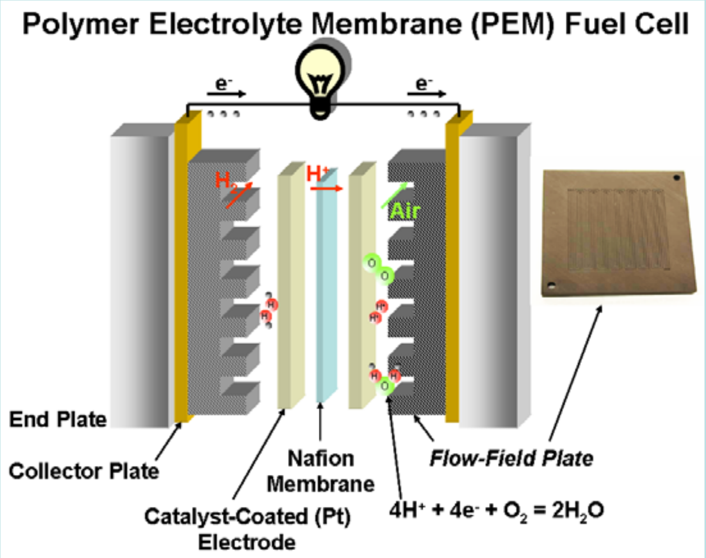
P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Objective: Develop a pre-competitive knowledge base of engineering data relating performance variation to manufacturing process dimensional variability.

Approach: Using a statistically based design-of-experiments, fabricate experimental "cathode" side flow field plates with various well defined combinations of flow field channel dimensional variations; then through single cell fuel cell performance testing using a robust protocol, quantify the performance affects, if any, and correlate these results into required dimensional fabrication tolerance levels.

Benefits (Relevance): Provide bipolar plate manufacturers and designers/modelers with the data necessary to make informed tolerance decisions to enable reduction of fabrication costs.



NIST

- Dimensional Metrology
- Manufacturing Metrology
- Statistical Engineering

LANL

- Operational Knowledge
- Advanced Testing Facilities

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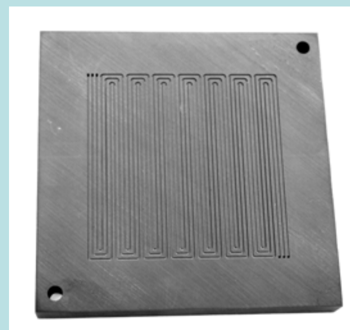
Overview

Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Cell Specifications

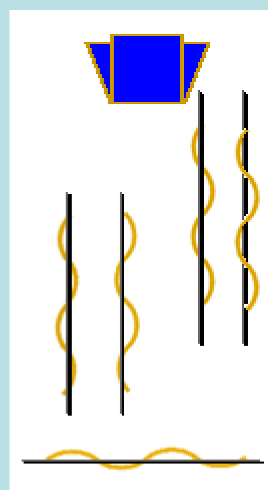
- 50 cm^2 Hardware (Teledyne CH-50)
- Gas Diffusion Media: SGL 25 BC
- Commercially Available CCM 0.1 / 0.2 mg/cm^2…Anode and Cathode
- Hydrogen Electrolysis-Grade) and Air (oiless-compressor)
- NIST Fabricated Reference Anode Plate and [10] Cathode Experimental Plates (POCO AXF-5QCF), Triple Channel Serpentine Design



Experimental Parameters and Level of Variability

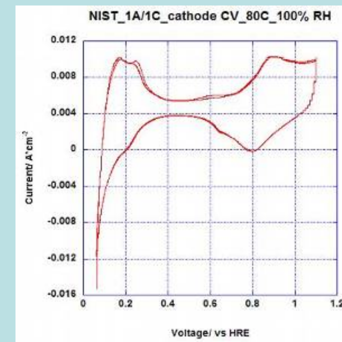
Fractional Factorial Design of Experiments 2 $^{(4-1)}$

- Sidewall Taper 0º to 10º
- Bottom Straightness 0 to 50 um
- Sidewall Straightness 0 to 50 um
- Variation-in-Width 0 to 100 um



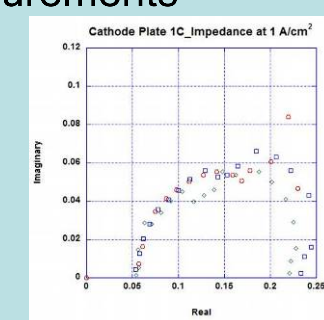
Beginning-of-Test (BOT) and End-of-Test (EOT) Diagnostics – MEA Q.C.

