High Energy Density Primary Li-O_2 Batteries

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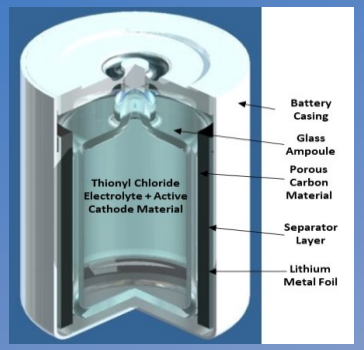
Wasatch Ionics Overview

- Salt Lake City, UT based start-up R&D company founded in 2018
- Business model to develop and de-risk early-stage technologies in the areas of next gen high energy density batteries and advanced materials discovery
- Focused on the development of high energy density LiO_2 batteries in collaboration with Brigham Young University and the US Army
- Our Core Competencies:
  - ✓ Next Gen High Energy Density Batteries
  - ✓ Electrochemistry
  - ✓ Novel Materials Development
  - ✓ Li-ion Battery Recycling

Primary Active and Primary Reserve Batteries for Military and Aerospace Applications

Wasatch Ionics

Reserve Batteries



Li-$SOCl_2$ Liquid Reserve Battery

Thermal Battery

Self-contained/hermetic, ultrafast on-demand activation (electric/mechanical/spin triggering), long shelf life >20y, wide temperature range (-40C to 85C), short duration times (seconds to a few days)

Active Primary Batteries

Li/CF_x-MnO_2

Ag-Zn

- 200 – 500 Wh/kg (Li-MnO_2 / Li-CF_x)
- 350 – 480 Wh/kg (Li-$SOCl_2$)
- 400 –500 Wh/kg (Ag-Zn)

Active Primary and Reserve Primary Battery Applications

Space
- Launch Vehicles
- Satellites
- Manned
- Interplanetary and Landers

Munitions
- Missiles & Smart Weapons
- Guided Bombs & Projectiles
- Electronic Fusing

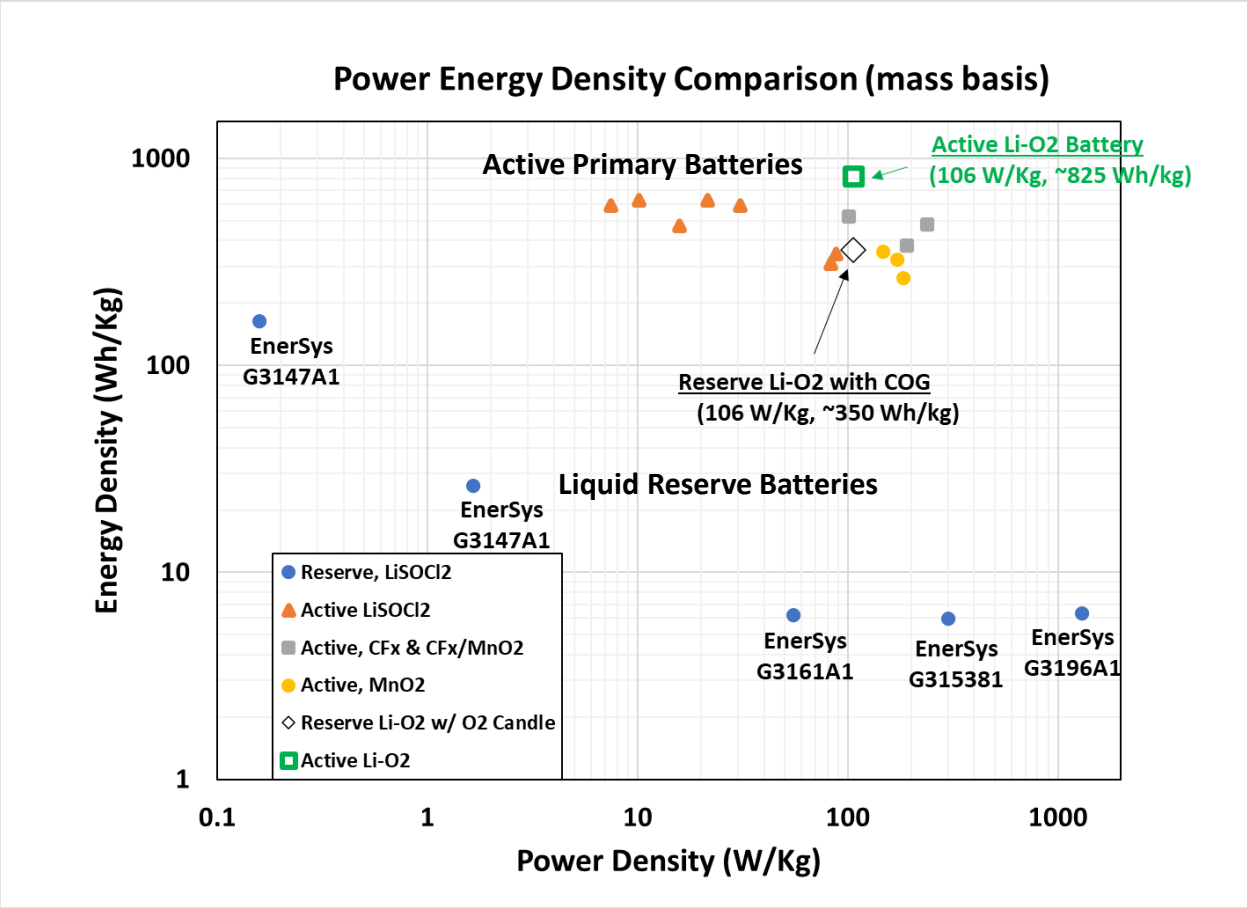
Sea
- Submarines
- Sonobuoys
- Unmanned Underwater Vehicles

