National Research Council Canada
Institute for Fuel Cell Innovation

An Overview of Fuel Cell R&D at NRC Institute for Fuel Cell Innovation, Vancouver, BC, Canada

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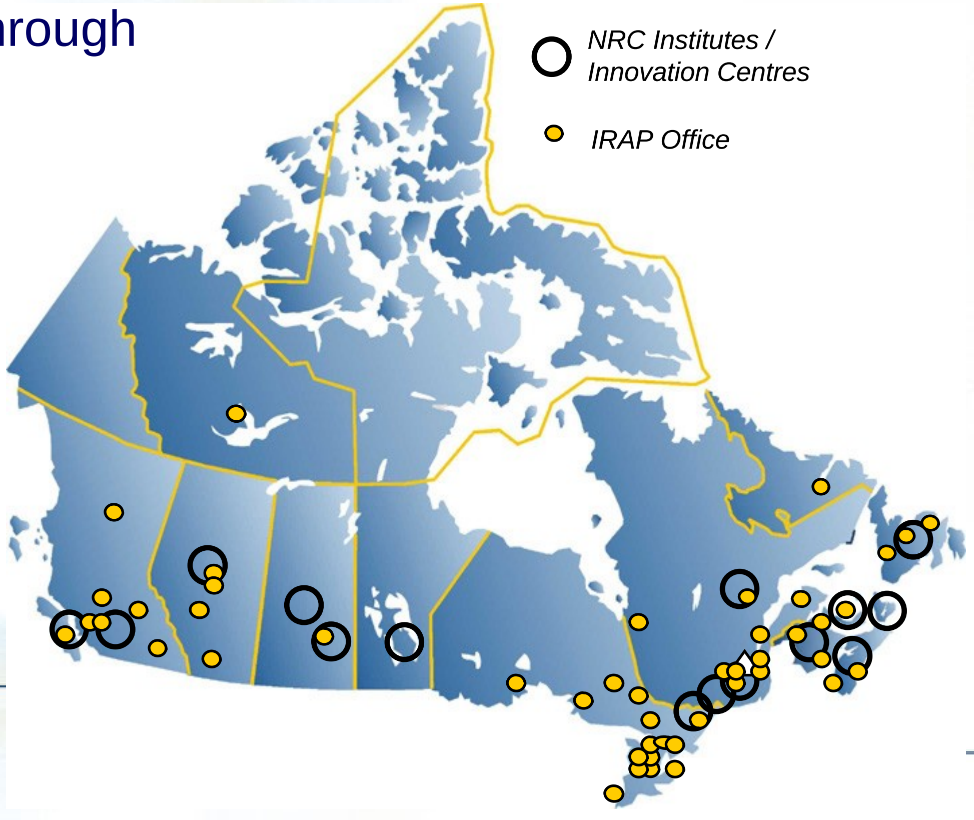
La Science à l'œuvre pour le Canada
Science at work for Canada

National Research Council (NRC) – overview

- Canada's premier R&D organization (established 1916)
- 4100 full-time employees, 1200 guest workers
- Labs and facilities across Canada
  - 19 research institutes, 2 technology centres (CHC, CSTT)
  - Community-based innovation through technology clusters
  - Industrial Research Assistance Program (IRAP)
  - Canada Institute for Scientific and Technical Information
- 2006/07:
  - Total expenditures: $847M
  - Total income: $170M



NRC Institute for Fuel Cell Innovation (NRC-IFCI)

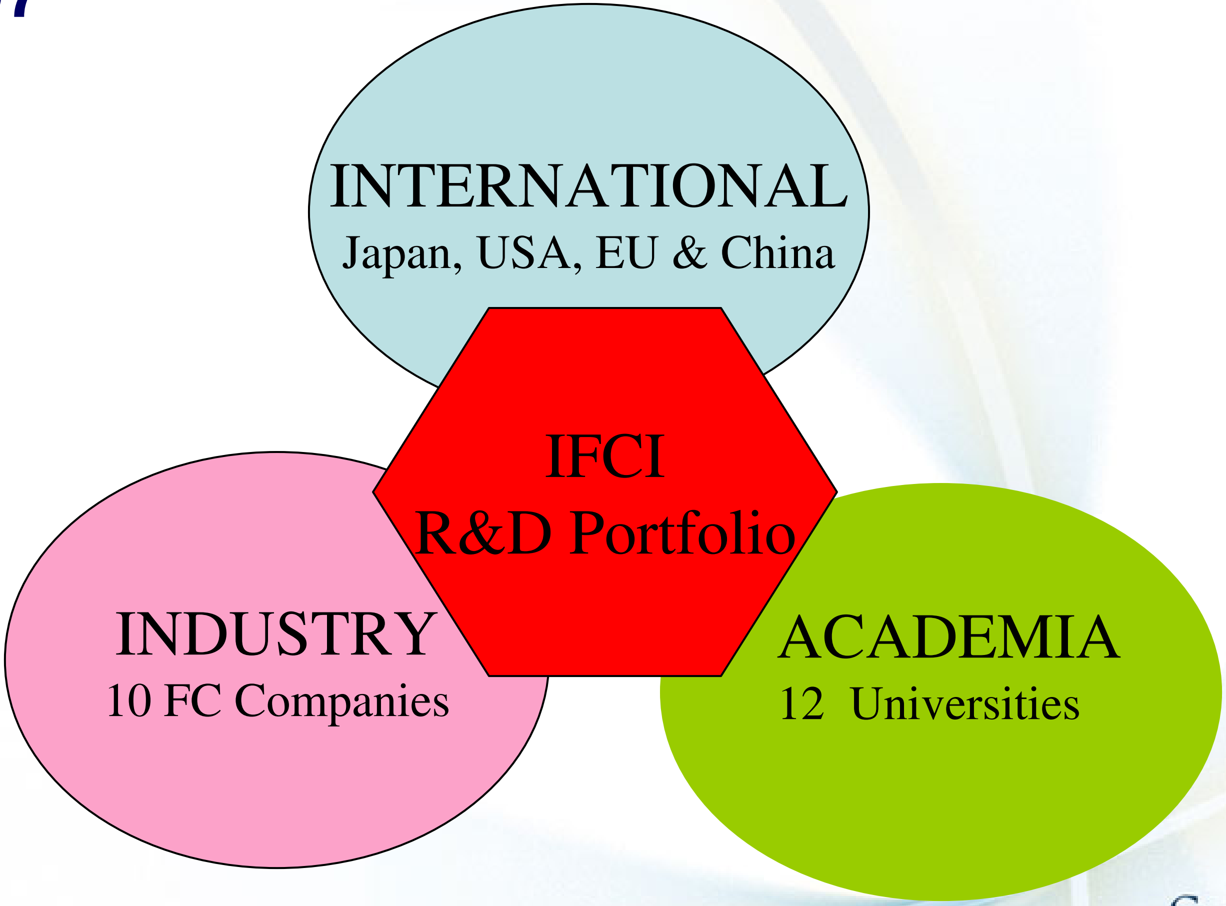
- Established 2002
- Moved into new building in 2006
- 88 full-time staff (139 PDF/students)
- Total building occupancy: 174 (incl. tenants, guest workers)
- Budget: $12M/yr
- Key roles:
  - Research institute
  - Demonstration site
  - Industrial partnership facility (incubation/acceleration)
  - Key Institute for NRC Fuel Cell Program

NRC-IFCI is now hub of Canadian FC industry

NRC-IFCI Facilities & Equipment

- A new $20M, +70,000 square foot facility
- 21 state-of-the-art labs, specializing in H_2 and fuel cell research:
  - **PEMFC fabrication and testing facilities**
  - **SOFC fabrication and testing facilities**
  - **7 hydrogen-safe labs and office/lab spaces for industry incubation**
  - **Hydrogen-safe Environmental Chamber (HEC)**
- Demonstration facility and capability
  - **Hydrogen-safe Vehicle Maintenance Bay (for 5 Ford Focus FC Cars)**
  - **H_2 Filling Station**
  - **Solar H2 generation (Photovoltaic panels, electrolyser)**
  - **5kW SOFC Generator**

Powering the Future through Partnerships 2006 - 2007



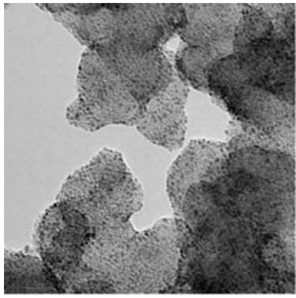
Focus areas

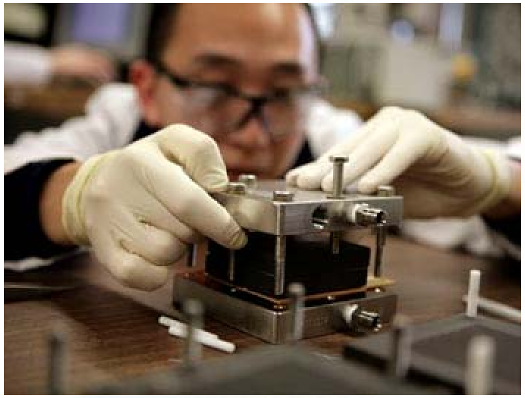
Competencies		Technology Focus Areas
Advanced Materials & Processing	→	**Fuel Cells** **PEMFC & Direct Fuel FC** **SOFC** **Hydrogen & Alternate Fuels** **Hydrogen Quality, Production & Storage** **Biofuels**
Novel Architecture Design	→	
Modeling & Numerical Simulation	→	
Unit & Integrated System Testing	→	
Sensors & Diagnostics Development	→	

Activities in Proton Exchange Membrane Fuel Cell (PEMFC)

Focus areas:

- High-performance, low-cost; high-temperature (120-200°C); direct fuel
  - MEA: theory modeling, fabrication & characterization
  - Catalysis
  - Failure modes: contamination, degradation, microstructural changes
  - Cell & stack: in-situ/ex-situ measurement & diagnostics; modeling & simulation
  - Sensor development





Successes:

- PEMFC catalyst layer model used by a major Japanese auto manufacturer
- Mass transport characterization & durability study for PEM porous materials (industrial collaboration)
- Cathode technology licensed to a Vancouver metal air fuel cell company
- Low-cost, non-noble catalyst developed

