

PENNSSTATE



# Neutron imaging at Penn State: Past, Present and Future

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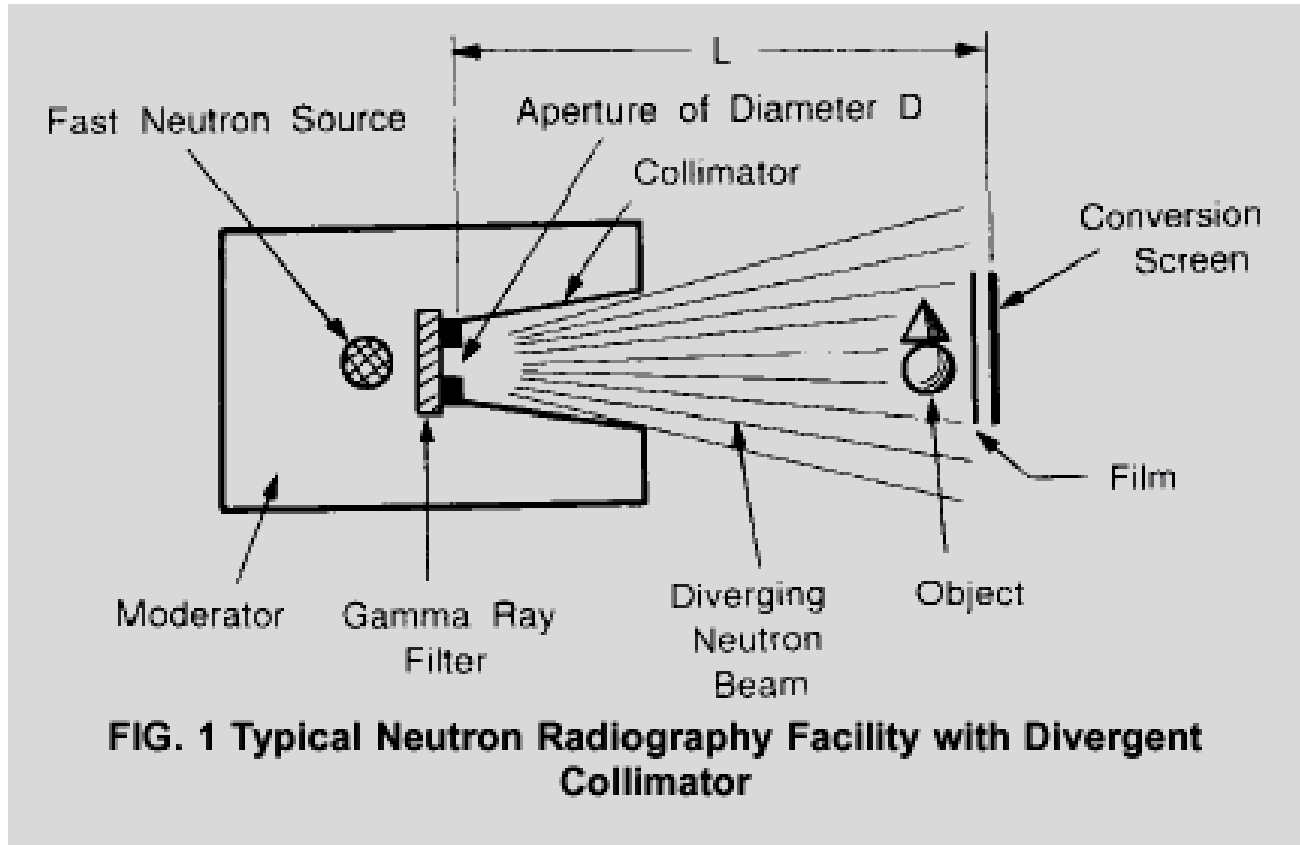


# Outline

- Brief Introduction to Neutron Imaging
- History of Neutron Imaging
- Current Experimental NR Facilities
- Example of Recent Activity: Fuel Cell
- Future Plans
- Conclusions



# Typical NR Equipment



From ASTM E-748



# Different Neutron Imaging Techniques

- Use higher or lower energy neutrons
  - cold, epithermal, fast neutrons
- Use activatable detector
  - make autoradiograph of activated detector
- Use an imaging plate detector
- Use a track etch film
- Rotate object to make neutron tomographs
- Use scattered neutrons to create image



# NR Applications

- Most NR uses fall into one of the following categories
  - Qualitative Examinations
  - Relative Density Measurements
  - Quantitative Density Measurements
  - Three-dimensional Imaging



# Radioscopic Applications

- Fluid flow in internal cavities
- Diesel fuel injection patterns
- Two-phase counter flow in heat pipes
- Fluid dynamics of molten metals
- Li-Al extent in tubular aluminum
- Dynamic combustion product formation



# Neutron Imaging at Penn State

- Imaging with neutrons started in the early 1970's
- Majority of work since 1984 has been radioscopy (real-time NR)
- Activity in NR diminished in early 1990's - now very active
- Flow visualization remains primary effort



# Important RSEC Upgrades

- **1965** conversion from MTR to TRIGA
  - Power upgrade from 200kW to 1000kW
  - Pulse capability up to 2000 MW
- **1970** extension of N-S rails
  - Core closer to beam ports
- **1971** thermal D<sub>2</sub>O column installed
  - Beam port flux  $\sim 10^{12}$  n/cm<sup>2</sup>-s
- **1980's** collimator, shielding and thermal column modifications