Aviation
- Fixed Wing & Rotary Aircraft
- UAV's & Target Drone

Land
- Combat, Tactical, & Unmanned Ground
- Microgrids & Forward Operating Bases

Emergency
- Backup Power, Sensors
- Remote Beacons, Lighting
- Field Medica Gear

Energy Density of Reserve and Active Primary Batteries



Specific Energy Density vs. Power Density for Liquid Reserve and Active Primary Batteries

- The heavy and bulky hardware required to store and isolate the electrolyte and the activation hardware significantly reduces the energy density and power rate of reserve batteries.
- **Li-O_2 Batteries** in both reserve (with integrated Chemical Oxygen Generation, COG) and active configurations can offer a significant energy density advantage over commercial primary battery chemistries such as: Ag-Zn, Li/$SOCl_2$, Li/SO_2Cl_2, Li/SO_2, Li/MnO_2, Li/CF_x-MnO_2, and Li/FeS_2

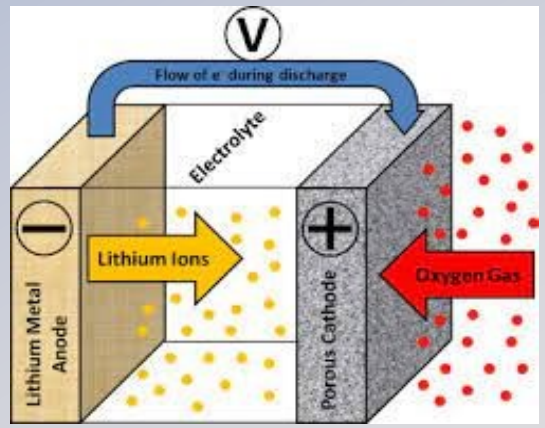
Primary Li-O_2 Batteries (LOBs)

Advantages:

- Highest theoretical energy density of all Li metal batteries (~3,860 Ah/kg).
- Potential for practical energy densities of 800 Wh/kg or higher.
- Active components made from inexpensive Earth abundant materials.
- Can be assembled in active or reserve/inactive configurations.
- Long shelf life and wide operating temperature range on closed sealed designs.

Challenges:

- Large overpotential due to slow oxygen reduction reaction (ORR) kinetics and slow mass transfer.
- Poor rate capacity due to clogging with solid products of discharge, and deactivation of cathode active sites.
- Highly reactive intermediate superoxide ionic species can react with electrolyte and other active battery components.
- Li metal corrosion from moisture, CO_2, and N_2, where air is used as the O_2 source in open battery configurations



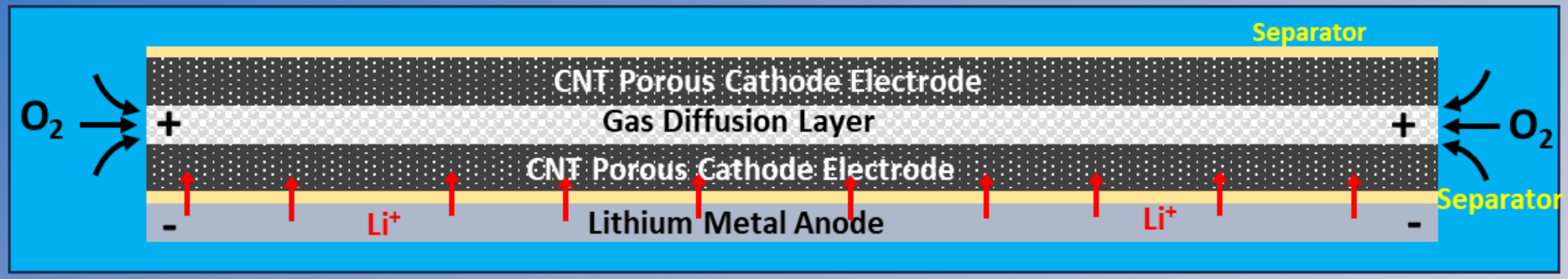
Anode Reaction: $2\ Li \rightarrow 2\ Li^+ + 2e^-$

Cathode Reaction: $2\ Li^+ + O_2 + 2e^- \rightarrow Li_2O_2$

Overall: $2\ Li + O_2 \rightarrow Li_2O_2$

(OCV~2.96 V vs. Li/Li^+)

Primary Li-O_2 Batteries (LOBs)

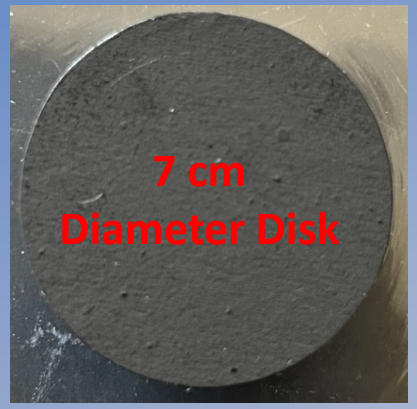


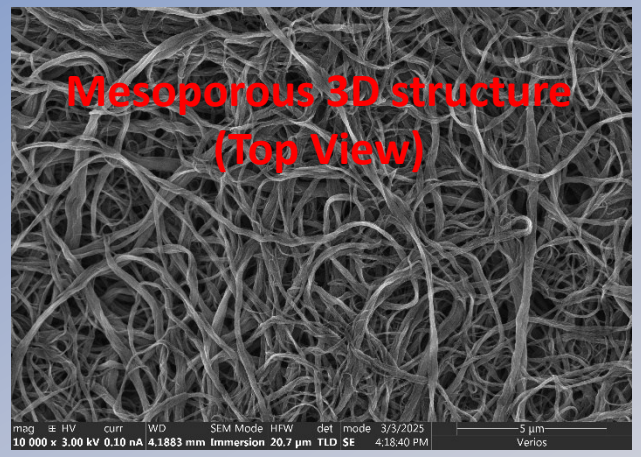
Discharge Rx: 2 Li+ $O_2 \rightarrow Li_2O_2$

