The Viability of High Specific Energy Lithium Air Batteries

October 7, 2010

Dr. Lonnie Johnson
Excellatron Solid State LLC

EXCELLATRON

LITHIUM-AIR PERFORMANCE PROJECTIONS FAR EXCEED CONVENTIONAL STATE OF THE ART CELLS

THEORETICAL VALUES OF SELECTED METAL/OXYGEN BATTERY COUPLES

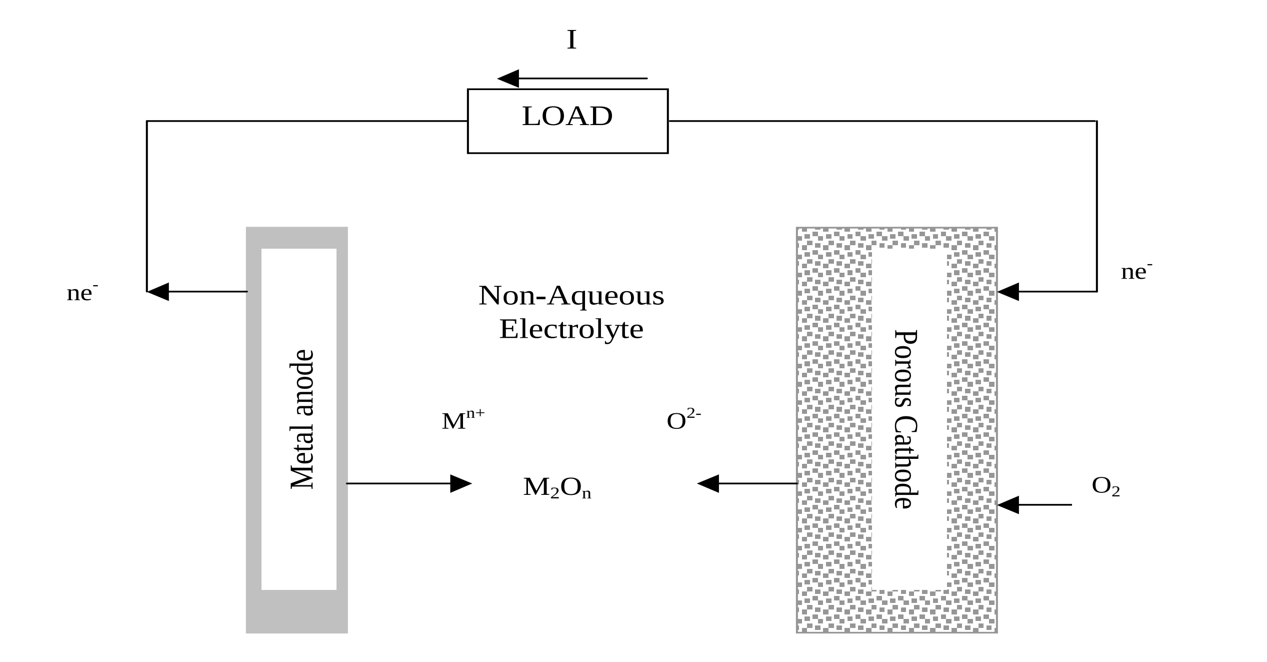
Metal/O_2 couple	Cell reaction	Open-circuit voltage (V)	Specific energy density (Wh/kg)	
			Including O_2	Excluding O_2
Li/O_2	$4Li + O_2 \rightarrow 2Li_2O$	2.91	5200	11,140
Ca/O_2	$2Ca + O_2 \rightarrow 2CaO$	3.12	2990	4180
Zn/O_2	$2Zn + O_2 \rightarrow 2ZnO$	1.65	1090	1350
Al/O_2	$4Al + 3O_2 \rightarrow 2Al_2O_3$	2.73	4300	8130

LITHIUM OXYGEN COUPLE OFFERS HIGHEST SPECIFIC ENERGY

LITHIUM-AIR PERFORMANCE PROJECTIONS

	Specific Energy (Wh/kg)	Energy Density (Wh/l)	Specific Power (W/kg)	Cycle Life
Lithium Air	2000	2000	400	500

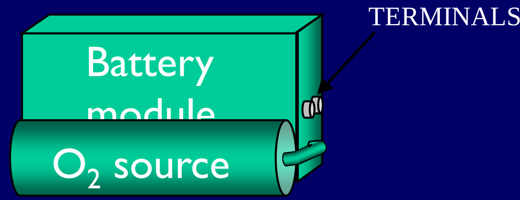
Non-aqueous metal/air battery concept introduced by Abraham in 1996

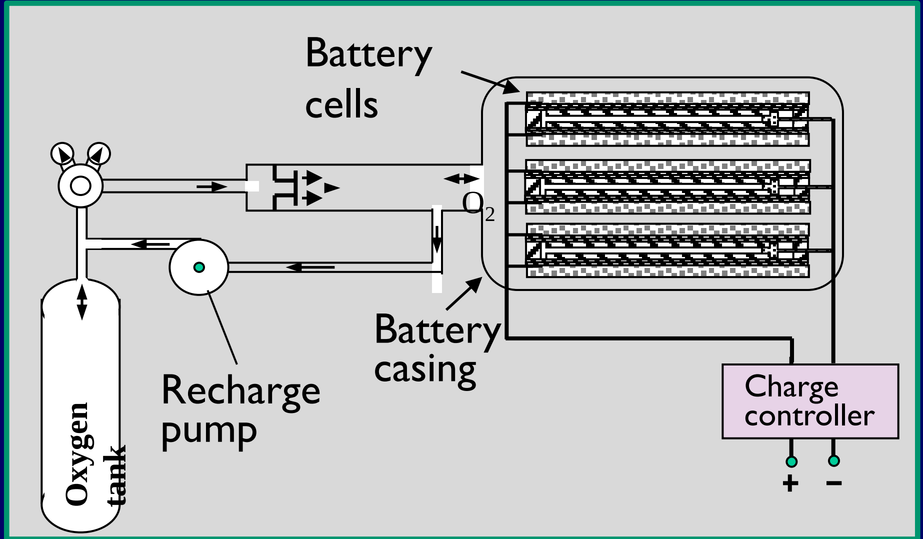


- Avoid water corrosion problems
- Discharge product deposits in cathode
- $2\ Li + O_2 \longrightarrow Li_2O_2 \quad E^0 = 3.10\ V$
- $4\ Li + O_2 \longrightarrow Li_2O \quad E^0 = 2.91\ V$