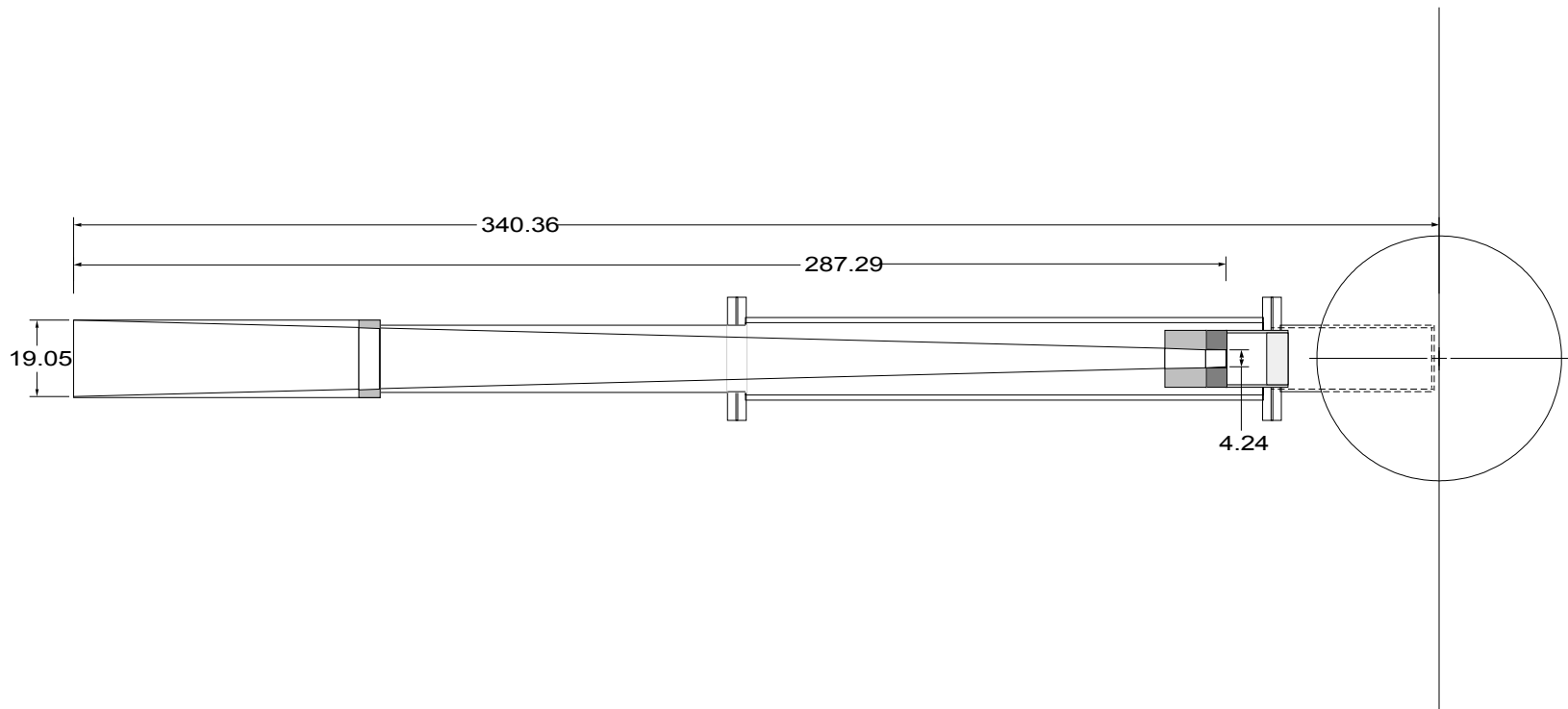
## Important RSEC Upgrades

- **1994** Reactor support structure modifications
  - Added rotational motion (360°)
  - Added lateral (east-west) movement
  - Permitted possibility of tangential NR beam
- **1997** D<sub>2</sub>O thermal column installed with NR beam nosepiece
- **1997** Simple collimator installed
  - NR beam now tangential to core
  - Improved n/γ ratio
  - Neutron flux  $2 \times 10^7$  n/cm<sup>2</sup>-s at 100 kW
  - Intensity overwhelmed existing shielding
- **1999** New shielding room installed



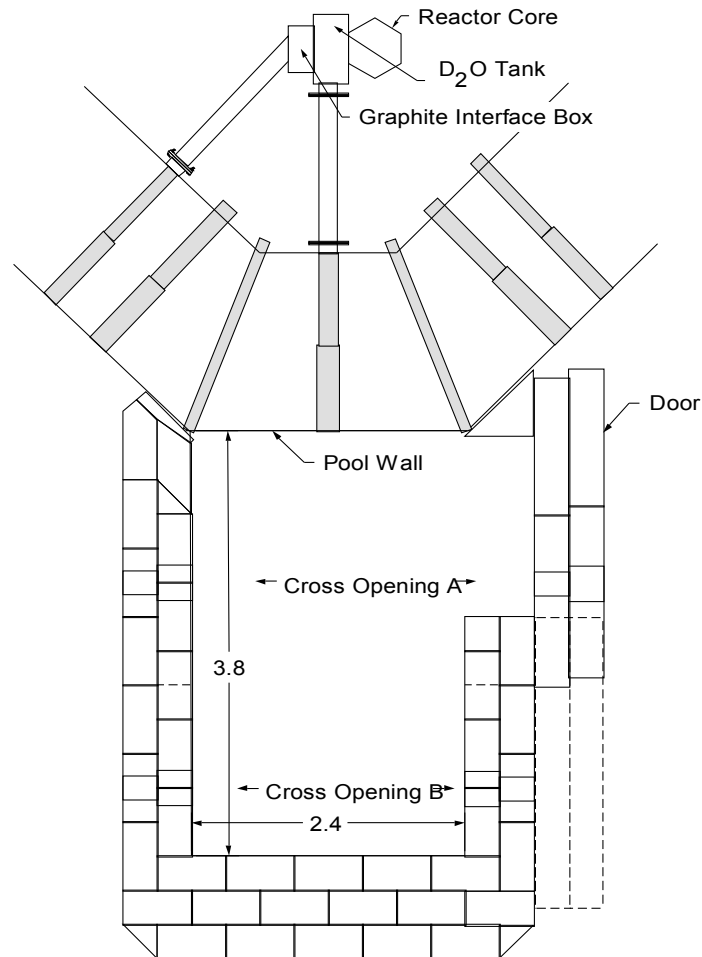
# Important RSEC Upgrades

- **1999** Replaced old collimator with “temporary” aperture/filter/collimator





# Current NR Facilities





# Current Facility

- 1999 collimator is satisfactory for now
- At first imaging position
  - Flux -  $2.8 \times 10^7$  n/cm<sup>2</sup>-s @ 1000kW
  - ASTM E 803 L/D ratio – 115
  - Cd ratio (Au Foils) - 5
- ASTM E 545 Category 1 facility
- L/D ratio of 155 in normal imaging position