- Oxygen gas diffuses from the surrounding through the GDL, entering the porous cathode electrode, and dissolving into the liquid electrolyte.
- At the cathode O_2 is reduced to non-conductive lithium peroxide (Li_2O_2) solids that accumulate within the electrode porous structure. At the anode, Li metal oxidizes to Li^+ ions to close the redox discharge reaction.
- The discharge reaction continues until either all Li metal is consumed, O_2 is depleted, or the cathode electrode gets fully saturated with Li_2O_2.
- O_2 and Li metal are usually in excess, so Li_2O_2 deposition capacity of the cathode electrode determines the maximum LOB discharge capacity.
- ORR kinetics, O_2 electrolyte solubility, and G-L-S mass transfer rates determine the power rate capacity.

Innovative SWCNTs Cathode Electrode

100% SWCNT Binderless Electrode Sheet



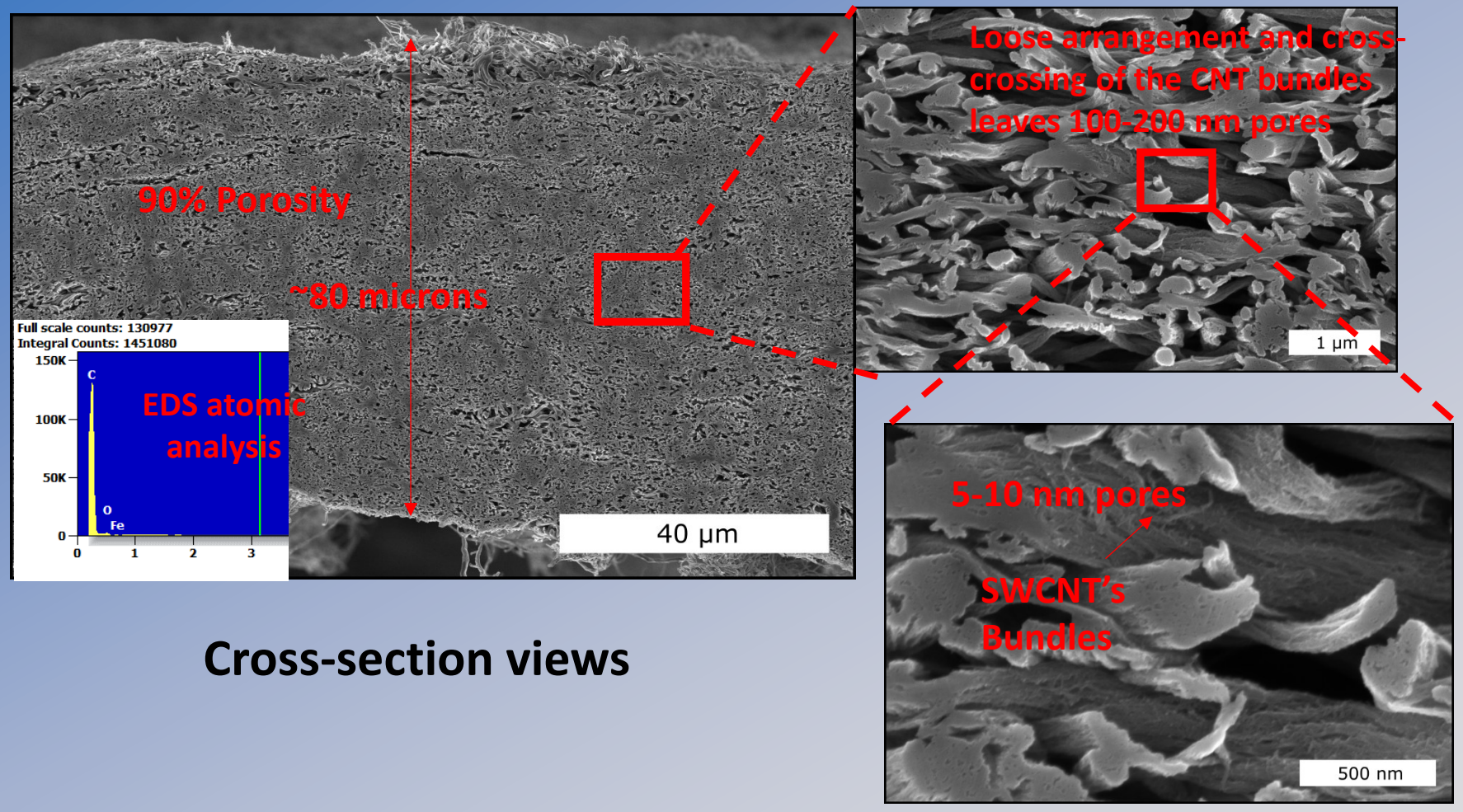


Electrode enables high energy and power densities of LOBs

- **Single Wall Carbon Nanotubes (SWCNTs) powder material**
  - Loosely distributed “wavy” SWCNTs bundles.
  - High surface area: >1,000 m^2/g.
  - Low density: 0.03-0.04 g/cc.
  - CNTs size: 2-5 nm diameter, 300-500 μm length.