- Electrochemical H_2 Crossover
- Cathode Side Active Area Measurements



Performance Testing (Gas Access and H_2O Mgmt Impacts)

- Polarization curves in air measured in both directions
- AC-Impedance measurements



Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Overview - Initial Protocol

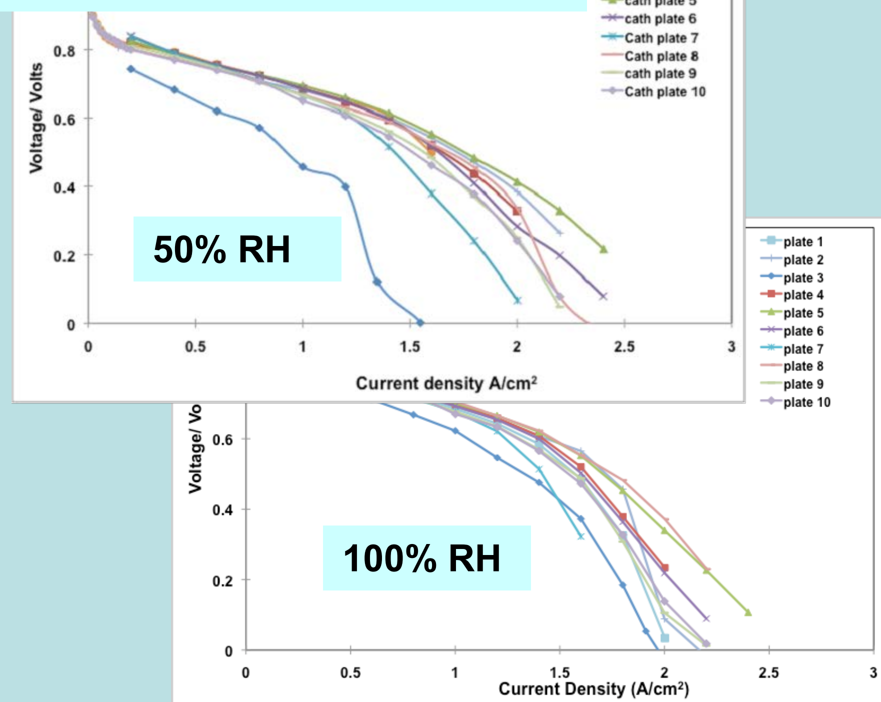
- Conditions 80ºC and 60ºC, 50% and 100% RH
- Data collected in constant current mode with 2 minute settling times
- Utilization Rates 83.3% H_2 and 71% Air
- CCM Usage:
  - Replaced between testing of each plate
  - Replacement from same batch and repeatability previously tested (< 5 mV)
- 25 psig back-pressure on both anode and cathode outlet sides

Technical Accomplishments and Progress

Initial Protocol Results (All Plates)

- **Status:**
  - LANL polarization data [Presented 2010]
  - NIST initial factor sensitivity statistical analysis [Ongoing 2012]
- **Take Away**
  - Factors and levels do have a noticeable impact
  - Reviewers in 2010 raised concerns about appropriateness of 25 psig back pressure
  - Incorporated an additional experiment with subset of plates for back pressure sensitivity testing [10 psig and ambient]

Initial VI curves for all plates @ 80ºC & 25 psig back pressure



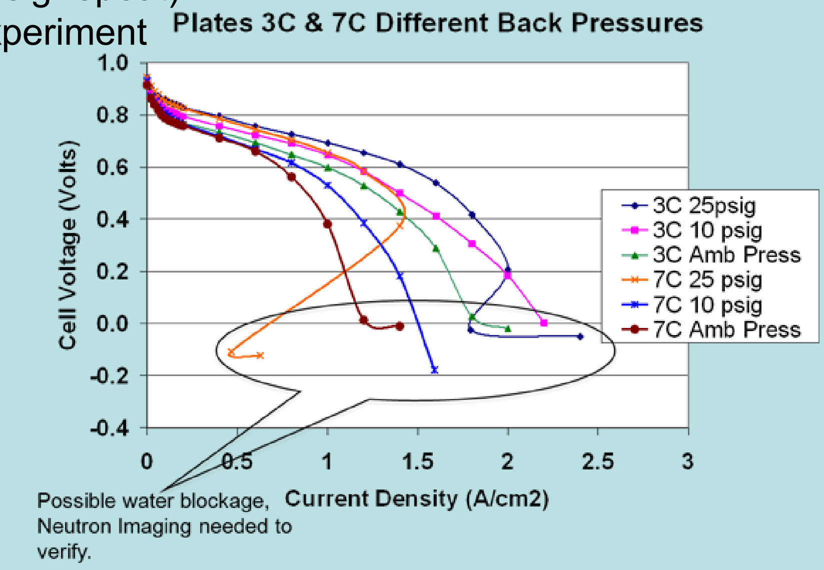
P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance
Technical Accomplishments and Progress