# Neutron Imaging Research

- 1970's - **Jacobs, Kenney**
  - Dynamic Radiography Using Neutrons
  - The Use of Coded Aperture Techniques in the Formation of Images with Scattered Radiation
- 1980's - **Hughes, Levine, Cimbala, Sathianathan**
  - Use of Real-Time Neutron Radiography
  - Neutron Radiography as a Flow Visualization Tool
- 1990's - **Sathianathan, Cimbala, Brenizer**
  - Theoretical Predication for Imaging Shock Waves in Gases Using Neutron Radiography
  - Flat Panel Imaging of Thermal Neutrons
- 2000's - **Cimbala, Brenizer, Mench, Ünlü**
  - Comparison of Experiments and 1-D Steady-State Model of a Loop Heat Pipe
  - Neutron Imaging of Two-phase Transport in a Polymer Electrolyte Fuel Cell
  - The Nature of Flooding and Drying in Polymer Electrolyte Fuel Cells



## The Nature of Flooding and Drying in Polymer Electrolyte Fuel Cells

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\*\*General Motors - Fuel Cell Activities  
Honeoye Falls, NY

Third International Conference on Fuel Cell Science, Engineering, and Technology  
Ypsilanti, Michigan  
May 23-25, 2005

# Polymer Electrolyte Fuel Cell Basics

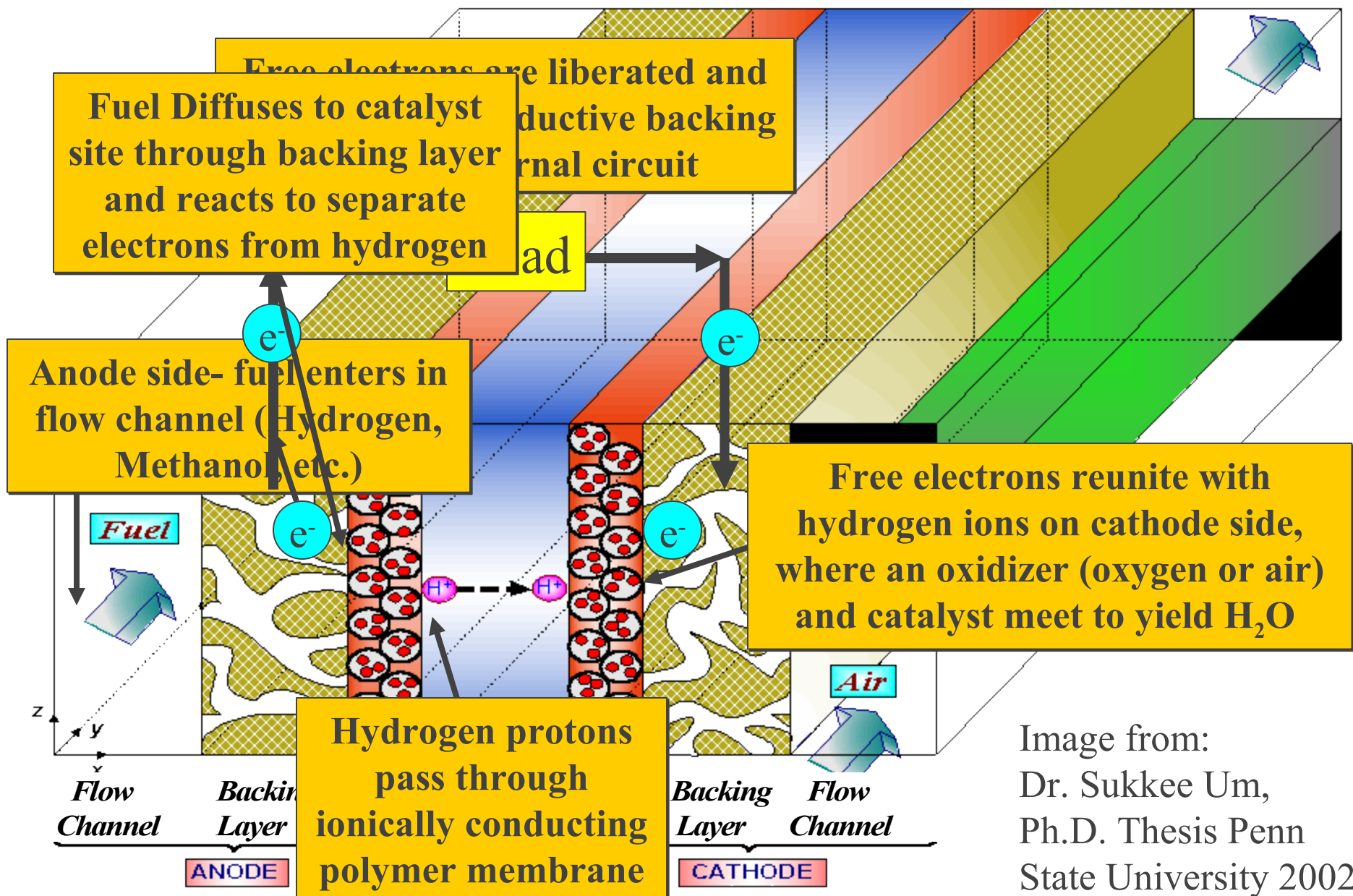
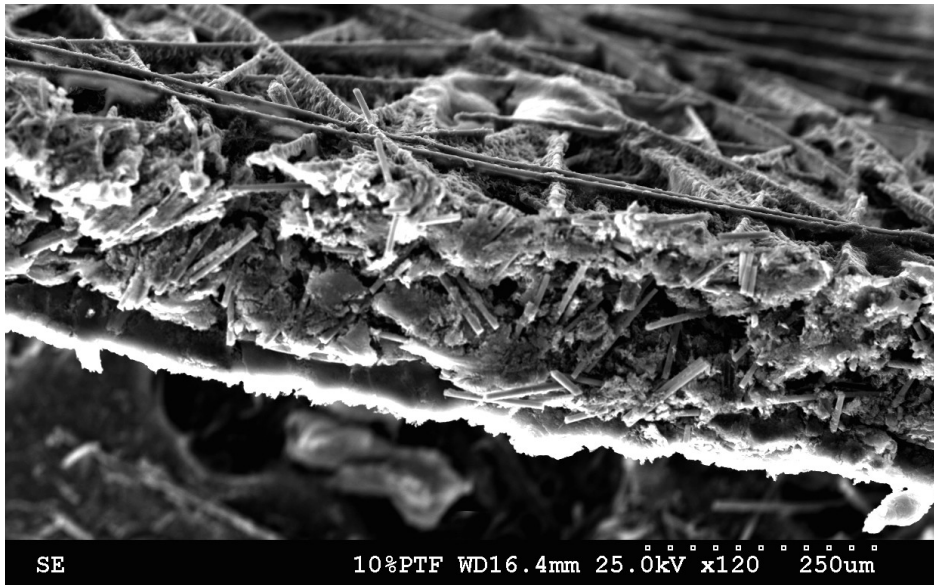