- **SWCNTs cast electrode sheet**
  - Wet casting manufacturing process.
  - No binders or additives --> 100% SWCNTs.
  - Tunable porosity (optimum: 90-94%) and thickness (optimum: 80-150 μm).
  - Wavy loosely structure of CNT bundles is kept in the sheet.
  - High porosity and optimal 3D bimodal mesopore distribution network (pore size: 5-200 nm) for fast O_2 diffusion, high Li_2O_2 storage capacity, and large electrolyte retention.
  - Superior mechanical strength to withstand extreme dimensional expansion after full discharge.
  - Electric conductivity ~10S/cm.
  - Can be folded into a jelly roll or other shapes.

Innovative SWCNTs Cathode Electrode

Pristine SWCNTs Cathode Electrode

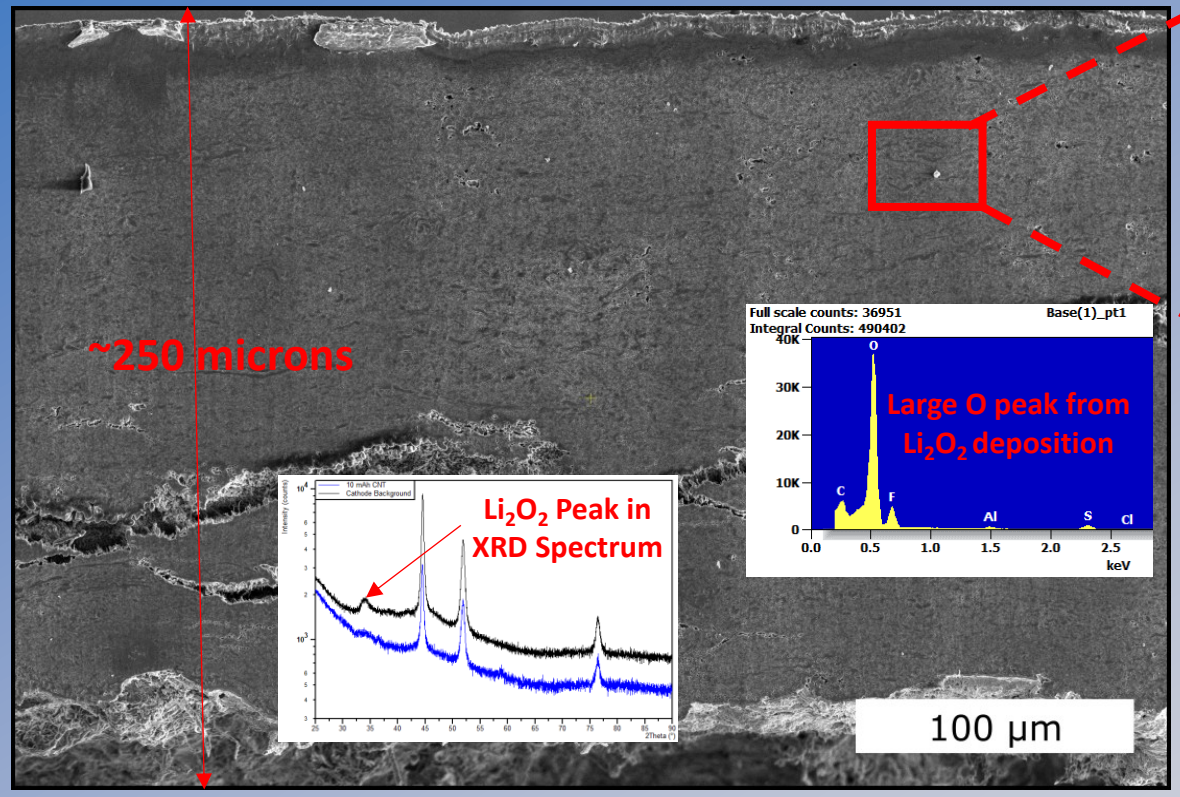


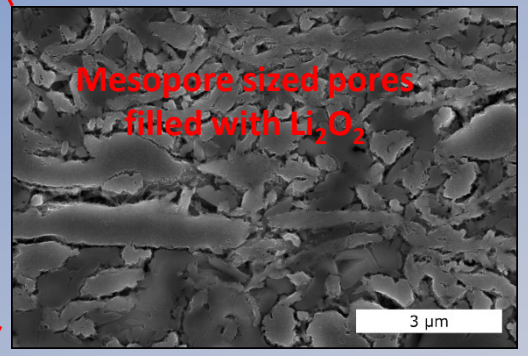
Cross-section views

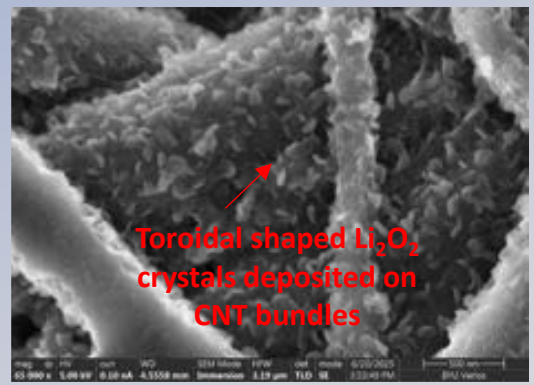
- Thickness: 80-120µm.
- Porosity: 90-94%.
- Sheet Density: < 0.18 g/cc
- Areal Density: ~2 mg/cm^2
- High electrolyte retention capacity.
- CNT fibers bundle crisscrossing for high electrical conductivity.
- Ideal porous structure enables large capacity:
  - > 10,000 mAh/g sheet
  - > 18 mAh/cm^2

