ACAL Energy PEM Fuel Cell Technology

Dr Andy Creeth
Chief Technology Officer
ACAL Energy

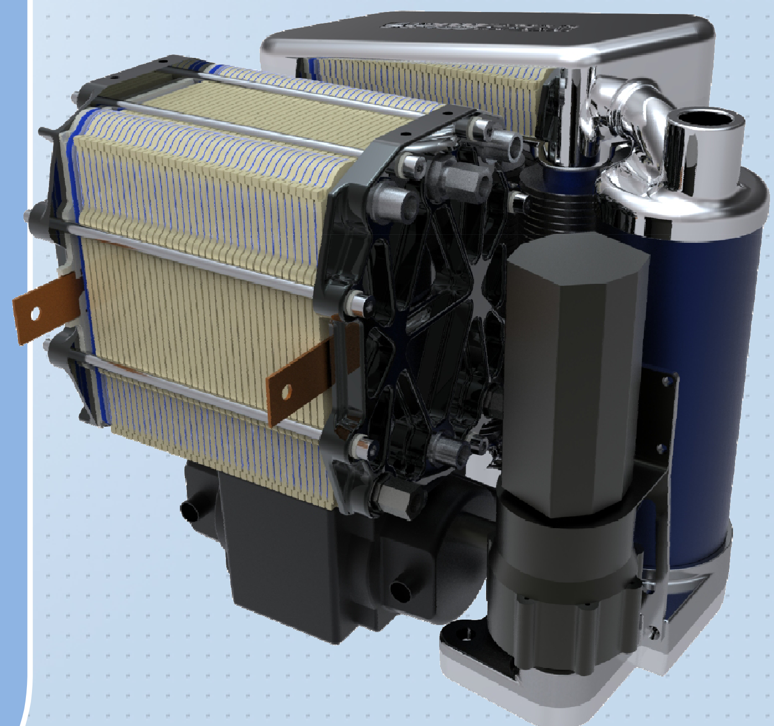
Agenda

- **ACAL Energy Company Background**
- ACAL PEM Technology
- Advantages of Technology
- Application Roadmap

ACAL Energy Ltd

Developing the Fuel Cell Engine

- ACAL Energy founded 2004 and based near Manchester, United Kingdom
  - Currently 31 people, mostly chemists and engineers.
  - Developing new Fuel Cell 'Engines' utilizing proprietary liquid catalyst system instead of Pt.
- Architecture enables very low cost and better reliability.
  - Will replace IC engines in stationary power and automotive.
- Backed by venture capital and corporate investors.
- Preparing to introduce first stationary power products in early 2012.



The ACAL Energy Team

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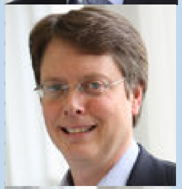
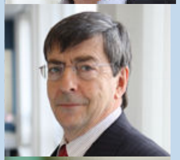
S.B. Cha, CEO

- Formerly with CDT, Philips, BCG; Texaco, PhD (Imperial College) and MBA (University of Chicago).



Andrew Creeth, CTO

- Inventor of the ACAL technology and co founder of ACAL in 2004, formerly Research Manager with Unilever. PhD (Imperial College), BS (Cambridge University)



Robert Longman, VP Engineering

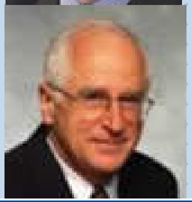
- Senior engineering positions at Plasmon Plc and PA Consulting. BS Mechanical Engineering (Cambridge University)

Bob Pettigrew, Chairman

- Co –founded Generics, and investor director BioWisdom, Zinwave, Oxonica, Chairman of Voxar Ltd, board member Antenova, the Synergy Fund, two Venture Capital Trusts listed on the LSE

David Fyfe, Non-Exec Director

- Chairman and CEO of CDT Ltd, CEO of Harris Specialty Chemicals (sold to SKW), Executive positions with ICI and Goodyear; Chaired and taken part in a number of industry focused government bodies.



Byron McCormick, Non-Exec Director

- 35 year automotive industry veteran. Former Executive Director GM Fuel Cell Development Team (1,500 engineers).

Our Core Activity is Chemicals Development

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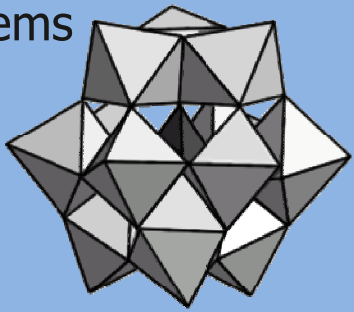
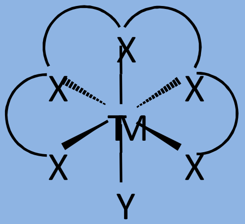
- Current Generation Systems
  - Highly Stable
  - Very High Durability



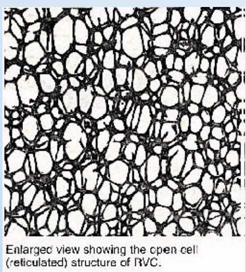
- Next Generation Systems
  - Higher potential catalyst ie able to beat Pt in performance
  - Major Cost reductions with higher performance



Also Developing Other Key Mechanical Components

- MEA structure optimized

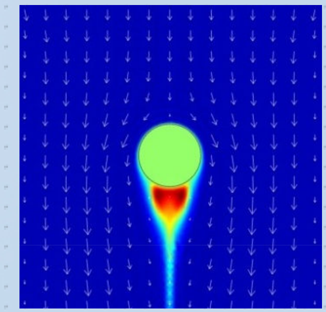
- 3-D electrode developed



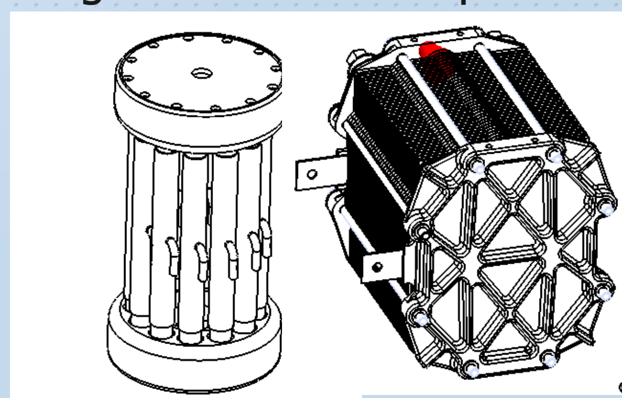
- New bi-polar plate design: simpler, controls leakage current

- Understanding of fundamental regeneration reaction mechanisms

Model of gas bubble reaction in POM

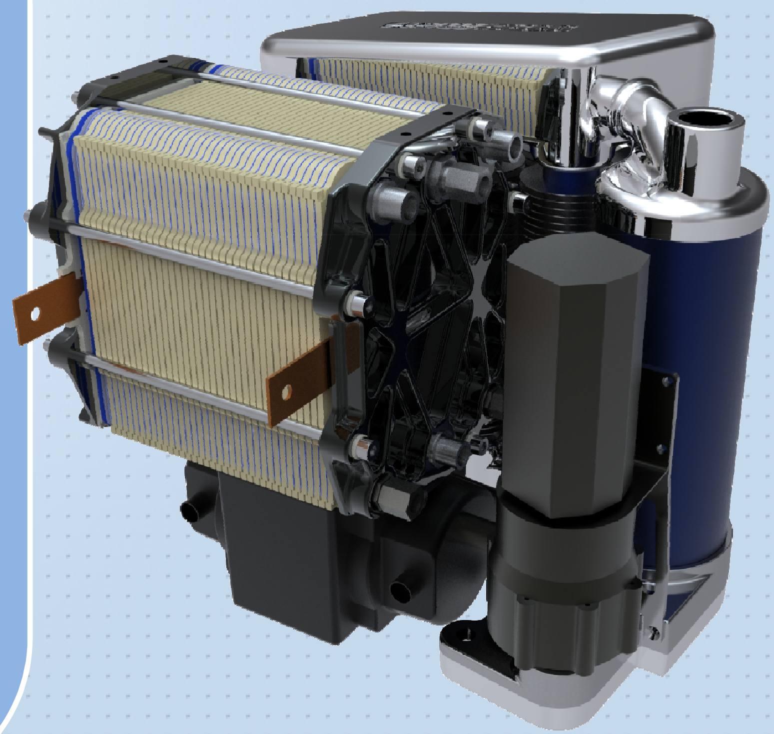


- Family of compact, low energy regenerators developed



ACAL Fuel Cell Engine
Fuel and Air in , Electrical Power Out

- ACAL fuel cell engine is a self contained power module:
  - Comprised of stack, regenerator, liquid circulation system, air blower, basic control system
  - No other major BOP needed
- ACAL Engine can be tightly integrated to save space
  - Large degree of packaging flexibility
  - Easy integration into system applications
- First engines for stationary power applications but automotive on the roadmap.



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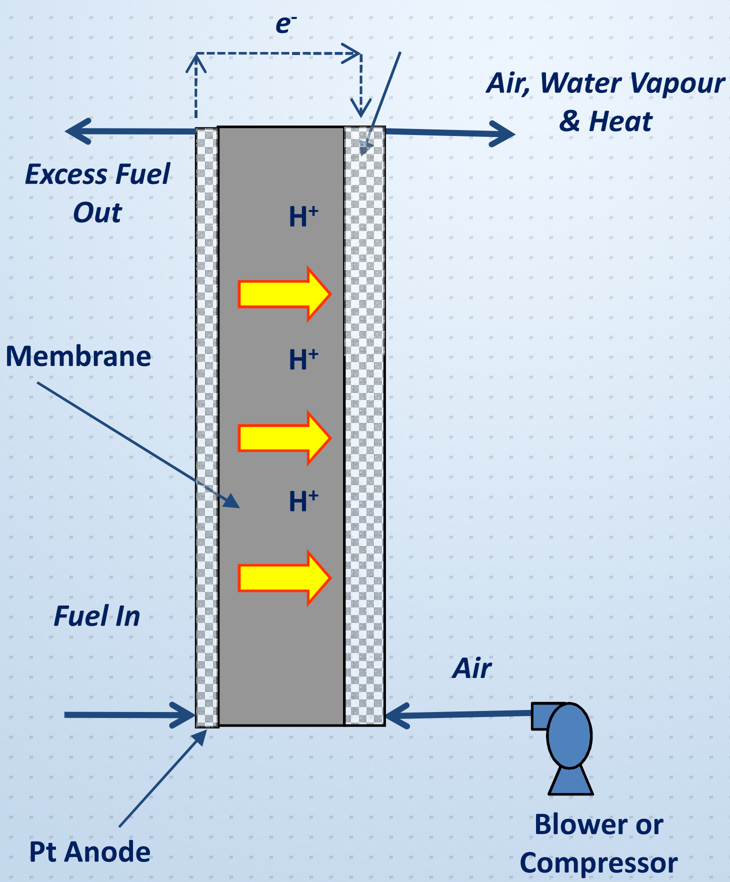
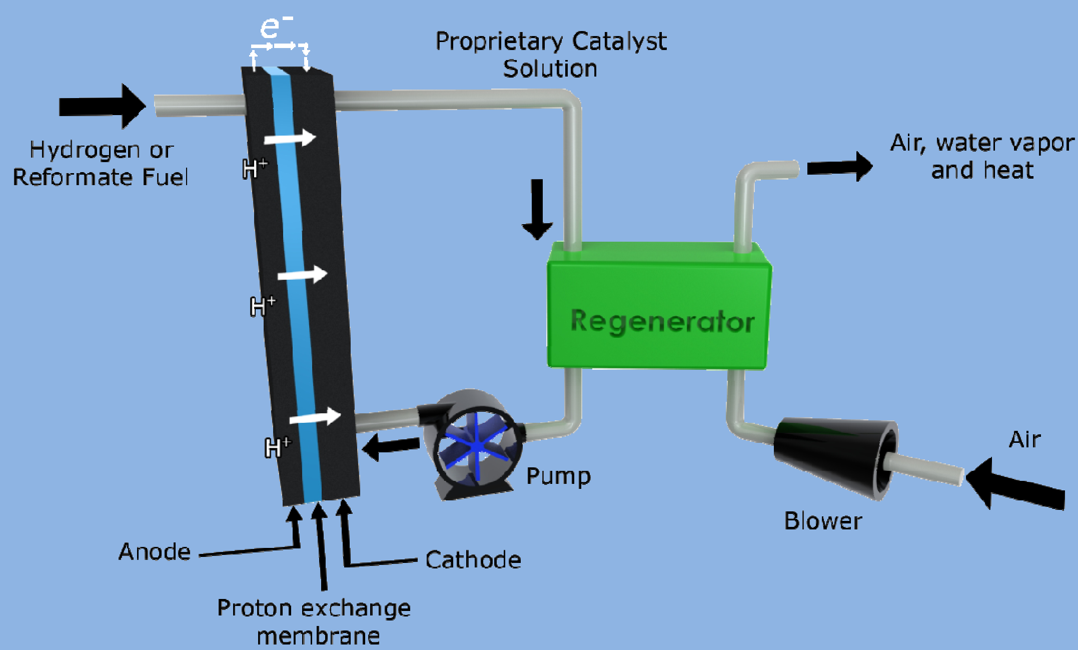
Conventional Cathode Source of Most Cost, Reliability Problems