PEMFC MEA Fabrication Facility

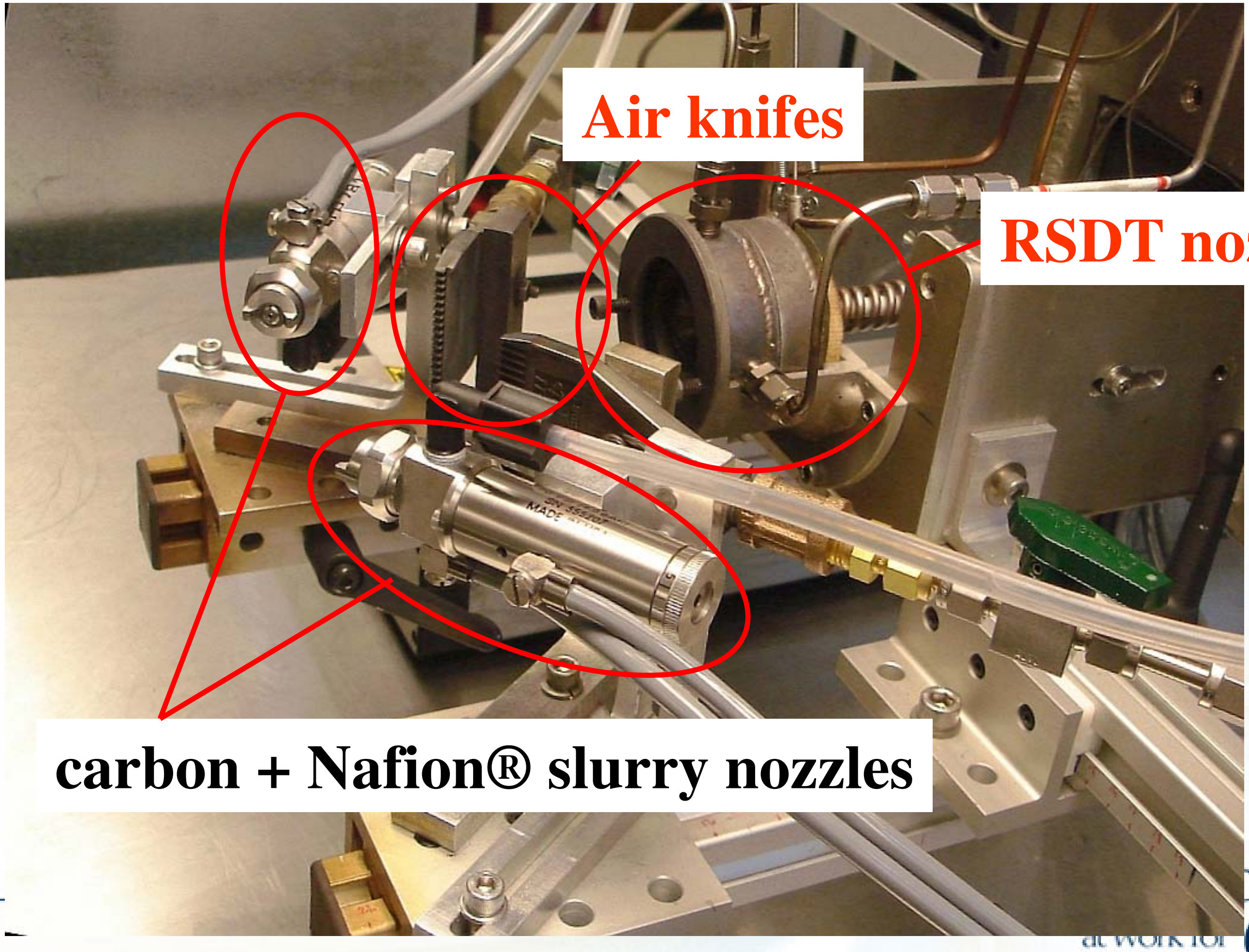
MEA Fabrication
- GDE
- Membrane
- Spray Coating/ Screen Printing
- Pressing
- Ovens

Characterization
- Electrochemistry
- H^+ Conductivity
- Thermal Properties
- Pore Size Analysis
- Mechanical Properties
- Electron Microscopy

Fuel Cell Test Stations

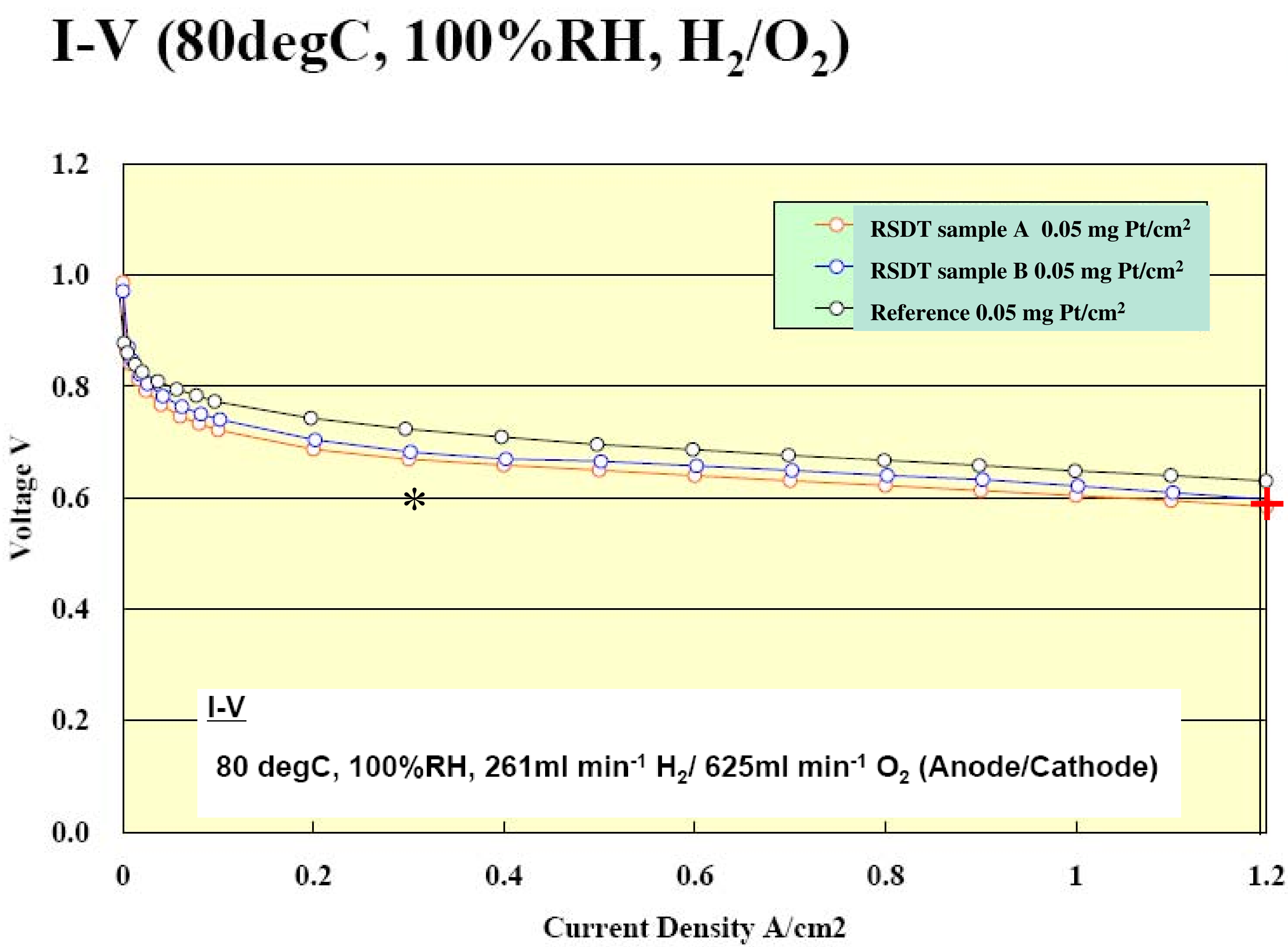
Reaction Vapor Depositon Technology (RSDT)