EXCELLATRON BATTERIES UNDER DEVELOPMENT

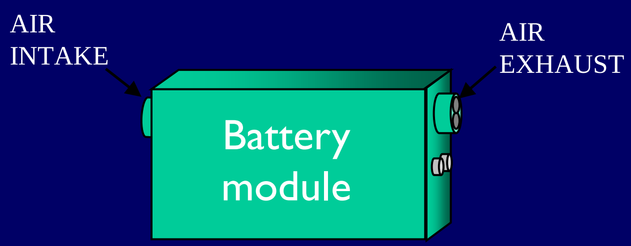
SELF CONTAINED OXYGEN IN

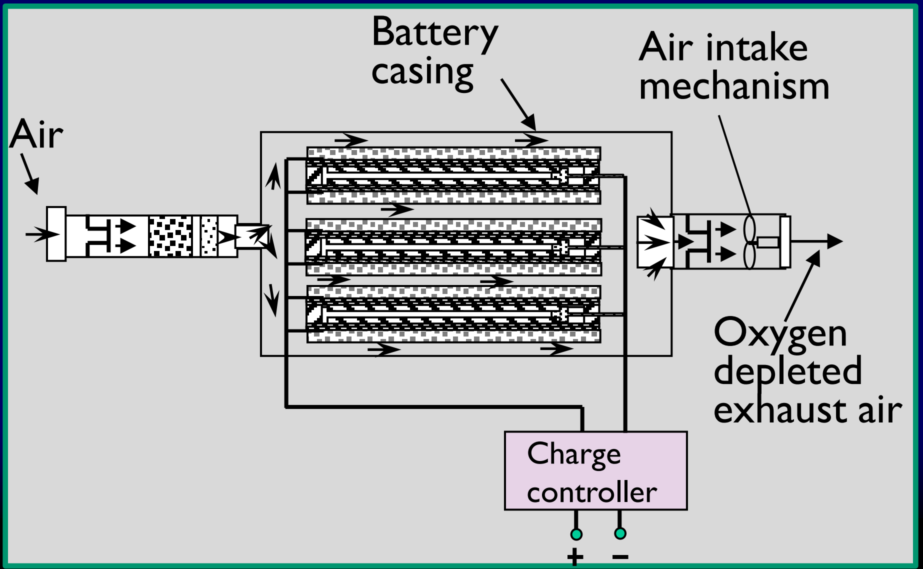




- •Under water, high altitude and space applications where ambient air operation is not practical
- •Uses pressurized tank or large ambient pressure oxygen enclosure
- •Rechargeable or non-rechargeable

OPERATE ON OXYGEN FROM AMBIENT AIR





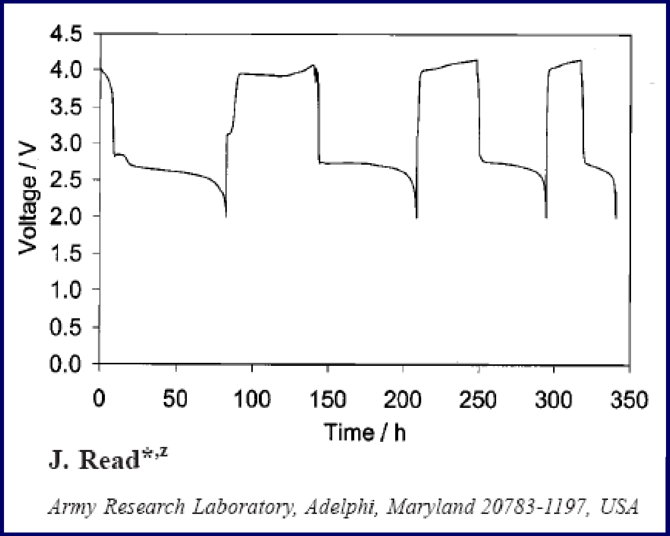
- •Compact size for portable power applications
- •Use desiccant to enable ambient air breathing system
- •Air intake mechanism activated only as needed to minimize desiccant pack size
- •Rechargeable or non-rechargeable

EXCELLATRON

Why the Breakthrough is Significant

Previous Efforts to Develop Li-Oxygen Technology:

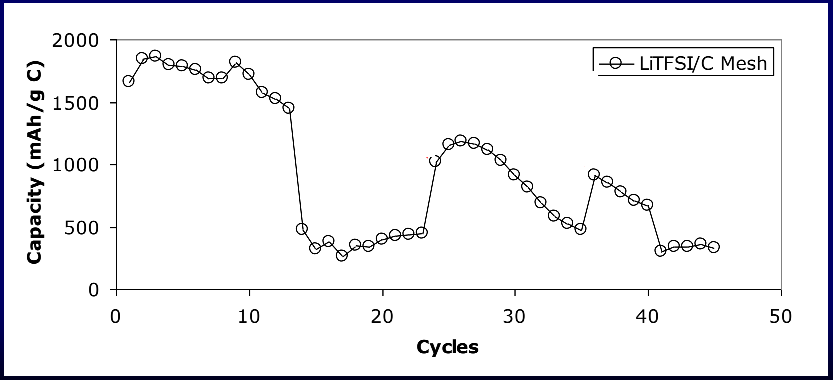
- Early work yielded only limited rechargeability (3 cycles, Abraham & Jiang, 1996)
- Research by at Army Research Lab yielded similar results (3 cycles, J. Read, 2002)
- Army presently focusing on non-rechargeable cells as rechargeability was considered not viable.
- No practical approach for using oxygen from ambient air



Excellatron Early Results:

•Electrolyte solvent found to be a critical element for O2 cathodes

•Improved cycle stability, but significant capacity fade experienced after just a few cycles