Innovative SWCNTs Cathode Electrode

Fully Discharged SWCNTs Cathode Electrode



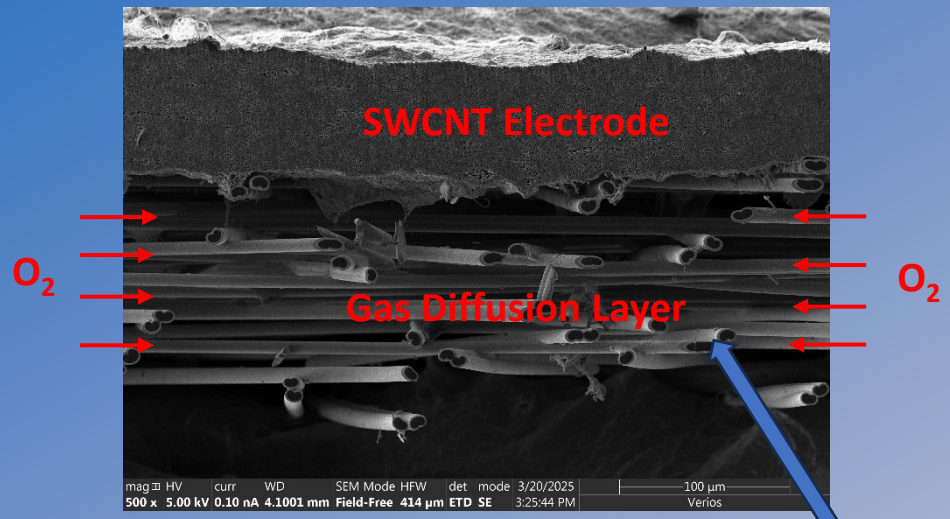




Cross-section views

- XRD/EDX demonstrate Li_2O_2 presence
- Mechanical strength: Up to 300% expansion after full discharge with no delamination or rupture
- Large Li_2O_2 deposit storage capacity
- Toroidal-shaped Li_2O_2 crystals grow from CNTs wall bundles without fully clogging 3D porous space during discharge

Gas Diffusion Layer (GDL)



GDL/SWCNT Electrode Assembly (single sided)