- Too Costly.
  - High platinum content
  - Expensive balance of plant
- Poor durability.
  - Membrane and catalyst suffer degradation.
  - Oxygen in the cathode can lead to corrosion

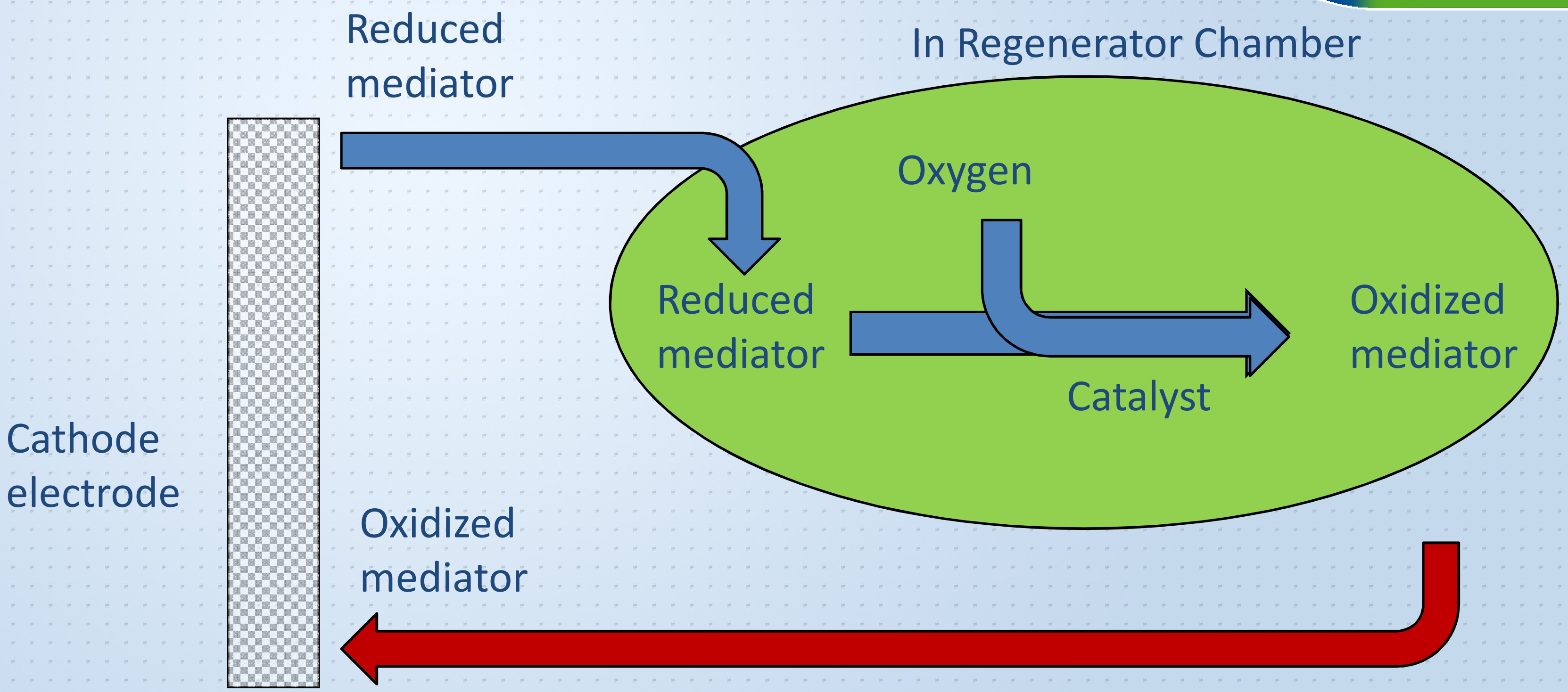
ACAL Concept

Liquid Phase Catalyst/Mediator to Drive Fuel Cell



- Indirect redox-type cathode, conventional anode
- Proprietary mediator dissolved in solution, reduced at cathode
- Solution flows into small external reactor. Mediator is oxidized by oxygen from air, aided by soluble catalyst forming water, which is released as vapour.

Overall System Dynamics



- Indirect redox cathode
  - Separate catalysis of oxygen reduction from electrochemistry
  - Change 3-4 phase system to two x 2 phase system

Overall Chemical Path

- Reaction in regenerator:

$$O_2 + 4H^+ + 4Med_{red} \xrightarrow{\text{Catalyst}} 2H_2O \quad 4Med_{ox}$$

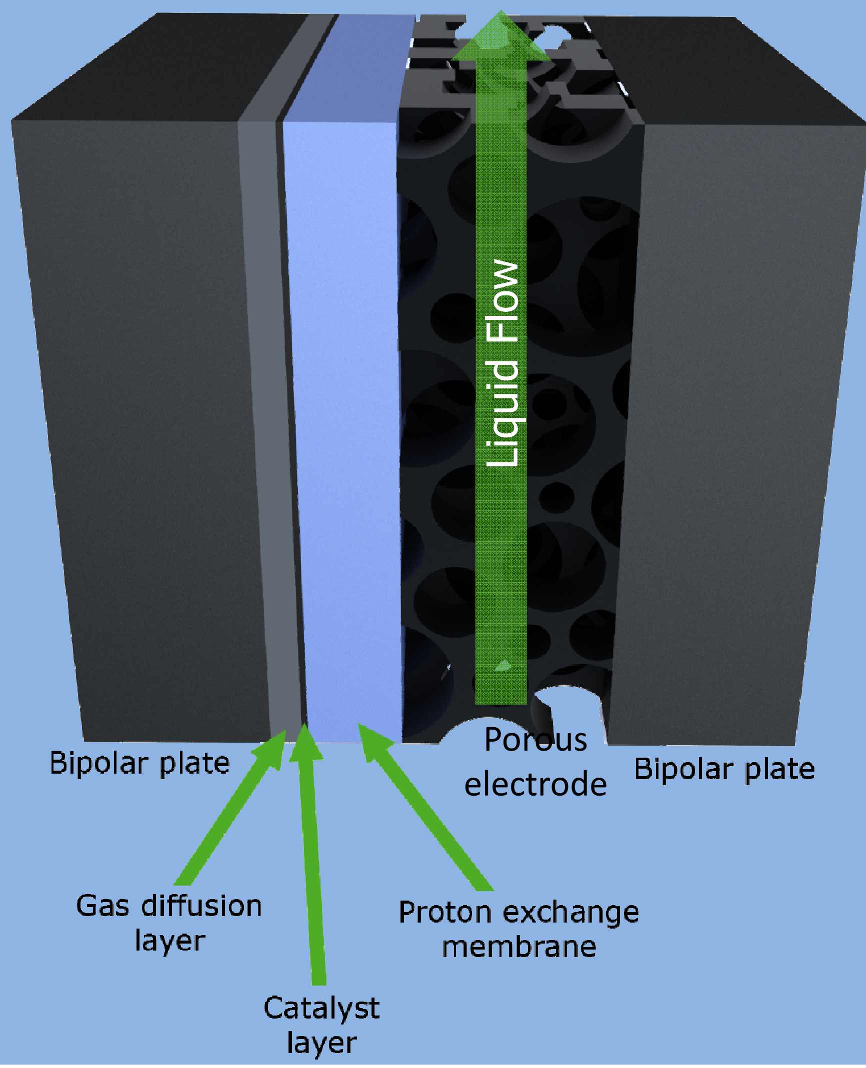
- Electrode reaction:

$$4Med_{ox} + 4e^- \longrightarrow 4Med_{red}$$

- Protons pass through membrane into solution to balance the charge and are consumed in the regenerator

- Oxygen never enters the fuel cell cathode.