Revised Protocol [Back Pressure Sensitivity Experiment]

Experiment involved worst performers 3C & 7C along with best performer 5C tested at 10 psig and ambient back pressures (anode and cathode)

Status:

- 3C & 7C tested, 5C broke during cell assembly (Presented 2011)
- 5C replacement
  - Plate material changed from POCO AXF-5QCF to AXF-5Q (for neutron imaging purposes)
  - Fabrication capability re-established (10/2011)
  - 5C fabrication completed (1/2012)
  - Dimensional verification (3/2012)
  - Pyrosealing by POCO (TBD) (additional sealing process due to material change)
  - Polarization curves by LANL (TBD)
    - Result correlation between materials (25 psig repeat)
    - Completion of back pressure sensitivity experiment



Take Away:

- Overall performance of each plate decreased along with back pressure [anticipated]
- Performance differences between plates remained, tracking nicely between back pressures
  - 5C testing not expected to change this conclusion

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance
Technical Accomplishments and Progress

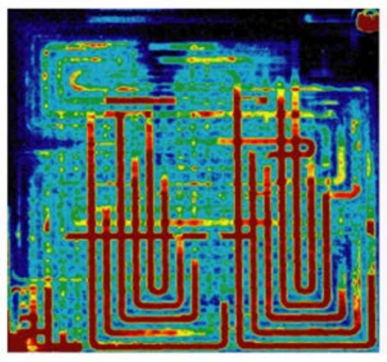
Neutron Imaging Experiment

Additional experiment based on questions raised at FreedomCAR Technical Team Presentation (3/2011)

Experiment planned using subset of plates representing best and worst performers along with the nominal design plate (rectangular cross-section with minimal dimensional variations) [1A, 1C, 3C, 5C, 8C]

Integrated 5C replacement with this activity to achieve two objectives

1. Repeat testing at 25 psig back pressure will serve to correlate any new results with previous results – eliminating material/material processing variable
2. Use replacement 5C, complete back pressure sensitivity experiment and this plate will be used in the neutron imaging experiment



Neutron Image Example Only

Status:

- Proposal for beam time experiment submitted (10/2011)
- Proposal approved (1/2012)
    - With positive reviewer comments
- NIST NCNR Imaging (NIST & LANL 7/2012 – Tentative)
- Modifications required for imaging (in-process)
    - Aluminum endplates to replace original stainless steel (12/2011)
    - Replicate plates for experiment must be made from POCO AXF-5Q rather than original AXF-5QCF due to hydrocarbon content of cured floran sealing material (fabrication, dimensional verification, and sealing – in process)

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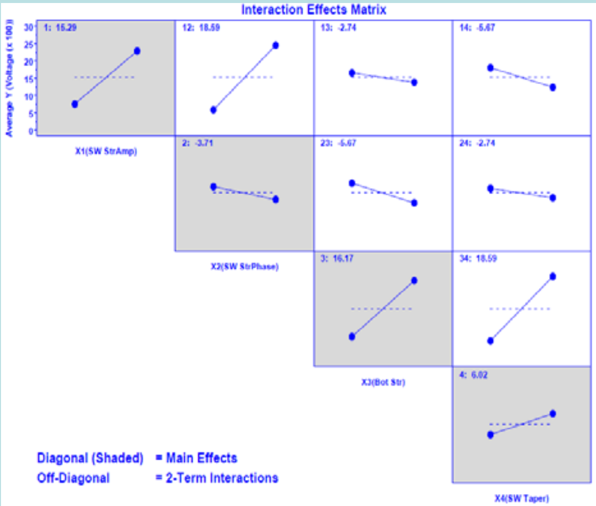
P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Technical Accomplishments and Progress

