AIC Applied Intellectual Capital
VENTURES IN SUSTAINABLE TECHNOLOGY

Some lessons learned from 20 years in RedOx Flow Battery R&D

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www.apicap.com

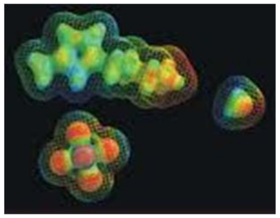
Contents

- AIC’s involvement in RFB R&D
- Some key lessons learned
- Some remaining challenges to be overcome

- Technology consulting
  - Electrochemical and materials focus
  - Clients include leading industrials, VCs, DOE, DOD and EPA
  - 33,000 ft. facility for laboratory, engineering, rapid prototyping and testing
- Technology venturing (own micro-fund)
  - IP generated by consulting and R&D
  - Leverages labs, facilities and consulting successes
- Combined resources
  - ☑ Proven business development team
    - ☑ Start-up to IPO
  - ☑ Strategic relationships extend our capability
  - ☑ 19 years of revenue generation and portfolio building

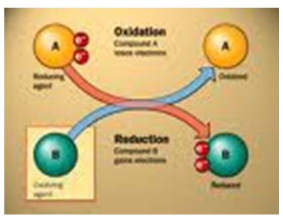
Simbol Materials: Lithium refining module. Built and tested in-house.

Core Technology and IP



- Ionic liquids (eutectic salts, Lewis acids)
  - Novel electrochemistry
  - Changes the electrochemical series
  - DSSC, MIL batteries, metals recovery

- Advanced materials and nano-structures
  - Novel catalysts
  - High performance electrode materials (Magneli phase Ti and Perovskites)
  - Novel membranes



- Reduction oxidation (RedOx)
  - Basis of many biological processes
  - Closed loop processes
  - Batteries, DSSC, bio-tech

- Electrochemical Engineering
  - Chemical Engineering, CFD, Stress, Heat, Current flow
  - Rapid prototyping
  - Pilot plant design and construction
  - Pilot Test Facility

AIC's work in Redox Flow Battery chemistries

- Some of the RFB chemistries we have worked on for others
  - Zn/Br, Zn/Cl, V/V, Fe/Cr
- Some of the RFB chemistries we developed privately
  - Ce/Zn
  - V/V
  - Zn/Air
  - Co/Zn
  - Ce/V
  - Ce/Ti
  - "Soluble lead" Pb/Pb MSA

Patented by AIC

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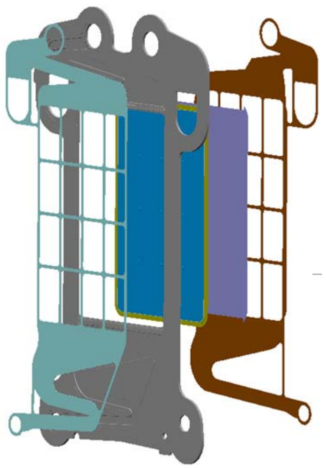
Plurion – 13 years of in-house RFB development

- AIC invented the Ce/Zn RFB in 1999
  - At 2.4V OCV it is the highest voltage aqueous RFB couple
  - Both Ce and Zn in Methane Sulfonic Acid deliver exceptional reaction kinetics
    - 10,000A/m2
  - The chemistry was novel and extensively patented
  - The materials used are low cost
- Between 1999 and 2009 AIC raised ~$40 million to support this R&D effort
  - In 2005 Plurion was relocated to the UK (Scotland) as there was zero support for RFB’s in the US at the time
  - In 2009 Scottish Enterprise purchased all of the outstanding shares in Plurion
  - In late 2009 Plurion was closed down because of the economic down turn and government cutbacks

RedOx Flow Battery engineering



- RFB flow cell design
  - Novel low restriction flow paths with zero bypass (shunt) current
  - Novel flow cell design with self balancing pressure (low Δp)
- Materials
  - Novel nano-structured non-carbon electrodes
  - Novel low cost membranes and membrane supports
- Materials testing and establishing QAS's
  - Electrolytes
  - Pumps, pipes and valves
  - Materials of construction