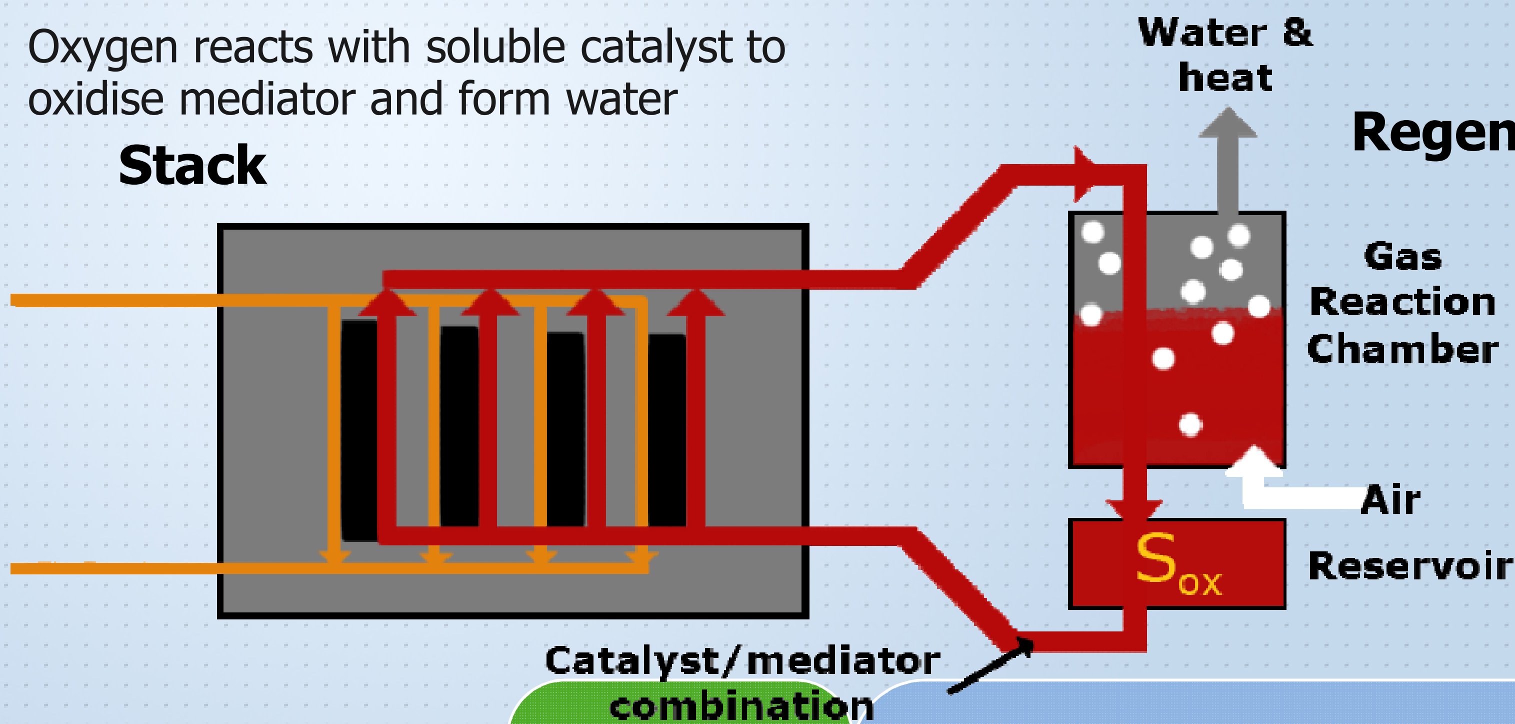
Basic Cell Architecture



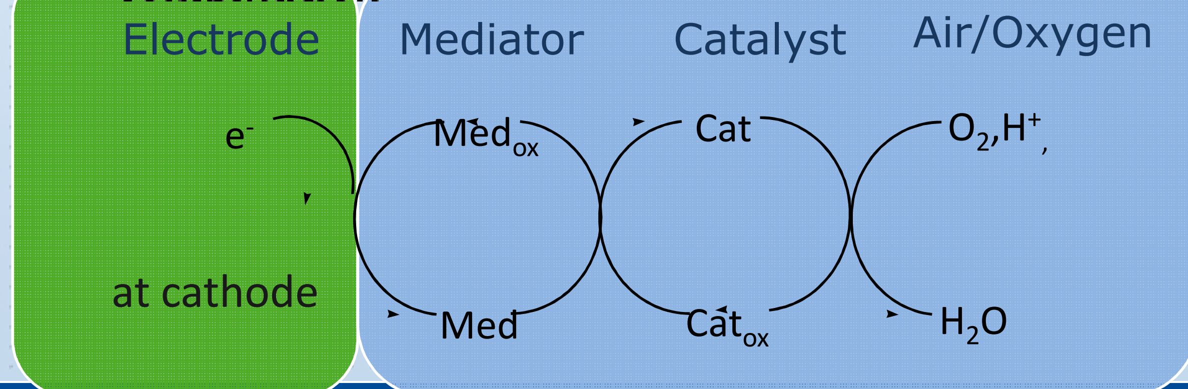
- Cell components are standard and readily available
- Compatible with multiple membrane types
  - Nafion & hydrocarbon membranes evaluated
  - Optimization needed
- Same fuels as standard PEM
  - Hydrogen, reformate and methanol evaluated

Stack Implementation

Oxygen reacts with soluble catalyst to oxidise mediator and form water

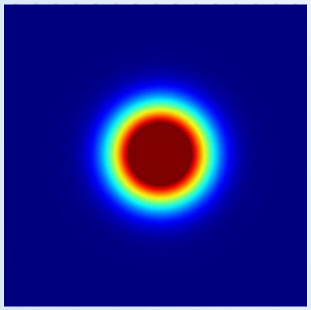


Electrode performance controlled by mediator properties.

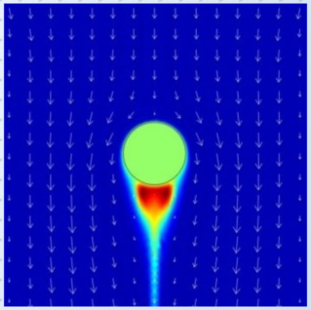


Regeneration Fundamentals

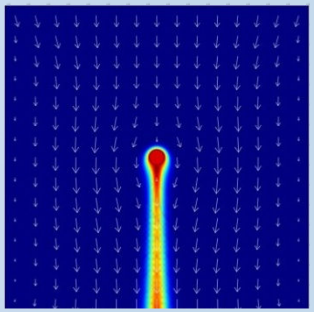
200µm Bubble
Stagnant in POM



200µm Bubble
Stoke’s flow in POM

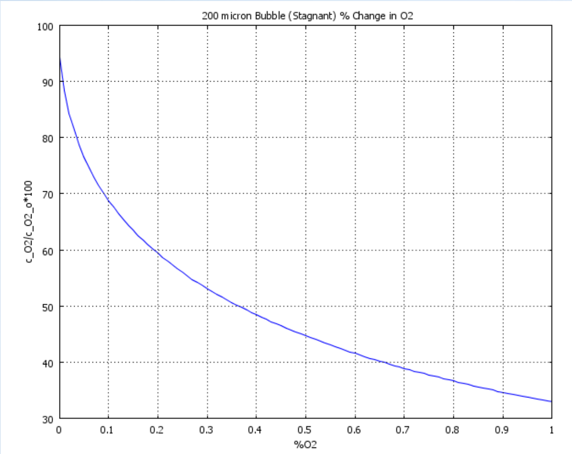


50µm Bubble
Stoke’s flow in POM



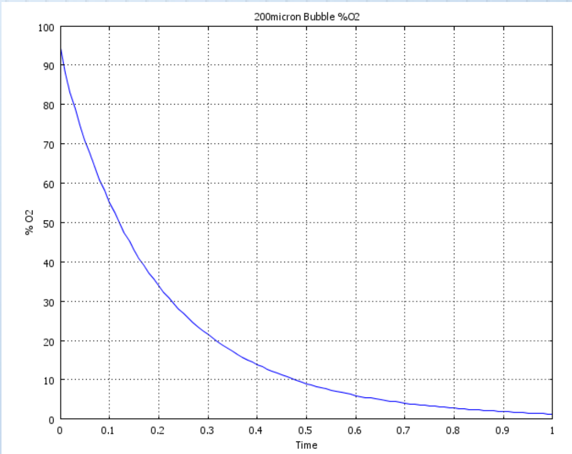
Oxygen loss as % of Original Concentration (21% O_2 in Air)

0.0 m/s



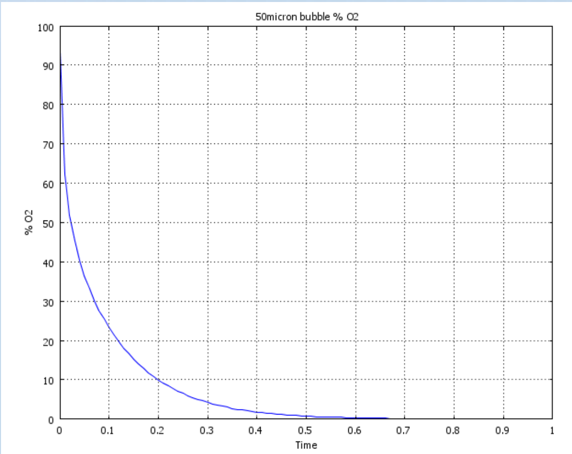
Time to 50% = 0.365 [s]

0.04 m/s



0.12 [s]

0.003 m/s



0.023 [s]

Rapid Regenerator Development

Smaller, More Efficient Designs in Development

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2008

Bubble plate

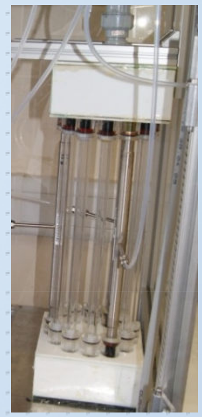
2009

In-line mixer

Early 2010

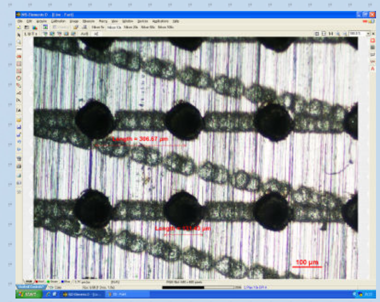
Air Injection I

Mid-2010



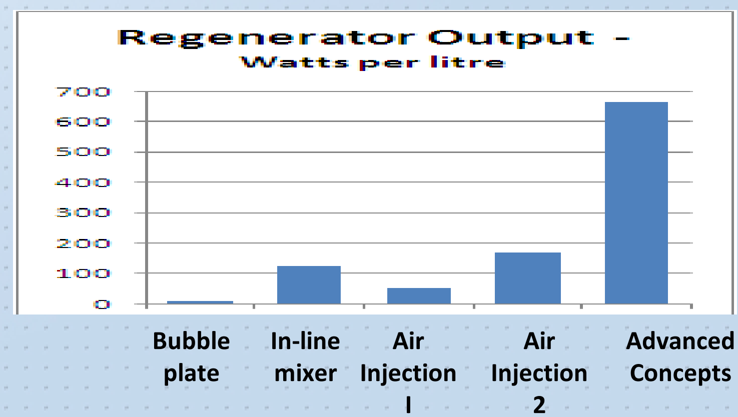
Air Injection II

2011



Advanced high efficiency concepts

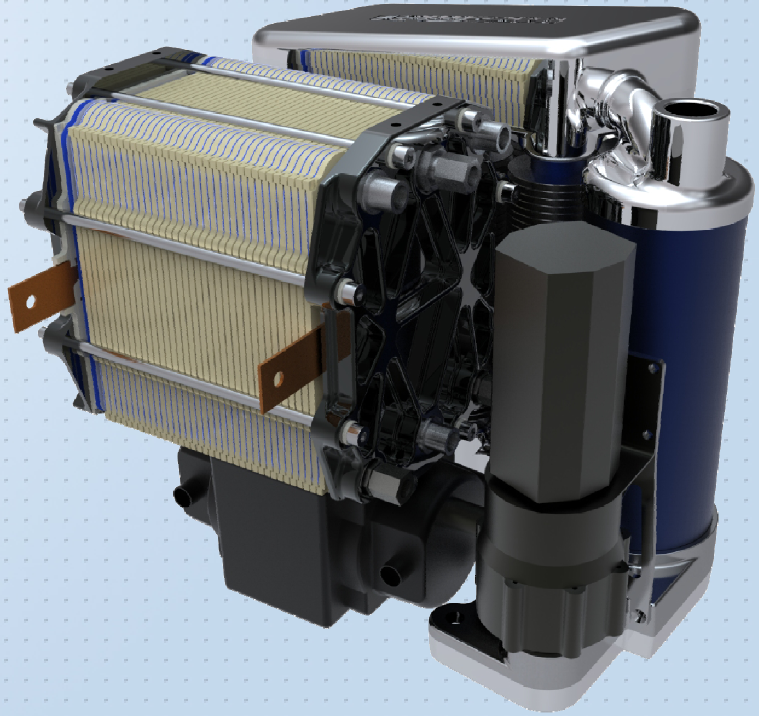
Regenerator has become smaller, more powerful and parasitic power has fallen from 100%+ to less than 7%. Much higher performance still possible.