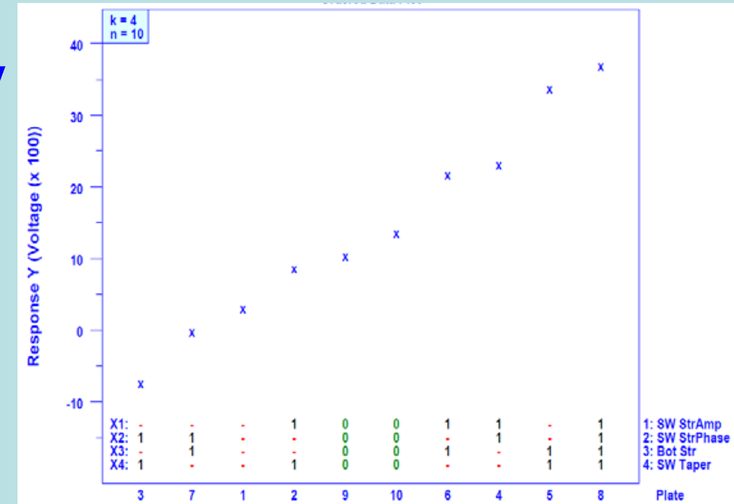


Initial Statistical Analysis of Results Factor Sensitivity

[100% RH, 25 psig back-pressure ,all plates, data extracted at 2 A/cm²,]

Ranked Order

Factor	Effect (V*100)	Rel. Eff %	Fcdf Stat %	
12 + 34	18.59			*
3	16.17	106	82.4	**
1	15.28	101	79.4	**
4	6.02	40	36.1	
14 + 23	-5.67			
2	-3.71	24	22.6	
13 + 24	-2.74			



- Interaction 12 or 34 or some combination of 1234 is most important
  [1 = sidewall straightness and 2 = phase of the sidewall straightness of one side in relation to the other (width variation and wiggle OR just wiggle)]
  [3 = bottom straightness (variation in depth) and 4 = sidewall taper]
- Factor 3 = bottom straightness (variation in depth)
- Factor 1 = sidewall straightness

** Inconclusive: A potential result of a fractional factorial experiment is that some two factor interactions can be “confounded”*
*** One negative aspect: although the relative importance of these three parameters is strongly suggestive the Fcdf statistic does not meet the criteria of being statistically significant > 95%.*

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Conclusions

- From VI data for both 50% RH and 100%RH, without statistics:
  - 5C and 8C best performers
  - 3C and 7C worst performers
  - 1C nominal rectangular cross-section made with exacting geometric precision NOT among the top performers.

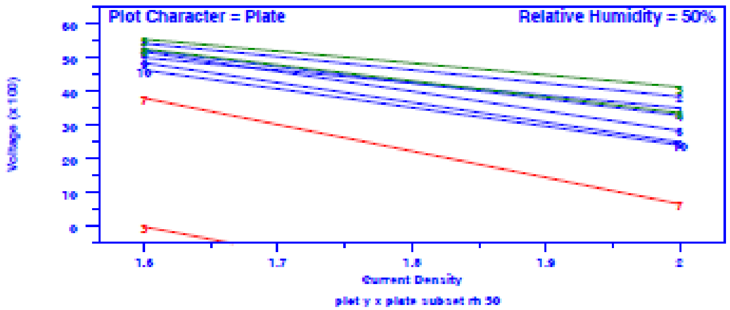


Plate	SW Am	SW Ph	Bo St	SW Ta
5	-	-	+	+
2	+	-	-	+
1	-	-	-	-
8	+	+	+	+
4	+	+	-	-
6	+	-	+	-
9	0	0	0	0
10	0	0	0	0
7	-	+	+	-
3	-	+	-	+

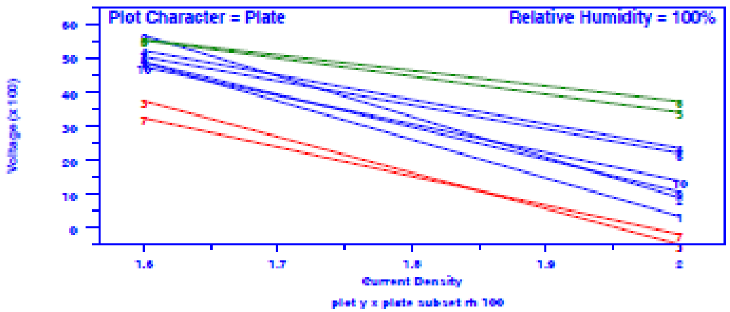


Plate	SW Am	SW Ph	Bo St	SW Ta
8	+	+	+	+
5	-	-	+	+
4	+	+	-	-
6	+	-	+	-
10	0	0	0	0
9	0	0	0	0
2	+	-	-	+
1	-	-	-	-
7	-	+	+	-
3	-	+	-	+

- Varying back pressure doesn't change performance differences between plates.