GDL Sheet Roll

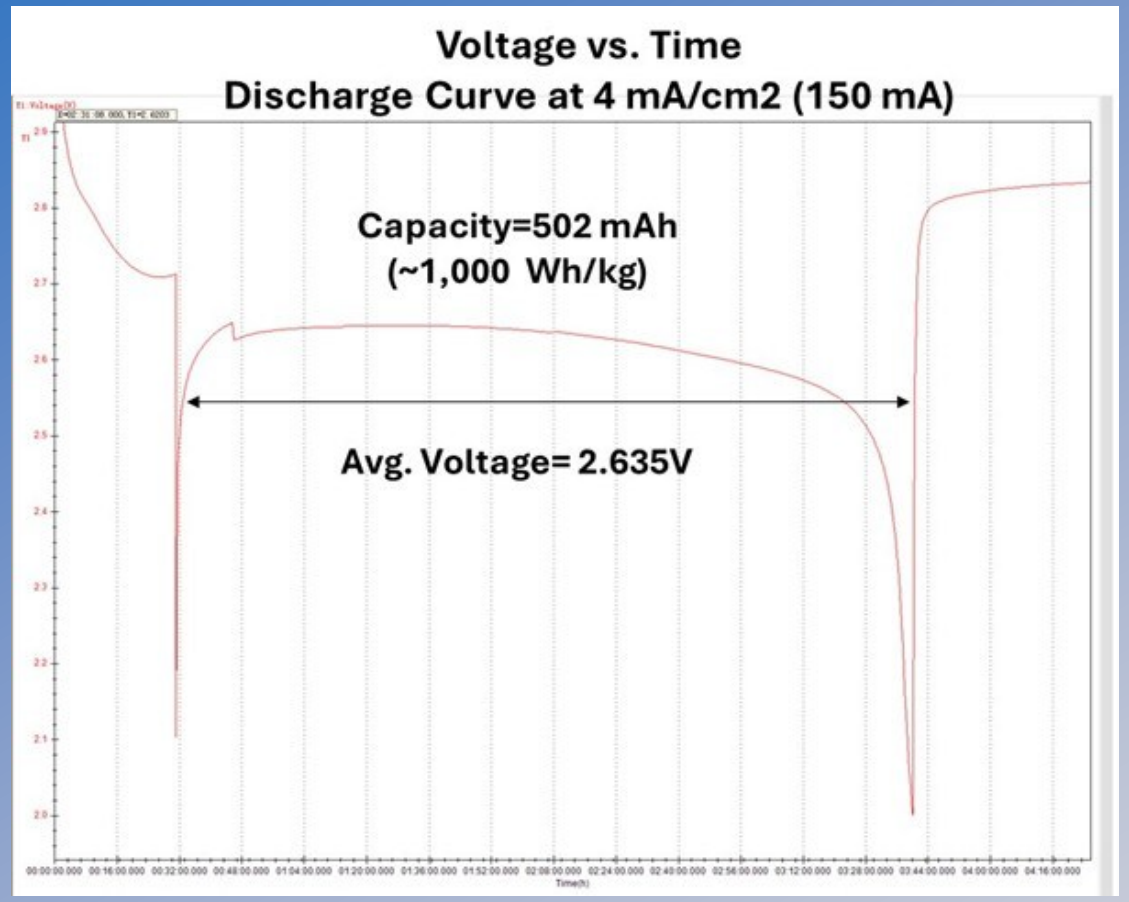
Metal covered carbon fibers

- Gas Diffusion Layer (GDL) role:
  - O_2 diffusion to the cathode electrode.
  - Cathode current collector.
  - Heat management.
  - Backing and support for CNTs electrode.
- GDL made of foldable non-woven metal coated carbon fiber sheet material:
  - Thickness~ 80 µm
  - High porosity (>98%)
  - Ultra low density (~2 mg/cm^2)
  - Electrically conductive (2,000 S/cm)
- GDL is attached to SWCNT cathode during electrode wet casting process.
- Single or double-sided GDL/CNT cathode assemblies are possible.

Liquid Electrolytes and Separators

- Proprietary liquid electrolyte composition optimized for high-rate capacity
  - ✓ Blend of high O_2 solubility aprotic solvents.
  - ✓ Contains SEI formation and Li-metal stabilization additives.
  - ✓ High ionic conductivity/low viscosity for low temperature performance.
  - ✓ High electrochemical resistance against oxidative decomposition by active superoxide radicals formed during the oxygen reduction reaction (ORR).
- Separators
  - ✓ Many types have been tested and qualified for LOBs use.
  - ✓ Standard thin polypropylene/polyethylene membranes coated with electrolyte wetting aids are preferred for high-rate performance.