Compact Integration Possible

Integration at Advanced Development Stage

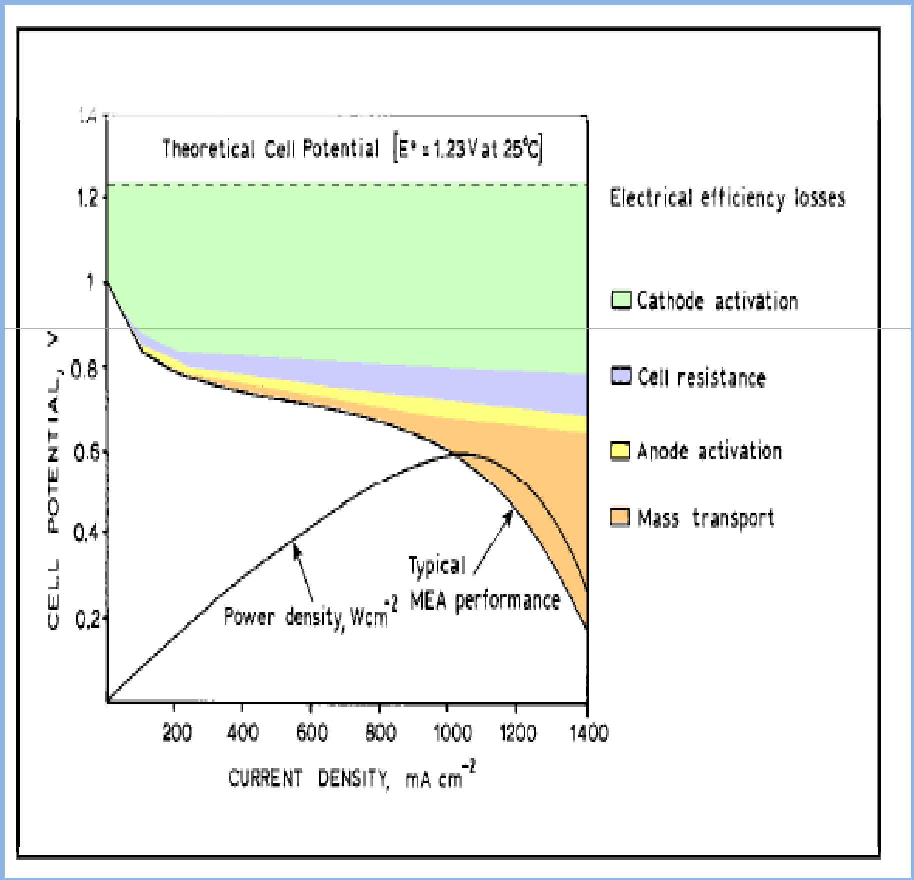
Third generation 1 kW demonstration unit being built……



….production modules will be compact

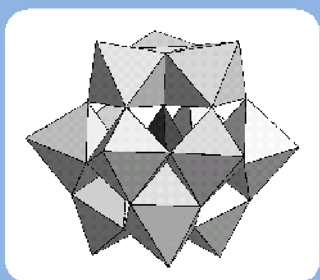
ACAL System Operating Theory

Fundamentally Different than Conventional PEM

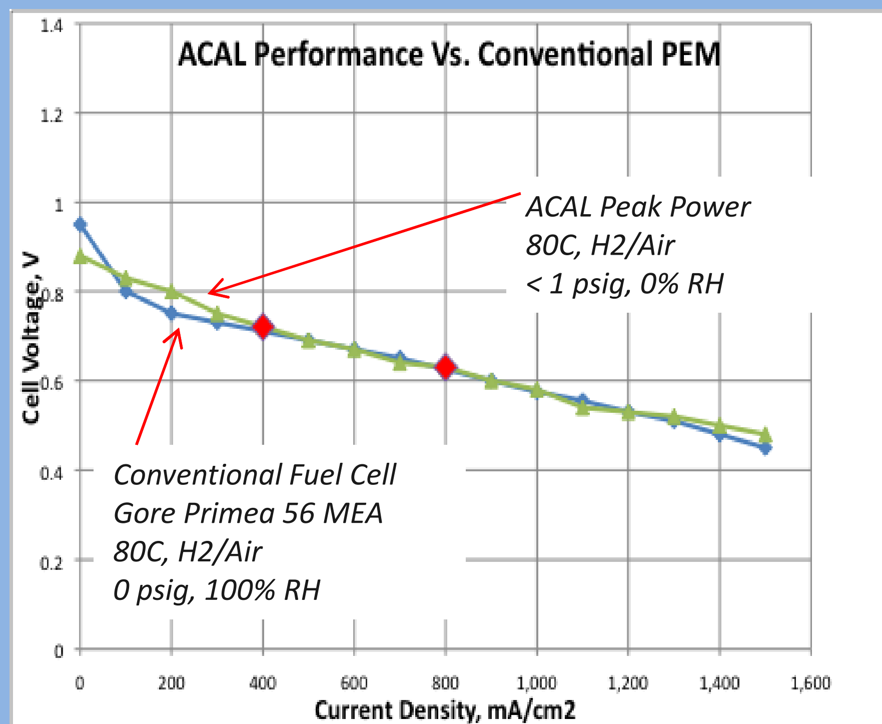


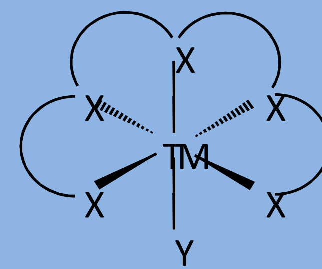
- Multiple material choices, OCVs higher than Pt possible
- Even with lower OCV, lower activation over-potential can result in no net loss of performance
- High concentration of mediator gives high currents in porous electrode, no transport losses seen
- Simple cathode system – no three phase system in the cathode

Good Progress in Chemistry
Materials Capable of Pt-Like Performance



First g
cataly
inorganic polyoxometallate structures. Robust, long life, low cost materials. Now delivering same performance as platinum.





Higher performing metal-hybrid materials being developed . Will deliver performance higher than platinum.

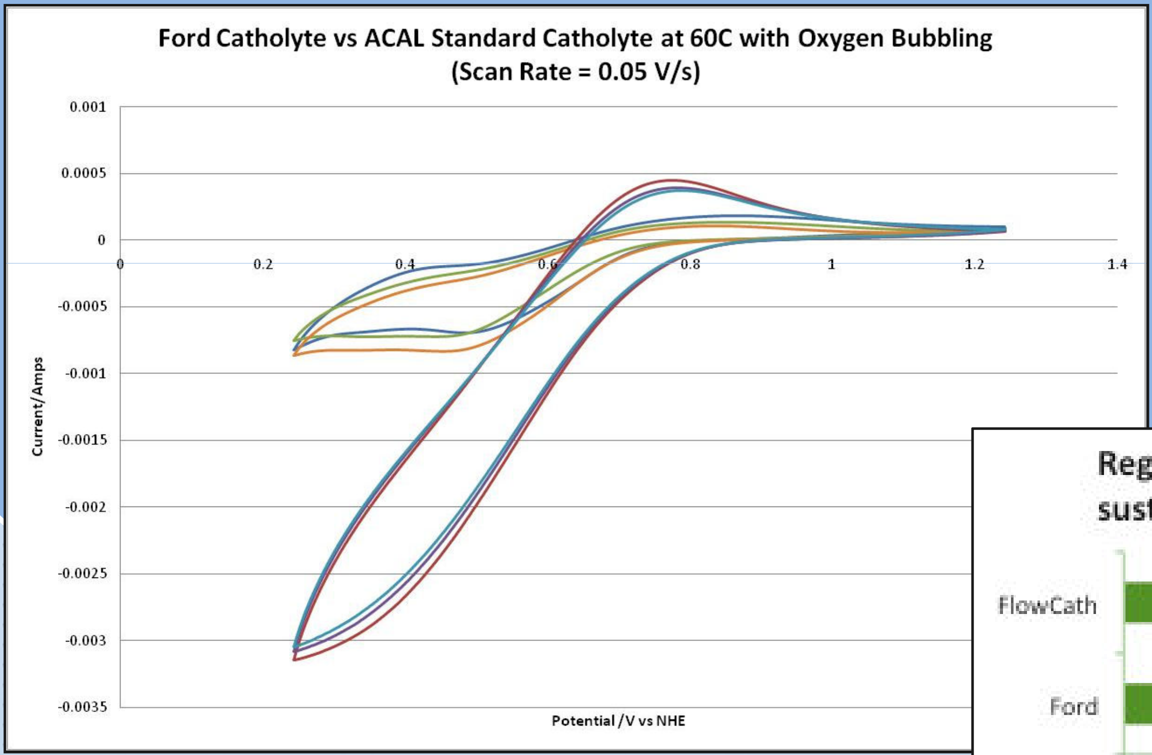
** Results are for a single cell running with hydrogen fuel, excludes regenerator performance. Conventional fuel cell is humidified while ACAL results use dry hydrogen and air.*

New families showing potential for $1W/cm^2$ and higher for auto applications.

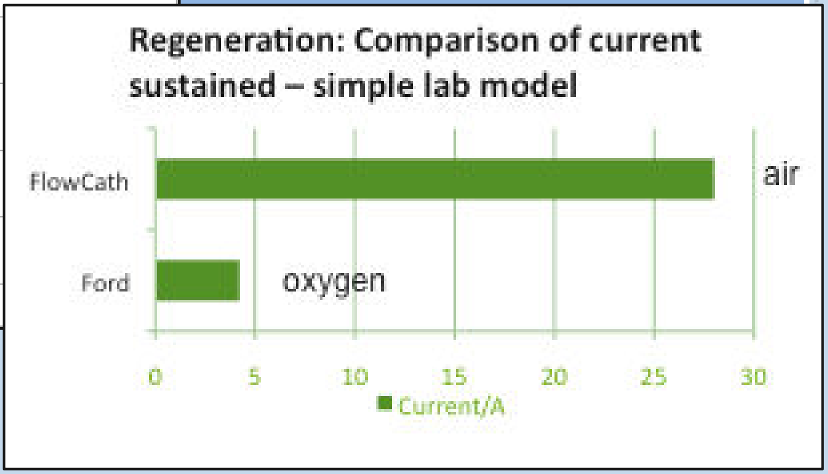
Approach Developed by Ford

ACAL Materials Substantially Better Performing

ACAL chemicals have much better electrochemical properties resulting in substantially higher efficiency…

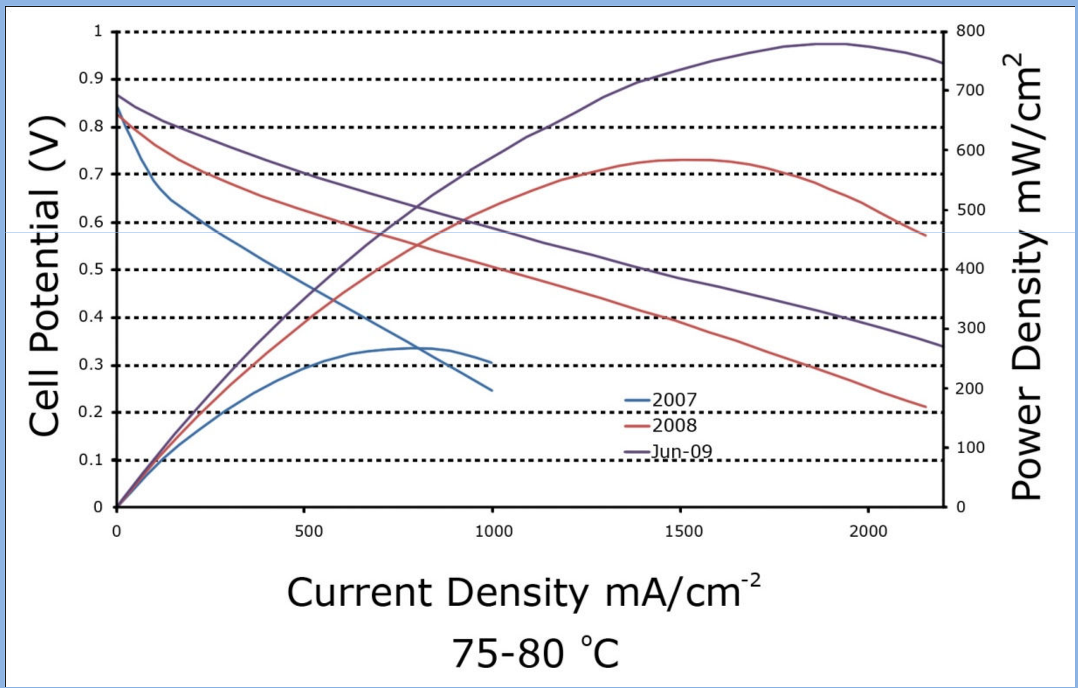


…and regeneration much faster so that it is in a different kinetic regime , which allows for a much smaller regenerator.