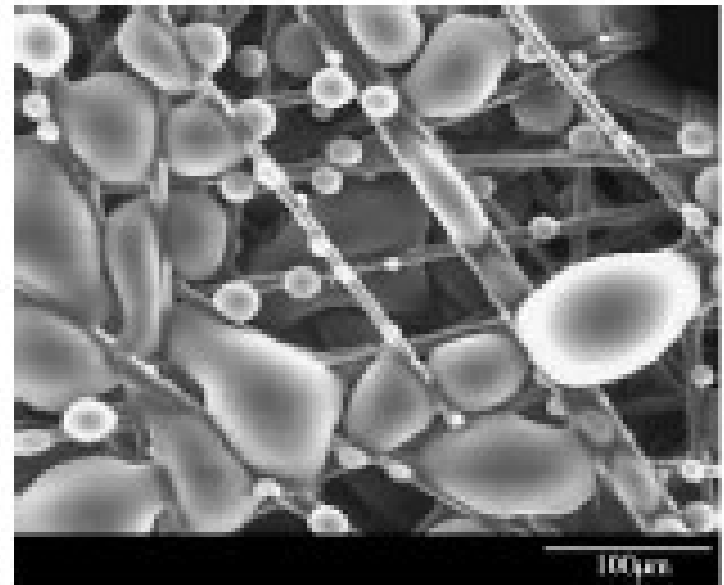
Image from:  
Dr. Sukkee Um,  
Ph.D. Thesis Penn  
State University 2002

# Moisture Control

- A key element in PEFC performance is keeping the electrolyte moist. Alternatively, the catalyst layer, gas diffusion layers, and gas channel must not be filled with liquid water, which will block gas-phase diffusion (“flooding”). Flooding causes poor performance and instabilities.
- *Channel level* and *gas diffusion layer* flooding are different phenomena.



Side-view of gas diffusion layer complex fibrous hydrophobic/hydrophilic Structure\*\*



Close-up of flooded gas diffusion layer\*

\*\*SEM by E.C. Kumbur of PSU FCDDL

\*Nam and Kaviani, *Int. J. Heat and Mass Transf.* 46, 2003.



# PSU Neutron Imaging Capability

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## Current Status

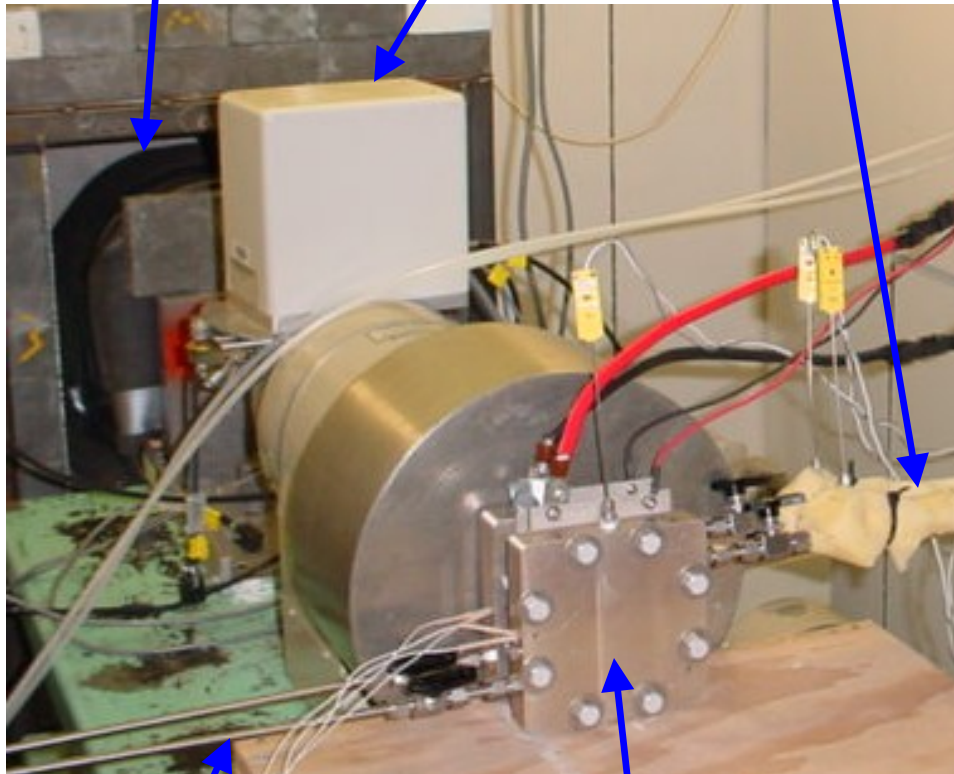
- Radioscopic (video) resolution at  $\sim 130\text{-}150\ \mu\text{m}$ , 30 fps
  - All digital imaging – no analog to digital conversion
  - CSF Thomson Intensifier with a CCD 1000 X 1000 X 10 bit
- Radiographic resolution at 30-60  $\mu\text{m}$ 
  - Resolution limited by geometric unsharpness
- DVD image data storage with movie capability *45 minutes at 30 frames/s*
- Customized software program to analyze data including water distribution,  $P(t)$ ,  $V(t)$ ,  $I(t)$ , etc.
- Tests recorded digitally; broken down by individual frames
- Quantification of water mass
  - In each frame
  - Selective area plots of water mass vs. time
  - False color map to water mass