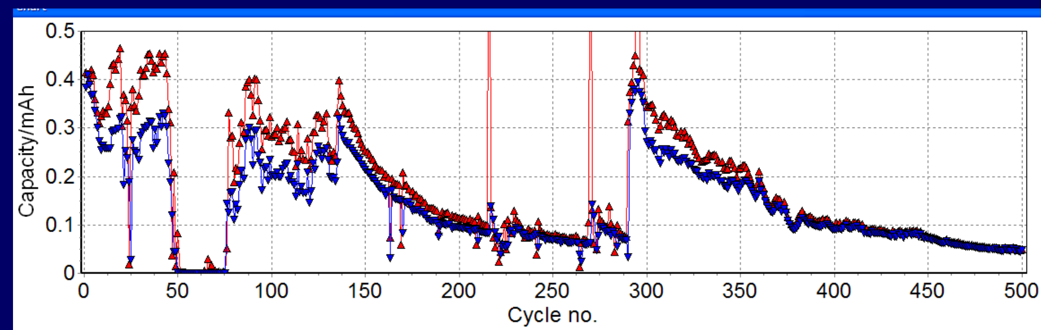


EXCELLATRON

Excellatron - Progress

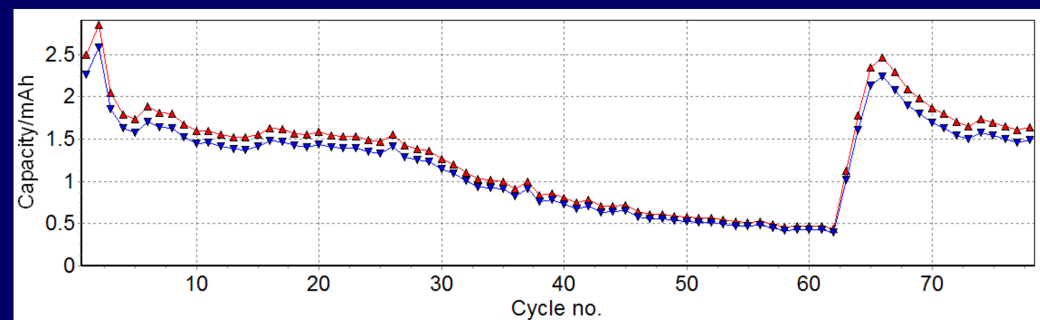
First Significant Estension:

- Increased capacity retention by 10X over earlier results (from over 30 to over 300 cycles)
- Cycle life extended, noisy results, electrolyte loss still a major problem
- Identified primary solvent loss mechanism as anode related



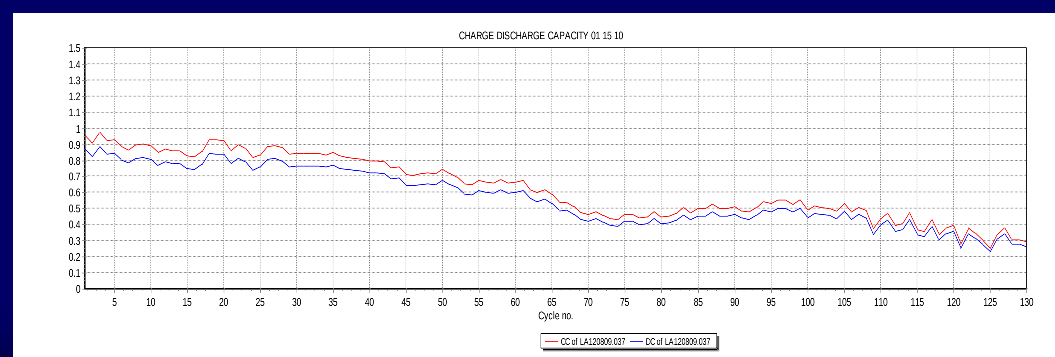
Further Extended Cycle Life:

- Increased round trip efficiency to 75% by the use of electrolyte additives
- Demonstrated extended cycle life of cathode through half-cell testing



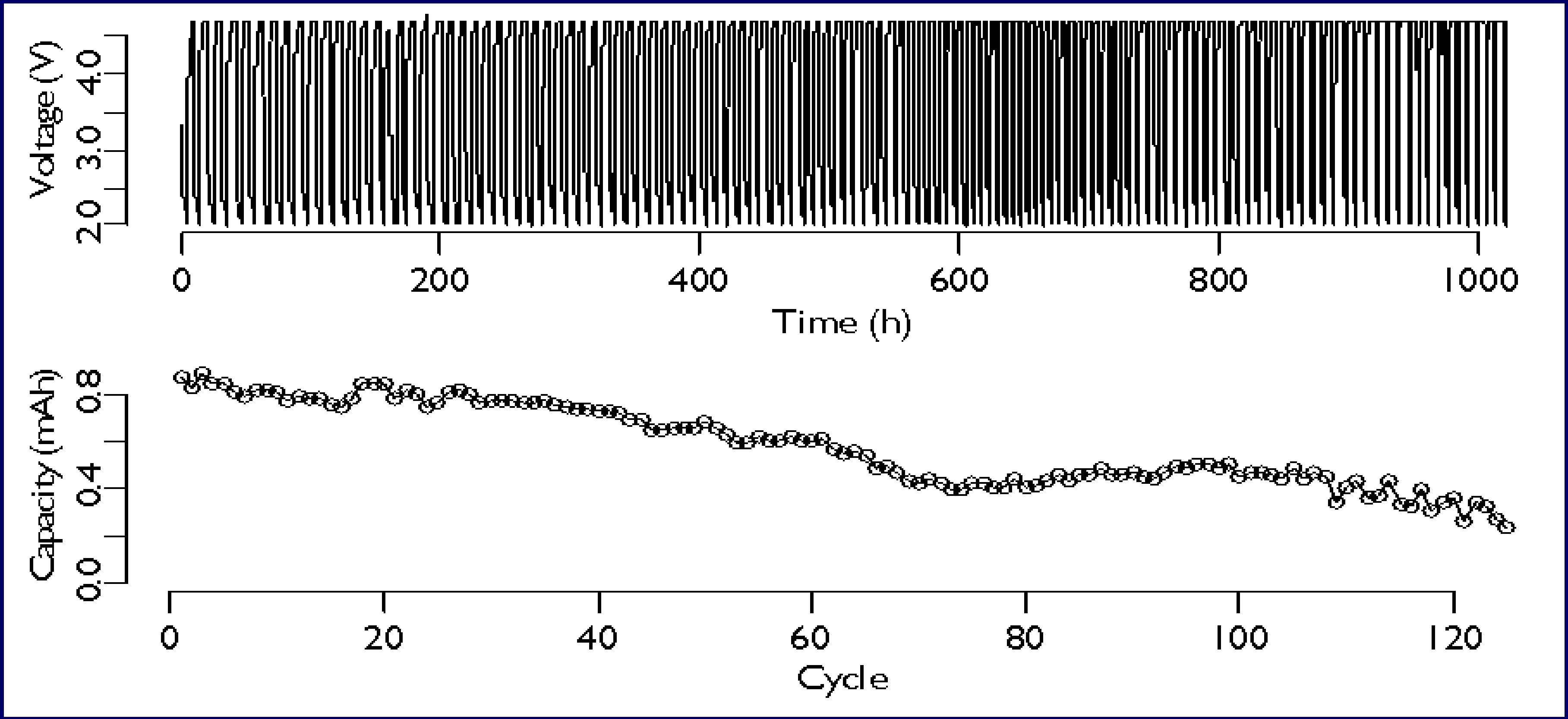
Achieved Major Milestone in Cycle Life:

- Demonstrated life of over 100 cycles using a combination of
    - electrolyte formulation including additives electrical charge protocols
- Verified specific energy goal of 1300Wh/kg using modeling to scale actual test data.
- Defined approach for using ambient air oxygen
- Verified high discharge rate cathode design
- Developed cathode design for high rate discharge

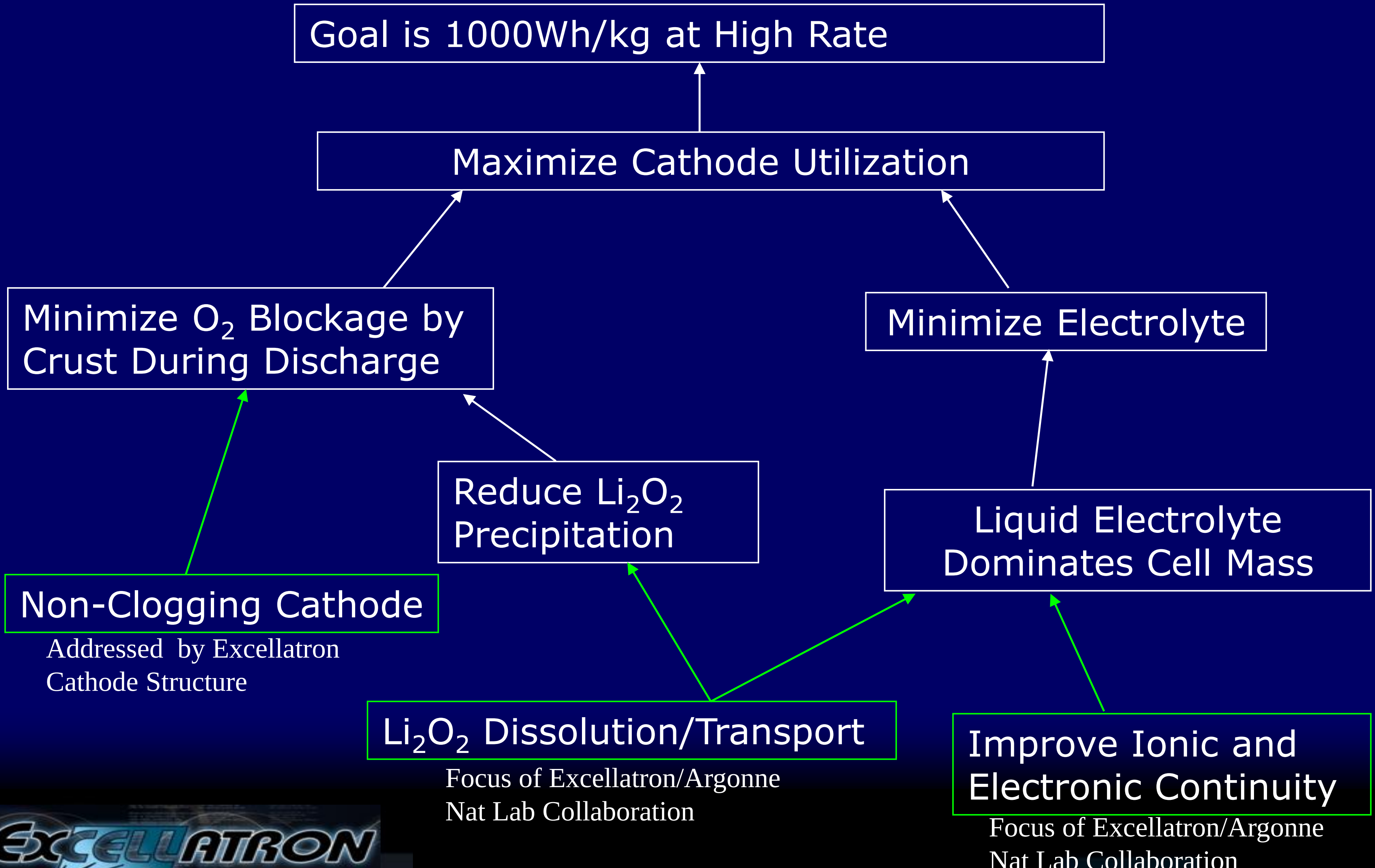


EXCELLATRON

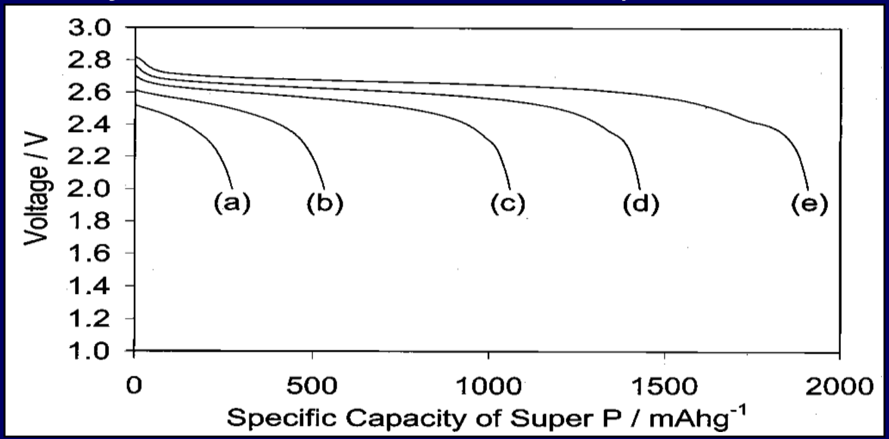
Breakthrough in Cycle Life Allows Excellatron to Now Focus on More Fundamental Cell Mechanisms