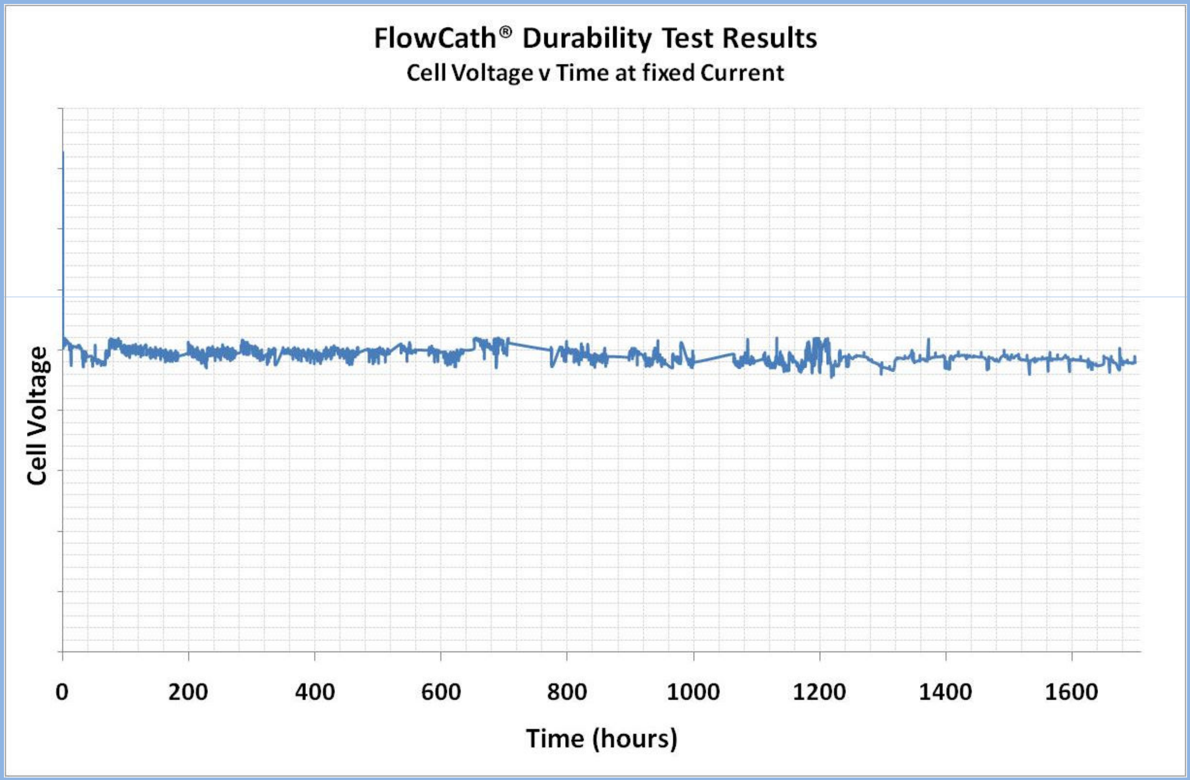
Performance Development

Rapid Improvement in Electrical Performance



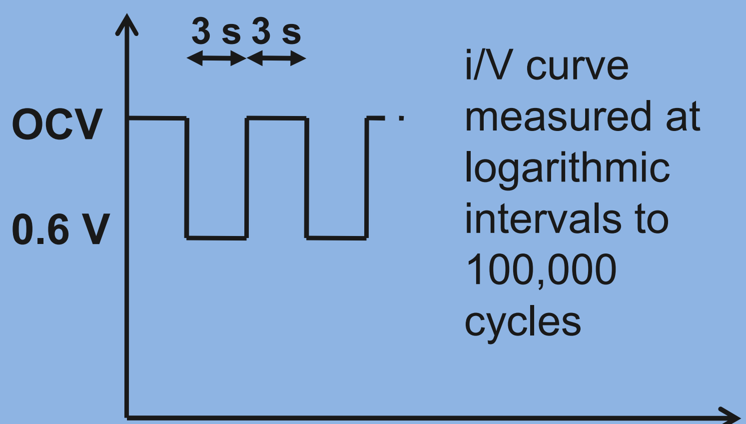
- Improvement by factor of 3 in 18 months
- Catalyst optimization to improve OCV
- Reduction of cell resistance and improvement in cell components and cell design
- No transport losses seen

Durability Testing
Single Cell Results Encouraging

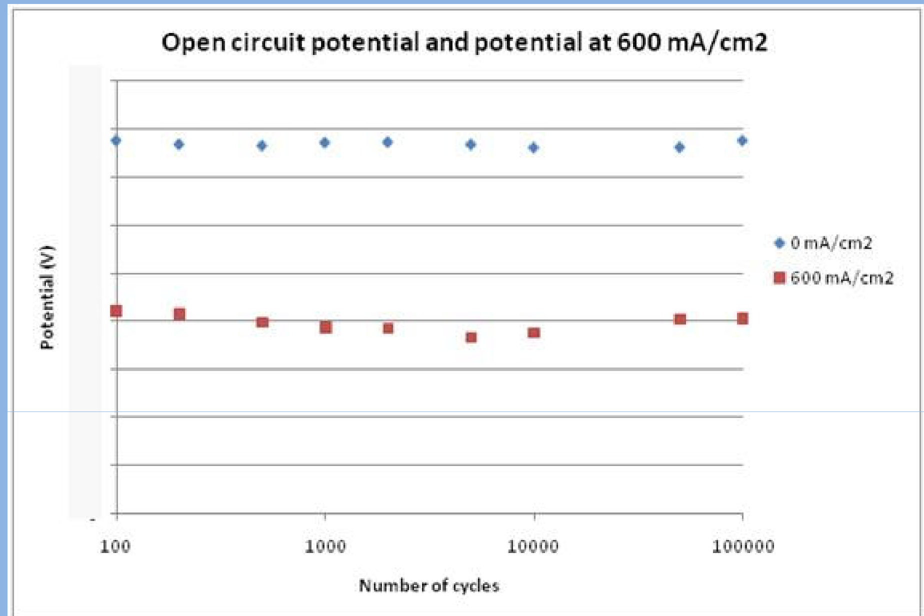


- > 1700 hour single cell durability, >50 stop/start cycles
- Chemicals tested to thousands of hours, no signs of degradation
- No membrane/ MEA degradation.
- Less sensitivity to cyclical loading and on-off power stresses

Accelerated Cycle Test



i/V curve measured at logarithmic intervals to 100,000 cycles



- Rapid cycle programme designed to accelerate degradation of cathode electrode structure
- Typically between 1 V and 0.6 V; in this case between OCV and 0.6 V
- No trend in OCV or potential at 0.6 A/cm^2 is observed

Basic Technology Almost Ready For Stationary Power Product

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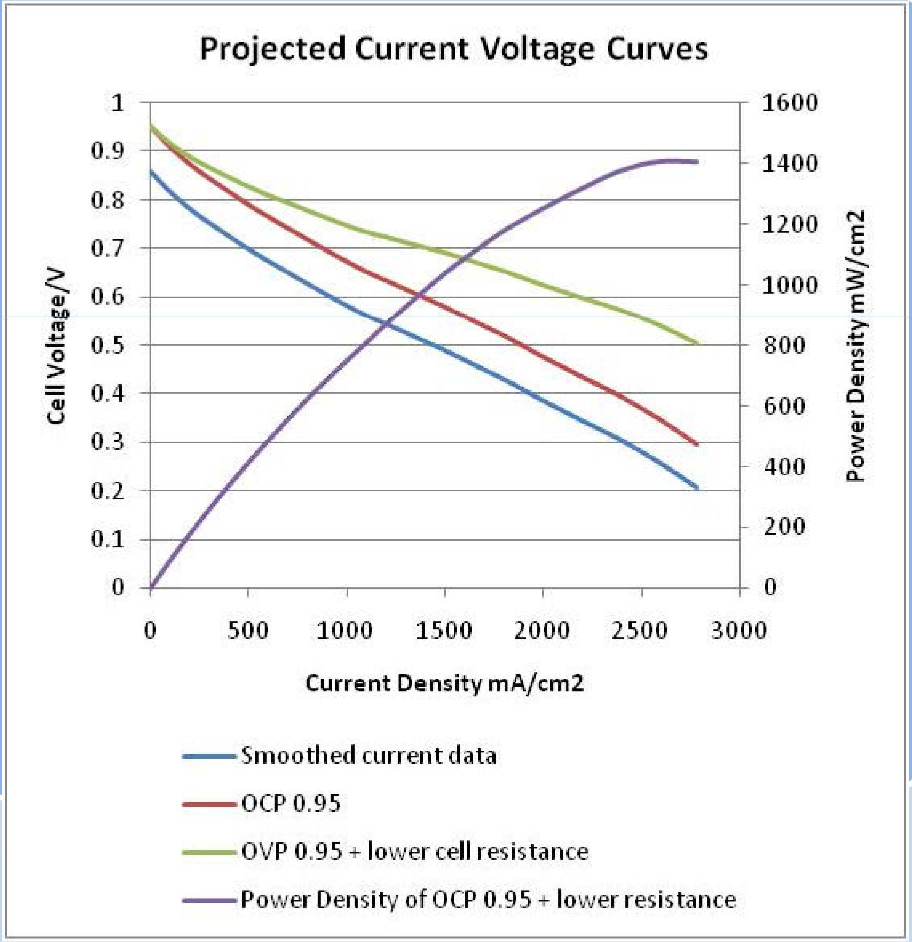
- Electrical efficiency – chemical performance acceptable but need to reduce stack resistance
- Lifetime – single cell results encouraging, stack testing proceeding
- Start-up and response time appear more than acceptable
- Operating temperature range now acceptable for many stationary applications, need to expand for automotive

Future developments targeted at higher efficiency, low temperature operation, smaller regenerator.

