HySafe Research Priorities Workshop
BAM Fed. Institute for Materials Research and Testing, Berlin

Date: Oct 16-17, 2012

Barriers to Commercialization & Critical Issues for Current & Next-Generation Technologies




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Smarter Solutions for a Clean Energy Future

By: Jake DeVaal Ph.D.
Product Safety Manager
Ballard Power Systems Inc.

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Outline: Commercialization Barriers & H2 Safety Issues

Purpose: Identify barriers to commercialization & critical issues

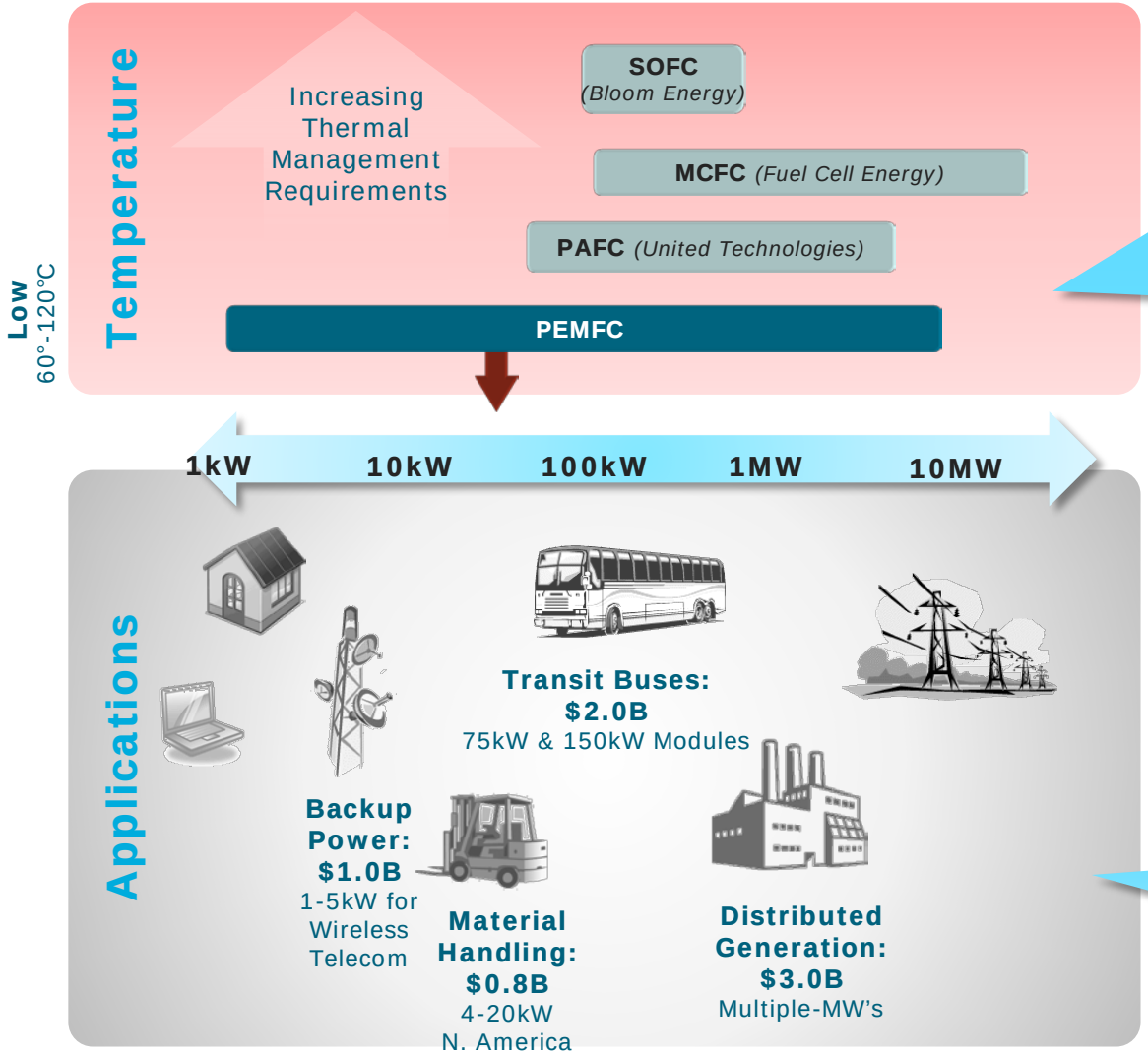
1. **Background on Ballard**
   - Ballard's current product lines & commercialization barriers
2. **Progress on understanding Fuel Cell product safety hazards**
   - Fuel supply versus operational hazards; Is it a 'bang' or just a 'pop'?
   - Stationary vs. motive product issues; emissions safety vs. worst-case leaks
   - Issue of 'flammable beyond discharge' versus inside piping emissions
3. **Coming at H2 Emission/Leak Issues Step-by-Step**
   - If we know what goes in, and what's used; what's left is emission/leak
   - Development of Fuel Flow Monitoring installed in 75 kW HD6 Module
4. **Conclusions to-Date/Next Steps**

1. Ballard Background

- **Ballard Power Systems Inc. is a recognized global leader in design & manufacture of clean energy, zero-emission PEM fuel cells**
- **Company founded in 1979, ~400 employees**
- **Portfolio of proven fuel cell solutions**
- **Strong delivery capabilities:**
  - Access to over 2,000 patents & licenses
  - High volume manufacturing facility
  - 100MW+ of fuel cell products shipped

Leading supplier of fuel cell solutions with strong commercial value propositions

Market Opportunity

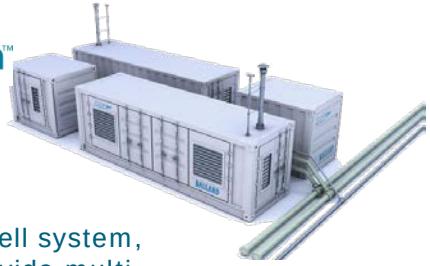


Proton Exchange Membrane (PEM) **fuel cell technology accounted for 97% of global fuel cell shipments in 2010 ... and 74% of total megawatts** (MW's)

Source: Fuel Cell Today Industry Review 2011

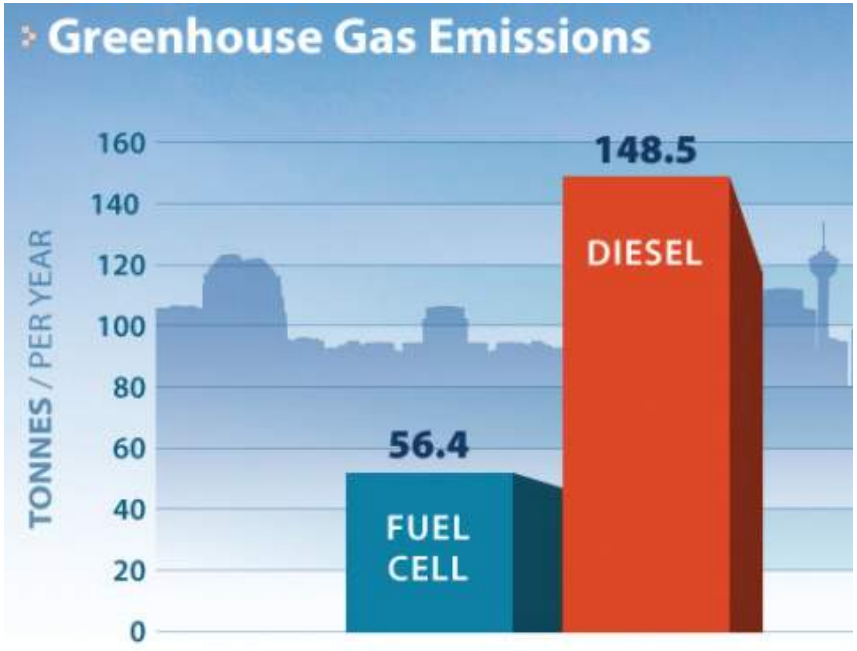
Ballard's Current Total Addressable Market Opportunity: $6.8B+

PEM Product Portfolio

Fuel Cell Stacks	 FCgen™-1020ACS • Power 500W-2kW • Operating life 2.5K-4K hrs • Primarily used for backup power systems	 FCgen™-1300 • Power 2-8kW • Operating life 20k- 30k hrs • Used for distributed power generation systems	 FCvelocity™-9SSL • Power 4-20 kW • Operating life 8k-12k hrs • Used for material handling systems	 FCvelocity®-1100 • Power 100 kW • Operating life >5k hrs • Integrated as part of HD6 bus modules
Fuel Cell Modules	FCvelocity™-HD6  • Power 75-150 kW • Operating life 12,000 hours • Used for bus applications			
Complete Fuel Cell Systems	Dantherm  DBX2000 (2kW)  DBX5000 (5kW) Complete backup power systems designed and configured for telecom customers requiring reliable, secure power infrastructure. *(Ballard has controlling interest in Dantherm Power)*		CLEARgen™  Complete fuel cell system, designed to provide multi-megawatt supply of clean energy.	

Why Fuel Cell Buses?

- **Completely eliminates tailpipe emissions**
  - NOx, SOx, PM
- **Noise reduction & comfortable ride**
- **Improved fuel efficiency**
  - 1.5-2.5x improvement over conventional diesel buses on an energy equivalent basis
- **Reduced Greenhouse Gas Emissions**
  - Demonstrated on a well to wheel basis

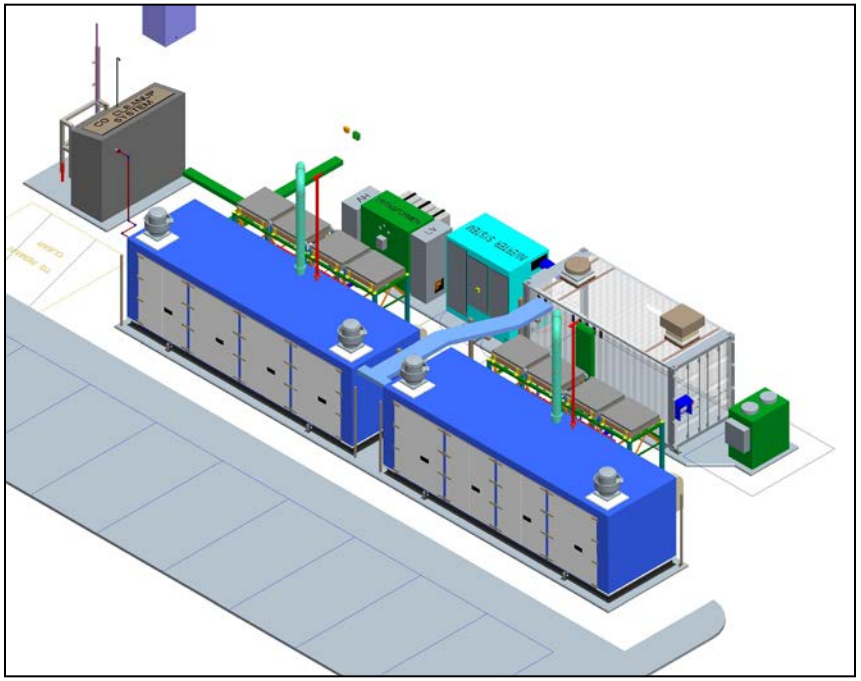


SOURCE: Prototype evaluation data (BC Transit, 2008)

BC Transit has calculated* a WTW reduction in CO2e emissions of 62% for the Whistler buses

Why Distributed Power Generation?

- **Availability of By-Product Hydrogen**
  - Up to 15% of by-product hydrogen produced by chemical plants is vented or burned
  - Biomass may also become a potential fuel source
- **Presence of Feed-in Tariff Programs or High Electricity Rates**
  - High industrial electricity costs and feed-in tariff programs for utilities favour green electrical production
- **US Federal Capital Purchase Incentive Programs for Fuel Cells**



1 MW CLEARgen DPG Plant at Toyota Motor's Head Office in Torrance California:

- reduces site carbon footprint
- fuelled as 75% directed biogas from nearby refinery
- subsidized through California SGIP

Commercialization Barriers: Fuel Cell Bus

Barriers:

- Purchase cost: 2-3x Diesel Bus
- More fuel efficient than Diesel: 1.8x
- Reliability: ~equal
- Fuel cost: H2 ~1.8x to 1.4x > Diesel
- Maintenance: 1.8x > Diesel

AC TRANSIT

Comparisons with Control Diesel Fleet

Metric	Fuel Cell Sep 2011 thru Mar 2012	Fuel Cell April 2012	Diesel Control Fleet 9/11-3/12
Availability	52%	84.4%	77%
Miles per Diesel Gallon Equivalent	7.36 (7.97 High)	N/A	4.01
MBRC – Vehicle	1,778	5,105 Chargeable	2,212
MBRC -- Propulsion	2,667	6,126	3,573
MBRC – Fuel Cell	6,902	30,630	N/A
Fuel Cost/Mile*	$1.43/Mile	$1.12/Mile	$.79/Mile
Brake Wear	15% @ 43k miles	N/A	28k and 32k mi
Maintenance Cost/Mile* (Shuttle and Training Time)	$1.62/Mile	N/A	$.91/Mile

* September 2011 through February 2012

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- Data courtesy Alameda-Contra Costa Transit District (AC Transit)

Source: National Fuel Cell Bus Program (NFCBP) Webinar May 17, 2012

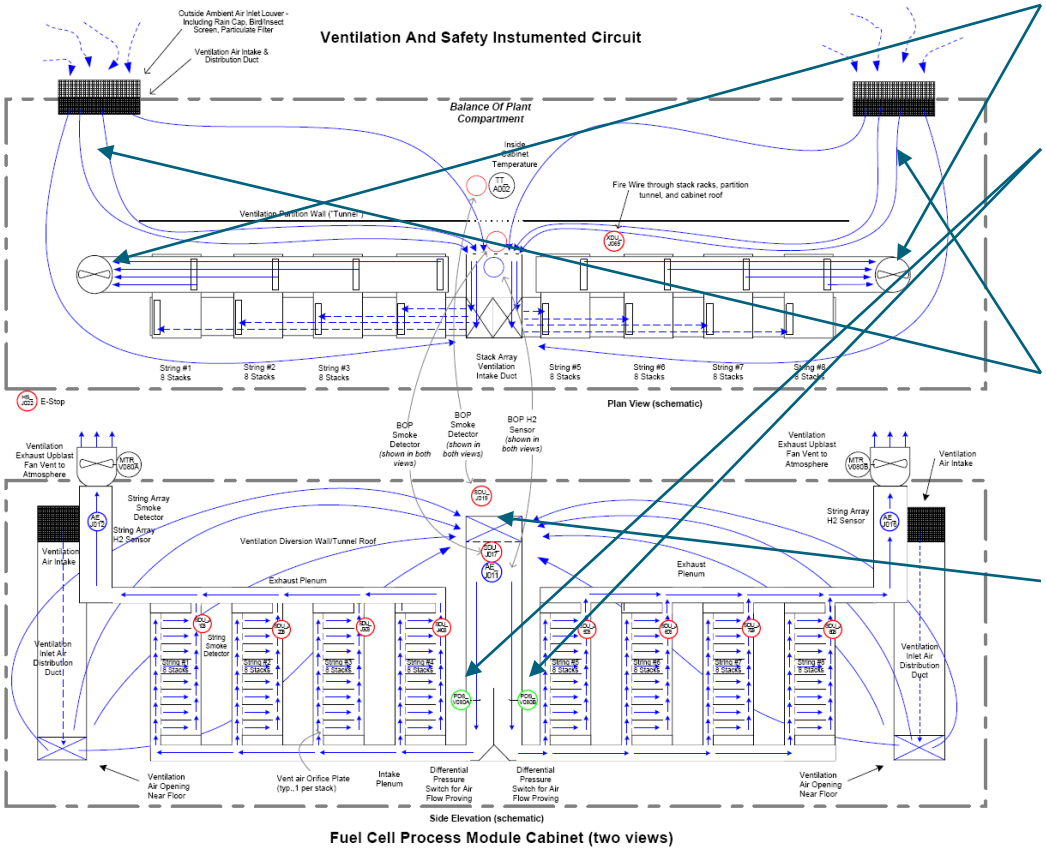
Commercialization Barriers: Distributed Generation

Barriers:

- **No equivalent product that H2 DPG is replacing; different uses possible**
  - Peaker power plant to augment grid on hot days in summer
  - By-product H2 to grid power
  - Green back-up generator
- **Long times between projects even with rapid development of prototypes**
  - Long waits to be paid
  - Expensive to certify
- **Customers are typically large utilities or chemical companies**
  - Want proof of durability & cost-recovery up-front
  - Can be H2 risk-averse

2. Progress on FC product safety hazards
Use of Forced-Ventilation (per FC1 for DPG) for Safety

- Top and Front View of 500 kW DPG Process Module showing Ventilation paths
- 8 Enclosed racks each contain 8 120-cell Ballard FCgen 1300 PEM Stacks
- Loss of ventilation gives shutdown



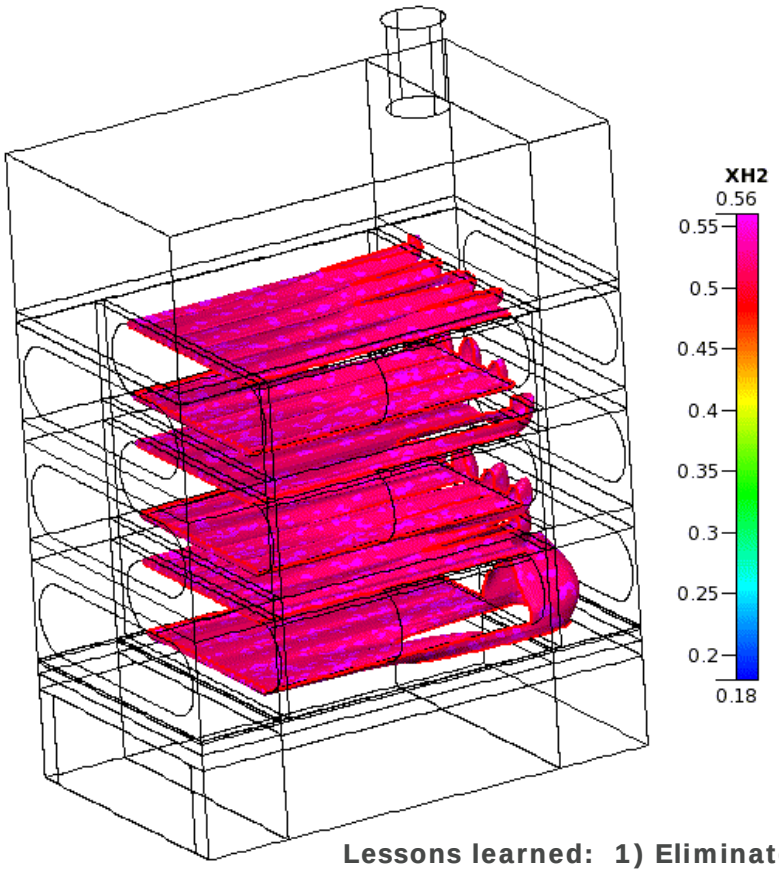
- Air Flow Basics; module is symmetric (2 Fans)
- Differential pressure switches (2) monitoring flow across vent inlets to stack racks (FC1 req't for Flow/Pressure verification)
- Use of duct on intake to force air to bottom of compartment and across Balance of Plant (BOP)
- BOP cooling vent air is then taken into another downcomer duct (in middle) & into stack ventilation plenums

See-through CFD Model of Early Stack Rack Design

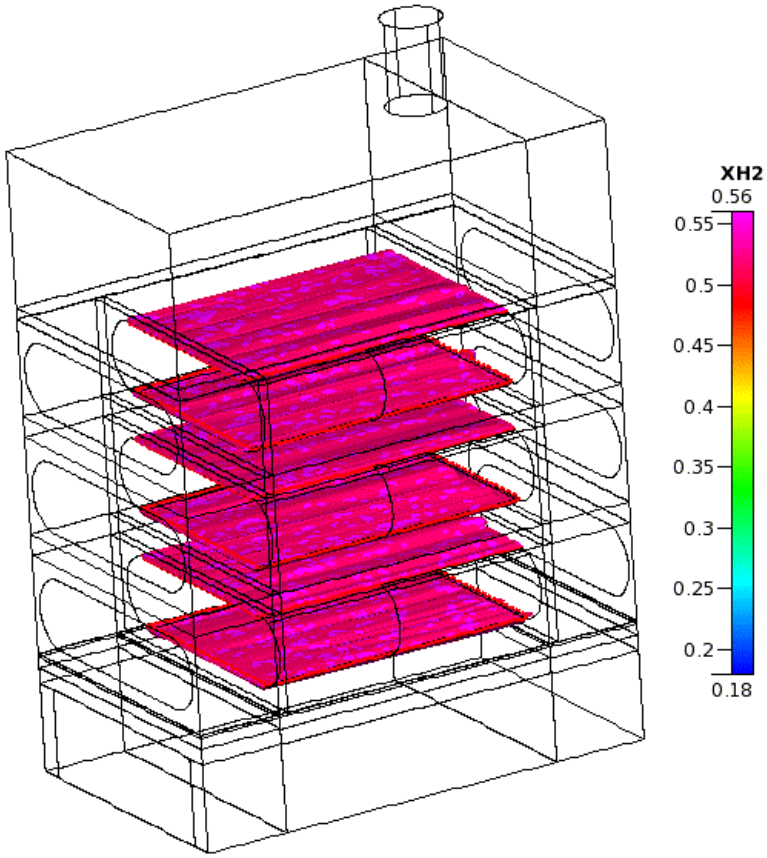
(Each Stack leaks 5 slpm H2; very low vent flow (left), vs. higher (right)

To Visualize use SLIDE MODE

Vent flow = 50 slpm/stack



Vent flow = 500 slpm/stack



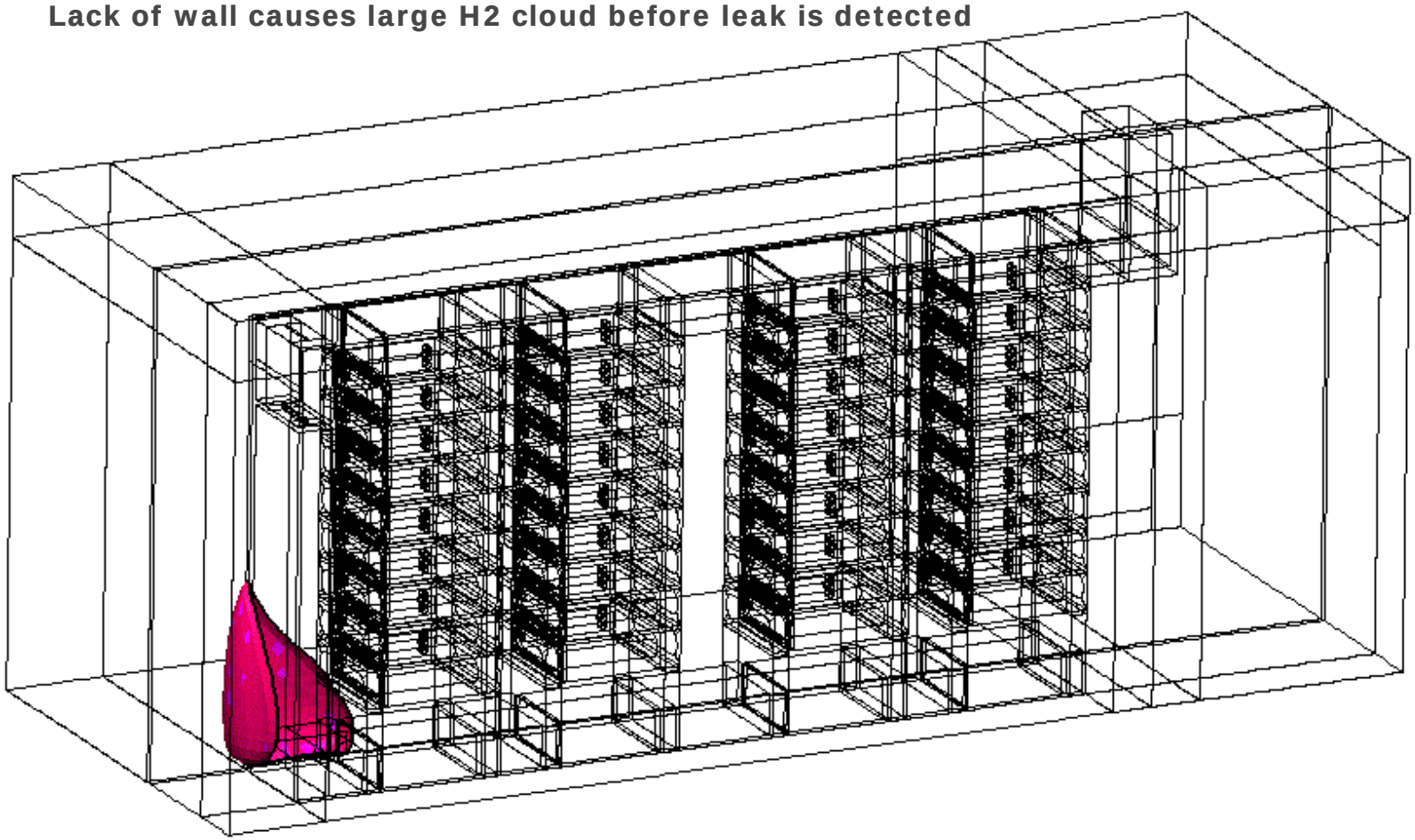
Lessons learned: 1) Eliminate 'dead' zones 2) With low flows, backlighting is possible

H2 Dispersion Inside Half-Enclosure CFD Model

(1% H2 Contour for ~700 slpm Release; first 8 seconds…)

Note: Simulation does not include 'wall' incorporated in design to give faster detection

Lack of wall causes large H2 cloud before leak is detected



Press Shift+F5 for animation

DPG Main Safety Lessons Learned

- Choosing stack ventilation level too low means lack of independence; possible for a failing stack to ignite its neighbour at End-Of-Life (EOL) leak rates
- Choosing stack ventilation level too high gives poor detection of individual stack failures; H2 sensors and Smoke detectors cannot 'see' smaller failures (where these are useful for diagnosing)
- Putting everything in one big box and ventilating it (even with FC1 flow- or pressure-detection of loss-of-ventilation) is likely not safest approach; used 'internal partitioning' wall, sequential ventilation path, H2 sensors, and rudimentary fuel flow monitoring to improve safety.
- Ventilating stacks in parallel requires distributing suction flow (which FC1 prescribes); this is not easy, but it can be done
- Enclosed racks (& 'wall) provide safety, with in-leakage through back of racks giving improved cross-dilution of large leaks

3. Coming at H2 Emission/Leak Issues Step-by-Step

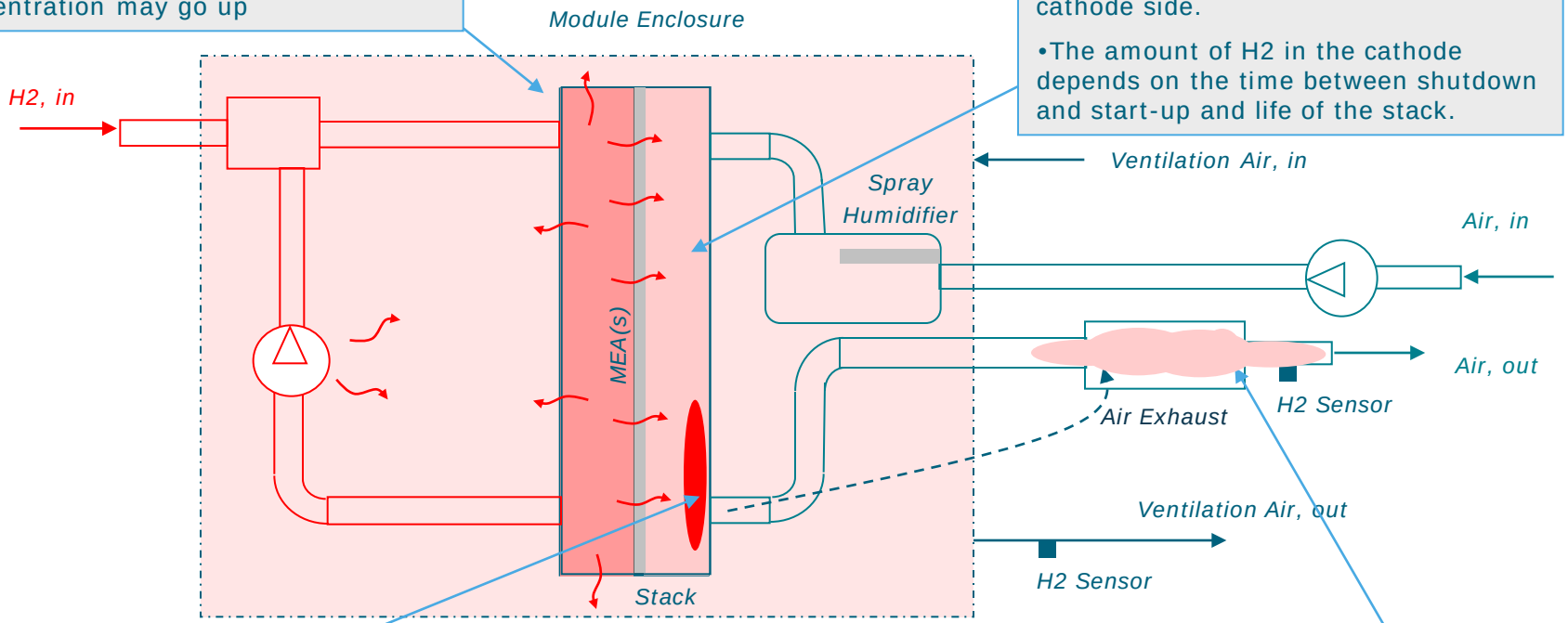
Where do Emissions Come from?

Simplified Schematic showing entire FC Stack as One Cell

•Hydrogen may leak through the Stack seals or from Anode loop HRB into the Bus Module enclosure and H2 concentration may go up

•Hydrogen left in the stack on shutdown will diffuse across the membranes and leak through any transfer leaks to the cathode side.

•The amount of H2 in the cathode depends on the time between shutdown and start-up and life of the stack.



•Some volume of potentially flammable gas may develop in the cathode side of the cells after shutdown in case of large transfer leak.

•This volume gets ejected (typically as a slug) on startup.

•Partial mixing of this slug with air occurs as it passes through the air exhaust system.

How Significant is Hazard of H2 Emissions in HD6 ?

- **External Stack & Anode Loop (H2 Recirc Blower) H2 Leaks are rare**
  - Primarily caused by stack overheat or severe fuel-starvation failures
  - Issue of flammability addressed by ventilating module interior
  - H2 Sensor & Smoke Detector placed in Vent outlet to detect large leaks
  - Module is shut down if/when emissions > 50%LFL (2%H2) occur

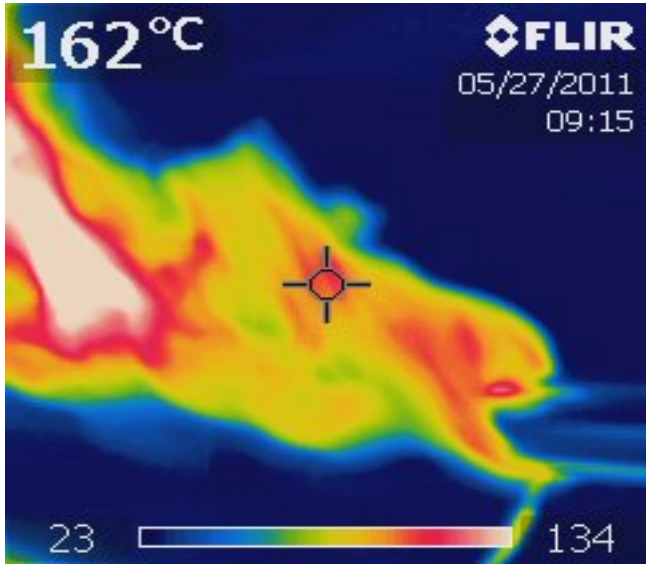
- **Internal Transfer (Crossover) Leaks cause Cathode H2 Emissions**
  - When cells/stacks are new, H2 emissions are minimal/non-existent
  - Diffusion across intact membranes causes O2 consumption of air in cells; produces mainly H2/N2 mixtures in Start-up 'slug'
  - H2/N2 mixtures (with less than 5%O2) cannot burn inside stack or exhaust piping; only when it discharges and mixes with outside air
  - Transfer/crossover leaks cause faster mixing of isolated cathode and anode loop contents; higher O2 levels possible as crossover forces air out of stack into piping
  - H2 Sensor in Cathode exhaust detects continuously high H2 emissions
  - Continuously high H2 emissions primarily caused by stack overheat or severe fuel-starvation failures

Expected Case: H2 Flammable Emissions

- **Expected-case Start-up H2 Emissions**

(Ballard HD6 150 kW Module with <u>intentional</u> ignition of exiting rich mixture)

Photograph (Left) of exhaust with Diesel glow plug, and Infrared Image (Right), from opposite side showing Start-up Flame from 150 kW Bus System Exhaust, with intentional ignition. Normal start-up condition is no ignition and dissipation of small flammable H2/N2 cloud within a few seconds.



Expected case may be a small 'pop' when air is present in start-up slug, but requires ignition

Coming at H2 Emission/Leak Issues Step-by-Step

What we do now, where we are going

- **Present HD6 safety systems: Vent & Cathode Outlet H2 sensors and Smoke Detector**
  - Require expensive periodic calibration; are 'safety critical'
  - Developing filters for H2 sensors to give improved lifetime (vent Ok; cathode next)
  - Would really like to 'move away from' H2 sensors as being 'safety-critical'
  - Thinking of Fuel Flow Monitoring as possible longer-term solution

- **Path to Implement Solution: Seek Funding, Work with Universities**
  - NSERC CRDPJ 412352-11 with Dr. Farid Golnaraghi at SFU (Modeling & Diag)
  - NSERC Automotive Partnership Canada Task 5.7 with SFU & UVic (Diagnostics)

- **Some recent Fuel Flow results installed in 75 kW HD6 Module**
  - Installed Hitachi Mass Flow Sensor and Test station Mass Flow Meter (for testing)
  - Working on Orifice limiting with use of pressure sensors for measuring flow
  - Have begun working on algorithms for pressure-sensor based input fuel flow mismatch with current-consumption flow (See Appendix for details)

4. Conclusions to-Date / Next Steps

Ballard's near-term Fuel Cell H2 research needs are:

- Continue development & implementation of fuel flow monitoring for Bus & DPG H2 leak detection & fault detection for H2 sensors
- Develop CFD tools and approaches for addressing emissions hazard created by H2 / N2 discharges on start-up
- Develop understanding of Fuel Cell recombination effectiveness, where recycling leaked H2 through stacks is highly effective at recombining fuel, but can also create crossover leaks
- Develop improved understanding of Fuel Cell cathode air filtration effectiveness and H2 fuel quality issues (e.g., biogas quality)
- Work with others to qualify / use risk analysis tools and to develop more meaningful standards

Acknowledgements

- **The author would like to thank:**
  - Sanjiv Kumar for performing the CFD simulations of H2 leaks inside DPG racks & enclosures
  - Daniel Zwart and Tyler Docherty from SFU's Mechatronics Systems Engineering department for their continuing work on fuel flow monitoring and H2 sensor fault detection
  - Ian Milne & Jason Cox at Ballard for performing the cathode exhaust ignition tests

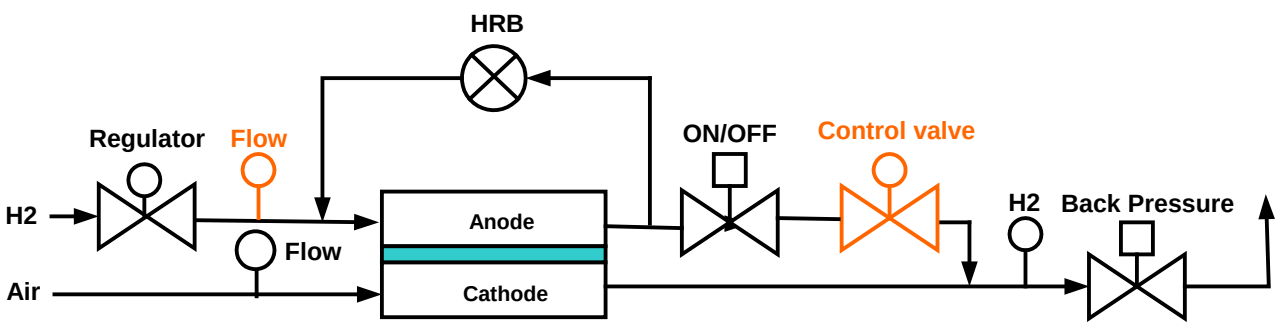
  - NSERC for partially funding this work through a CRD with Drs. Farid Golnaraghi & Erik Kjeang at SFU, and through the Automotive Partnership Canada FC Bus Project with SFU and UVic, and…
  - The NSERC Hydrogen Canada (H2CAN) Strategic Research Network for providing the ongoing opportunity to work with other researchers on interesting hydrogen-related topics

Appendix: Progress on Fuel Flow Monitoring

APC Project Task 5.7 (Overview of approach)
In-situ calibration and fault detection of hydrogen sensors

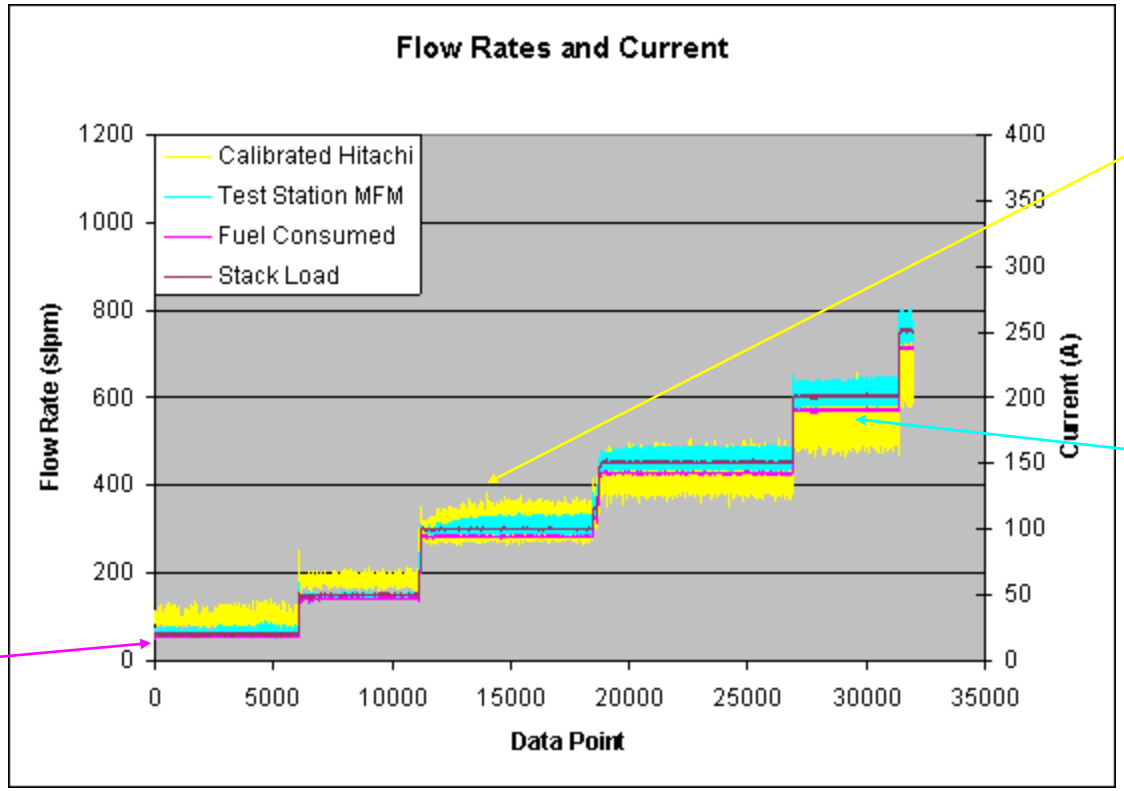
- **Short Term Objectives:**
  1. **Automatic sensor calibration**
     - Reduce service cost
     - Increase sensor lifetime
  2. **Sensor fault detection**
     - Increase system reliability
- **Longer Term Objectives**
  1. **Eliminate cathode sensor**
     - Reduce cost
  2. **Estimate anode hydrogen concentration**
     - Improve fuel utilization

- **Build redundancy in hydrogen emission reading**
  - **Add hydrogen flow sensor**
  - **Add control valve for hydrogen flow control (continuous purge)**
  - **Use flow measurements to estimate hydrogen concentration**
    - Reduce fuel overpressure to eliminate leak
    - Use Kalman filter for real time monitoring
      - Treat leak as disturbance



Results of Fuel Mass Flow Monitoring (after Instrument Checkout)

2012 June 1: Refined Hitachi MFS signal by adding longer tubes; addressed scaling issues in Test Station software; can now see purging & fuel loss more clearly



Less noise in Hitachi signal when longer flow tubes added

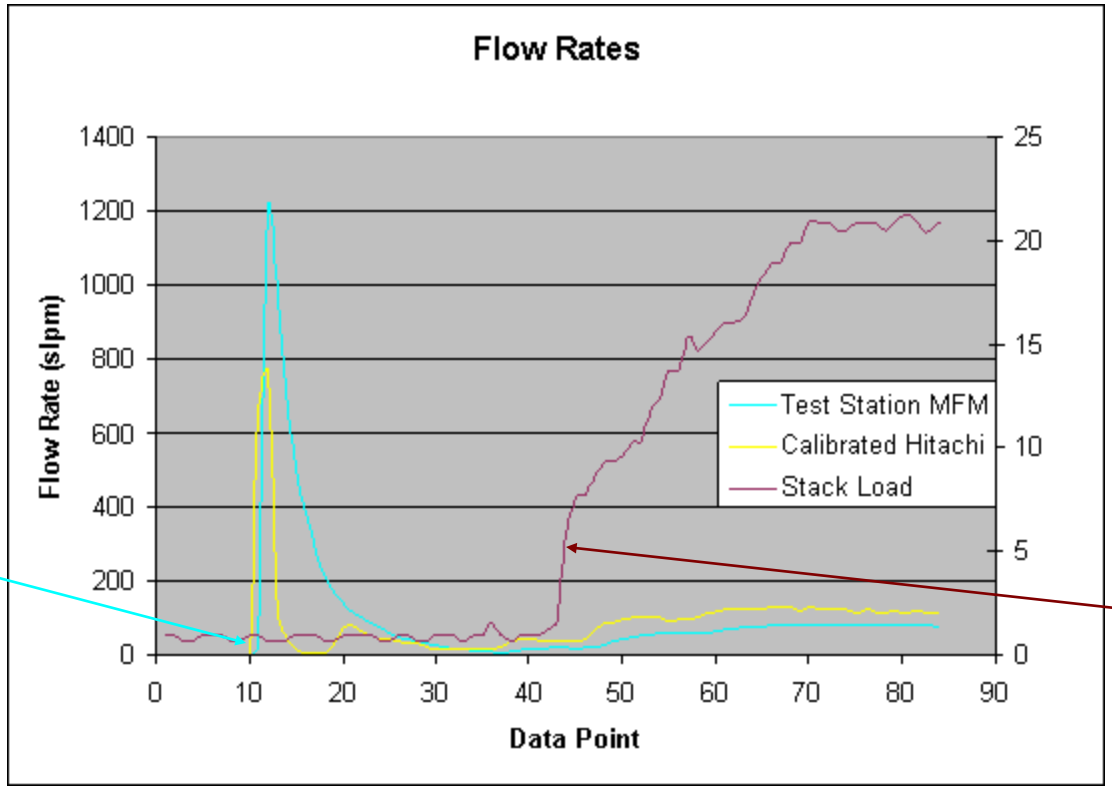
Fuel Consumed by Stack Current is sometimes higher than measured input flow at high currents; suspect MFM calibration or Current Sensor reads low; or reality may be that transfer leaks seal due to high water production (?)

Fuel Consumed by Stack Current (pink lower line) is typically lower than measured fuel flow at lower current levels

Data scan-rate is 10 points/second; 1000 points is 100 seconds

Results of Fuel Mass Flow Monitoring (after Instrument Checkout)
(Start-up 'looks' like a big leak…)

2012 June 1: Start-up Testing reveals large 'spike' in fuel flow as system initially fills; spike falls quickly for Hitachi hot-wire anemometer but slower for upstream Bronkhorst MFM



Fuel supply valve (SOV:H0) opens causing brief surge in fuel flow as system charges

Once stack voltage has come up, current draw can begin

Looking at 'fill'-time effect, detection of very large H2 leaks may be possible in under ~2 sec!

Data scan-rate is 10 points/second; 10 points is 1 seconds;
'Fill' time is ~1 second or less depending on flow measurement device.

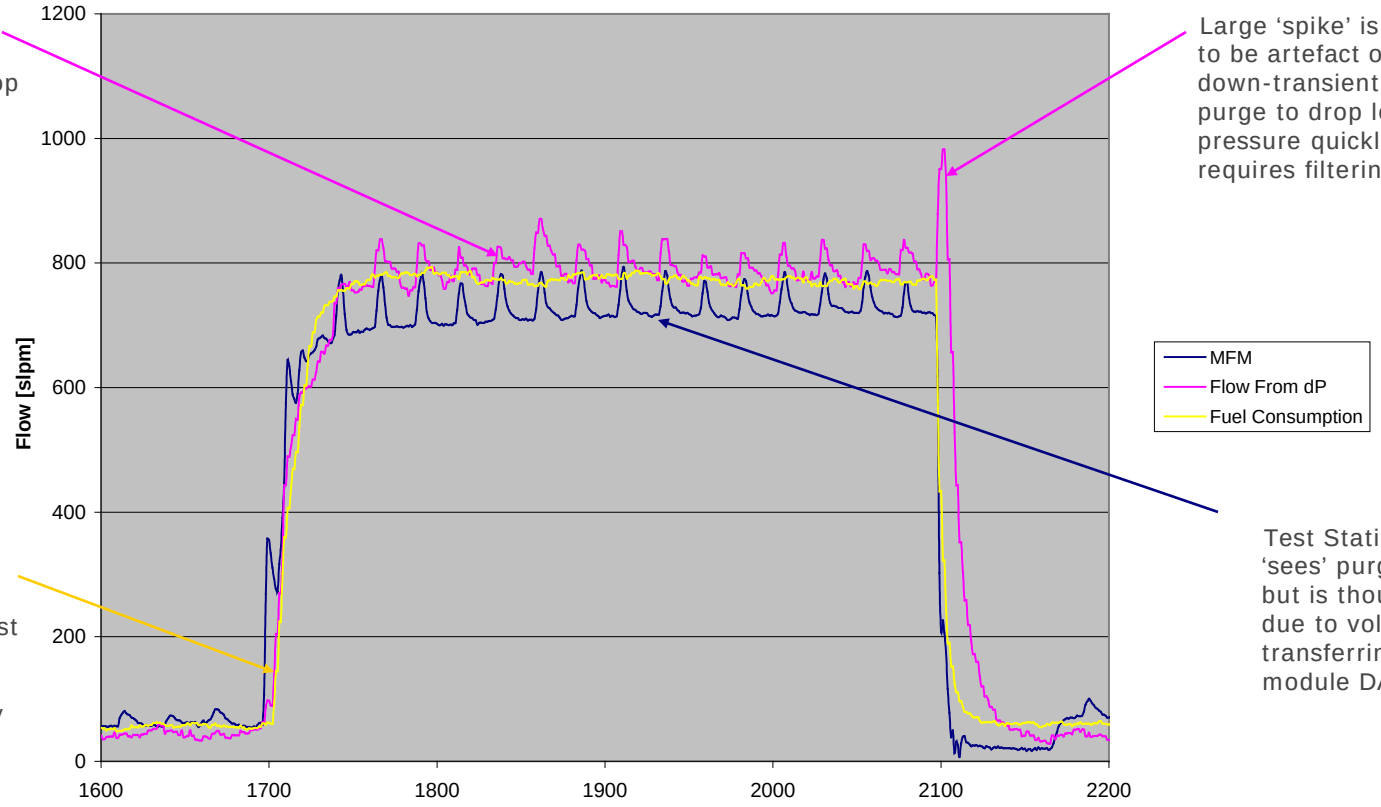
Preliminary Results of Pressure-Sensor-Based Input Flow vs. Current Consumption Flow (Step Current from 20A to 250A & down to 20A)

2012 Oct 12: Comparison between Fuel consumed by current (Yellow curve) and Input Fuel Flow calculated from dP across 0.086" orifice (Pink Curve) shows latest transient response & issues

Single Cycle Flow Comparison (High Current Step)

Small 'spikes' are H2 purges from anode loop

Large 'spike' is thought to be artefact of sudden down-transient (or big purge to drop loop pressure quickly); likely requires filtering



Current based flow signal should lead Test Station MFM; possibly some unknown delay in current sensor.

Test Station MFM also 'sees' purging 'spikes' but is thought to be low due to voltage loss in transferring signal to module DAQ

Data scan-rate is 10 points/second; 100 points is 10 seconds

Conclusions to Date / Next Steps

Conclusions:

- Use of fuel flow monitoring appears viable to find large H2 leaks quickly
- Fuel flow measurement devices are expensive and their response and accuracy affect ability to detect leaks quickly and accurately
- Use of an orifice as a method for both limiting flow and increasing dP suggests that simple pressure transducers can work for flow measurement
- More testing is needed before this idea can be used to 'correct' or replace H2 sensors, but initial work is promising
- This type of sensor development is well-aligned with Mechatronics Systems Engineering areas of expertise, and collaboration with SFU has been useful & rewarding