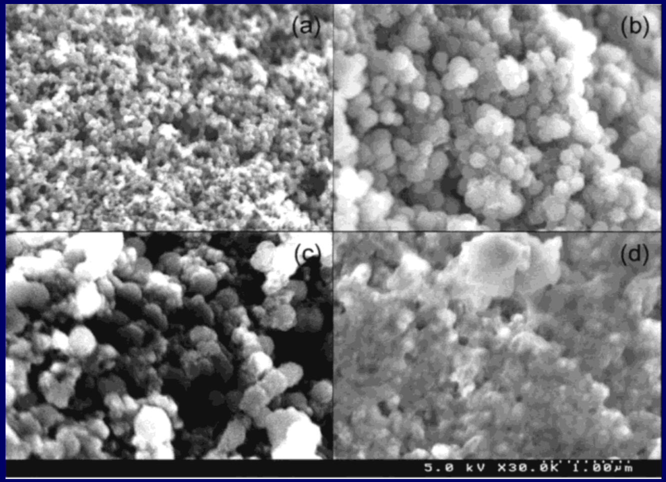


R&D Issues Relating to Discharge Rate Capability

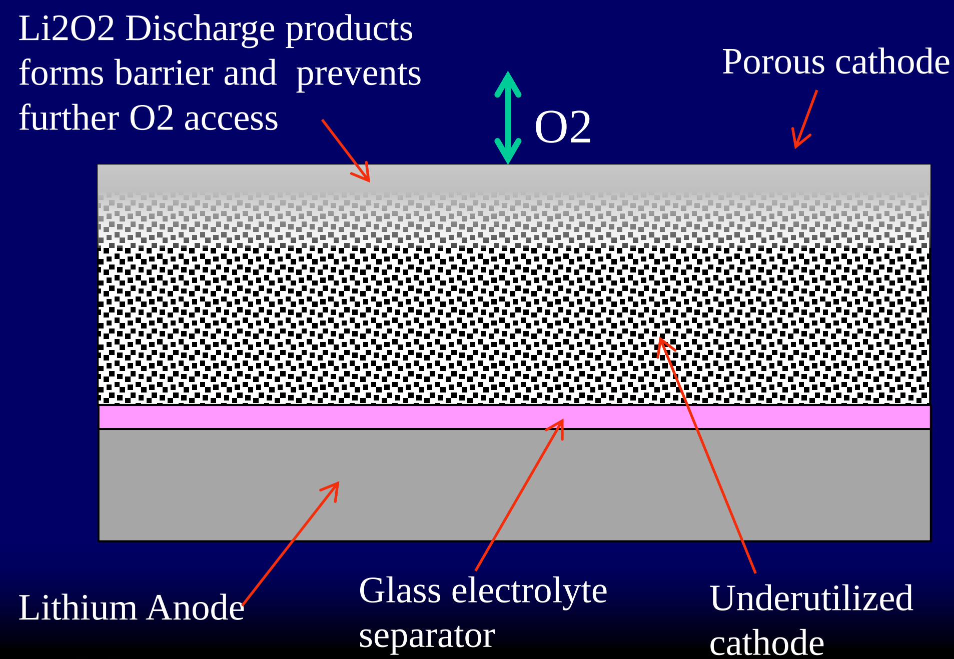


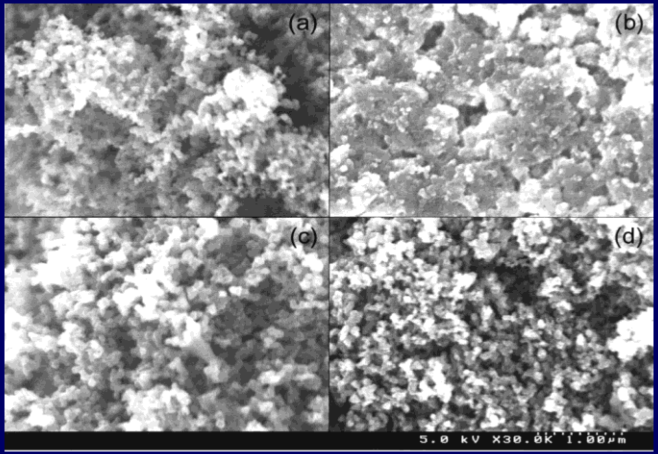
Specific capacity of Super P in PVDF air cathodes: a) 1.0mA/cm^2, b) 0.5mA/cm^2, c) 0.2mA/cm^2, d) 0.1mA/cm^2, and e) 0.05mA/cm^2. (*J. Read; Journal of The Electrochemical Society*, **149** ~9! A1190-A1195 ~2002)





SEM micrographs of PTFE air cathodes (air side of electrode). a) Not discharged and discharged at b) 0.05mA/cm2, c) 0.2mA/cm2 and d) 1.0mA/cm2

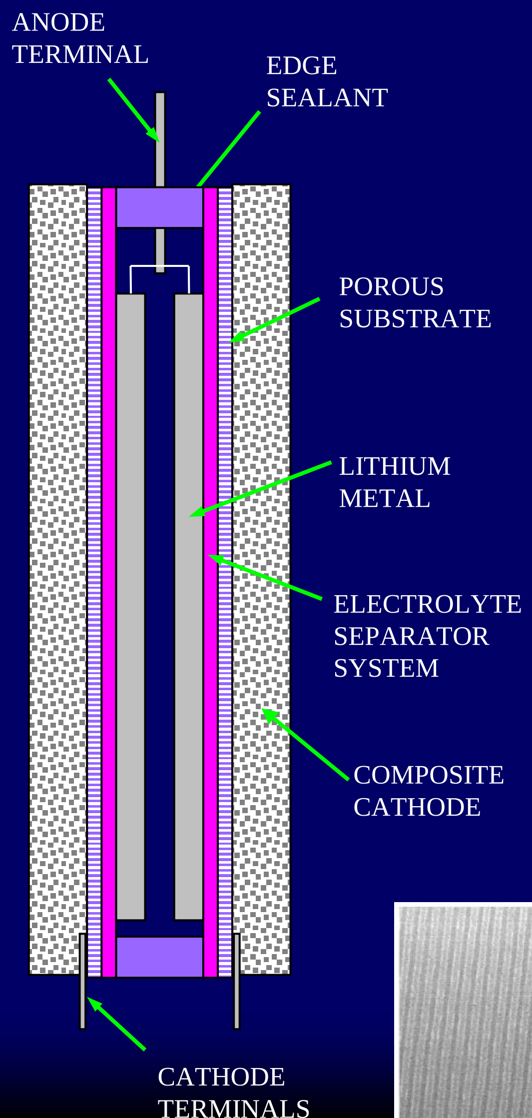


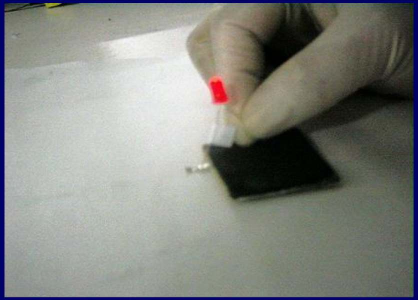


SEM micrographs of PTFE air cathodes (center of electrode). a) Not discharged and discharged at b) 0.05mA/cm2, c) 0.2mA/cm2 and d) 1.0mA/cm2