# Fuel Cell Setup in Front of Neutron Camera

Neutron Beam Catcher

Image Camera

Insulated Gas  
Inlets Lines

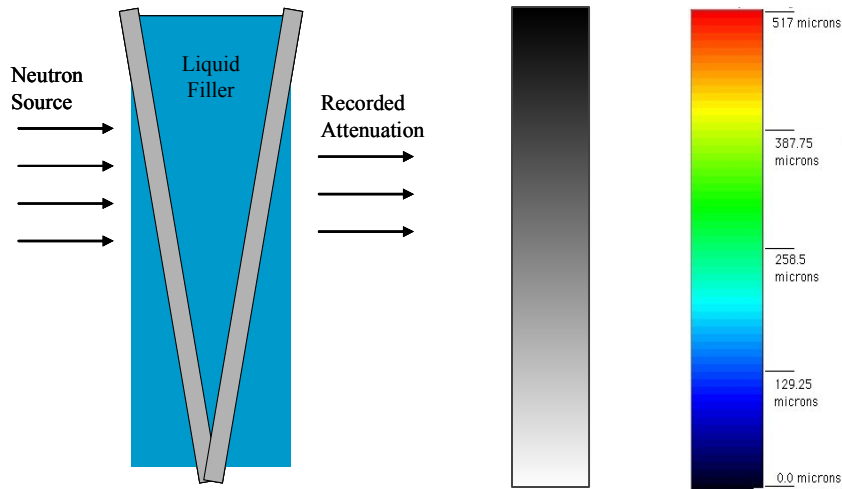


Gas Exits Lines

Fuel Cell

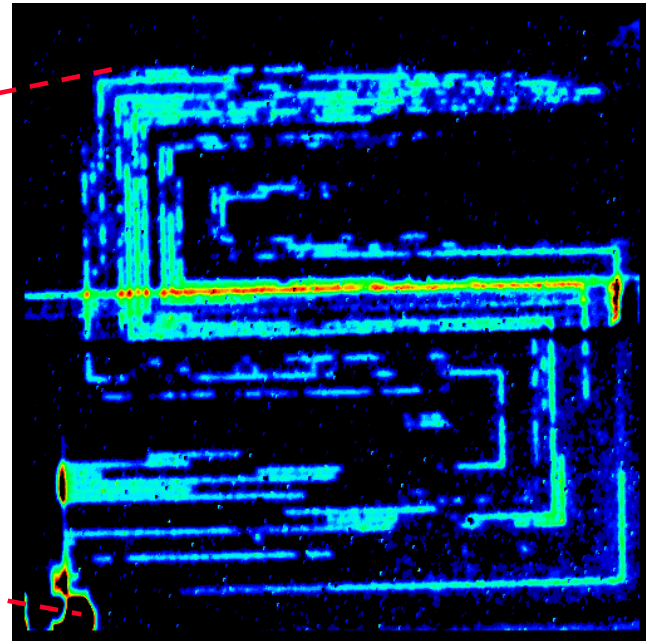
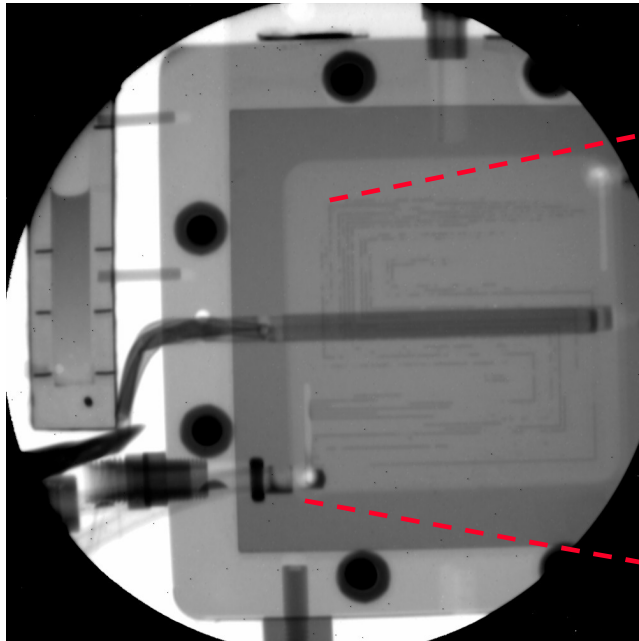
- Active in NR for fuel cells since 2002
- Breazeale Nuclear Reactor, PSU
- Reactor power: 1 GW
- Neutron Flux:  $3 \times 10^7$  neutron/cm<sup>2</sup>-sec
- PSU NR capability:
  - 30 fps at 130  $\mu$ m
  - Digital image
  - Continuous data storage for 40 mins