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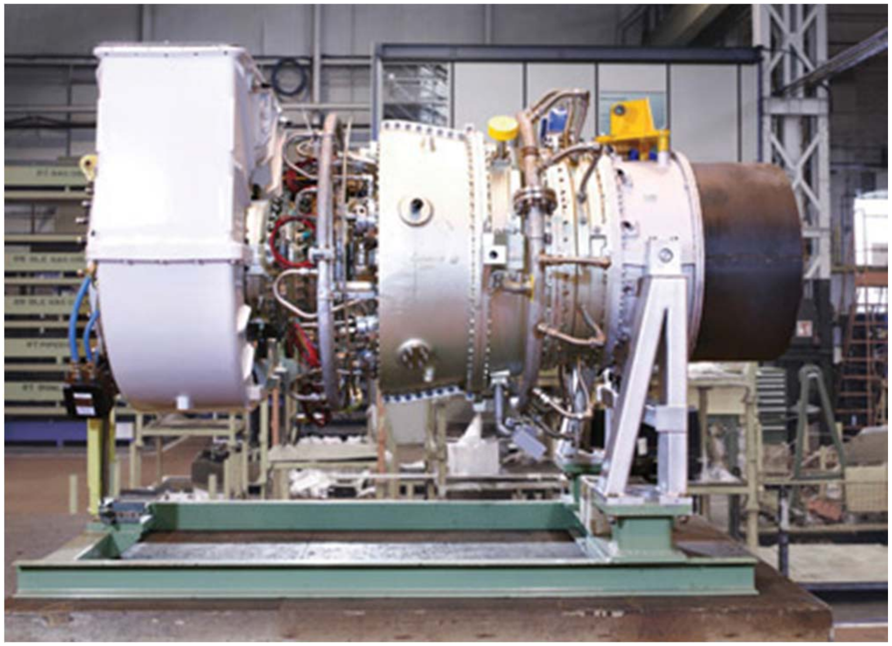
Know your competition



- Gas turbines are the default option
  - Now ubiquitous on all large wind farms
  - Utilities understand them – and feed them
- Extensively engineered, high reliability, plug and play, leased not purchased

An RFB is Not a fuel cell

- Fuel cells are only ever discharged - an RFB must be charged as well
  - Charging is far more challenging than discharging
  - Materials that are robust in discharge reactions often fail under charging - e.g carbon
  - Good discharge catalysts may be poor charging catalysts
- An RFB will need to store charged liquid electrolytes for extensive periods of time

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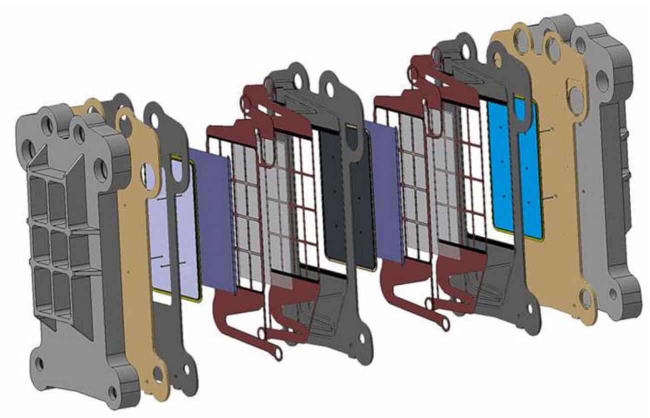
RFBs require trade-offs and compromises that are unique to RFBs

- An RFB must power itself and this imposes complex trade offs, e.g:
  - High voltage couples and reactive chemistries v materials of construction
  - Low voltage couples and low reactive chemistries v large footprint and electrolyte lakes
  - Shunt (bypass) current losses v pumping losses
  - Expensive catalysts v electrolyzer power density
  - Good reaction kinetics and temperature v materials
- An RFB must be able to self start with zero external power