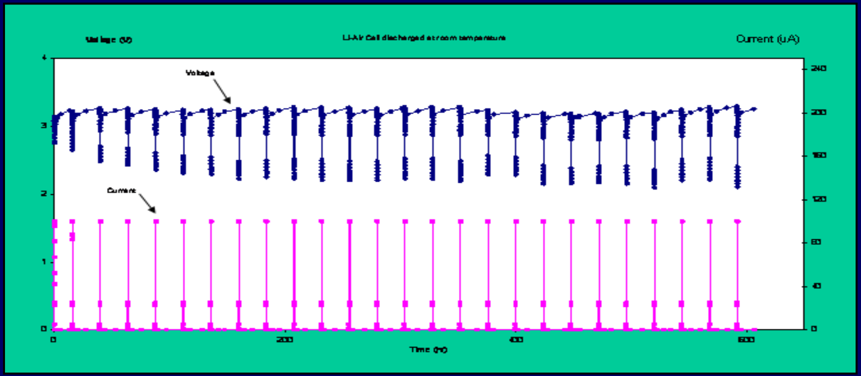
EXCELLATRON

CELL DEMONSTRATED USING THIN FILM LiPON GLASS ELECTROLYTE BARRIER TO PROTECT LITHIUM

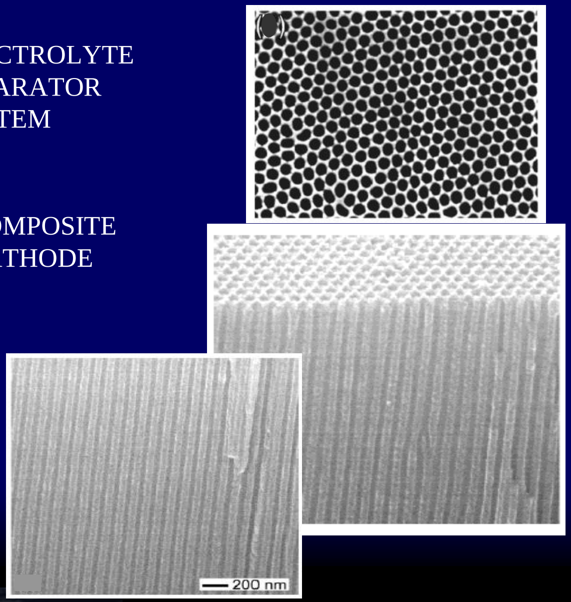


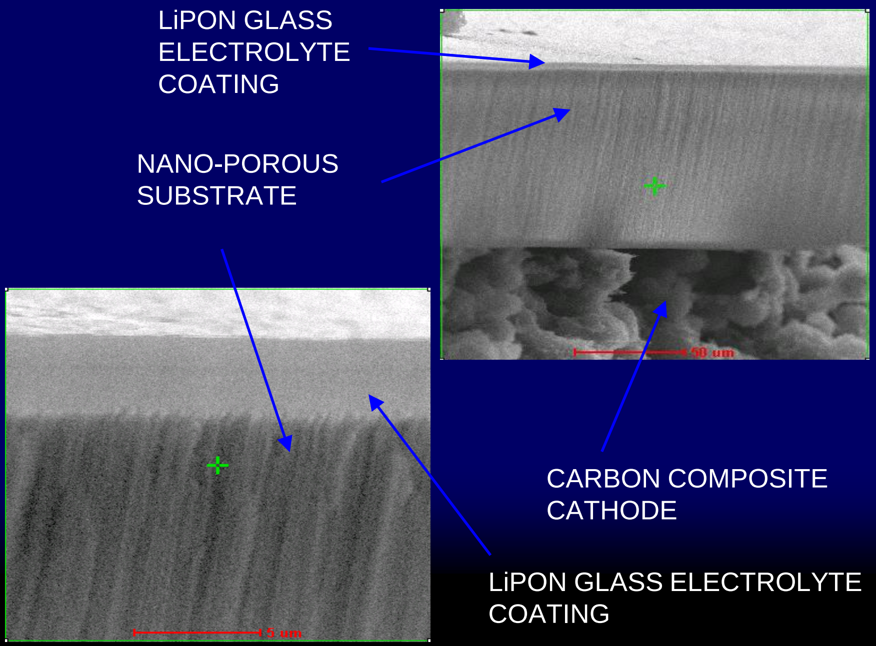


DEMONSTRATED PRIMARY LITHIUM AMBIENT AIR CELL



SINGLE BARRIER CELLS DEMONSTRATED STABLE DISCHARGE IN AMBIENT AIR FOR OVER 3 MONTHS

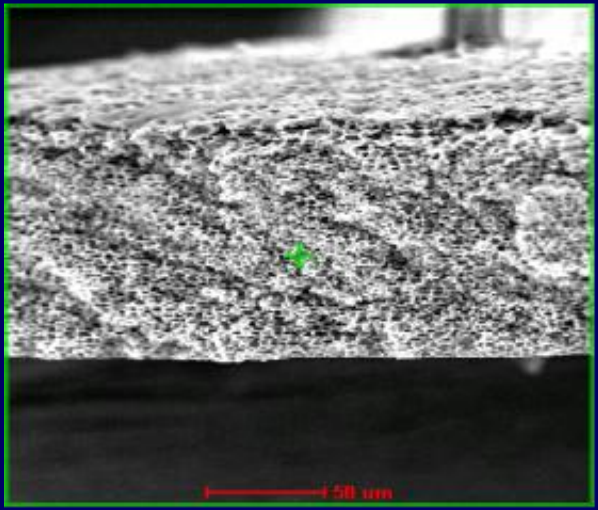




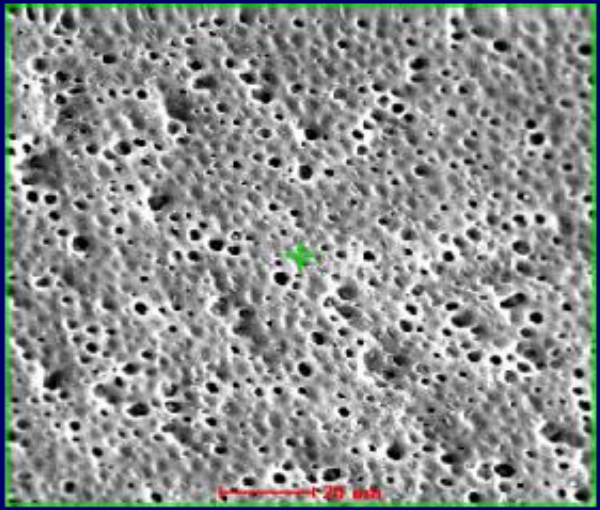
EXCELLATRON

Develop Flexible Porous Support for Large Area Thin Glass Barrier Electrolyte System