-A Flame Vapor Deposition Process



Standard RSDT cell architecture

- IV characterization

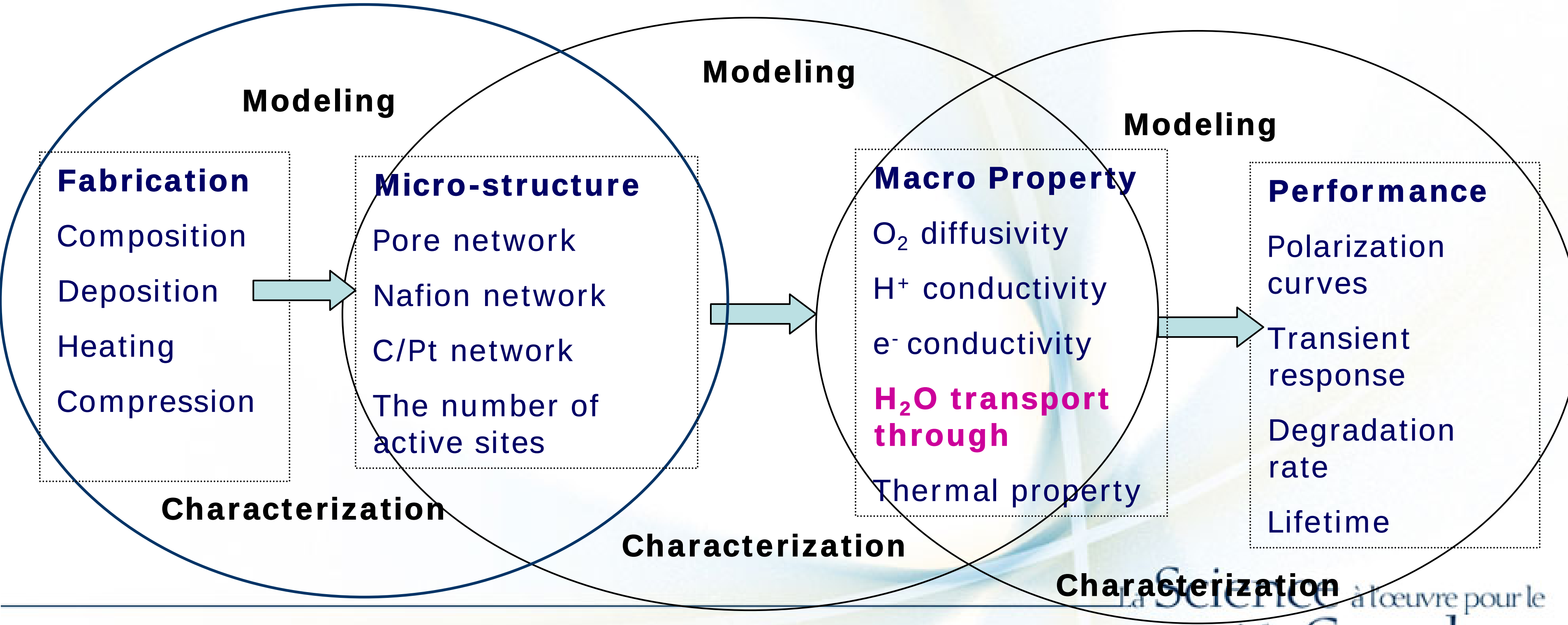


MEA Performance Theory & Fabrication

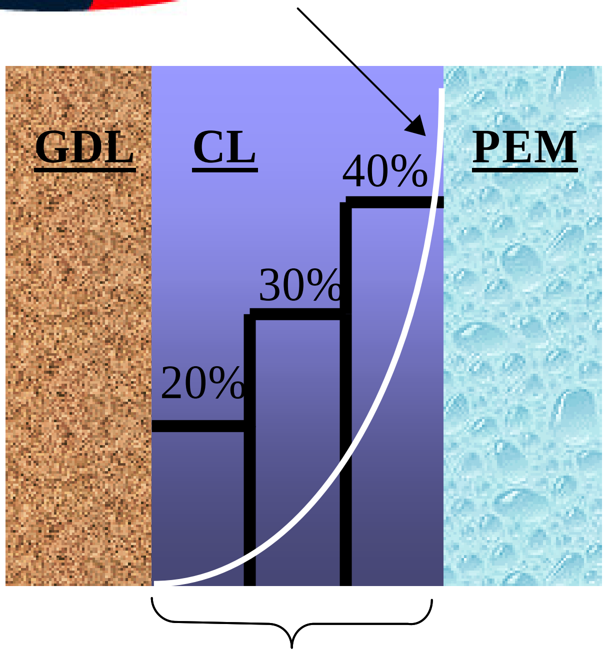
MEA (Catalyst Layer): Theory Modeling, Fabrication & Characterization

Primary Goal: to establish the dependence of performance upon composition & fabrication condition of catalyst layers

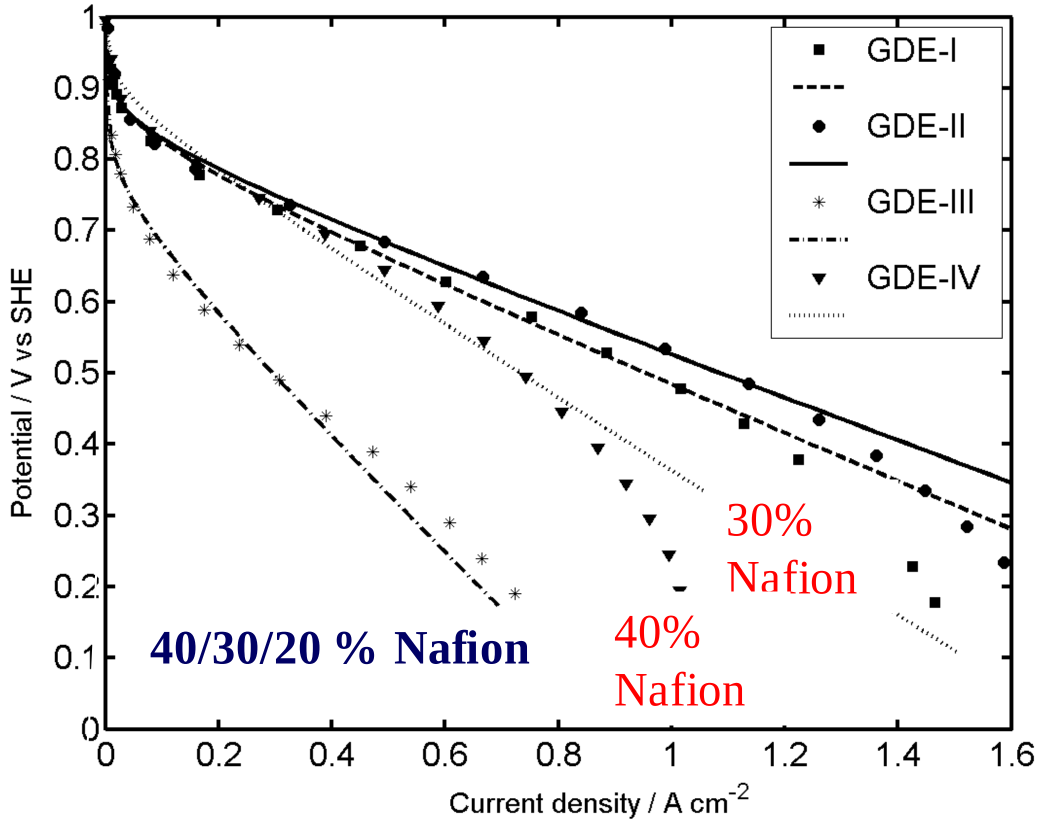
Cost: $1.5M/yr



Engineered MEA



Nafion Gradient



Higher proton conductance (EIS) where needed

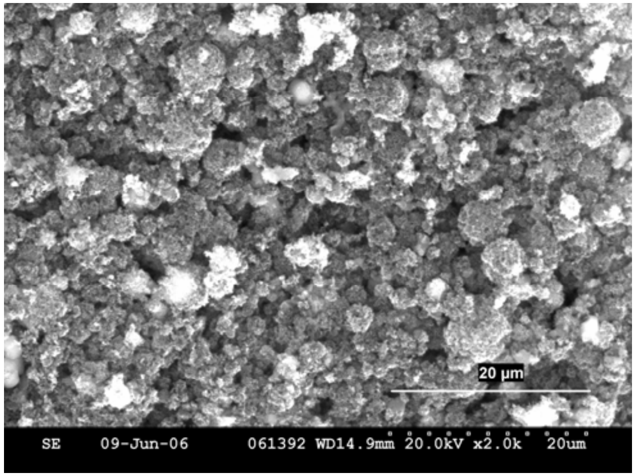
Solid Lines (simulated from ex-situ data)

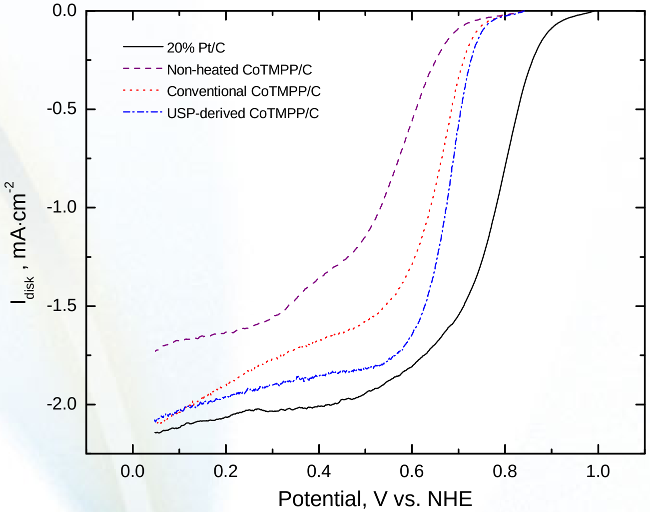
Larger porosity where needed

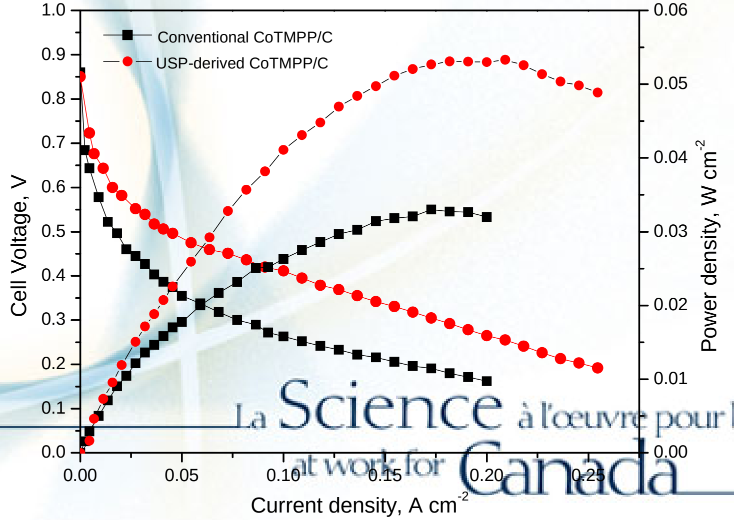
Reaction Zone in the catalyst layer (from modeling studies)

PEMFC Catalysis

High performance CoTMPP/C prepared by ultrasonic spray pyrolysis







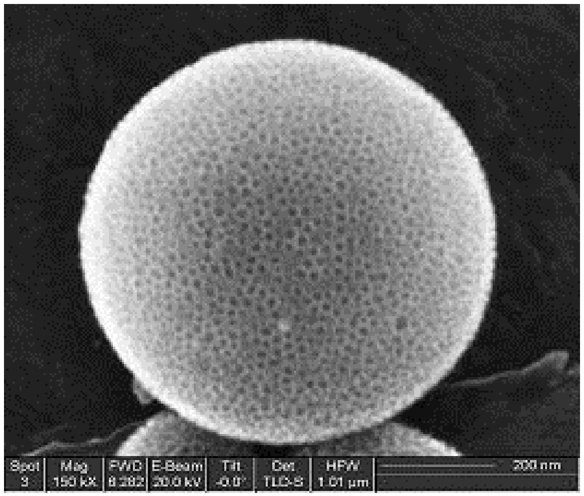
➢Spherical, porous and uniform catalyst with high surface area

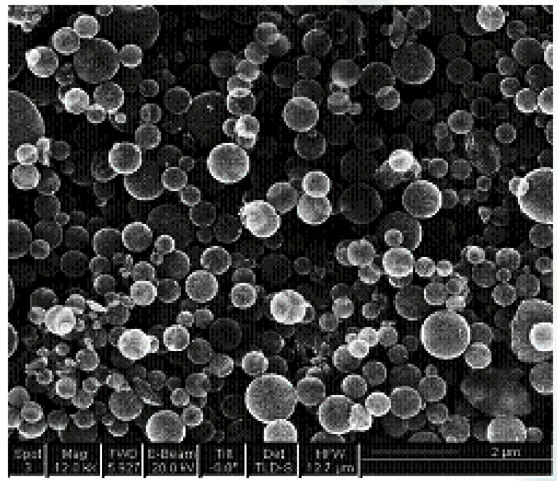
➢Double catalytic activity @ 0.4V cf. conventional CoTMPP/C

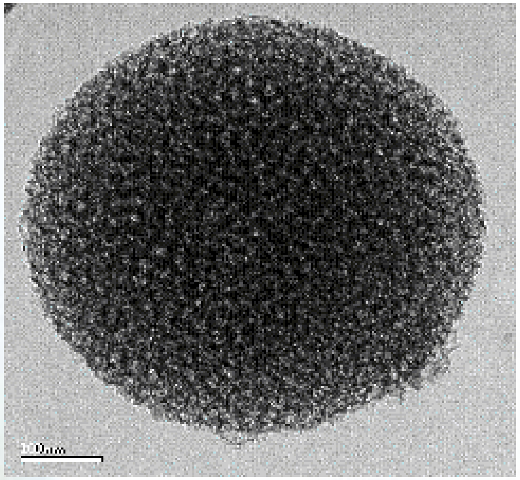
NRC-IFCI Porous Carbon Sphere

Patent application in progress

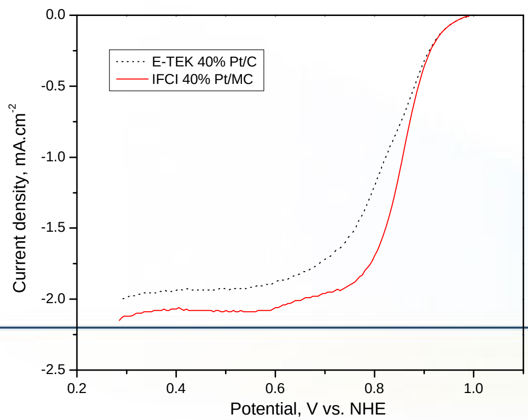
- Controllable surface area and porosity
- Multiple applications



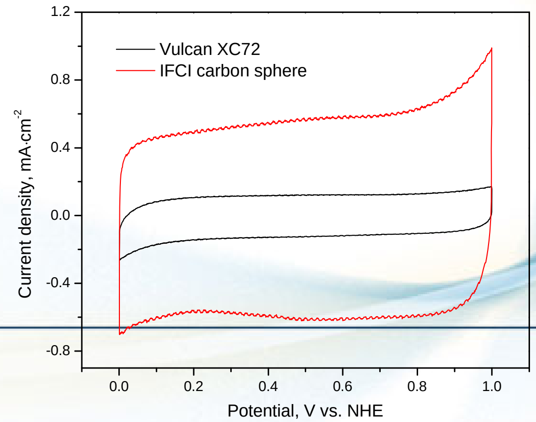




◆ Fuel cell catalyst support



◆ Supercapacitor electrode



Other applications:

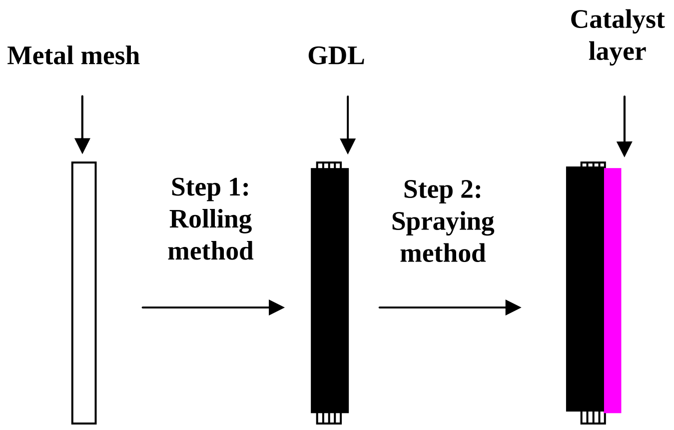
◆ Hydrogen storage material

◆ Li-ion battery electrode

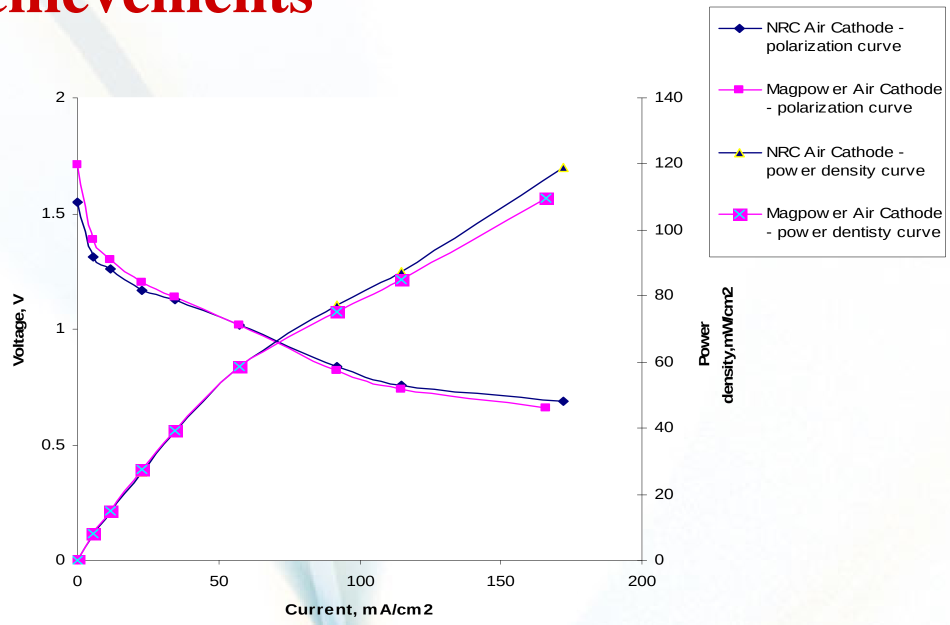
◆ Drug delivery media

Non-noble catalyst content air cathodes for Metal-Air fuel cell

Technical Achievements



A schematic fabrication process of
the developed two-layer structure air cathode



Magnesium-air single cell performance of the developed cathode
vs. commercially available cathode

- Simplified fabrication process
- Cost-effective materials and components
- Higher performance and longer lifetime

MagPower / NRC-IFCI Collaboration

(Non-noble catalyst content air cathodes for Magnesium-Air fuel cell)

Business Impacts

- Helped MagPower to close a $22 million deal.
- At least 25 times less expensive than commercial
  air cathodes.
- Patented technology
- Manufacturing capability in establishing stage.
- Usable for other metal-air fuel cells/batteries applications.

MagPower Magnesium-Air Fuel Cell

PEMFC Performance Durability & Reliability

Failure Mode: Contamination

Primary Goal

- **Develop & validate kinetic models for anode & cathode contamination**
- **Predict cell performance in the presence of contaminants**

Contaminants:

Fuel Impurities

Hydrogen (reformed): CO, CO_2 H_2S, NH_3 CH_4, metal/organics

Air: N_2, NO_x (NO, NO_2), SO_2, NH_3, O_3

Metallic Impurities

Cations from bipolar plates: Fe^{3+}, Fe^{2+}, Ni^{2+}, Cu^{2+}

Cations from Nafion: Na^{+}, Ca^{2+}

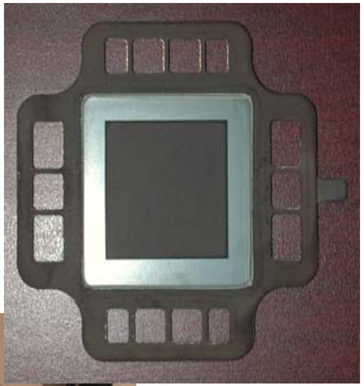
Other Impurities

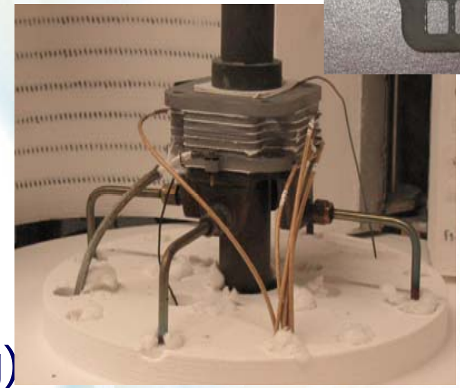
From accessories: Si gasket; from coolants: Si, Al, S, K, Fe and Cu: from battlefield pollutants: SO_2, NO_2, CO, propane, benzene; from compressors: oil

Activities in Solid Oxide Fuel Cell (SOFC)

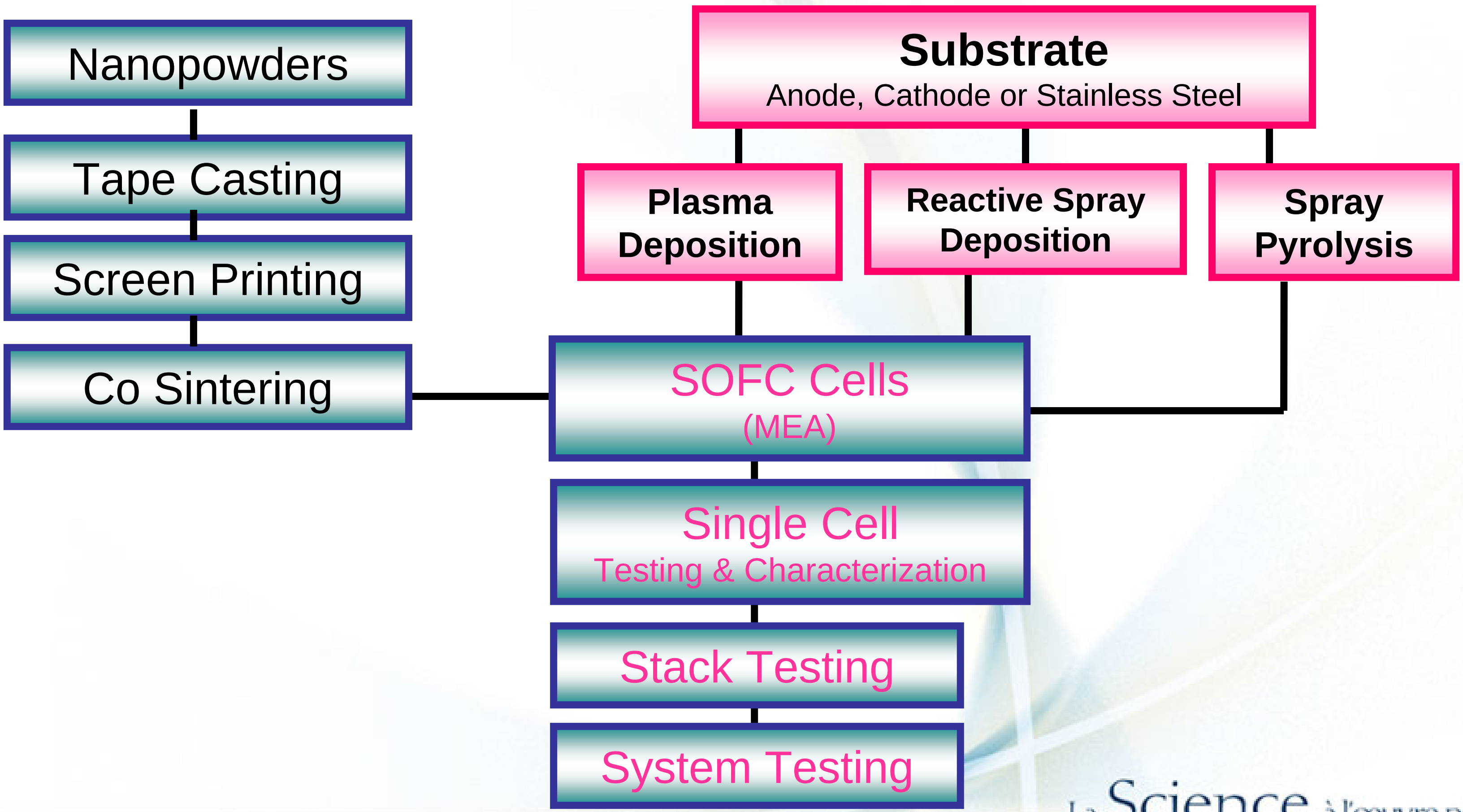
Focus areas:
- Low-temperature, low-cost SOFC (450-650°C)
- Fuel-flexible SOFC (diesel, biofuels, biogas)

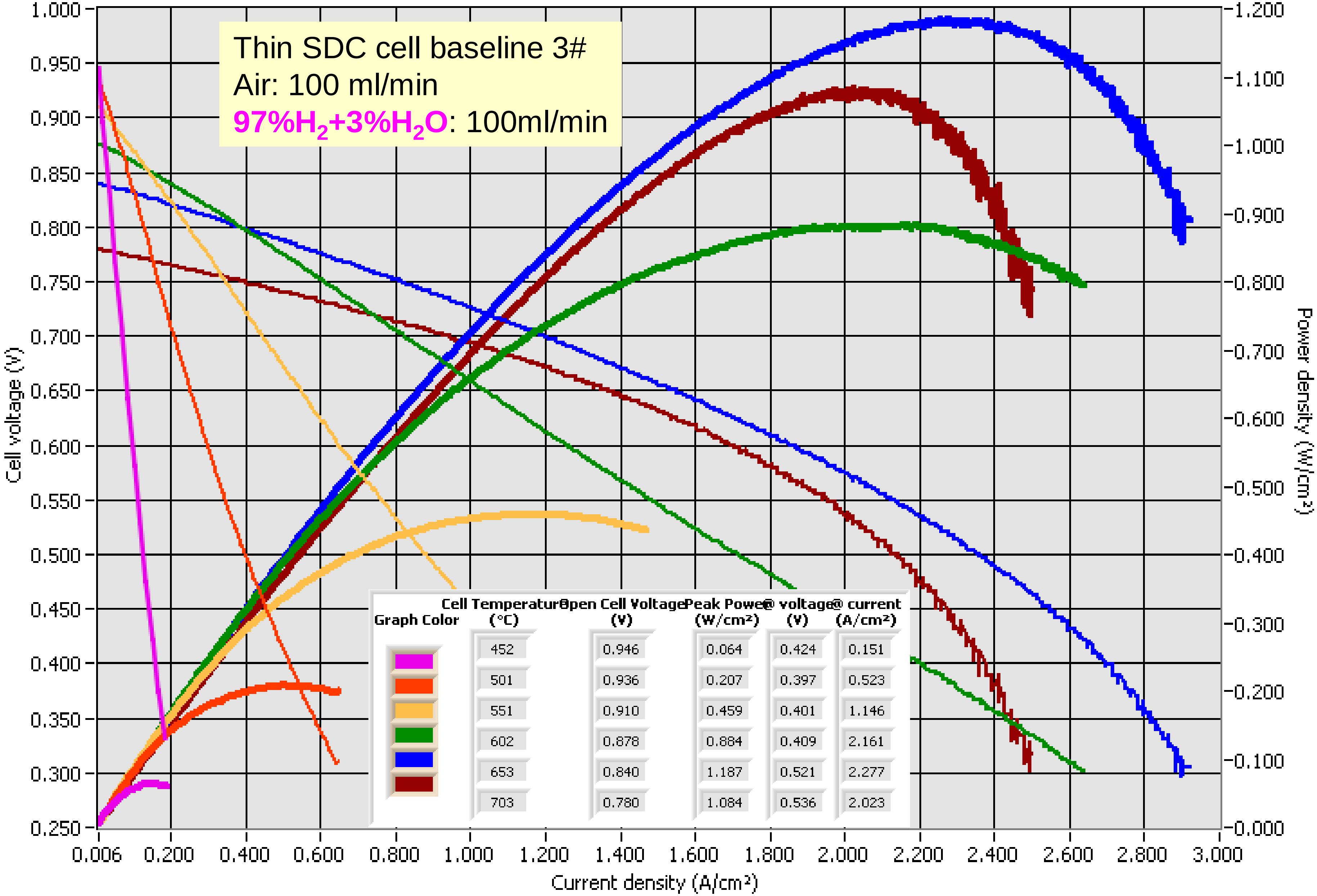
Successes:
- Demonstrated SOFC stack technology operable at 600°C
- Cermet supported cells with bi-layer electrolyte
- New low temperature cathode materials (patent pending)
- New sealing materials
- Metal supported cells for cost reduction
- New spray deposition techniques (patent pending)
- Benchmark technology for the EU project SOFC600
- Metal supported cells with similar performance to cermet cells





SOFC Fabrication Facility

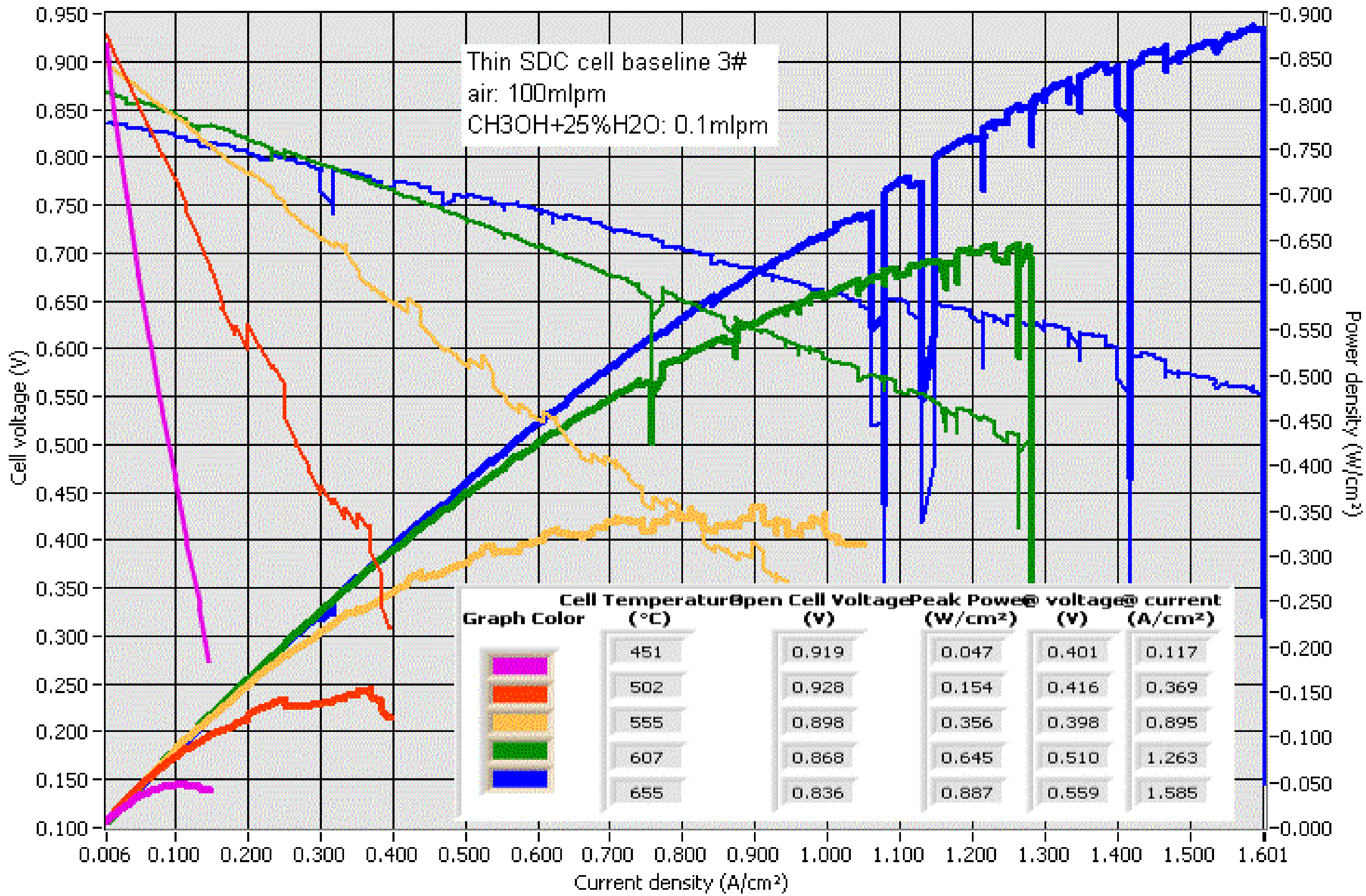



Thin SDC cell baseline 3#
Air: 100 ml/min
97%H_2+3%H_2O: 100ml/min
Cell voltage (V)
Power density (W/cm²)
Current density (A/cm²)
Graph Color | Cell Temperature (°C) | Open Cell Voltage (V) | Peak Power (W/cm²) | @ voltage (V) | @ current (A/cm²)
452 | 0.946 | 0.064 | 0.424 | 0.151
501 | 0.936 | 0.207 | 0.397 | 0.523
551 | 0.910 | 0.459 | 0.401 | 1.146
602 | 0.878 | 0.884 | 0.409 | 2.161
653 | 0.840 | 1.187 | 0.521 | 2.277
703 | 0.780 | 1.084 | 0.536 | 2.023

Thin SDC cell baseline 3#

Air: 100 ml/min

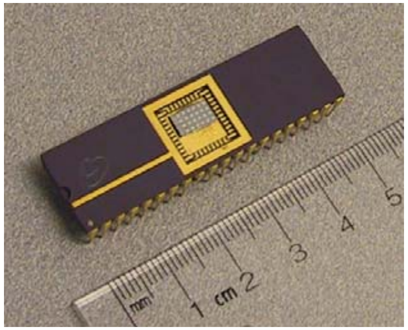
CH_3OH+25%H_2O: 0.1ml/min



H2 Technologies

- Hydrogen Quality
  - → H_2 Fuelling (Pacific Spirit Fuelling Station)
- Hydrogen Production
  - → H_2PoD
- Hydrogen Storage
  - → H_2 Electrochemical Compressor
- Hydrogen Sensor

Sensing Technologies



MOS Hydrogen Sensor Array

- *High sensitivity for leak detection (patent pending)*
- *Wide dynamic range for gas concentration monitoring*
- *High spatial resolution for gas distribution mapping*

Palladium Nanowire Array Sensors

Methanol Concentration sensor for DMFC systems

Gas sensor test station

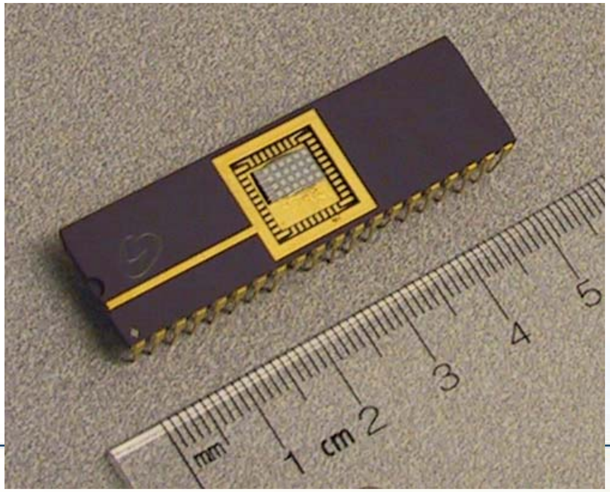
- *Sensor Characterization*
- *Accurate Monitor and Control*

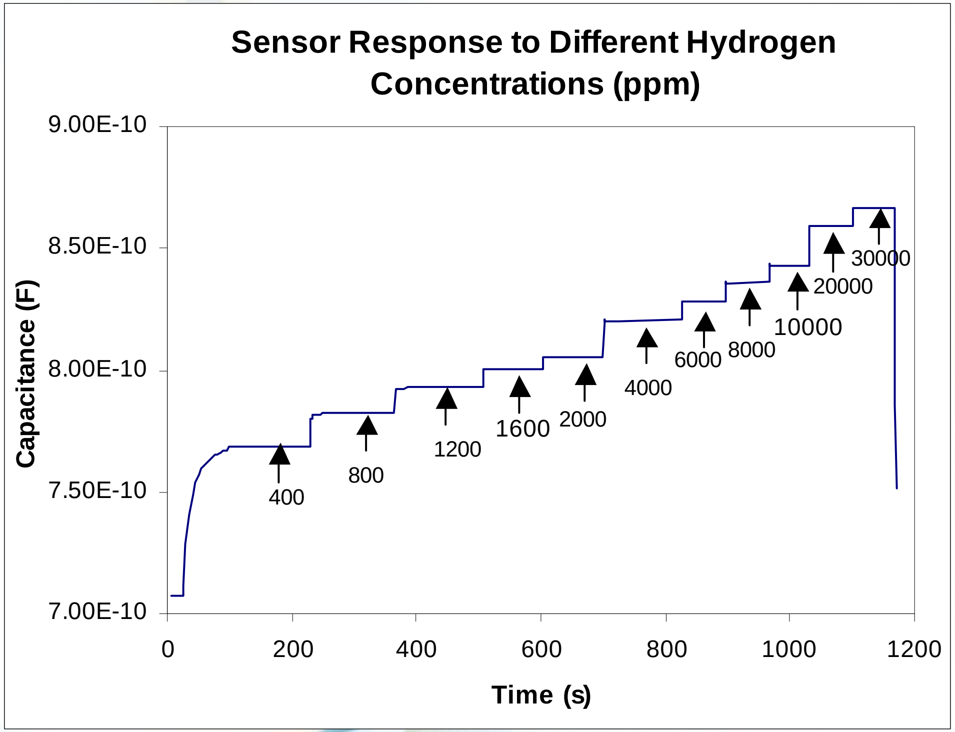
Sensing (cont.)

H_2 sensor development

Low concentration MOS H_2 sensor

- **Sensitivity:**
  - ***high end : 30,000 ppm***
  - ***low end : 10 ppm***
  - ***Linear response***



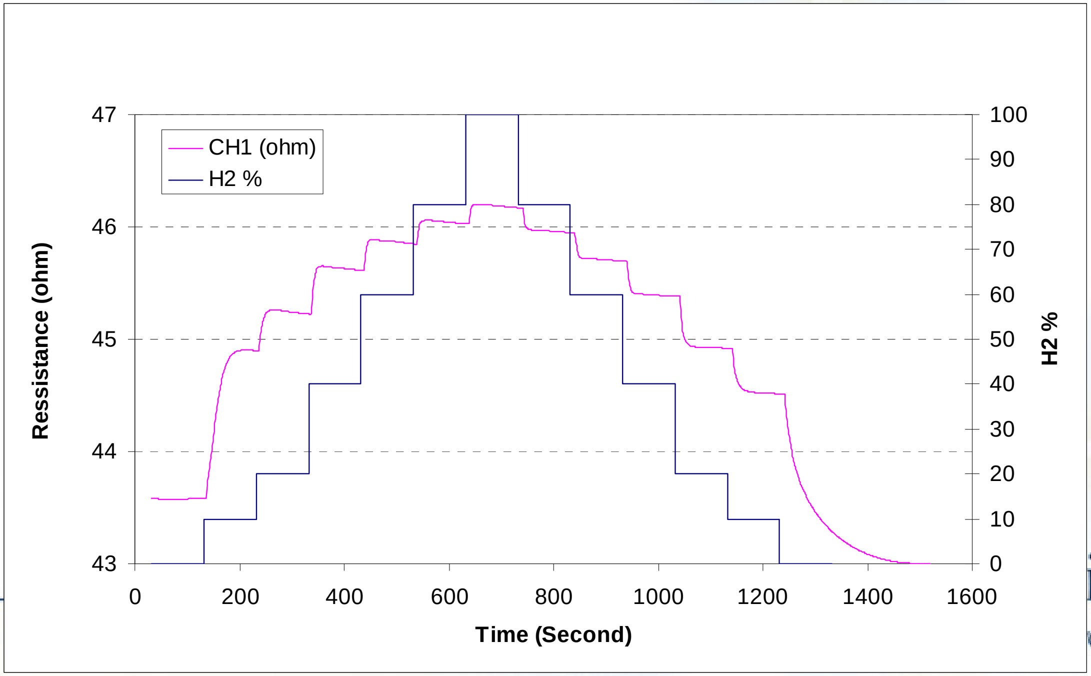


Sensing (cont.)

H_2 sensor development

High concentration H_2 sensor

- Sensitivity range: 10% to 100%, measurable transfer function with even 1% H_2.
- No cross sensitivity to CO, CO_2, ISO Butane, Ethylene, etc.



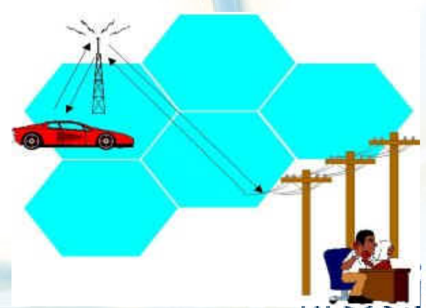
The Pain: On-Demand Power Requirement

Emergency Back Up Power

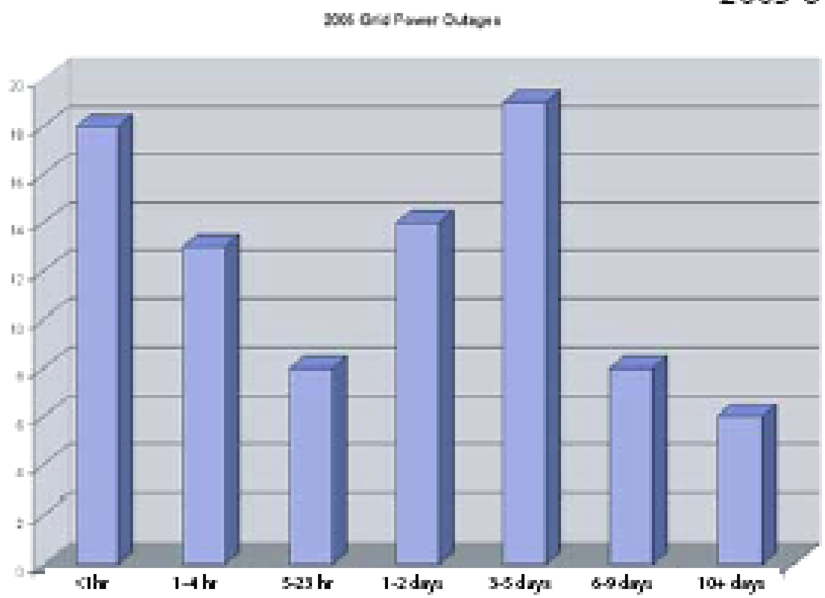
- 1998 Ice Storm in Eastern Canada: no heat & power for weeks/months, at least 25 deaths, $5 - 7 billion in damages! *(Source: Wikipedia)*
- 2003 Blackout in Ontario & U.S affected 50 million people, billions $ in economic cost !! *(Source: NRCan)*

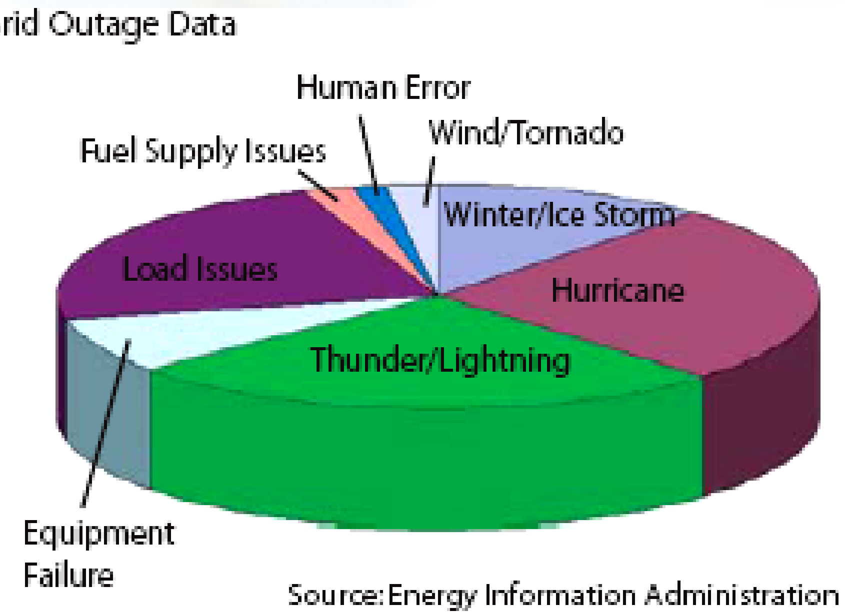
Mission Critical Applications

Cost of power outages for bank and telecom companies can be enormous, reaching $6 million per hour or more!!
(Source : First National Bank of Omaha)



The Pain: 2005 US Grid Outage Data





Problems & Opportunities

- **Existing solutions for back-up / uninterruptible power supply (UPS)**
  - Battery-based UPS : short run times, only 5 - 10 minutes, enough to safely shut down system
  - Diesel Gen-Set : high maintenance cost with environmental pollution, noise

- **PEM Fuel Cell is an elegant solution**
  - Clean - only exhaust is water (indoor use)
  - Silent (almost!)
  - Continuous power as long as fuel (H_2) is available
  - Present Barrier :The **“Fuel Issue”** :

Opportunity : PEMFC Backup System

Types of Backup System	Low Cost	Low Maintenance	High Reliability	Long Run Time	Low Pollution	Long Life
Engine Generator	No	No	Yes*	Yes	No	Yes
VLRA Battery	Yes	No	Yes*	No	No	No**
Flywheel	No	Yes	Yes	No	Yes	Yes
Ultracapacitor	Yes	Yes	Yes	No	Yes	Yes
Fuel Cell***	Yes	Yes	Yes	Yes	Yes	Yes

* Reliability is determined by routine maintenance.

** Assuming valve regulated lead-acid (VRLA) with an average life of 5–7 years.

***Hydrogen-based PEM fuel cell.

Source : US Federal Energy Management Program/DOE

Opportunity : PEMFC Backup System

Backup Power System	Initial System Cost	Maintenance Costs	Battery Replacement Costs[b]	PV Life Cycle Cost[c]
VLRA Battery	$29,000	$600/yr + $3,000/2 yrs[a]	$20,260	$53,250
PEM Fuel Cell	$31,000	$600	$1,100	$36,457

[a] Performed capacity test every other year.

[b] 5-year life expectancy for VLRA batteries.

[c] Based on 10-year life expectancy and using NIST BLCC 5.3.

Source : US Federal Energy Management Program/DOE

Current Hydrogen Fuel Issue

- High pressure containers
  - 2600 psi DoT limit – low weight density
  - 1% hydrogen content by weight
  - High shipping costs
  - Storage regulations
  - Safety
- Onsite manufacturing of hydrogen
  - Steam reformation of natural gas or methanol
  - Hydrogen separation and pressurization
  - Long start-up time
  - Only practical at high volumes

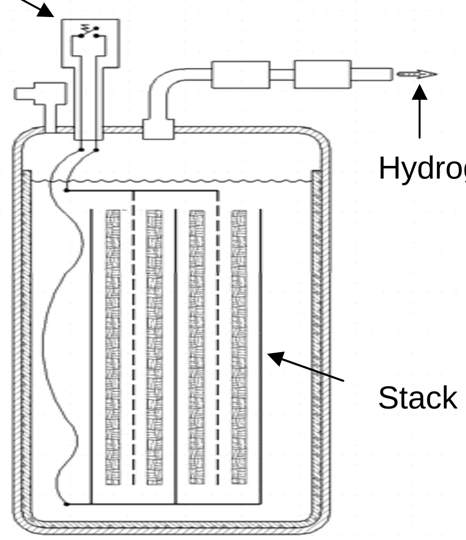
*US **DOE** states 'The **high cost** of hydrogen production, **low availability** of the hydrogen production systems, and the challenge of providing **safe production** and **delivery** systems **are early penetration barriers**' to commercialization of fuel cells*

(DOE: http://www.eere.energy.gov/)

Pain: Mobile Electronics Running Out of Power

- Convergence to the all-powerful, full-featured, multimedia handset
- Need 6 times capacity of current batteries
- Battery development reaching power limits
- Hydrogen has the highest per weight energy density
- Miniaturized hydrogen PEM fuel cells are the answer – but need hydrogen source
- **Need safe, inexpensive, controllable, on-demand hydrogen generation system**

NRC-IFCI's Hydrogen Power On Demand (HyPoD)



D. Ghosh et al.: "Hydrogen -on-Demand"
- *US patent appl. # 11/156,548*
- *Canadian patent application #: 2,510,371*
- PCT application June 2006

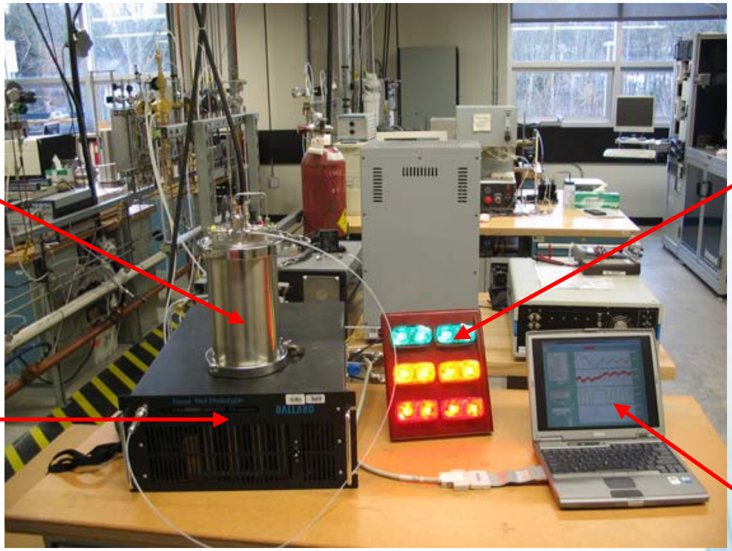
Meeting Market Requirements:

- **Truly 'on demand' H_2 - switch controlled**
- **Totally safe – no H_2 stored in system**
- **High purity PEM grade H_2 produced (>4N)**
- **High gravimetric & volumetric H_2 storage density(DOE V Targets met)**
- **High pressure H_2 generated without compression (up to 1000 bara-15,000psi)**
- **Passive system - no moving parts**
- **Environmentally friendly & recyclable raw materials & by-products**
- **Scalable – mW to kW**
- **Low cost**
- **Lab demo run on commercial PEM fuel cell system for hours continuously**

HyPoD Laboratory Demonstration

Switch Controlled Hydrogen Generator

Electrical Load

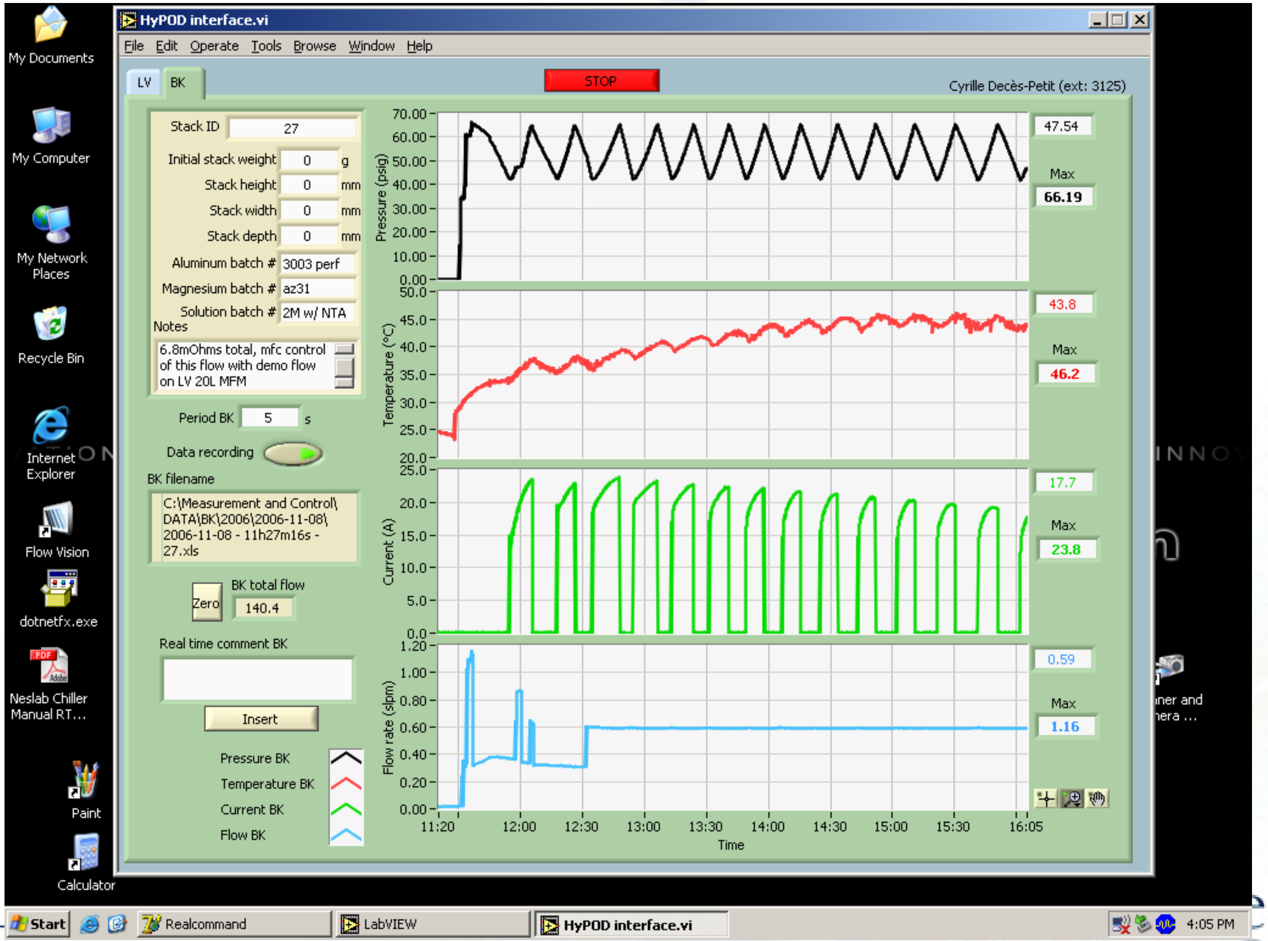


PEM Fuel Cell

Data Acquisition System

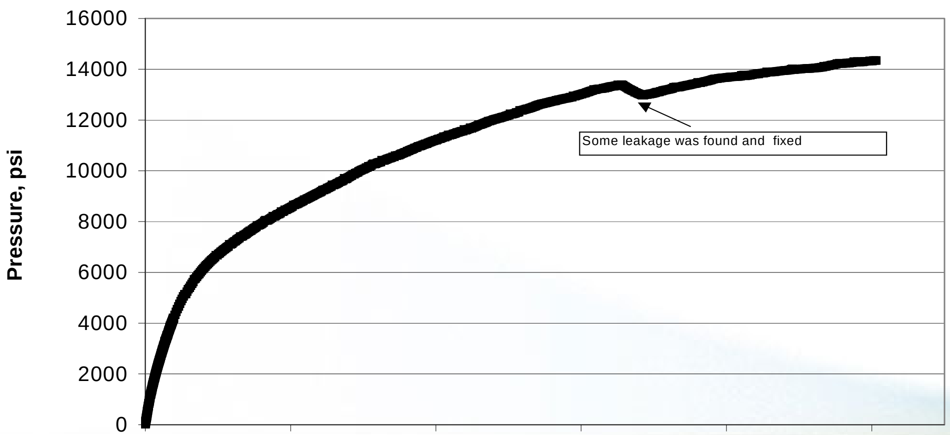
Completed laboratory demonstration with PEM Fuel Cell System, continuously run for tens of hours