# Liquid Water Thickness Quantification

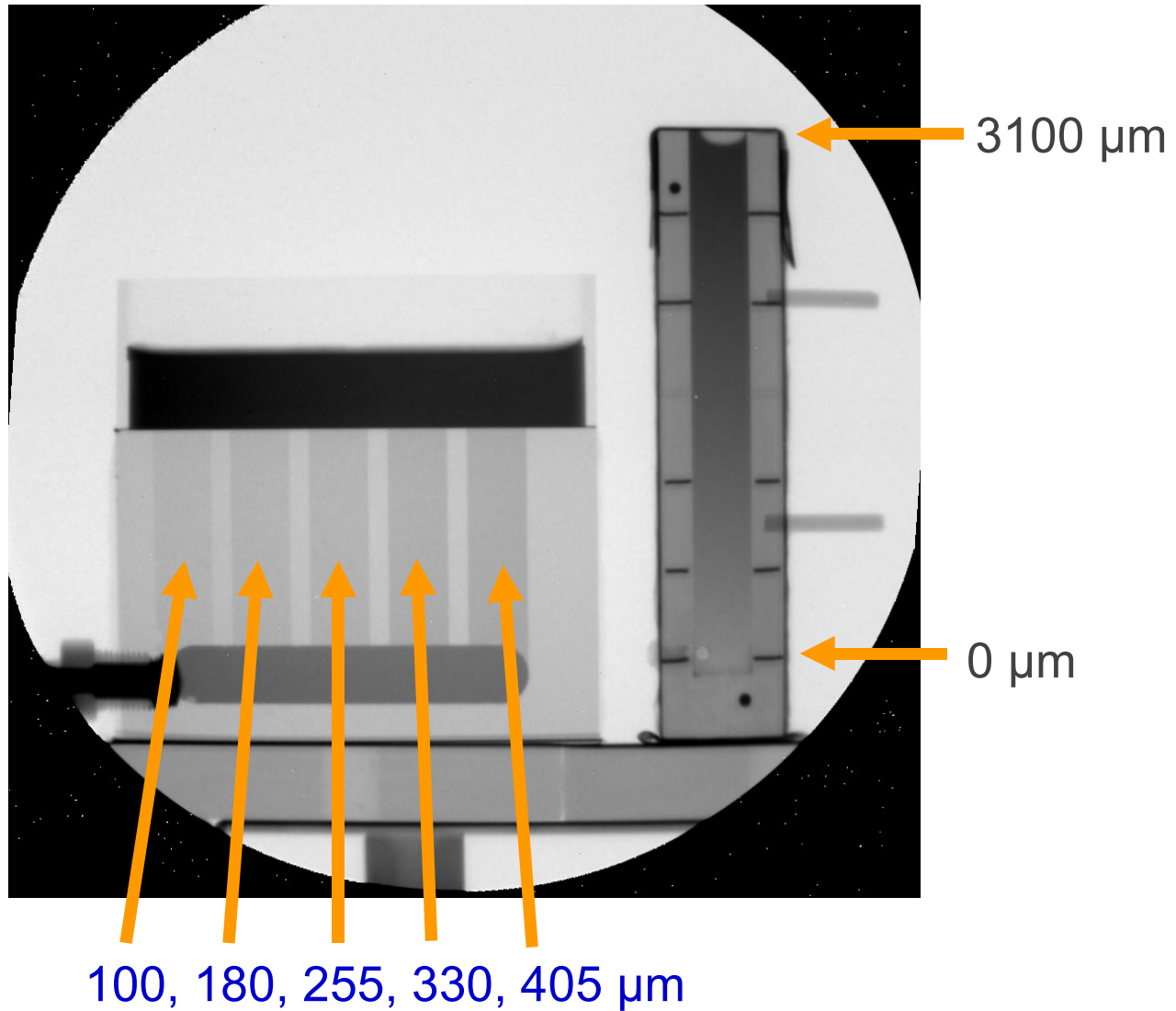


● *Visualization of liquid water down to 12.7  $\mu\text{m}$  thickness.*

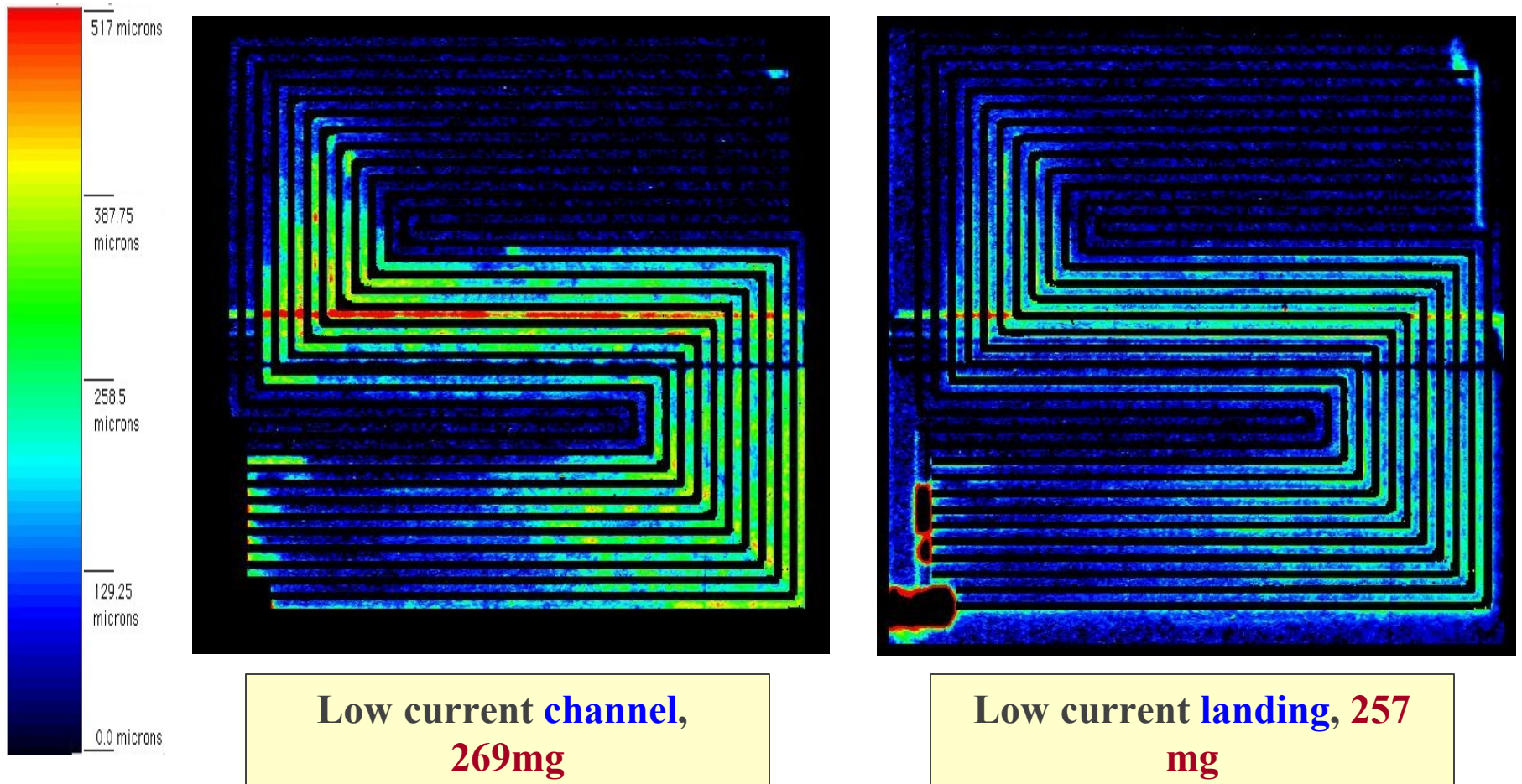
➤ *We can see liquid water, but not gas-phase water in vapor form*