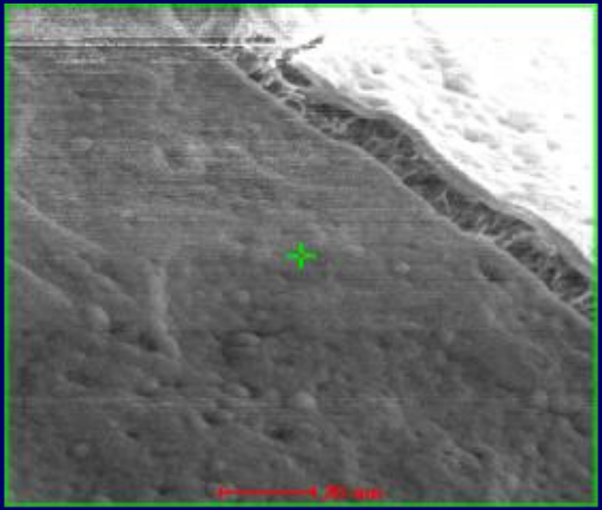
Results of earlier material development efforts



Edge view of porous substrate



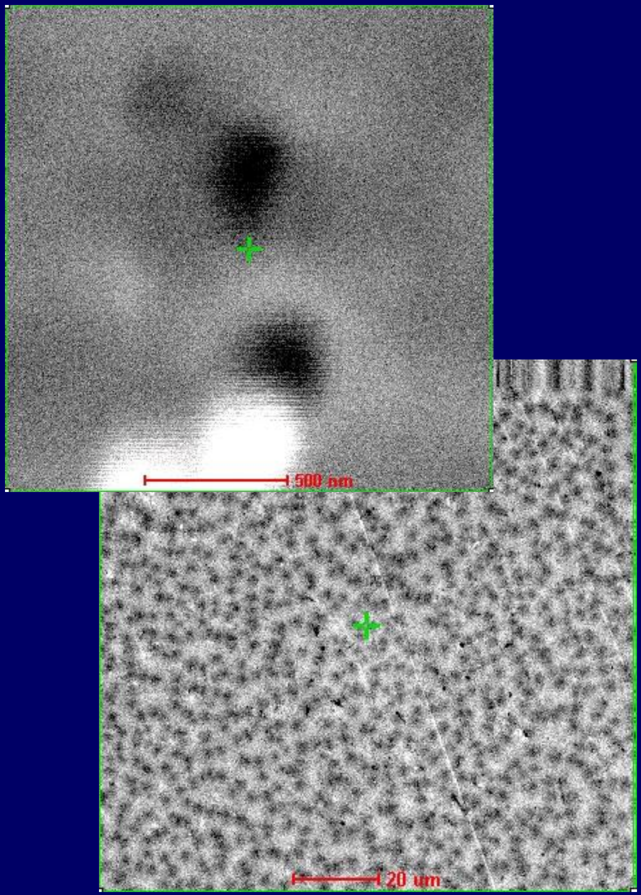
Porous substrate surface



Glass coating on porous substrate

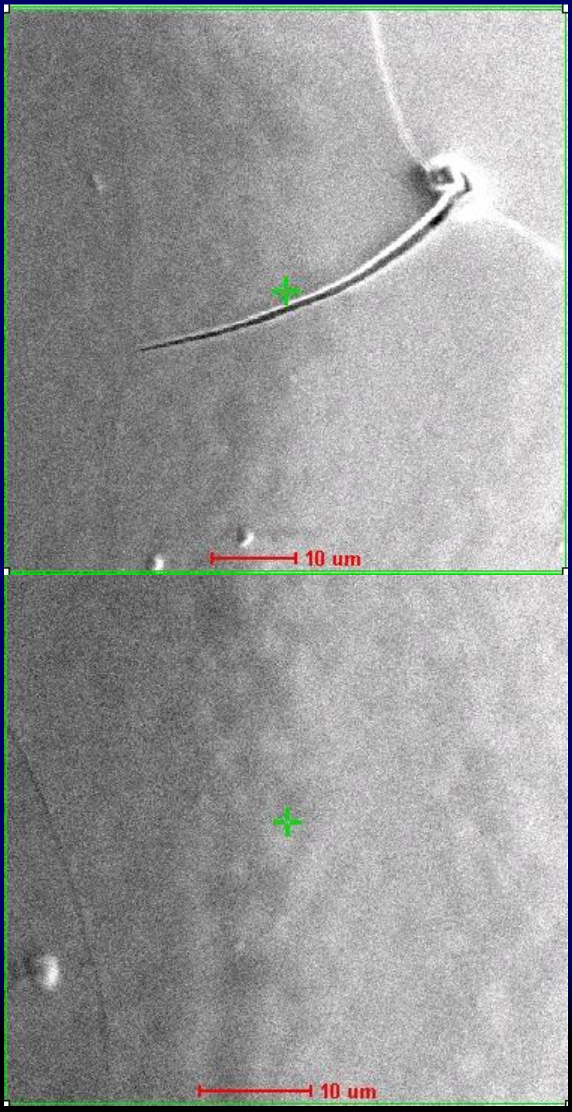
- Support must tolerate processing Environment
- Small pores needed to allow support of thin glass coating
- Smooth surface needed for high quality thin coating

Barrier Electrolyte System using Excellatron Glass Coating Projected Cost on Order of $1/m2