Future Performance Development Strategy

- Chemicals development
  - Target OCP 0.95 V
- Cell optimisation
  - Design and resistance removal
- Overall efficiency development
  - Low parasitic power from liquid system
- Volume and mass intensification
  - Metal bipolar plates
  - Regenerator technology development

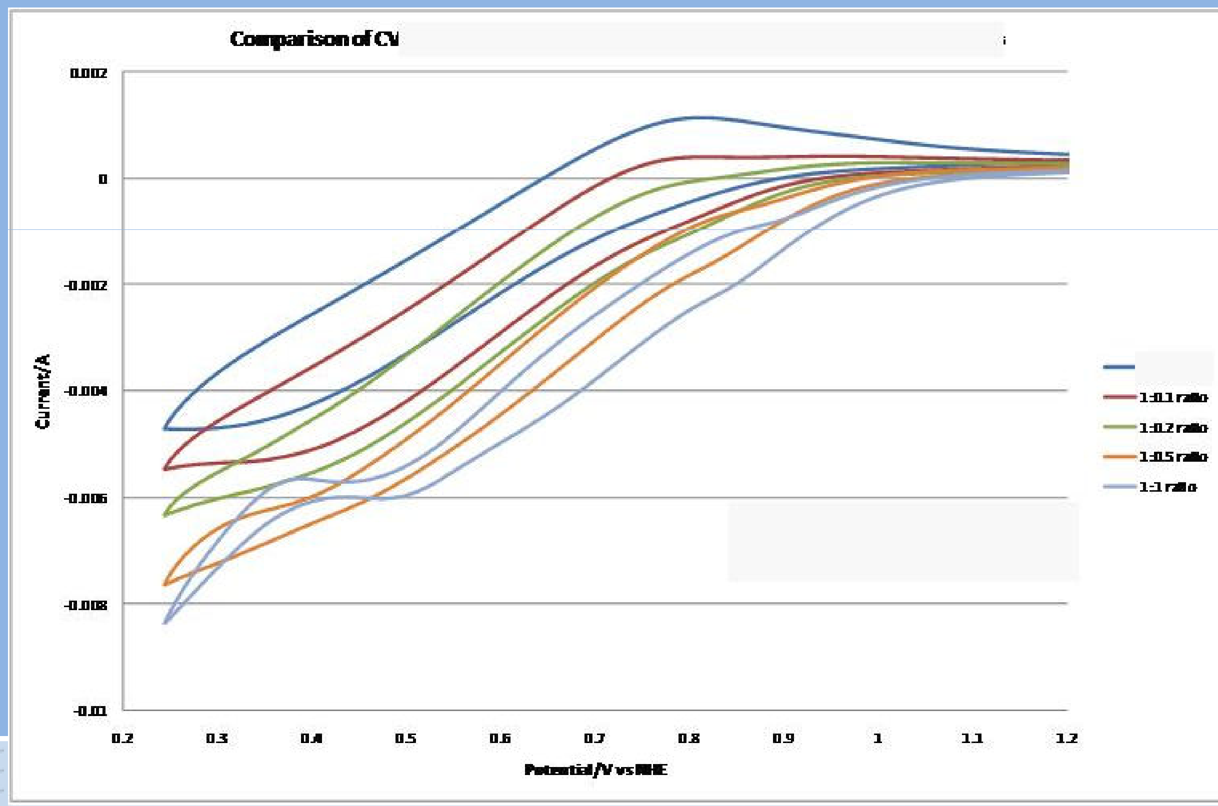


Higher Performance Possible

Additives For POM Being Developed

Example: Affect of additive

- Conductivity improves
- Electrochemistry improves
- Several potential additives being investigated



Higher OCV Possible

Modifications of POM Structure Promising

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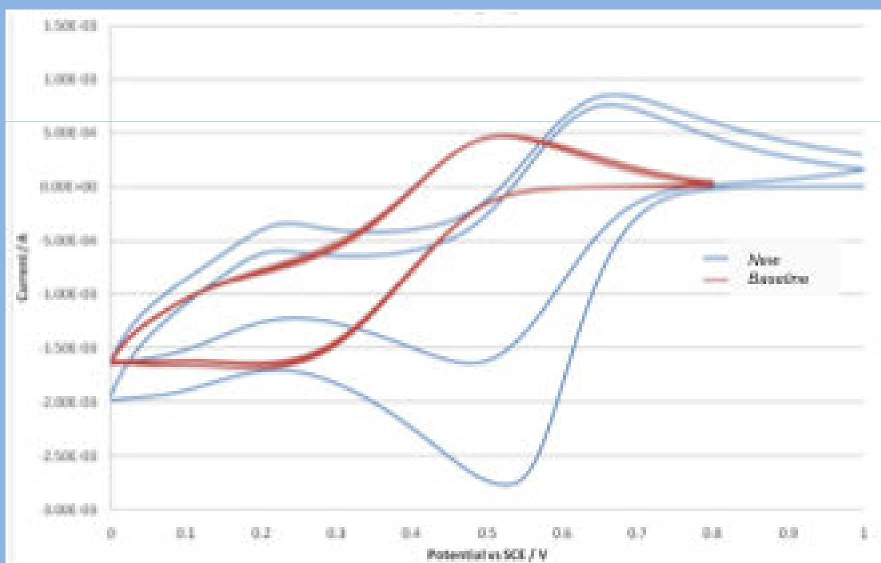
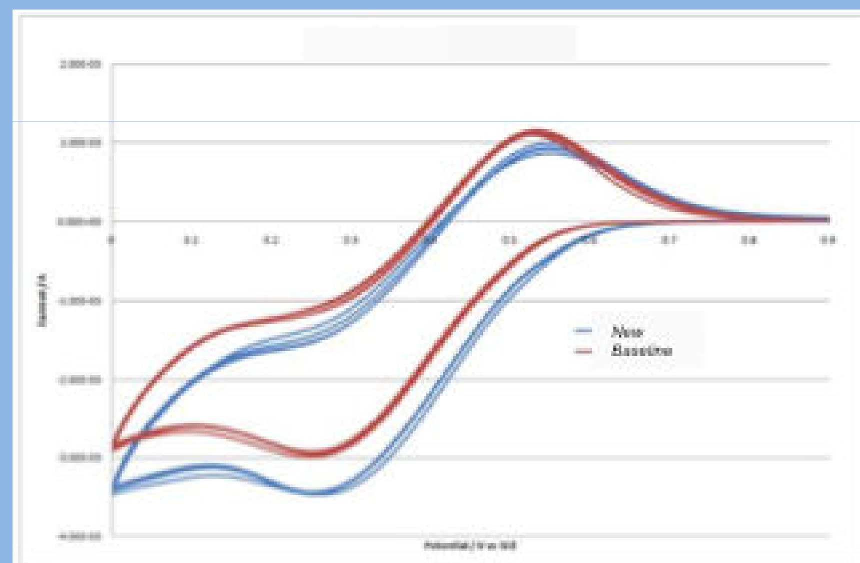
Examples: Modified POM materials

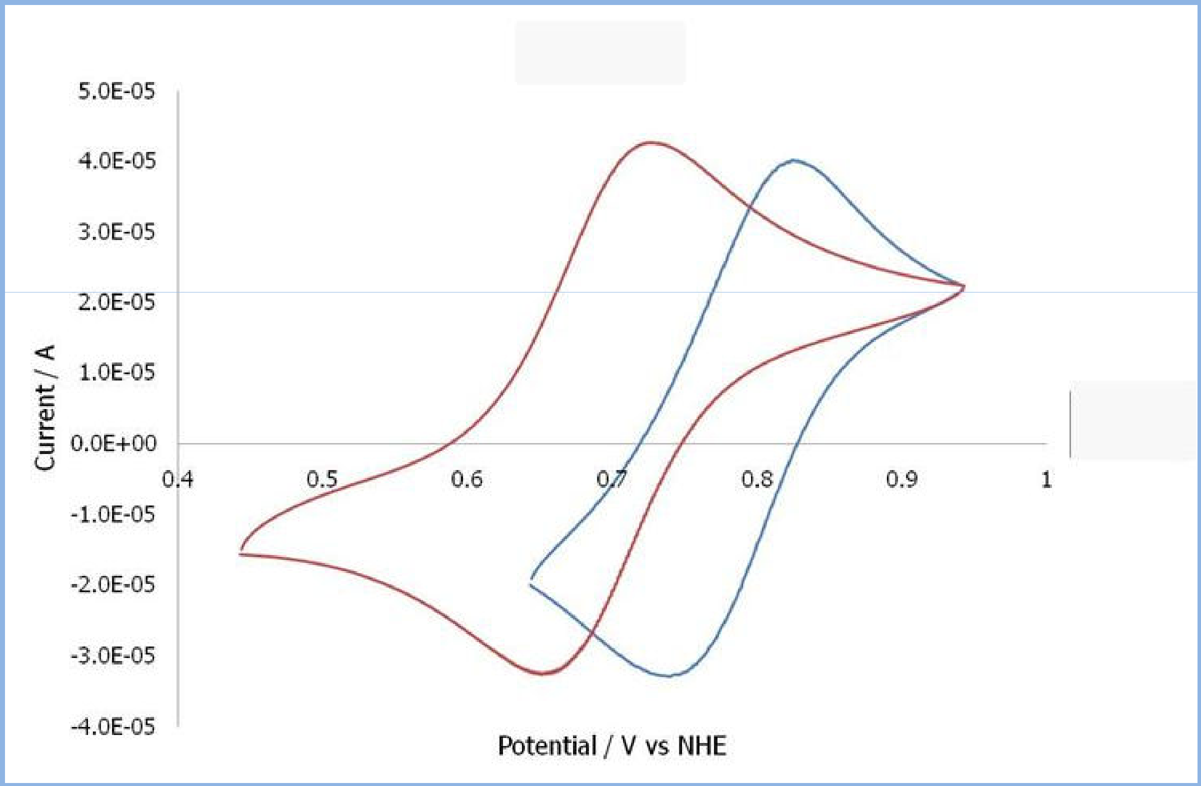




Organic Materials in Development

New Mediator Example

CV data – 100 mVs^{-1} ; 20 C



- High redox potential
- Very rapid electrode kinetics, electrochemically reversible

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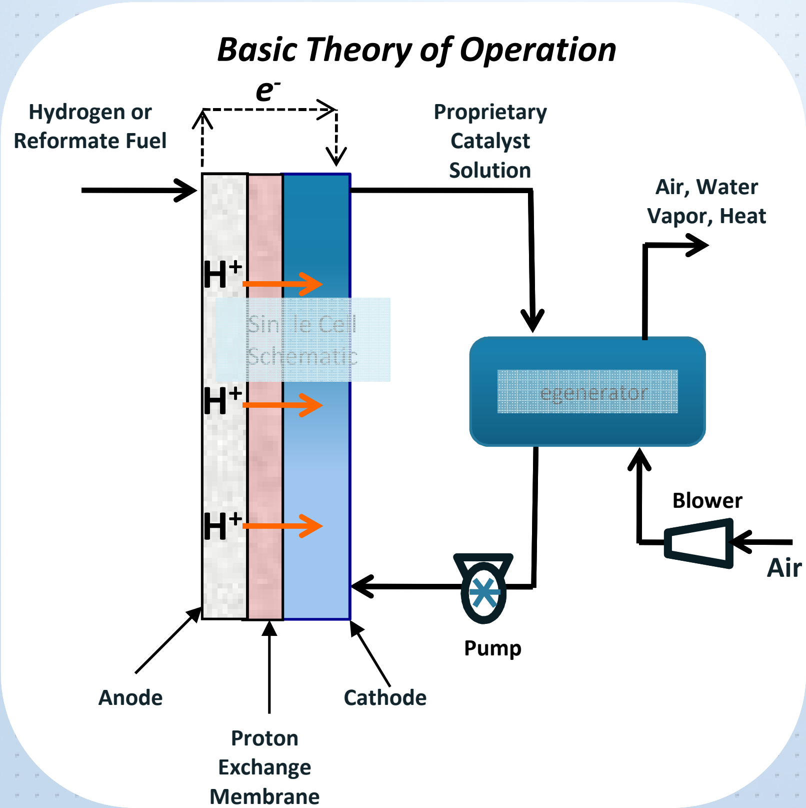
Technology Benefits

Lower Cost, Improved Reliability Possible



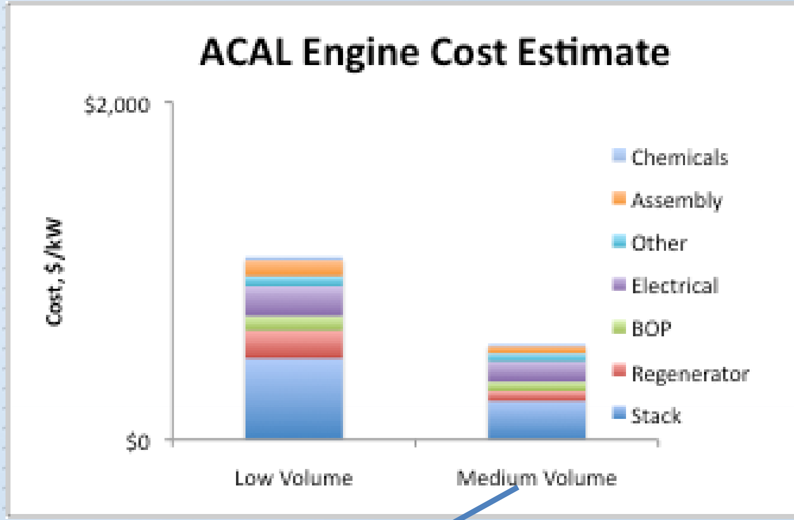
- Significantly lower system cost
  - Up to 90% Platinum eliminated
  - ACAL catalyst low cost
  - Simpler balance of plant, less battery bridge needed
- Fundamentally more reliable
  - More stable membrane environment
  - No oxygen in the cathode
  - Milder corrosion environment
  - Catalyst solution replaceable
- Wider operating envelope
  - Air humidity not an issue
  - Very low temperature development in progress

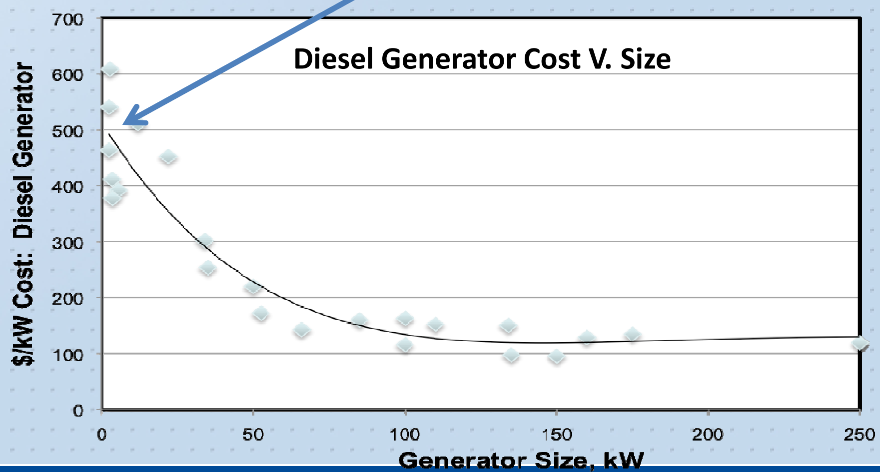
Low Cost FC Engines Possible

Can Match Diesel Generator Costs

- Lower cost cell and stack
  - 90%+ less platinum, ACAL catalyst very low cost
  - Simpler bi-polar plates, no cathode spiral, no cooling channels
  - Higher power densities from new catalysts will improve savings
- Significant balance of plant savings
  - No fuel or air hydration system
  - Low pressure blower instead of air compressor
  - Regeneration system replaces water cooling system

Source: ACAL estimate based on vendor data





Very Low Cost Possible

For high volume automotive applications

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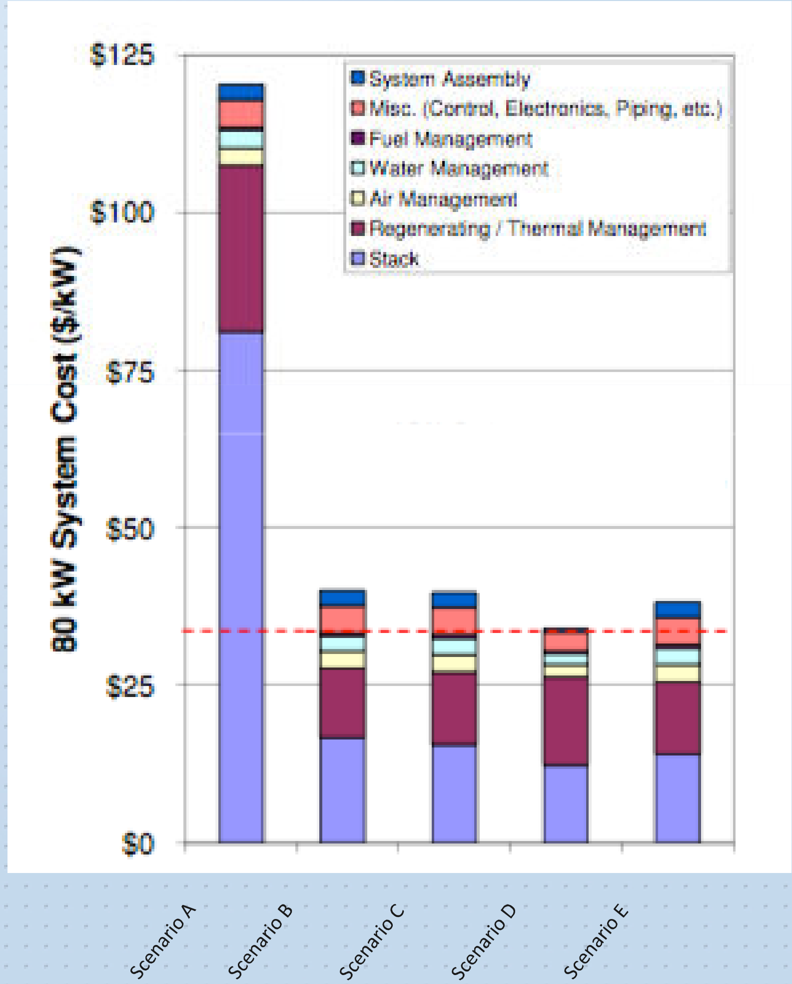
Model Parameters	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Volume Basis (Units/Year)	500,000	500,00	500,000	500,00	500,000
Power Density (mW/cm2)	325	750	1,000	750	1,200
Anode Pt Loading (mg/cm2)	0.2	0.1	0.05	0.05	0.05
Pt Cost ($/oz)	1,100	1,100	1,100	1,100	1,100
Membrane Cost ($/m2)	22	22	22	22	22
Chemical Cost ($/liter)	10	10	10	10	10
Labor Cost	Med	Very Low	Low	Very Low	Med



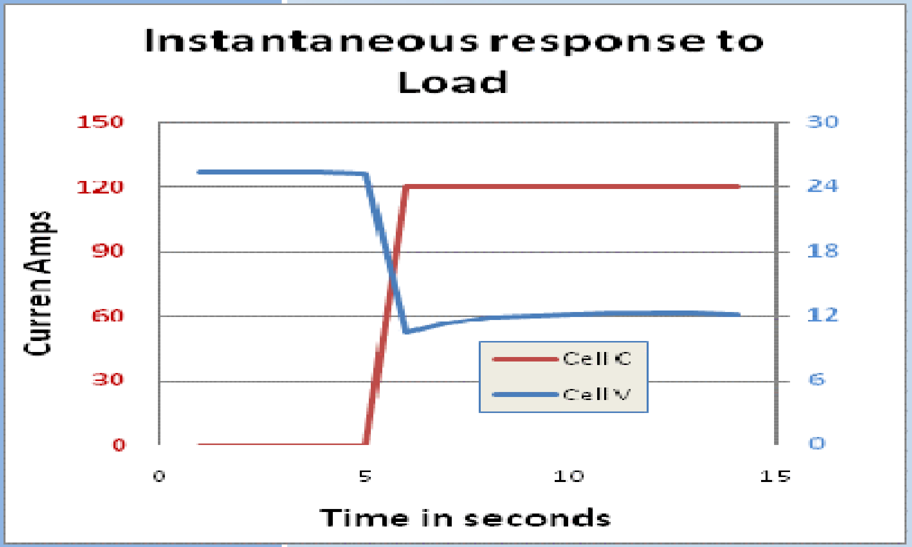
Using same methodology, conventional auto fuel cells estimated at $100/kW

Source: AP Consulting Study for CTI

Improved Operability, Reliability

Rapid Start-up and Response possible

- Operability improved
  - Near instant start-up possible, reduces need for battery bridge
  - Significantly less sensitive to humidity and altitude
  - Better heat removal
  - Robust strategies possible for very cold operation
- Key failure mechanisms eliminated
  - Membrane dehydration risk eliminated
  - Catalyst agglomeration eliminated
  - Liquid catalyst replaceable if contaminated
  - Corrosion risk significantly reduce – cell voltage can never exceed 1V, oxygen never enters the stack



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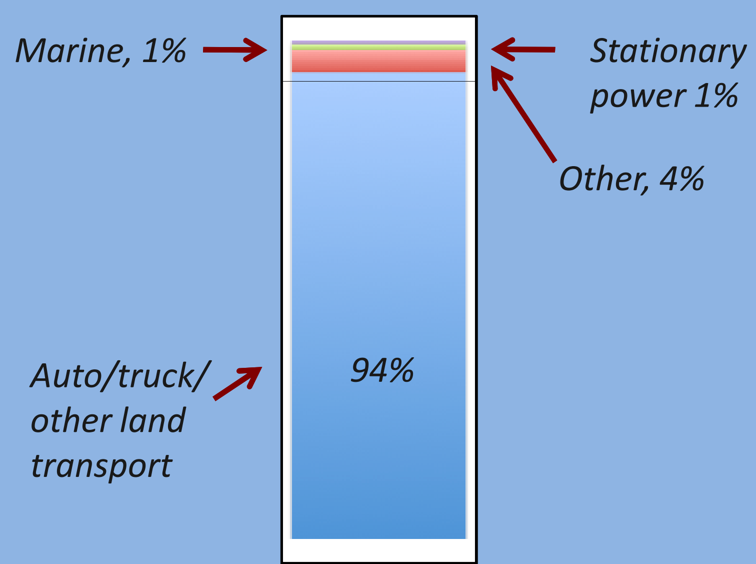
ACAL Market Opportunity

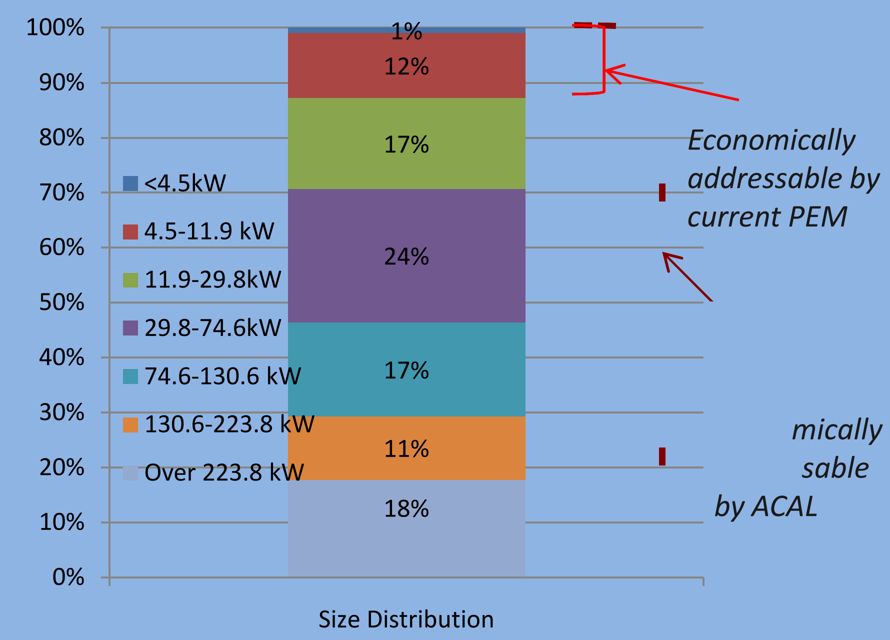
Fuel Cell Engines to Replace Combustion Engines

~75 Million combustion engines produced globally every year....