# Water Calibration Verification

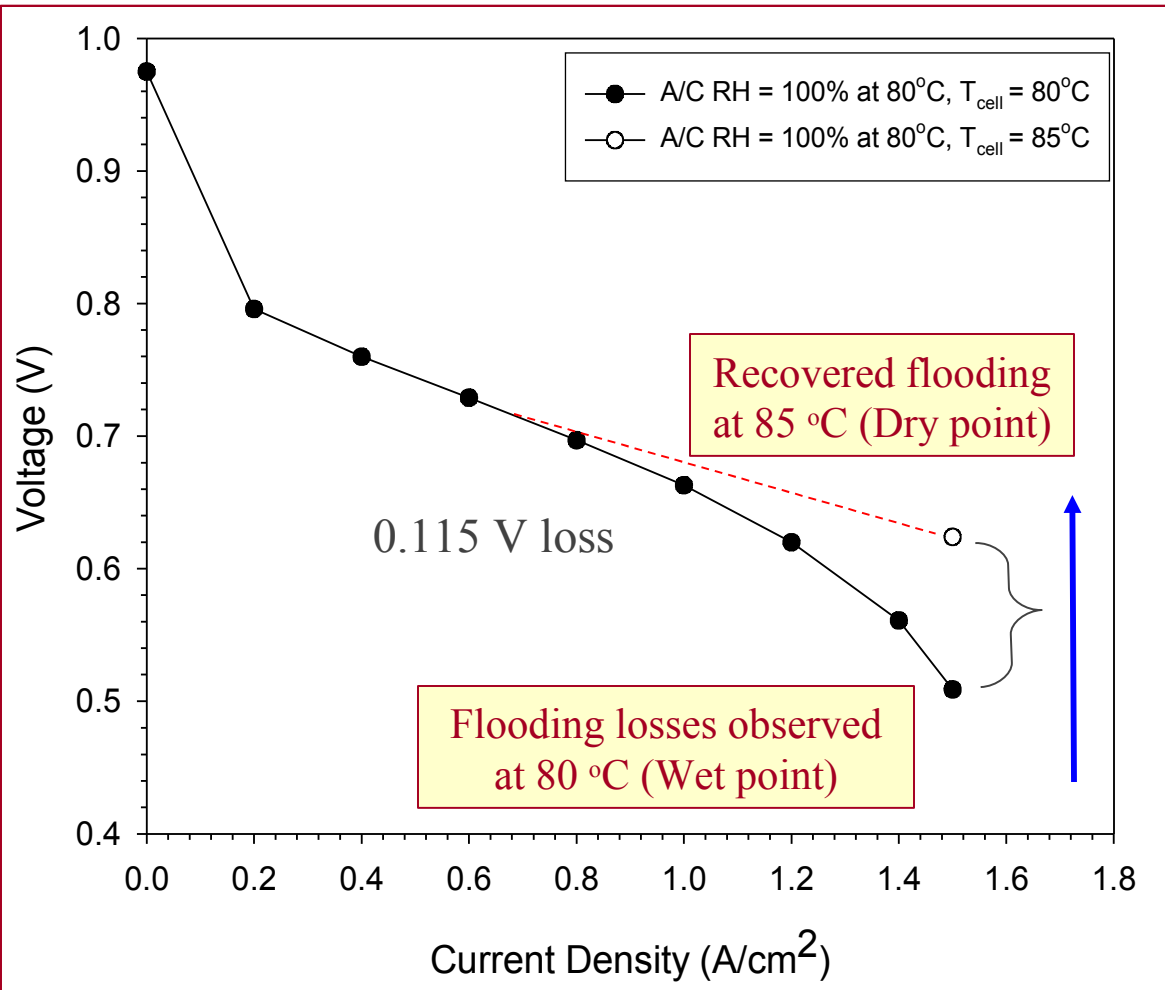


# Channel/Land Water Quantification



With a masking technique, liquid water under the landings and under the channels is calculated.

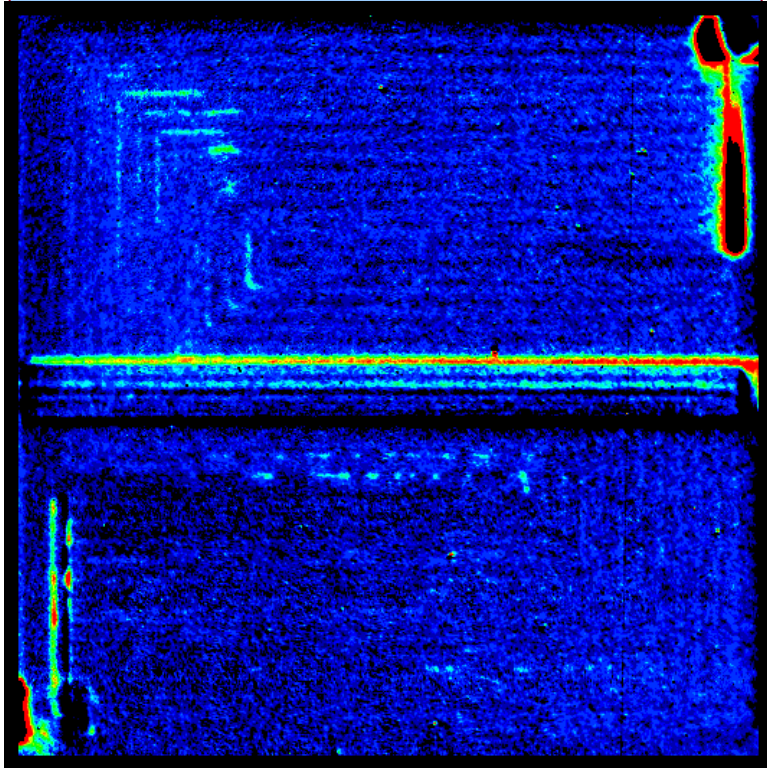
# Analysis of Flooding Threshold



- Different cell was operated at steady state where significant flooding was observed. Then, the cell control temperature was increased (all else the same) to 85 °C until **flooding is eliminated.**
- Images taken for flooded and non-flooded conditions

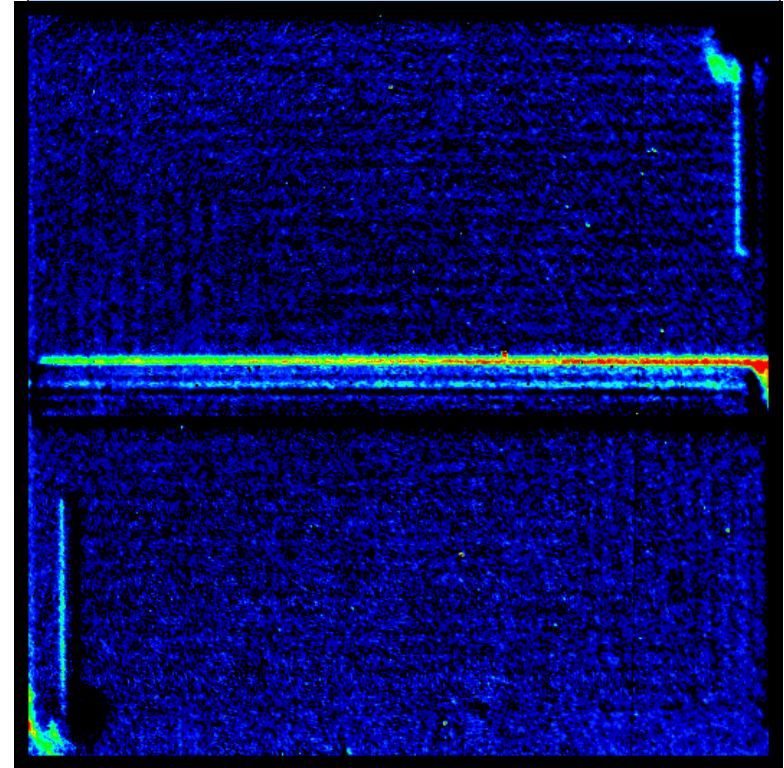
# Analysis of Flooding Threshold

80°C – flooded (Wet)



Voltage: 0.509V; Water = 381mg

85°C - non-flooded (Dry)



Voltage: 0.624V; Water = 206 mg

Difference

**1.5 mg/mV**

# Channel-Level Water Accumulation at High Power

- Water buildup at  $90^\circ$  turns in flow channels is common
- Accumulation caused by recirculation of flow at walls and corners, as well as surface wetting of flow channel. Low local performance can also cool the landing, inducing condensation on GDL surface.

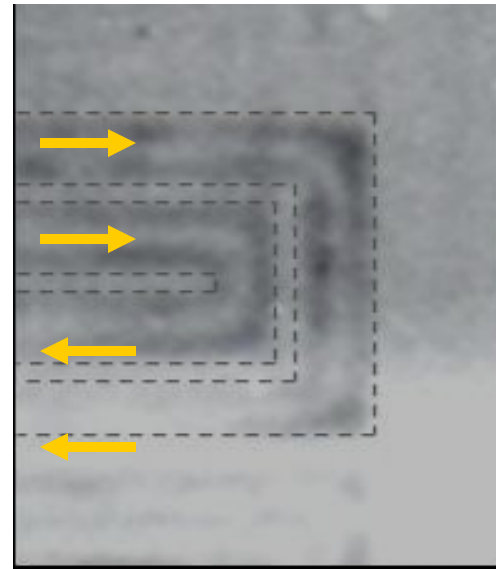
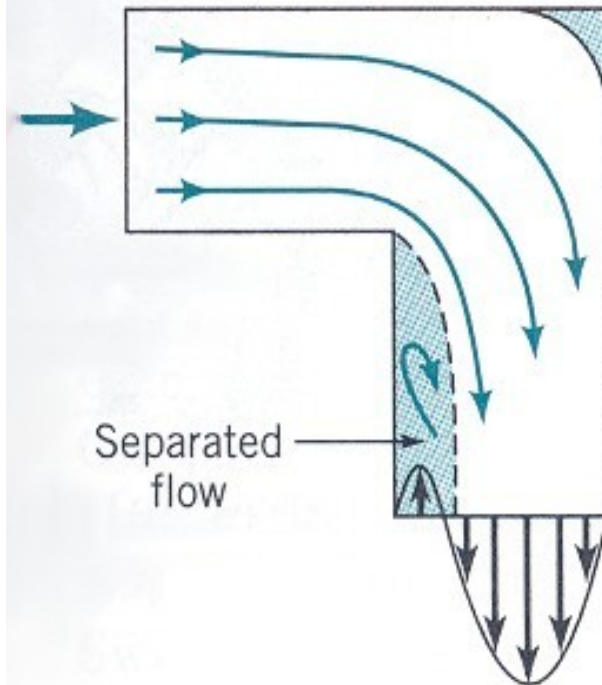


Image from:  
N. Pekula, M.S. Thesis  
Penn State University 2002



## Video at 5 fps (no frame averaging) Fuel Cell Anode Flush



In this video, anode flow is increased, flushing water from channels.

- Droplet velocity is not constant, due to surface tension and drag.
- Droplet shape changes continually throughout movement.
- Selected droplet movement: Anode flow rate at 0.4 m/s, single droplet observed with velocity range of 0.08 to 0.134 m/s, indicating *slug flow*.
- Homogeneous model is *not* appropriate for low power *channel-level* flooding.



# Status of Future Work

- Neutron computed tomography
- Cold source design
- New neutron beam port design and layout
- Neutron beam hall expansion
- Beam port installations
- Cold source and guide tube installation
  - Cold Neutron Prompt Gamma Activation Analysis
  - Neutron-Induced Fission Fragment Analysis
  - Neutron Reflectometer
  - Neutron Powder diffractometer
  - Cold neutron imaging



## Conclusions and Future Work

- RSEC has long history of neutron imaging
- NR facilities still undergoing major improvements
- Need to interleave improvements with ongoing research and service work
- Planned expansion will yield a first-class neutron imaging facility