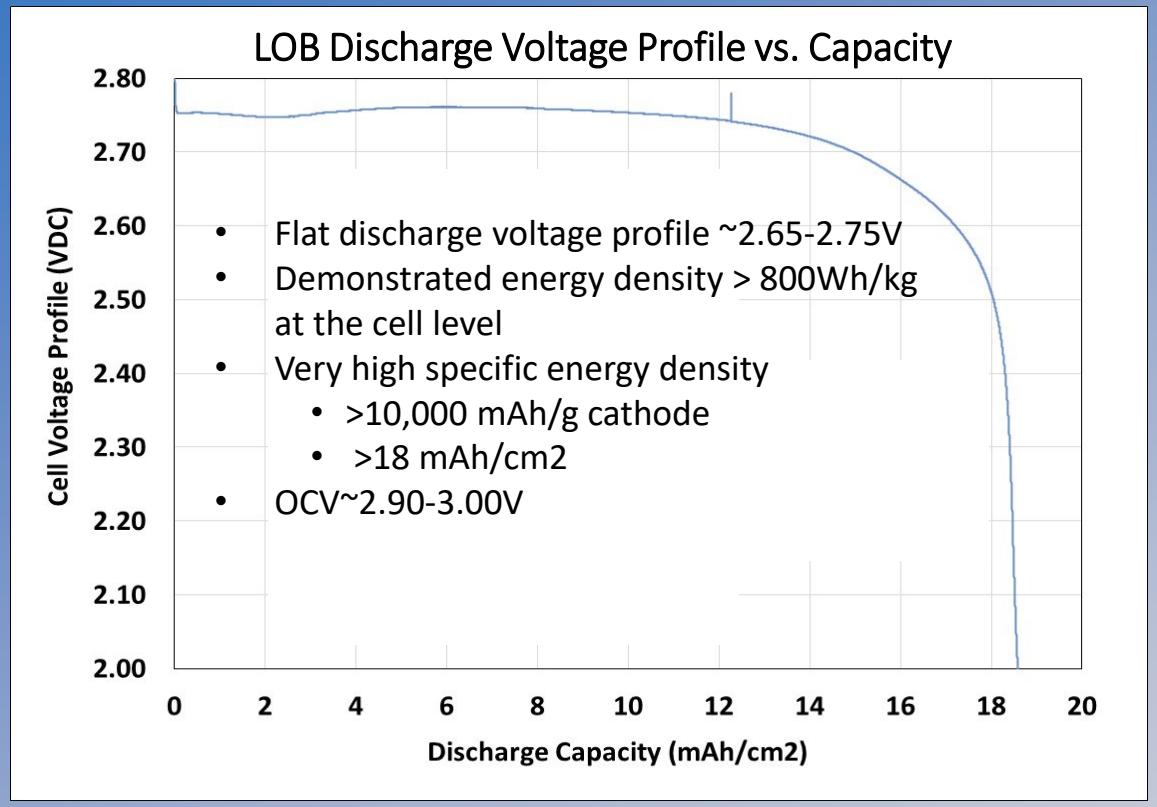
LOB Electrochemical Performance



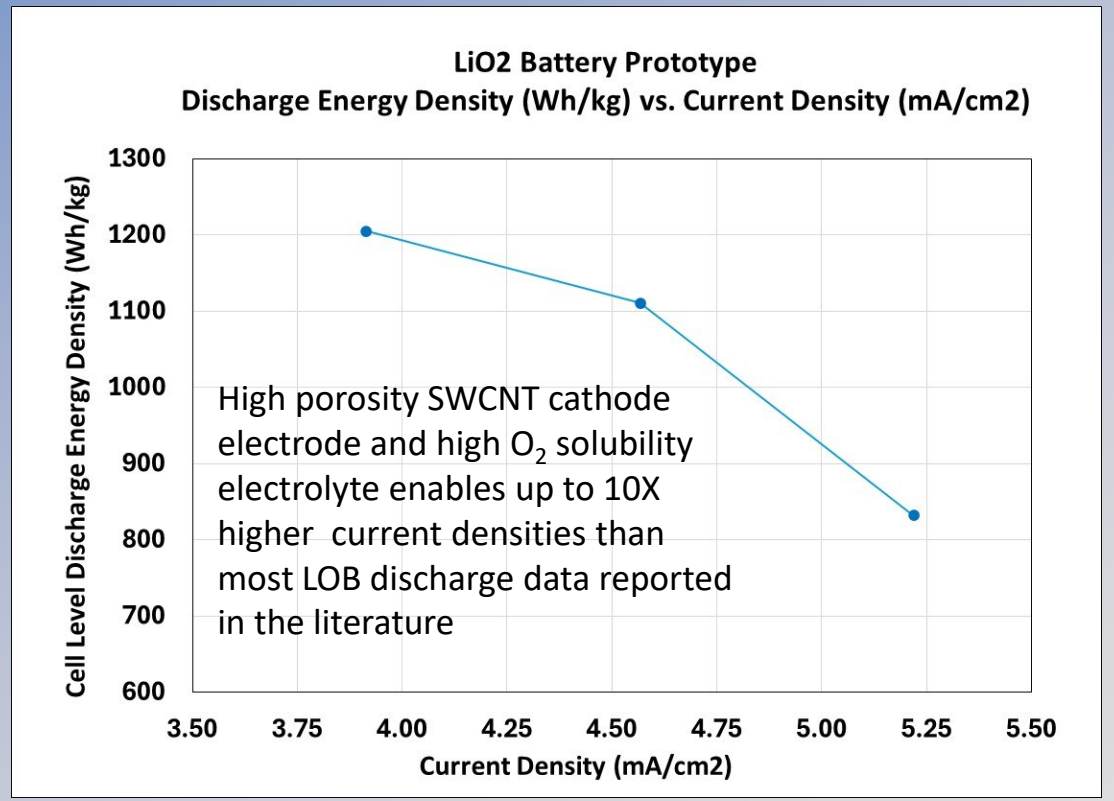
Electrochemical Performance of Pressurized 0.5 Ah LOB Prototype discharged at 4 mA/cm²

- Evaluated electrochemical performance with lab scale LOB prototypes of multiple sizes and capacities.
- Tested single sided SWCNT cathode electrodes in pressurized LOB coin cells up to 70 mm in diameter.
- Fabricated doble sided electrodes up to **150x150 mm** square for stacked multicell LOBs.
- Discharge tests consistently demonstrate **>10,000 mAh/g**, **>18 mAh/cm²** energy storage capacity up to **5 mA/cm²** current density.
- Experimental data supports potential to produce LOBs with a specific energy density, at the cell level, greater than **800 Wh/Kg.**

LOB Electrochemical Performance

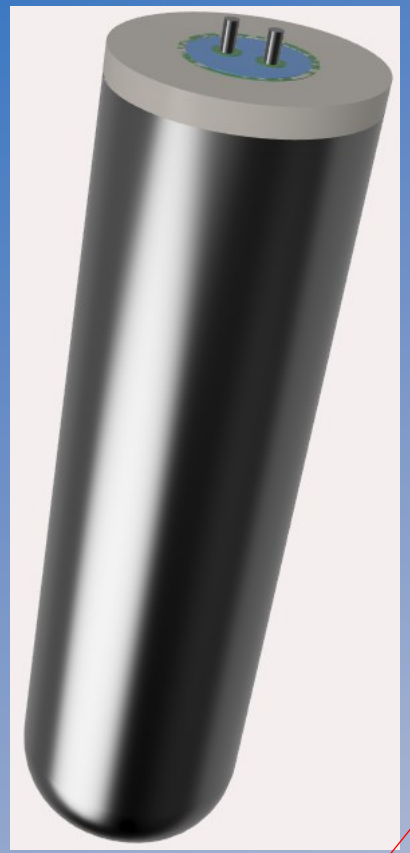


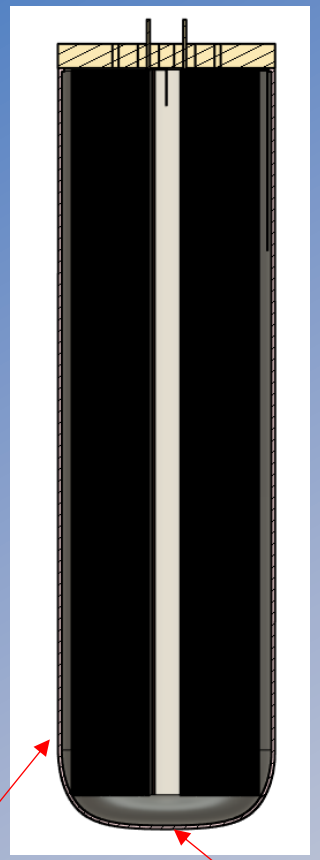
Typical LiO_2 Battery Discharge Curve



Specific Energy Density (Wh/kg) as a function of current density (mA/cm^2)