Annual Global Combustion Engine Production by Application

Size Distribution of US Diesel Generator Population



....first market target, $10B stationary power segment, commercial CHP, auto/truck applications next

ACAL Business Model

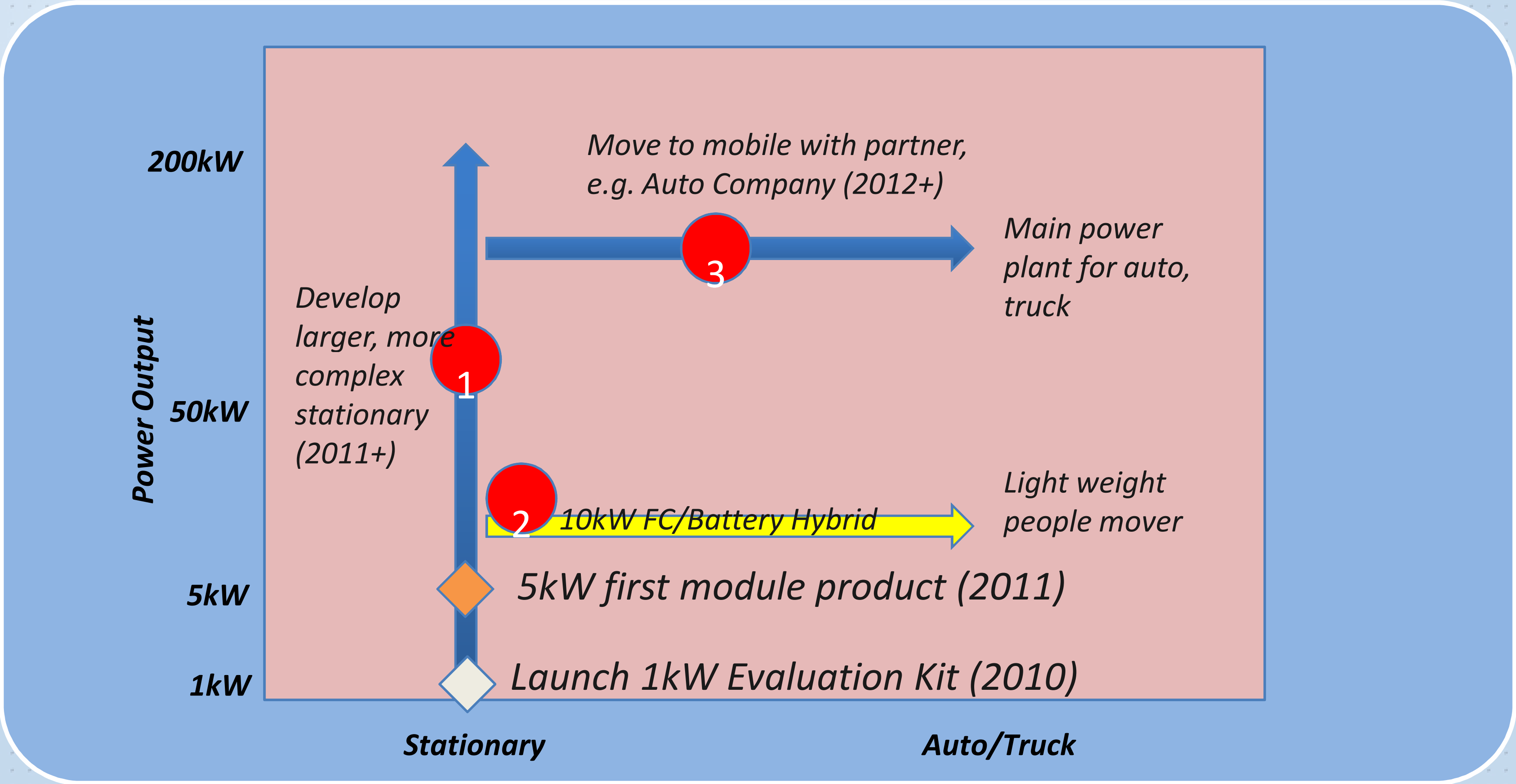
Fuel Cell Engines to System Integrators

- ACAL's basic business approach: provide fuel cell engines, chemicals and design expertise to system integrators for easy integration into their products.
- ACAL Engine includes stack and regenerator, ready to integrate into the manufacturer's products.
- ACAL will license mechanical technology and supply chemicals to large automotive companies and for niche applications
- Outsource and/or partner for chemicals and engine production.

Commercial Scale Chemical Production Demonstrated

- Scale up partner is Thomas Swan, speciality chemicals maker
- 1st formulation scaled up to 200 liters
- Performance identical to laboratory materials
- Multi-batch trials later this year

Overall Product Development Strategy



Stationary power first, small hybrid fuel cell next, large auto main power plant last. Some short term niche applications emerging.

Commercialization Roadmap

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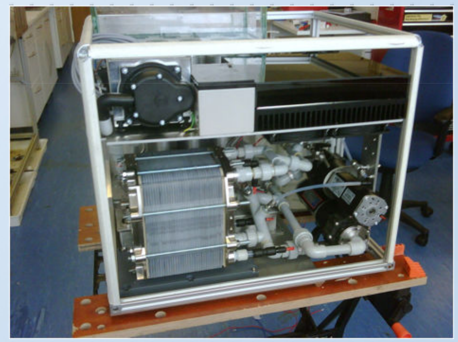
2008	2009/10	2011	2012
Proof of concept demonstrated	Scale-up and optimization	Field validation of technology	Commercialization

50W Test Platform

1-3 kW Demonstrators



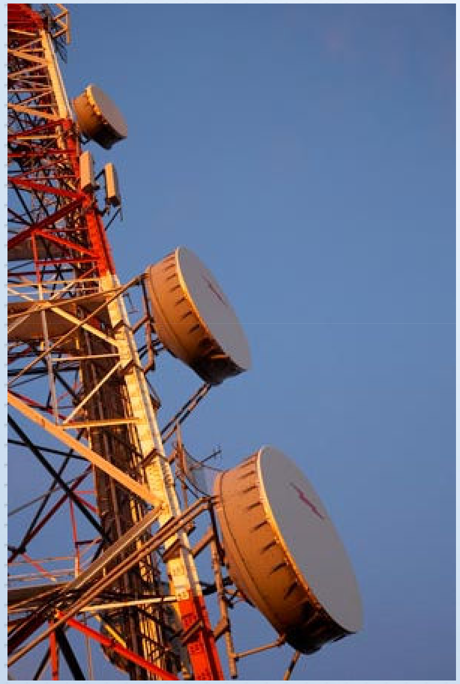
5kW Field Trial Unit at Solvay Plant

1-10kW Modules for OEMs

First Product Concept: 5kW Fuel Cell Engine

Specification	Value
Fuel	Hydrogen
Output	Unregulated DC power based on customer specification.
Cathode catalyst	POM
Anode catalyst	Platinum, anode loading at $0.1 mg/cm^2$ or less.
Scope of supply	Engine includes stack, regenerator, liquid solution, engine control system, and basic DC/DC convertor to power engine components.
Stack electrical efficiency	48%+
Internal power consumption	Less than 10% of gross engine output
Start-up time to full power	Less than 1 minutes at room temperature.
Stack operating temperature	80C
Ambient operating temperature range	-10 to 40C
Air humidity range	0 to 100%
Lifetime	5,000 hours initial but increasing to 10,000

ACAL Fuel Cell in Telecoms Back-up Power



- Fuel Cells offer better performance than existing technologies:
  - Longer run times and daily use
  - Well suited to poor grid supply in developing countries
  - Quiet operation and can be located in rural areas like batteries
- ACAL makes Fuel Cells more affordable and reliable
  - Substantially reduced capital investment, potentially 50% or more at volume
  - Increased durability for >4hrs and daily operation
  - Near instant response reduces cost of initial investment in batteries and reduced maintenance over lifetime

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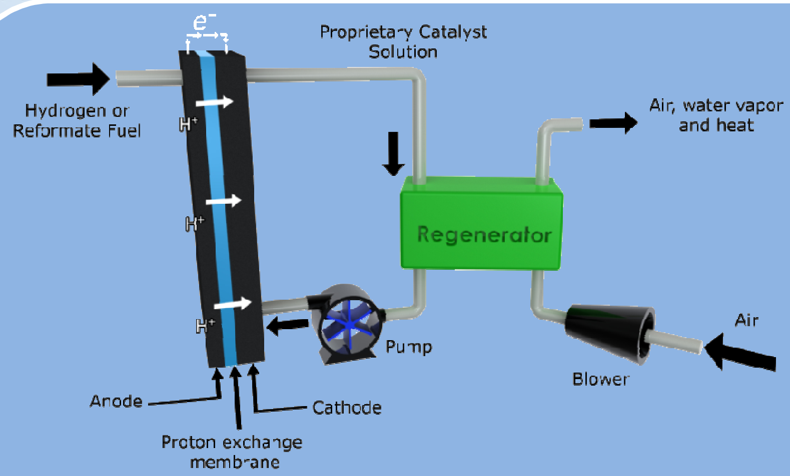
Good Early Stage Progress Being Made in Auto

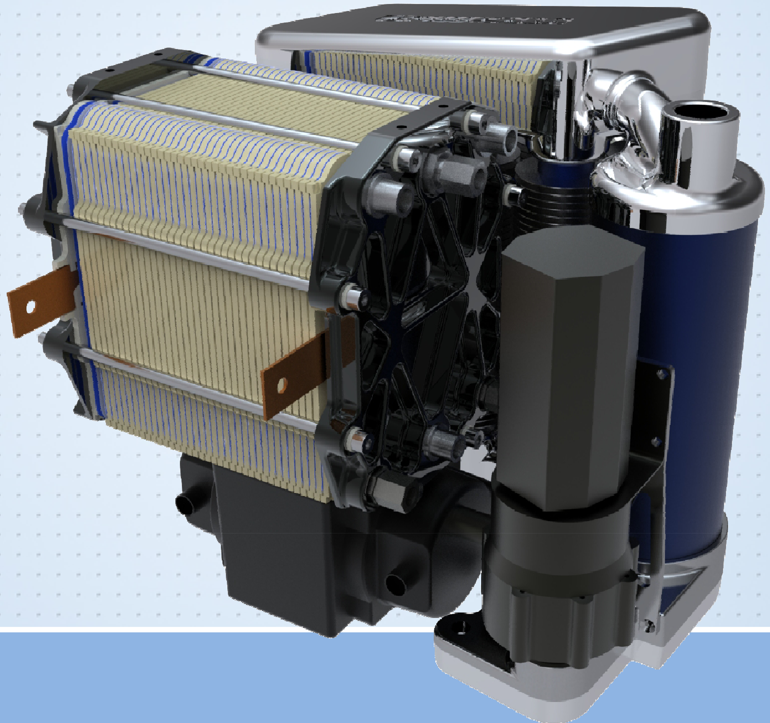
- Currently negotiating £6M funding from UK Government to fund auto development
  - Technical evaluation passed, negotiating funding terms
- Investigating demonstration project with lightweight auto design company for 'green people's car' targeted to Asia
  - Potential partner has EV car platform
  - Initial engineering concepts for 10kW unit
- Building auto experienced engineering talent network
- In dialogue with Japanese and German Auto Companies for longer term main power plant development

Summary

The New Fuel Cell Engine from ACAL



- Liquid cathode architecture lowers costs, improves reliability.
- Current chemicals performing as well as platinum.
- Basic technology ready for stationary power applications, first products in 2012.
- ACAL developing new generation of chemical and mechanical technologies for automotive use.



Thank you for listening

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