Understanding these compromises requires tools and skill in using them



- Designing an RFB requires comprehensive design tools
  - Computational Fluid Dynamics
  - Flow path and Shunt Current modeling
  - Heat management
  - Vibration and stress
- But most of all – it needs a holistic "Performance and Economics" model

Expect your designs to change - often

Don’t even think about ordering injection moulds for your RFB electrolyzer - until you have a fleet of RFB’s operating flawlessly for 20,000 cycles

Expect to pull pilot cells apart - often

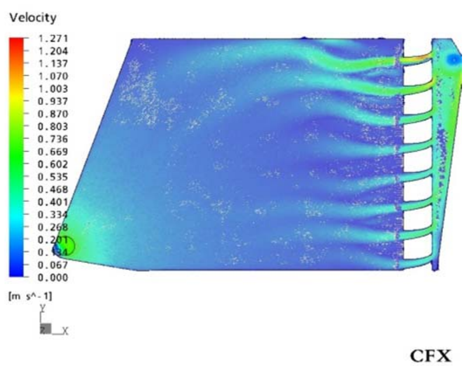
Don't act surprised when you need to pull that shiny new electrolyser apart after 3 cycles

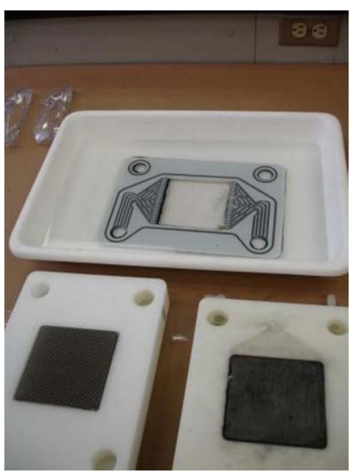
Design your pilot systems to support regular, efficient tear down and re-assembly

Avoiding the "Death by Demonstration" trap

- Learn from the gas turbine industry
  - Never, ever, ever demonstrate in public
  - "Demonstrations" must be flawless re-enactments of perfect runs
- Build your own test facility and <u>test at scale first</u>

Pilot testing drives performance and economics – not computer simulation





- Make the effort to validate your CFD models
  - They generally don't handle electrode reactions well
  - Often assume water as the fluid
- Develop and validate scalable systems
  - 1/100th to 1/10th to test materials, designs and chemistries at high cycle life
  - ¼ to Full Scale to validate the system
- Use these to drive the "Performance and Economics Model"

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A key unresolved challenge of RFB's is Round Trip Efficiency

- Customers are just not buying that "60% RTE is good enough"
- RFB electrolyzer designs need to move beyond conventional electrolyzer concepts
  - Micro channel architectures
  - Plug flow systems
  - Self Fluidized Beds
- Electrode surfaces and catalyst interfaces need to be optimized for charging and discharge

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Another unresolved challenge of RFB's is cost per unit

- Like it or not, the default storage technology is Lead Acid
  - Already widely accepted in China with growing acceptance in India
  - Proven at scale in the US – Chino the biggest storage project you have never heard of
- High quality LAB's are now as low as \$100/kWh and projected to drop to \$70/kWh
- Developments in Bipolar Lead Acid may deliver 10,000 cycles at >80% DOD

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A larger challenge is the scale up of RFB production facilities

- In 2007 we modeled the minimum economic scale for an RFB manufacturing facility to be 2GWh of shippable RFB products/year
  - At a cost of $1-2 million/MWh/year, this would require a capital investment of $2 billion
- This is similar to the cost of building a new Gas Turbine manufacturing facility
- Compare this to the cost of a “green field” Lead Acid facility at $50,000/MWh/yr

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But the biggest challenge is the scale and nature of RFB R&D

- Even with its current popularity, funding of RFB R&D is sparse and often poorly applied
- What little there is, is spread over countless start-ups
  - Many are walking down the same blind alleys that others have walked down before
- There are no centers of excellence in the key elements of RFB R&D
  - How many times do we need to reinvent this wheel?
- Even with $40 million in funding, and some novel approaches to RFB development, Plurion was chronically underfunded and failed to thrive