- Controlled dimensional "chaos" or very controlled complex geometry (whichever is your preference) seems to be more beneficial than simple straight geometric shaped channels made with dimensional perfection.

- Neutron imaging will hopefully produce insight with regards to how the water moves in the different cell configurations.

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Conclusions

- Employed statistical analysis in an attempt to uncover what factors and two-factor interactions were most important.
  - Results of the statistical analysis are preliminary only, further review of the data is needed prior to making definitive conclusions with regards to factor sensitivity, beyond the obvious.
  - Due to the "fractional" factorial nature of the design of experiments the two factor interactions identified by this analysis come in pairs and are "confounded"; meaning that you don't necessarily know without physics based interpretation which of the two interactions is most important.
  - Initial results using voltage data from each curve at 2 A/cm^2 from the 100% RH dataset we obtain a "strongly suggestive" but not "statistically significant" ranked order.
  - Initial results using voltage data from each curve at 2 A/cm^2 from the 50% RH yields a different ranked order, again suggestive but not statistically significant.
  - Common to both data set analyses is the significant importance of factor 1 (sidewall straightness)
  - Data needs to be investigated further at different current densities to evaluate consistency.
  - Analyses raises questions
    - Should the results from both datasets be consistent or different?
    - Is strongly suggestive versus statistically significant enough to make some conclusions?
  - Physics based insight is needed and an expert in the field of micro-fluidics and two-phase flow in fuel cells is currently reviewing the data.

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Future Work

- Integrate physics based expertise
- Investigate statistical analysis further to understand potential inconsistencies
- Scrutinize data sets to ensure completeness
- Complete back-pressure sensitivity experiment with 5C testing
- Complete all fabrication and verification work in support of neutron imagining experiment
- Complete neutron imaging experiment
- Integrate what imagining reveals to better understand effects.
- Publish results by end of 2012

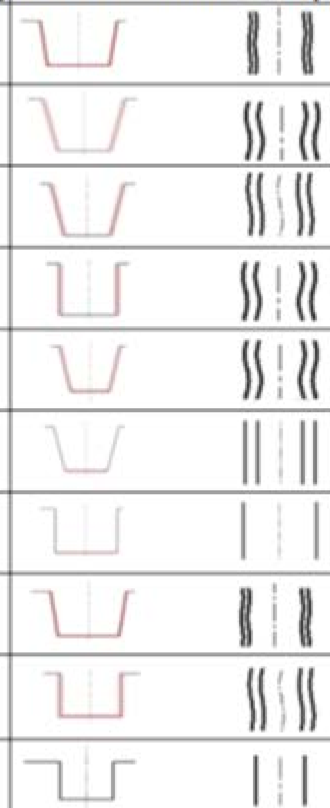
Technical Backup Slides

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance

Technical Accomplishments and Progress

Design of Experiment Full Factorial 2 $^{4-1}$ (4 dimensional parameters, 2 levels each with center replica point)

	2^{4-1} Fractional Factorial Design with replicated center point (k=4,n=10)								
	Sidewall Straightness	Sidewall Straightness	Bottom Straightness	Sidewall Taper					
	Amplitude	Phase	Amplitude			Sequence		Drawing	
Part	*X1*	*X2*	*X3*	*X4*	*Machining*	*Measuring*	*Perf. Testing*	*Cross-Section*	*Top*
9	0(25µm)	0(90)	0(25µm)	0(5)	1	1	1		
3	-1(0)	+1(180)	-1(0)	+1(10)	2	2	2		
2	+1(50µm)	-1(0)	-1(0)	+1(10)	3	3	3		
4	+1(50µm)	+1(180)	-1(0)	-1(0)	4	4	4		
8	+1(50µm)	+1(180)	+1(50µm)	+1(10)	5	5	5		
5	-1(0)	-1(0)	+1(50µm)	+1(10)	6	6	6		
7	-1(0)	+1(180)	+1(50µm)	-1(0)	7	7	7		
10	0(25µm)	0(90)	0(25µm)	0(5)	8	8	8		
6	+1(50µm)	-1(0)	+1(50µm)	-1(0)	9	9	9		
1	-1(0)	-1(0)	-1(0)	-1(0)	10	10	10		



Deliverables 3rd Quarter FY2009 – End of FY2011

P1 Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance