BALLARD®

power to change the world

Membrane Requirements for Stationary Applications




Ballard Power Systems

High Temperature Membrane Working Group Meeting

November 16, 2009

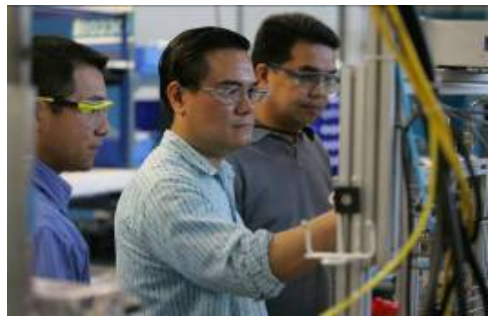
Outline

- Introduction to Ballard and its Market Focus
- Comparison of Stationary and Automotive Requirements
- Membrane Testing Methodology
- Results & Summary

About Ballard

CLEAN ENERGY FUEL CELL PRODUCTS…

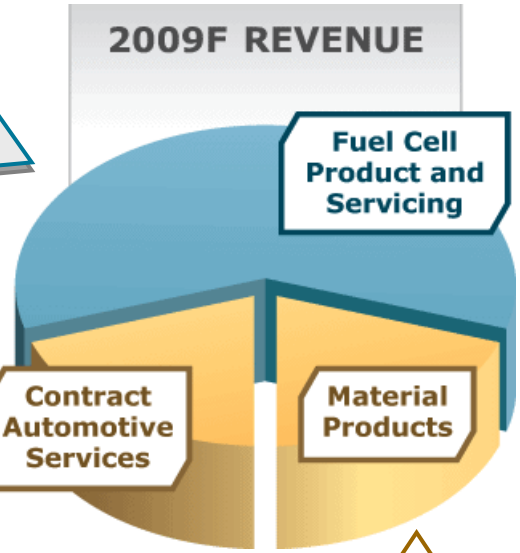
- OUR COMPANY
  - Approximately 335 employees
  - World-leading R&D & manufacturing facilities
  - Locations in Vancouver, Canada (HQ) & Lowell, MA
- OUR BUSINESS
  - Design, manufacture, sale & service of hydrogen fuel cell products
- OUR CUSTOMERS
  - System integrators and OEM's addressing end-user needs: materials handling, telecom backup power, residential cogeneration, and transit buses
- OUR FOUNDATION
  - *Technology Leadership* – 350+ Patents and patent applications
  - *Production Expertise* – Shipped over 100MW fuel Cell Products
  - *Expanding Go-to-Market Capabilities* – Powered over 1,000 stationary installations and over 200 heavy and light duty vehicles



Lines of Business

Clean Energy Fuel Cell Products

Motive Power	Stationary Power
	



Contract Automotive Services – contract technical & manufacturing services

Material Products - Carbon fiber products & gas diffusion layer materials

Fuel Cell Growth Markets

BALLARD

Fuel Cell Growth Markets

Stationary Power		Motive Power	
Backup Power	Distributed Power Generation	Material Handling	Heavy Duty
			
	FCgen™		FCvelocity™

Leading Fuel Cell Products Portfolio

PRODUCTS	Power Level (gross)	Life	Product Positioning
Stationary Power			
FCgen™-1020ACS	0.3 – 3.4kW	4,000 hrs	Telecom backup power
FCgen™-1300	2.3 – 11kW	10,000 hrs	Telecom backup power
Motive Power			
FCvelocity™-9SSL	4.4kW – 19.3kW	10,000 hrs	Material handling applications
FCvelocity™-HD6	75kW & 150kW	6,000 hrs	Bus & other heavy-duty applications

Market Focus: Backup Power

Market Opportunity

- Initial focus on replacing batteries in wireless telecommunications
- In areas with a highly reliable electrical grid
- Addressable market: ~$350M

Drivers

- Extended runtime
- Highly durable, even at extreme temperatures
- Minimal annual maintenance
- Regulatory requirements for extended runtime (e.g. TETRA)

Channels

- System integrators – key relationship with Dantherm/Motorola (123 stacks delivered)
- Network equipment providers
- Power equipment OEMs

Market Focus: Supplemental Power

Market Opportunity

- Initial focus on replacing diesel generators and batteries in wireless telecommunications
- In areas where the electrical grid is unreliable, e.g. developing countries
- Addressable market: ~$1bn

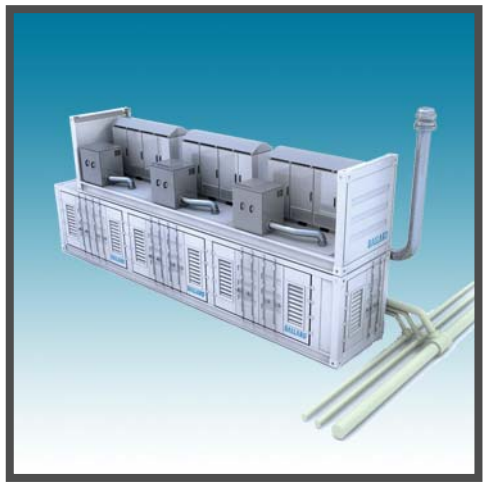
Drivers

- Lower maintenance costs due fewer moving parts
- Lower noise and reduced emissions
- Broader fuelling options
- Lower fuel costs due increased efficiency

Channels

- System integrators – key relationship with ACME/IdaTech (~620 stacks delivered)
- Network equipment providers
- Power equipment OEMs

Market Focus: Distributed Generation



Market Opportunity

- Utility peak load management
- Megawatt-scale applications where there is byproduct hydrogen available and a feed-in tariff program in place to underpin demand

Drivers

- Supportive feed-in tariff policies (Korea, Germany, California, etc.)
- Increased utility focus on clean energy generation

Channels

- Direct with chemical company or utility
- Demonstration program with FirstEnergy
  - Portable 1 MW peak load management solution
  - Delivery scheduled in Dec/09

Market Focus: Material Handling

Market Opportunity

- Addressable market: Plug Power indicates ~380k trucks of an installed base of 1.7M trucks in North America
  - Market potential > $1.5bn
- Reference sites in place, full-facility implementations beginning
- Initial focus on battery replacement in high volume distribution centers in North America

Drivers

Productivity gains from:

- Increased lift truck uptime
- Consistent power
- More productive warehouse floor space

Channels

- Ballard is exclusive supplier of fuel cell stacks for Plug Power's GenDrive™ product line of fuel cell battery emulators through December 31, 2010
- Over 850 systems deployed to date with key customers, such as Wal-Mart, Sysco, Bridgestone, Central Grocers

Market Focus: Bus

Market Opportunity

- Zero-emission public transit
- Government supported programs in countries throughout the world (e.g. Canada, UK, Brazil, Germany)

Drivers

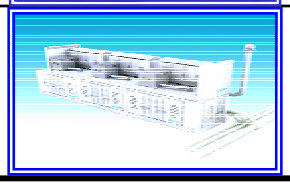
- Government subsidies
- Reduction in GHG emissions & elimination of SOX / NOX

Channels

- Bus OEM's and Systems Integrators
- ISE/New Flyer (BC Transit 2010 Olympic Fleet – 20 buses for the largest fuel cell bus fleet worldwide)
- FC buses have transported +8M passengers in revenue service in 15 cities worldwide

Durability Requirements

*DOE '11-15 targets

	Application	Hours
	Materials handling	10,000
	Backup power	4,000 -24,000
	Residential cogeneration	40,000*-80,000
	Automotive (light duty)	5,000*
	Automotive (bus)	20,000
	Distributed Power Generation	30,000+ (up to 120,000)

Product Development Capabilities

Durability as a Function of the Operating Condition Dynamics

85 kW

Mark 902
Light Duty
Transportation

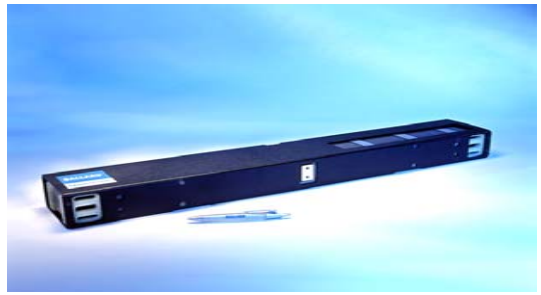
- Pressure: 3 bara
- Duty cycle: Fast Dynamic
- Durability: ~1,000 hr

180 kW

Mark 902
Heavy Duty
Transportation

- Pressure: 3 bara
- Duty cycle: Medium Dynamic
- Durability: ~3,000 hr

4 - 21 kW

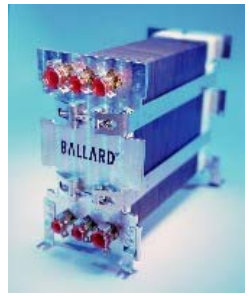


Mark9 SSL™
Forklifts

- Pressure: 2 bara
- Duty cycle: Slow Dynamic
- Durability*: ~10,000 hr

* Based on limited product test data

1 kW



Mark1030 V3
Cogeneration

- Pressure: 1 bara
- Duty cycle: Slower Dynamic
- Durability*: >40,000 hr

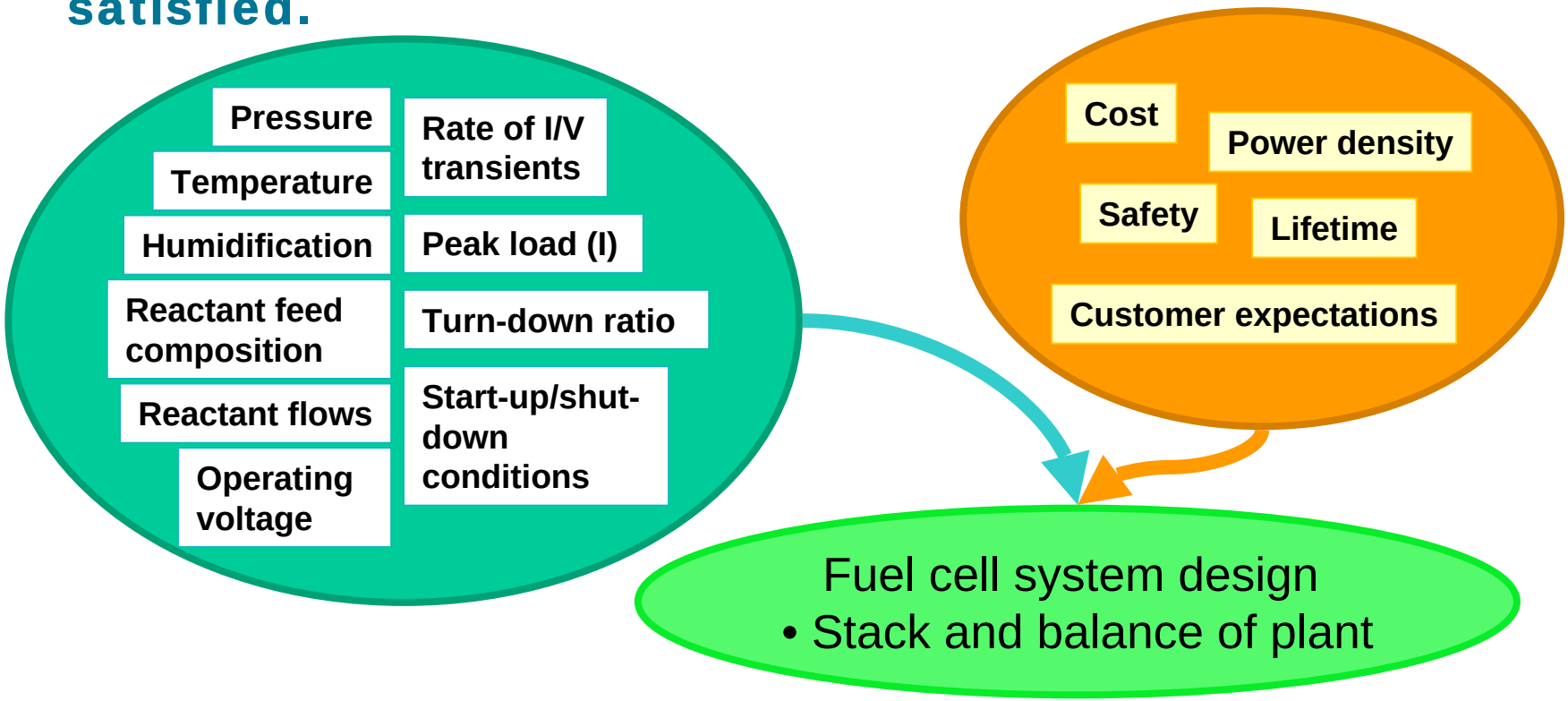
* Based on ASTs

Same Stack Technology….

- Meets needs of many applications
- Durability is dependent on operating conditions

Lifetime Requirements

- **Required lifetimes must be achieved over a range of operational conditions, both expected and "out-of-spec".**
- **Other key system attributes must be simultaneously satisfied.**



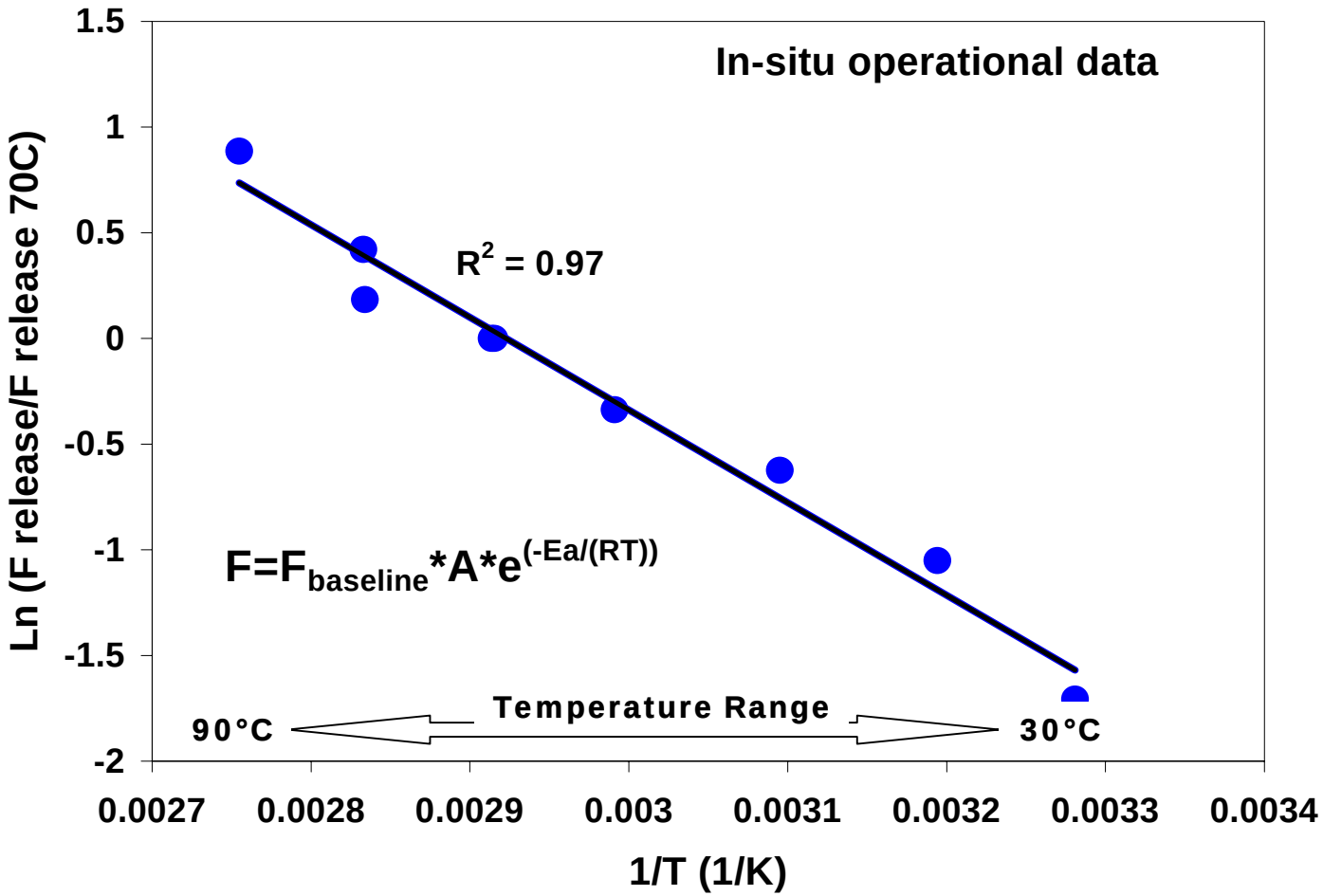
Requirements Comparison

Stressor	Stationary	Automotive
Efficiency	Fuel efficiency critical, drives V to ~0.7 or higher	Peak operating point generally <0.7V
Temperature	Fairly steady operation, high temperature maintained over duty cycle, depends on co-gen requirement.	Higher temperature required, but generally only at peak power.
Humidification	Drive to reduce humidification, simplify control systems	
Transient operation	Very slow dynamics, fairly steady state	Can be very rapid dynamics
Fuel	Reformate (CO, airbleed)	Hydrogen
Accelerated testing requirements	40,000h+ requires predictive capability	5000h allows screening accelerated tests only
Lower cost materials	Increased contamination levels	
Freeze-start	Less critical, freeze-thaw generally okay.	Required.

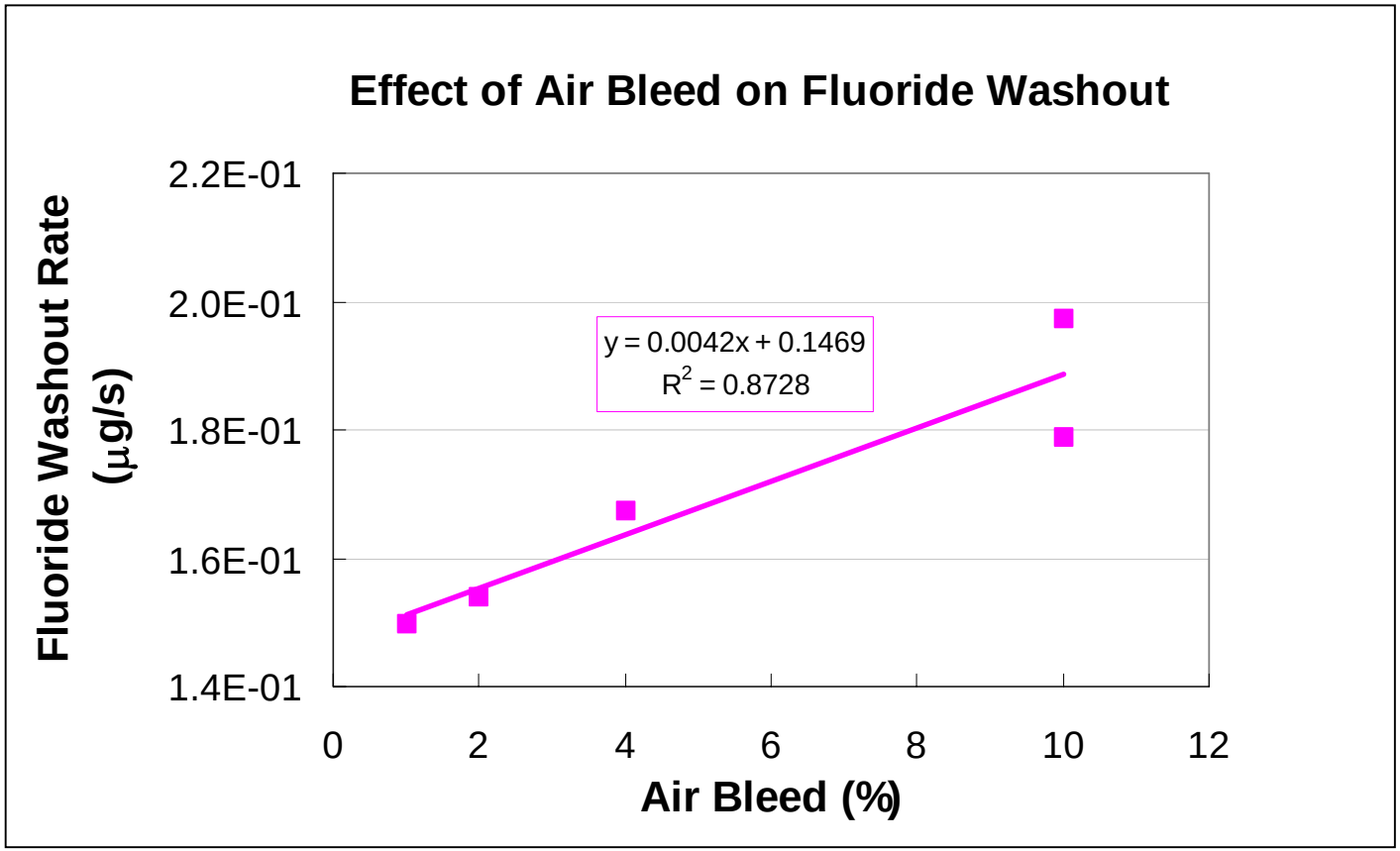
Temperature has a Strong Impact on Membrane Degradation

BALLARD

Arrhenius Plot for Membrane Degradation

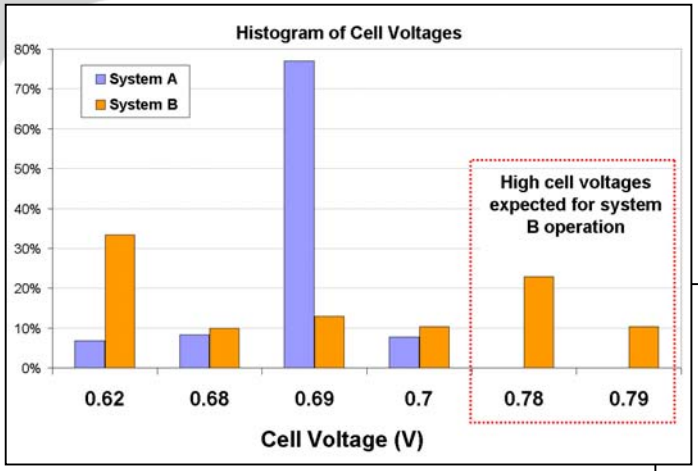


Air Bleed Effect



- Increased AB results in increased local temperatures
- Oxygen on anode creates peroxides

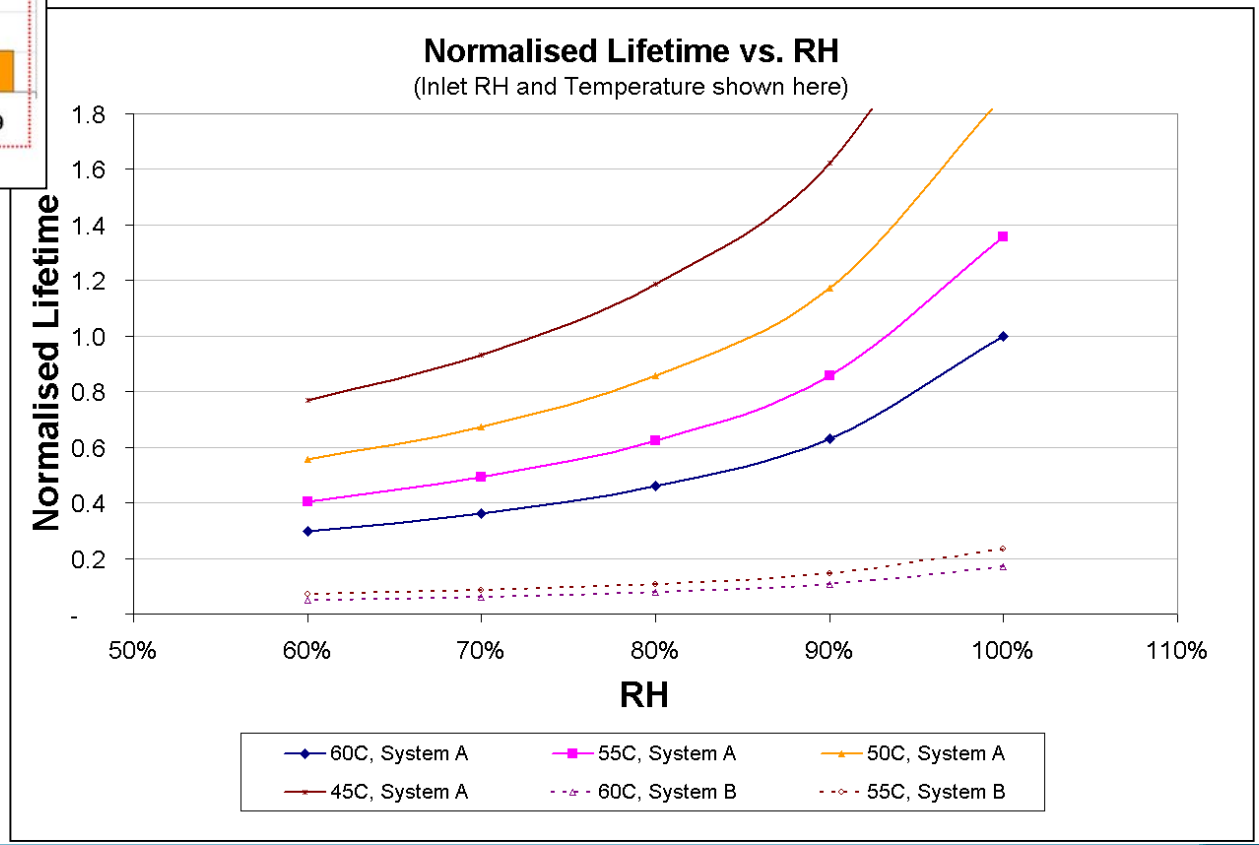
Effect of Operational Stressors on Predicted Membrane Lifetime



Operating Voltage

Relative Humidity

Temperature



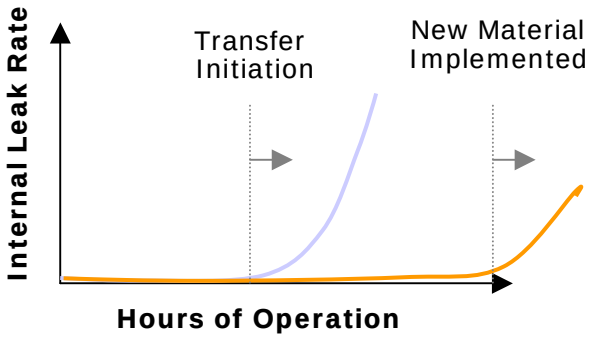
Membrane Testing Methodology

- **Accelerated stress test (AST) for screening purposes**
  - COCV and OCV tests
  - A “hammer” test to screen components efficiently for relative durability comparisons
- **Accelerated durability test (ADT) with predictive capability**
  - Test failures are correlated to field failures
- **Lifetime tests**
  - Tested by programs at BPS or customer sites
  - Provides validation to accelerated durability tests

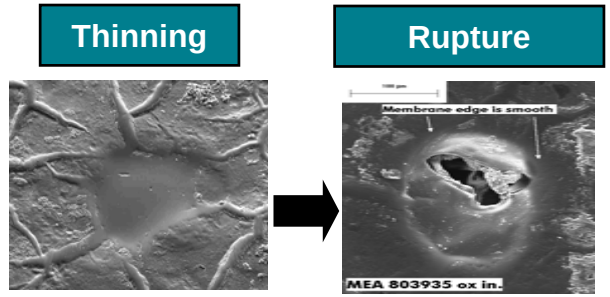
Membrane AST

Internal Transfer Development – Peroxide Radical Attack on Perfluoroionomers

OBSERVATION OF FAILURE MODE

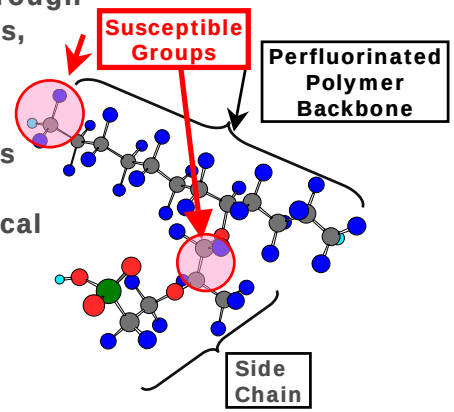


FAILURE ANALYSIS

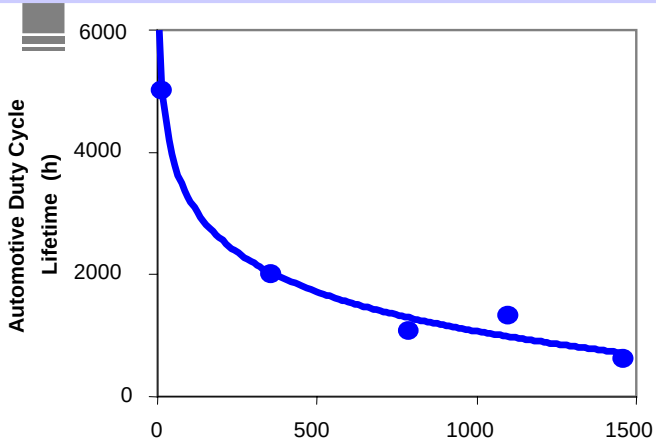


FUNDAMENTAL UNDERSTANDING

1. Peroxide generation in fuel cell
2. Peroxide radical production through reaction with Fenton's catalysts, such as iron (Fe^{2+})
3. Attack of membrane by radicals resulting in loss of material (thinning) and loss of mechanical strength
4. Rupture of membrane due to mechanical stresses

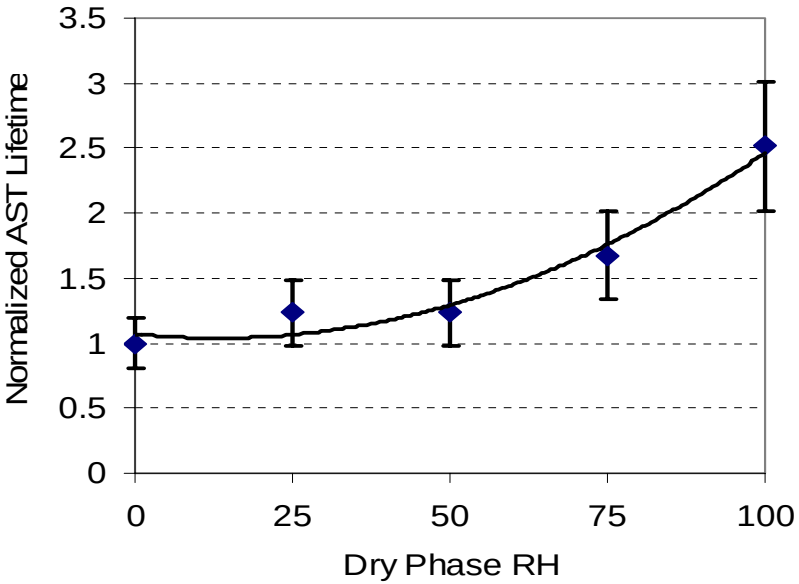


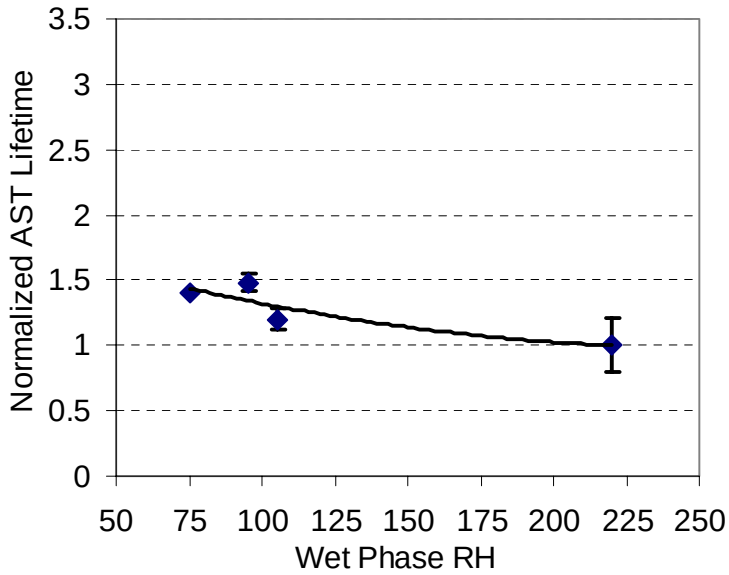
ACCELERATED STRESS TESTS



Membrane AST (cont.)

Mechanical Stressor Sensitivities





- Under wet-dry cycling, humidity transients to even 50% RH reduced the AST lifetime by 50% while larger transients show little additional effect.
- Over-saturated RH transients also reduced lifetime, but to a lesser extent than did the dry-phase.

Membrane ADT Development

Objective

To accelerate membrane failures by a factor of 20 to 40 times, so that 40k hours can be tested in 1k to 2k hours.

Approach

Fundamental understanding from R&D

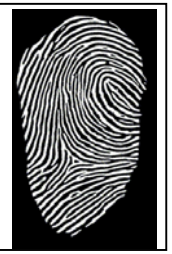
- Understand membrane degradation mechanisms
- Understand stressors that accelerate membrane degradation

Identify stressors due to system operation

- Temperature, RH, air bleed, wet-dry cycles

Characterization of failure finger print

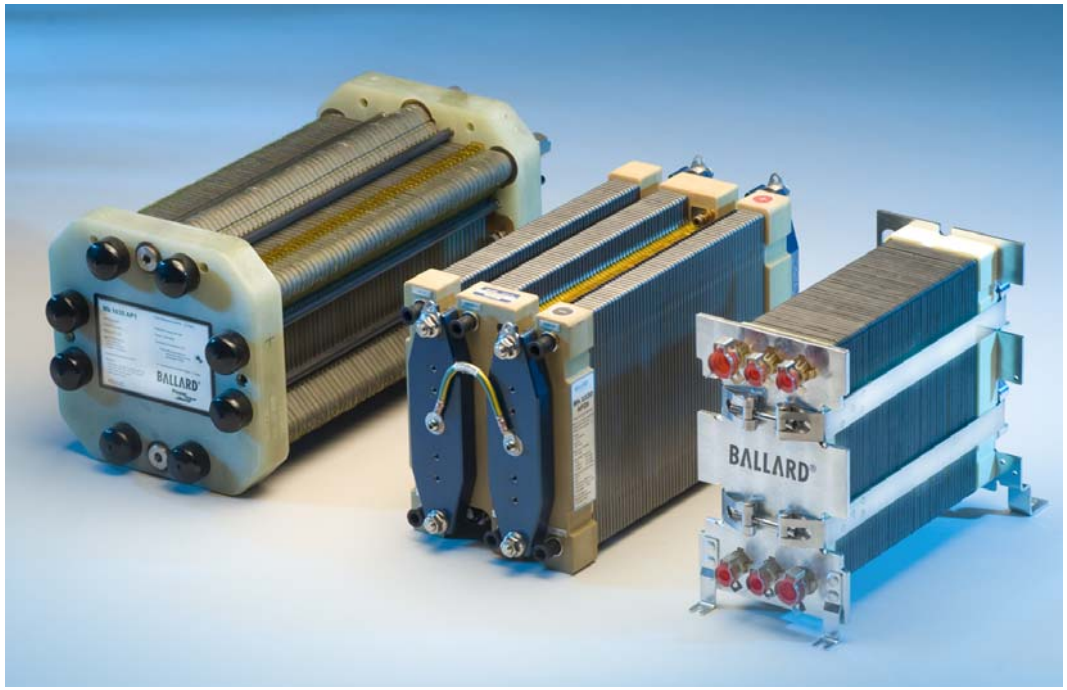
- Failure analysis of membrane from field return stacks
- Characterize membrane thinning, divots, tears



Develop accelerated tests to replicate failure finger print

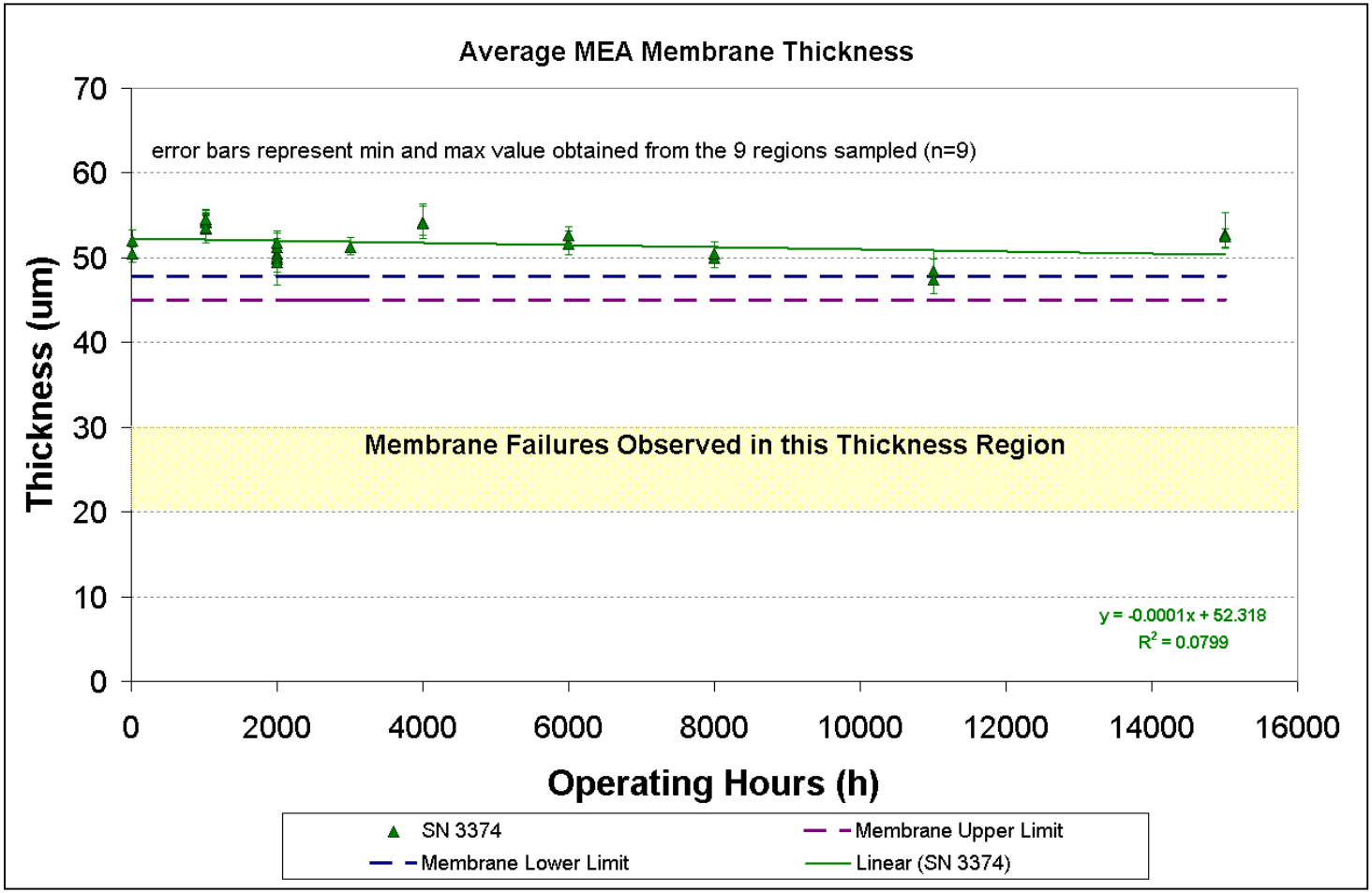
- Tune stress levels until test failure finger print matches with field return

Cogeneration Product Lifetime



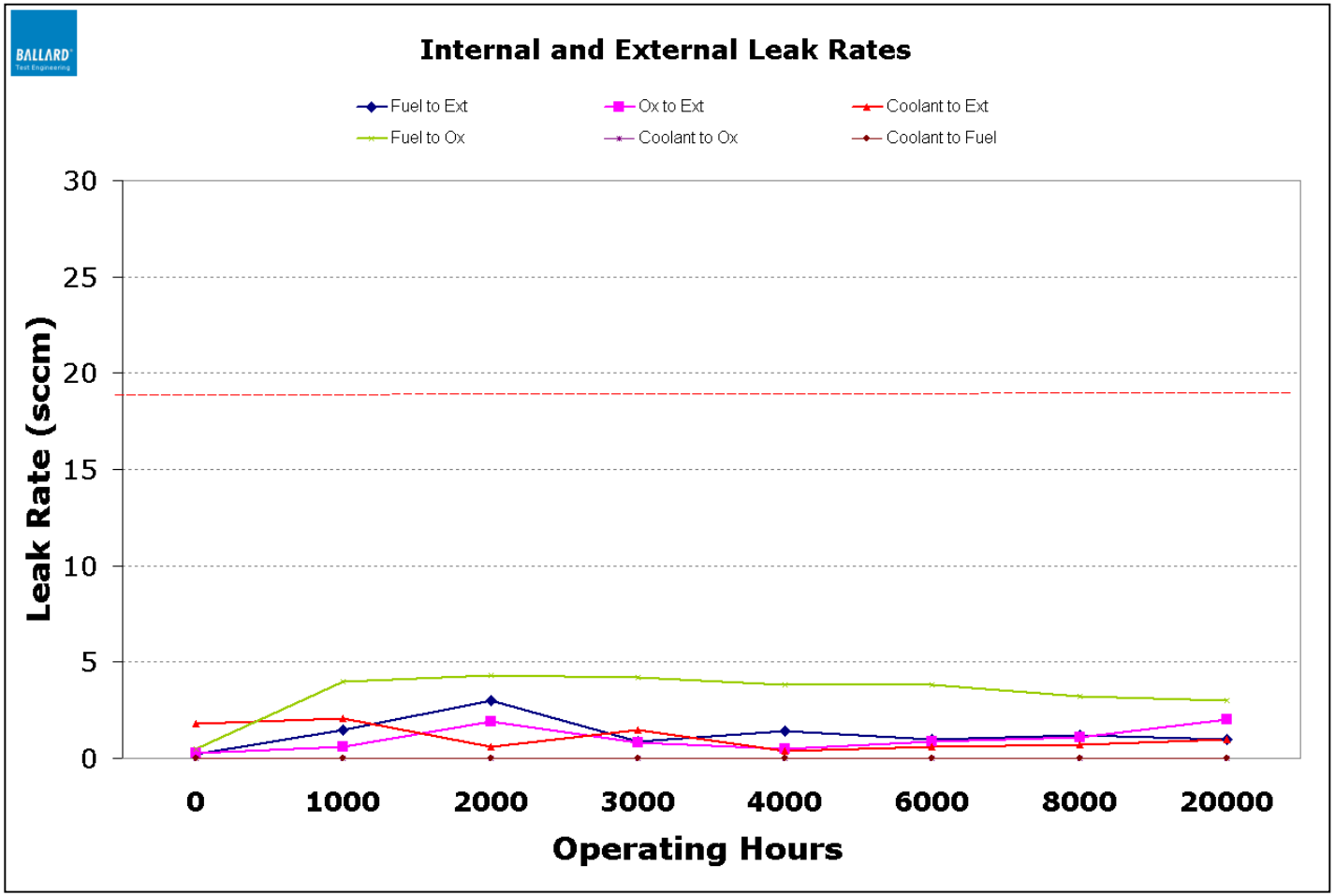
Stack Design	ADT (hours)	Actual Lifetime (hours)	Acceleration Factor	Predicted Lifetime (hours)
AP2a	300	7500	25	
AP2b	1600	20,000+ (no failure)		40,000
V3	>1600	20,000+ (no failure)		> 40,000

Stack Lifetime Data
Membrane Thickness



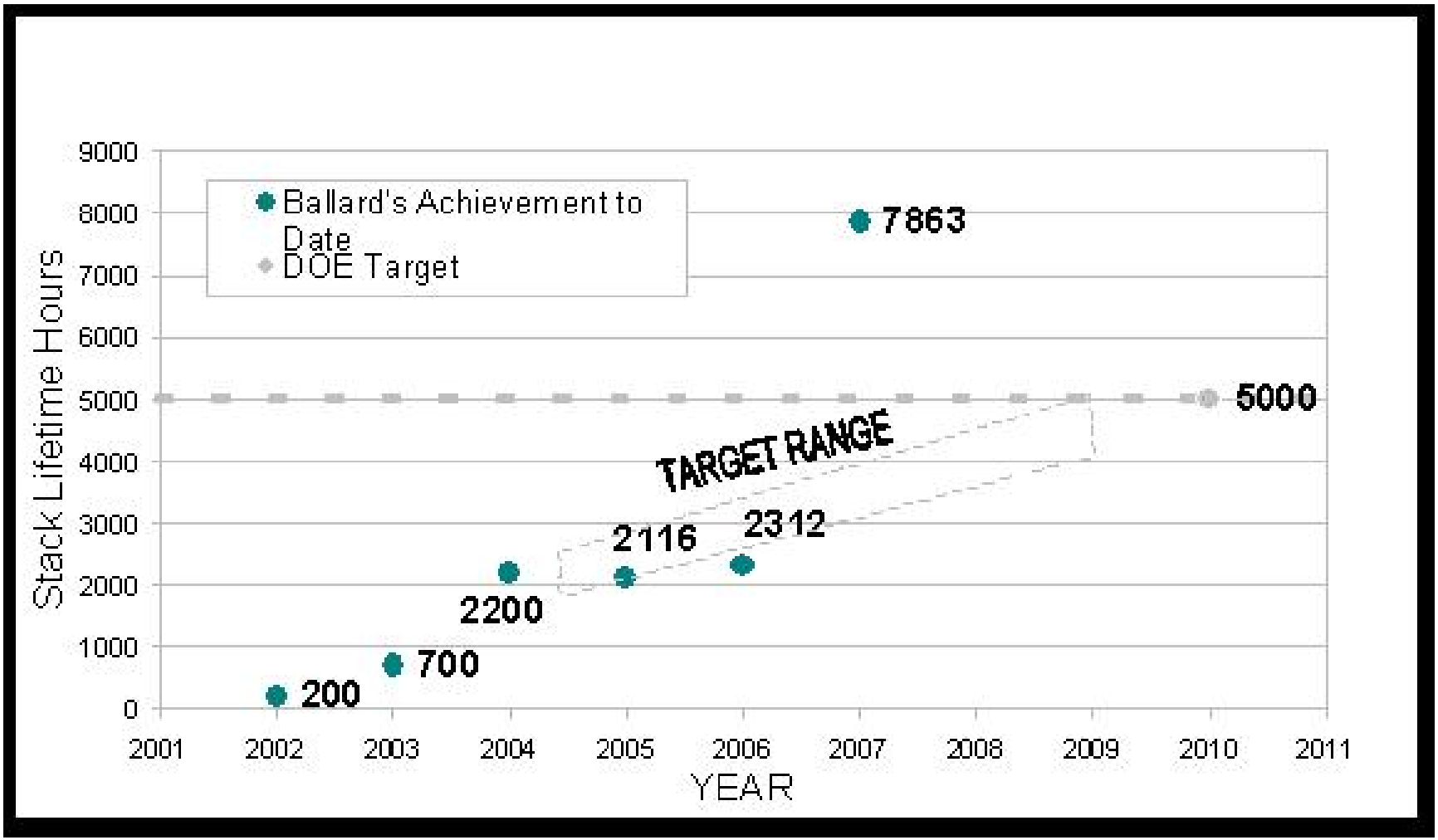
- **No membrane thinning observed up to 15,000 hours**

Stack Lifetime Data
Leak Rate



- No external leaks observed up to 20,000 hours

Durability Progress - Automotive



Chiem, B. et al., "The Development And Demonstration Of Technology On The Path To Commercially Viable PEM Fuel Cell Stacks", *ECS Conference*, October, 2008

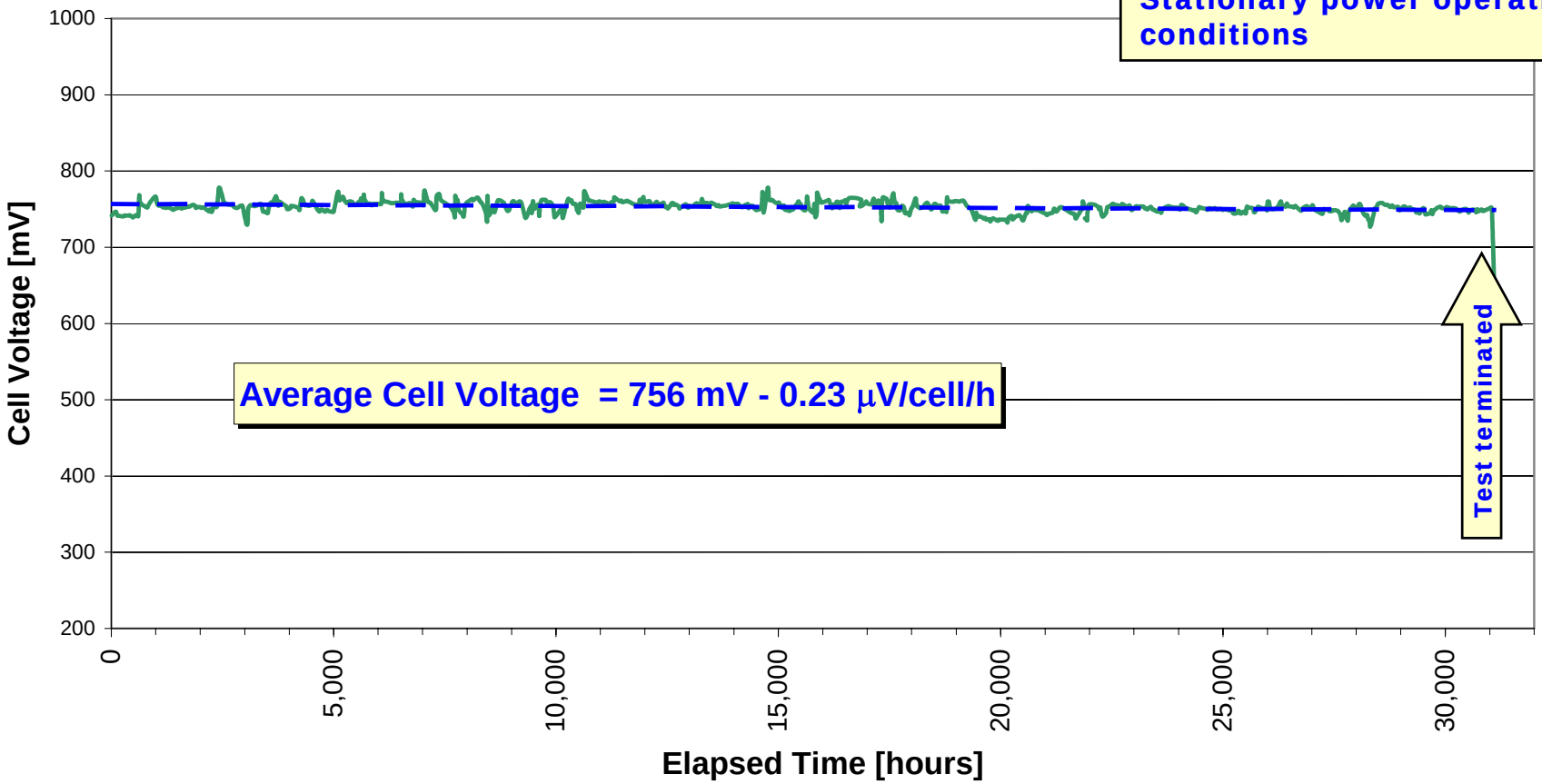
Stationary Power Laboratory Testing

>30,000 hours Lifetime Achieved

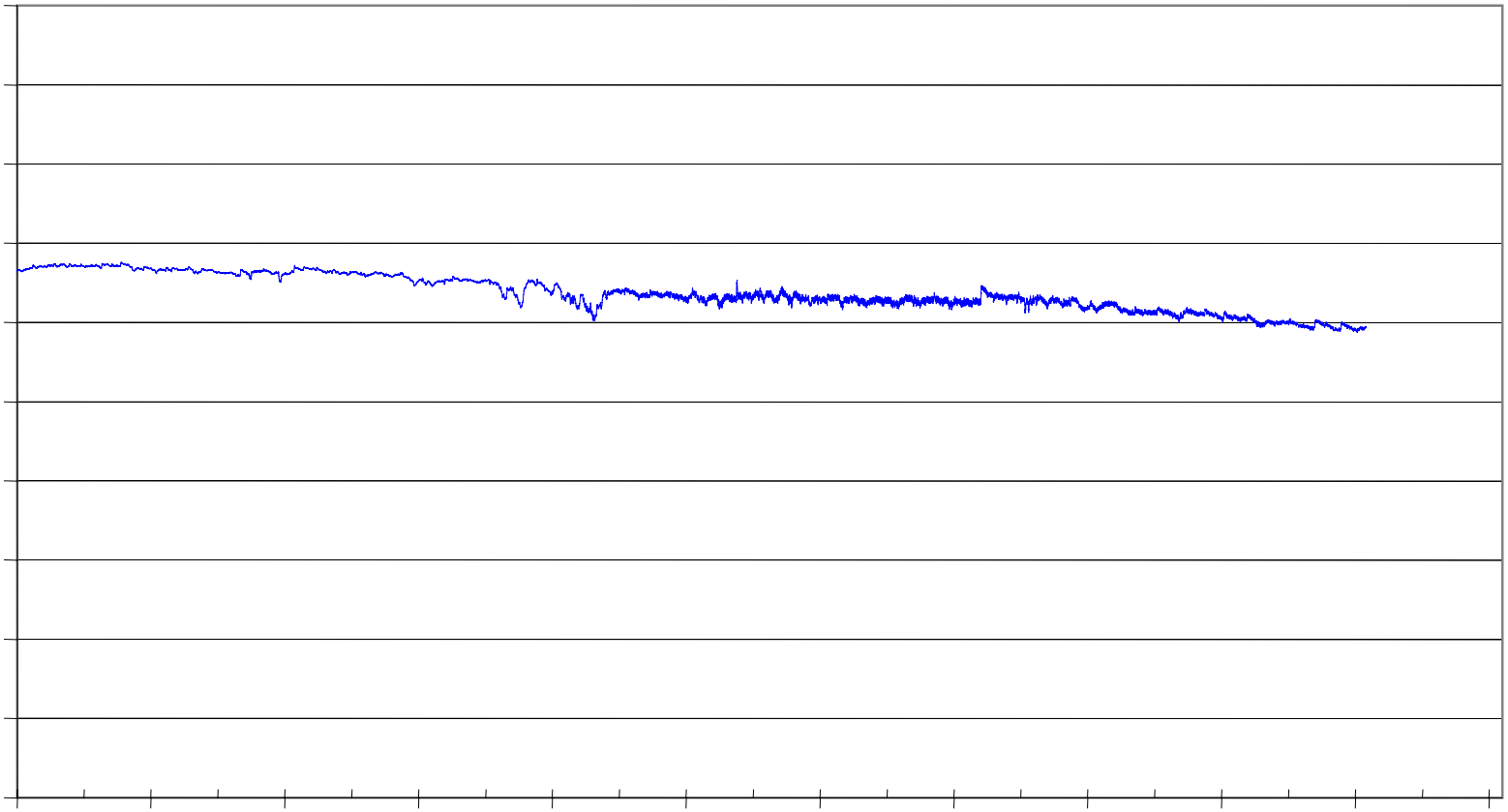
BALLARD Test Engineering

EDH 156.02 - Operating at 0.163 A/cm^2
June 29, 2001 - Apr. 24, 2006

20-cell stack
1.3 mg/cm2 supported Pt
50 micron membrane
Stationary power operating conditions



FCgen™-1020ACS Lifetime



Summary

	Air Cooled	Liquid Cooled
Cost ($/m2 @ 5000 m2/year)	~100	~100
Lifetime (hrs)	20000	> 15000
Voltage (V)	0.5 to 1.2	0.7
Turn down ratio	20	5
Temperature (°C)	85	>70
Peak Temperature at outlet (°C)	90	80
Relative humidity at inlet (%)	0	60 -100
RH cycles (% range)	0 - 100%	50 - 100
Reactant gas pressures (Bar a)	0 to 1.5	1.05
Pressure differential across membrane (Bar a)	0.5	< 0.5
Freez-thaw (°C)	-40	n/a

- **Ballard is global fuel cell product leader offering a leading clean energy alternatives**
- **Significant advances in fuel cell durability have been achieved in recent years**
- **Stationary applications provide further technical challenges for fuel cell membrane development**

Acknowledgements

- **The following Ballard employees should be recognized for contributing to the content of this presentation**
  - Bien Chiem
  - Shanna Knights
  - Mike Lauritzen
  - Yeng Lim