Switch Controlled on-off Generation



HyPoD Technical Specifications

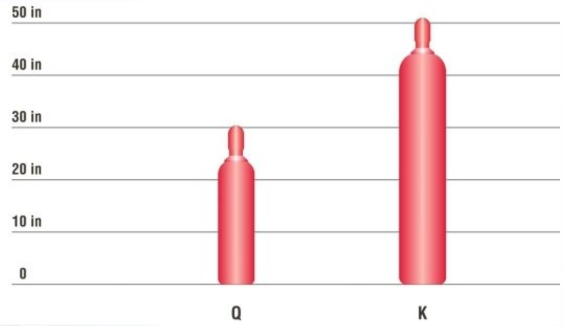
Technical Specifications	
Gravimetric energy capacity, Wet(dry)	3.0(6.0%) by weight
	1.0(2.0) kWh/kg
Volumetric energy capacity, Wet(Dry)	1.5(3.0) kWh/L



- **High pressures** of over 1000 bara(15,000 psi) obtained **without compression**
- Pressure can be easily controlled to any set value through a simple pressure control switch

NRC Confidential Document

Existing Market : High Purity Hydrogen Gas Supply - $2B worldwide market

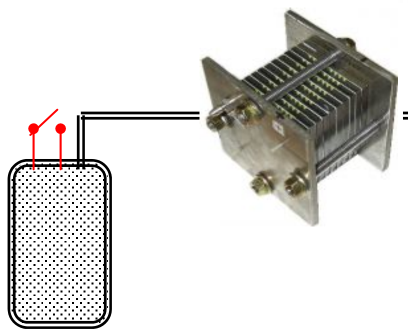


- Existing worldwide market – $ 2Billion/yr
- High purity hydrogen supply for laboratories, semiconductor manufacture, float glass, specialty chemicals & pharmaceuticals
- Cost of storage and transportation of hydrogen is a major contributor to total cost of hydrogen
- HyPOD Hydrogen cost lower than T cylinder, similar to tube trailer

Description	Wt. % H_2	Price/Cost $/M³	Rent $/mo
T cylinder	0.9 – 1.0	8 - 10	2 - 4
Tube Trailer	1.0	3.0	3000
HyPOD (dry)	6.0	2.2	-

HyPOD Applications

PEM Fuel Cells



Switch-controlled hydrogen generator based on the principle of electrochemical reactions to generate H_2 from water using sacrificial electrodes

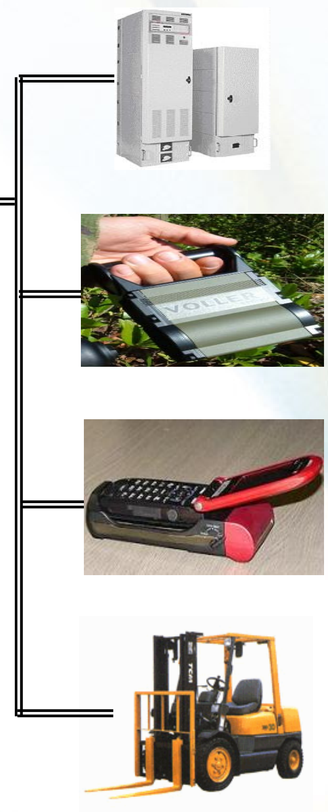


Figure 3: HyPoD application examples

Backup / Remote / UPS Power Market

- **World UPS Market (2005) - US$ 5.76B**
- **Telecommunication Backup Power – 1 to 10 kW**
- **IT backup power – 0.1 to 5 kW**
- **Trend to more days of backup power**

Market Opportunities - Backup / Remote / UPS

- Remote Power: cell phone towers
  - Installed base: 1 million units world wide
  - Annual increase: 125,000 units
  - **$280 million** TAM HyPod system (10% of installed base)
  - **$120 million** market for replacement HyPoD modules pa (3 days of outage)
  - **12.5% pa** growth
- Uninterruptible Power (UPS): **$50 million pa**

Mobile Electronics :Disposable Hydrogen Cartridge for Micro PEMFC

- Battery replacement or battery charger for mobile electronics: cell phones, laptops, digital video cameras

- Lightweight small plastic container
  - contains electrodes and water > snaps into fuel cell module
  - discarded or recycled

Potential Military Applications of HyPoD –

Applications requiring low noise & heat signature

Disposable H_2 Supply for PEM Fuel Cells

- Soldier Power
- Battery Charger/ Replacement (mW to 250 W)
- Portable power (up to 1kW)
- Power for “Silent Watch” (~5 kW – 72 hrs mission)

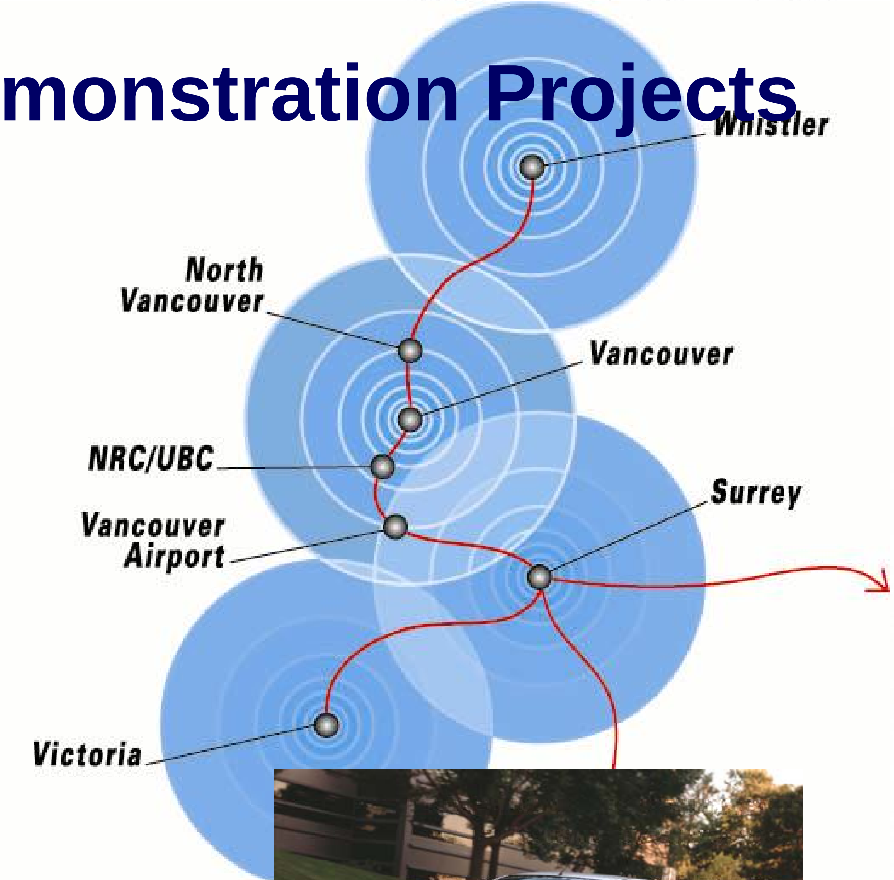
Technology Demonstration Program

NRC-IFCI has the facilities and capabilities to host integrated technology demonstration projects,

Current integrated projects include:

- Pacific Spirit Filling Station
- Vancouver Fuel Cell Vehicle Program support
- Hydrogen Quality Assurance Project
- Solar Hydrogen Generation
- Building Integrated SOFC generator
- **Specialized Applications Testing**
- Hydrogen Environment Chamber (HEC)

Demonstration Projects



- Hydrogen Highway
- Ford Fuel Cell Cars and Fueling Station
- Sustainable Energy System – Solar energy to hydrogen to PEM fuel cell
- Solid Oxide Fuel Cell for heat and power

HYDROGEN HIGHWAY CANADA ™

Vancouver Fuel Cell Vehicle Project

- Five Ford Focus Fuel Cell Vehicles
- Partnership of FCC, Ford Motor Company, NRCan, NRC-IFCI and BC Government
- Project will provide information needed to:
  - Improve vehicle performance, reliability and durability
  - Assess user interaction and comfort with fuel cell technology and with hydrogen refuelling infrastructure

Hydrogen Fueling Station

- Hydrogen Fuelling Station
  - Supplied by General Hydrogen and BOC Gases
- Hydrogen Production
  - Electrolyzer (PEM)

BOC

Demonstrations

- Regenerative Integrated Energy System
  - Photovoltaics (St. Gobain & BCIT)
  - PEM Electrolyzer (Hydrogenics)
  - Compression and Storage (Hydrogenics)
  - 20kW PEM back-up system for NRC building (Ballard)
- Stationary SOFC Development
  - Two 5 kW multi-fuel (FCT & Acumentrics)
  - Fuel: natural gas, methanol
  - Combined heat and power for NRC building

PEM Electrolyzer

Alkaline Electrolyzer

Hydrogen-Ready Environmental Chamber

Unique Public Facilities in North America

- **Only public facility of its kind in North America**
- **Hydrogen-ready**
- **Controlled for temperature, humidity and altitude**
  - **Temperature Range: -60ºC to 140ºC**
  - **Relative Humidity: 5%-95% between -10ºC and 65ºC**
  - **Altitude: 3000m or 70 kPa absolute pressure**
  - **Dynamometer: 187 kW max power / 100 kph max speed**
  - **Dimensions: 3m wide X 3m high X 7.6m long**
- **Equipped with a dynamometer**

New one-of-a-kind facility allows companies to test fuel cell systems under any environmental conditions.