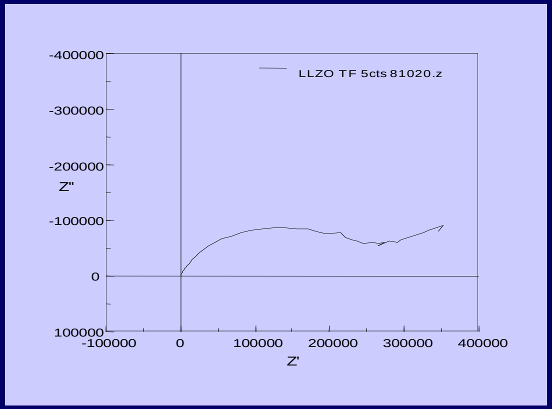
Decreased pore size to 200nm and increased pore density

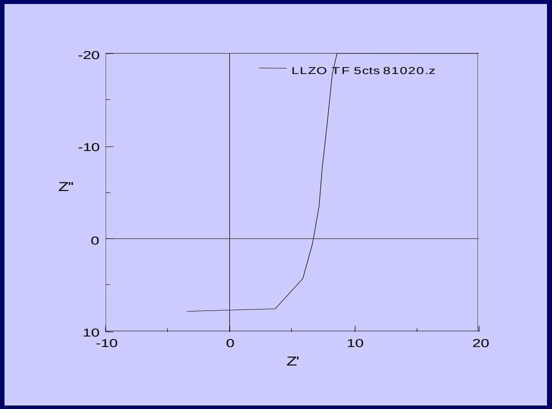
Coating appears to be of high quality except for imperfections associated with dust particles

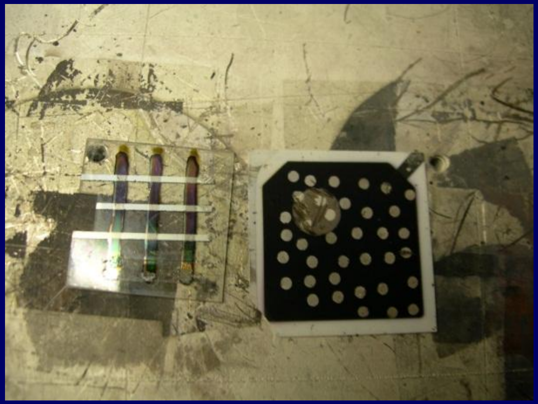


EXCELLATRON

Excellatron Glass Electrolyte Results







Lithium stablility in contact with Excellatron glass demonstrated over several weeks in glove box

Li ion conductivity > 1E-3 S/cm from high frequency intercept

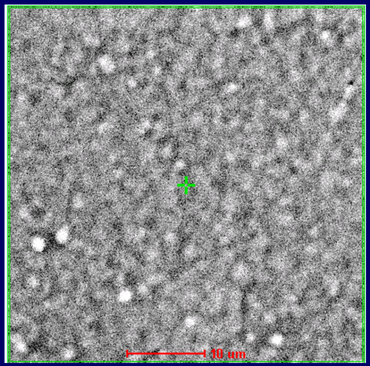
Glass appears stable in organic liquid electrolytes and water

More cost effective and higher performance alternative to LiPON

EXCELLATRON

Micro Batteries Using Excellatron Glass Electrolyte

Glass coating

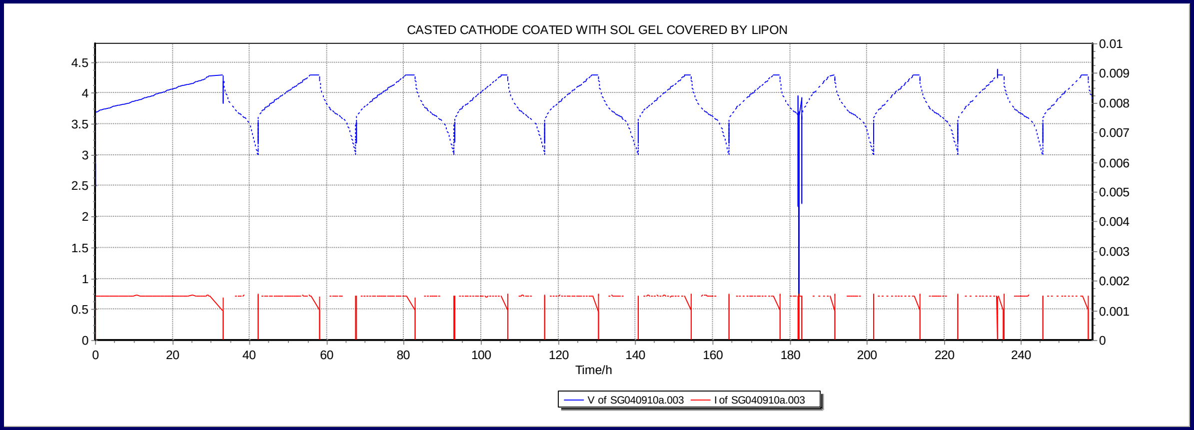


Next steps:

Eliminate glass film imperfections such as debris and isolated cracks

Remove LiPON from glass electrolyte separator component

Integrate Excellatron glass electrolyte into Lithium Air battery separator system



Li/LiPON/Excellatron Glass/LiMnOx cell:

OCV maintained for several weeks in direct contact with lithium

LITHIUM AIR CAN EXCEED ALL USABC GOALS

Lithium ion close to USABC performance goals but falls far short of cost goals

	USABC MINIMUM LONG TERM PERFORMANCE	STATE OF THE ART LITHIUM ION @200Wh/kg	EXCELLATRON Li-Air SMALL BATTERY OPTION (1,300Wh/kg)
ANODE		Graphite	Lithium Metal
CATHODE		LiCoO2	CARBON + O2 FROM AMBIENT
VOLUME (L)	300Wh/l	66.6L BATTERY (@ 600Wh/l)	166L BATTERY
WEIGHT (kg)	200Wh/kg	200kg BATTERY	76kg BATTERY
POWER (kW)	80kW (400W/kg)	80kW	49kW
CAPACITY USABC (Wh)	40kWh	40kWh	104kWh
COST	$100/kWh (USABC GOAL)	$500.00/kWh (BASED ON PRICING OF $0.50/Wh OR $100/kg @200Wh/kg)	$73.00/kWh (BASED ON Li-Ion PRICING OF $100/kg)
RANGE PER CHARGE (MILES)	200	200	468
INTEGRATED LIFE RANGE	1000cycles	1000 CYCLES FOR 200,000 MILES	430 CYCLES FOR 200,000 MILES
COST	$4,000	$20,000	< $7,600 ($4,843 if 2,000Wh/kg)

Compa