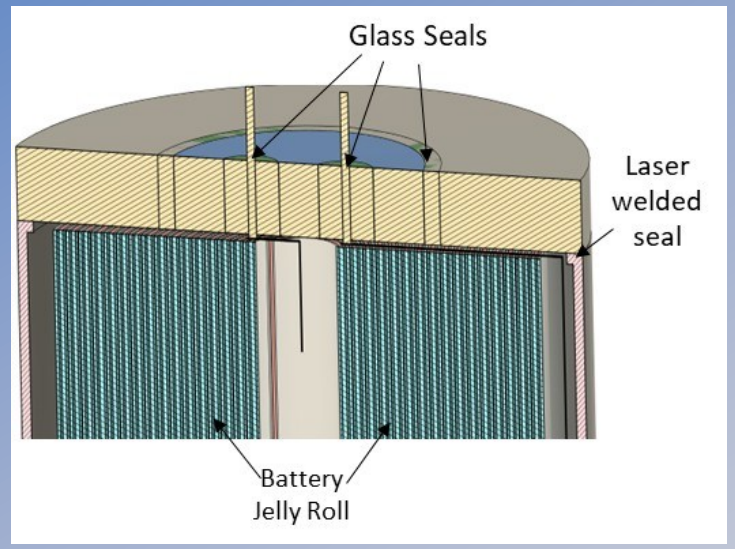
Cylindrical LOB Preliminary Designs

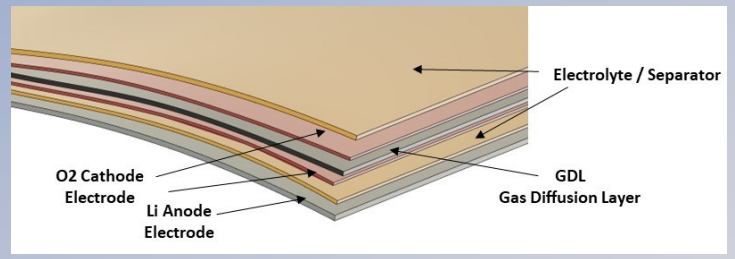




Carbon fiber composite overwrap

High strength stainless steel alloy liner with ellipsoidal bottom

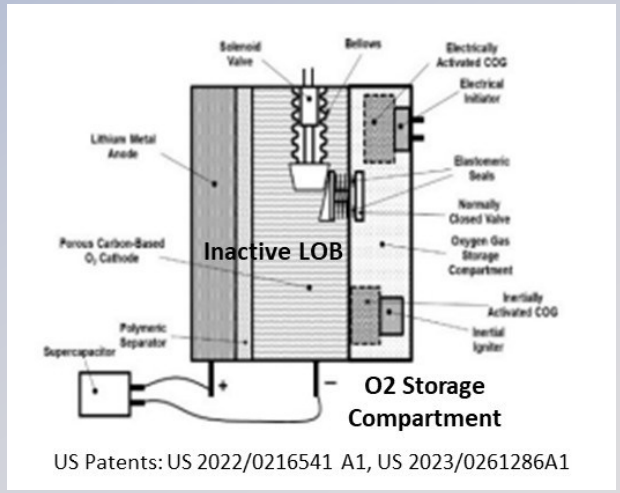




- Evaluated several designs of cylindrical pressure vessels to house LOB jelly roll assemblies.
- Metal liner made of high strength grade stainless steel alloy with ellipsoidal shaped bottom.
- Carbon fiber composite overwrap for enhanced pressure rating with overall weight reduction.
- Low profile metal lid, laser welded to the steel liner.
- Electrical connection pins and pressure relief device glass sealed to the lid.
- Oxygen gas inlet fill port integrated in the lid design.

Reserve/Inactive Primary Li-O_2 Batteries

- Unique advantage of LOBs is that they can be assembled in inactive (reserve) configurations stored under an inert gas atmosphere (e.g. Ar).
- Battery can be quickly gas activated by exposing cathode electrode to oxygen.
- Fully sealed designs preferred, where oxygen can be chemically generated (COG) or sourced from compressed storage.
- Activation triggering can be accomplished by mechanical or electrical impulse, shock, spin, etc.
- Faster activation times with gas vs. liquid electrolyte.
- Even with mass/volume penalty, due to O2 storage or generation system, reserve LOBs have a significant energy storage density advantage over commercial Li/$SOCl_2$ liquid reserve batteries.
  - Estimated energy density ~350 Wh/kg for reserve LOBs with COG



US Patents: US 2022/0216541 A1, US 2023/0261286A1

Patented implementations where O_2 can be delivered to the battery on-demand at desired rate

Chemical Oxygen Generation (COG)

- High purity oxygen gas can be generated chemically by thermal decomposition of alkali metal chlorates/perchlorates. These devices are also known as "O_2 Candles".
  - $NaClO_{4\,(s)} \rightarrow NaCl_{(s)} + 2O_{2\,(g)}$
- Best performing candles for LOBs made from a $NaClO_4$+Fe powder fuel + catalyst + inerts mixture, yielding **0.36 g of O_2/g mixture**, O_2 equivalent to **~600 mAh/g** of O_2 candle mixture with 99% chlorate to O_2 selectivity conversion efficiency.
- The O_2 stream produced contains no chlorine and less than 100 ppm moisture.

Ignition Primer or Electrical Initiator

Fuel Pellet

Chlorate Candle Pellet

Filter

0.35 cm³ COG concept prototype produces enough O2 for full discharge of a 0.5 Ah LOB

Summary/Conclusions

- Wasatch Ionics has demonstrated concept feasibility of novel primary LOBs with the potential of delivering a specific energy density greater than **800 Wh/kg** at the cell level.
- Innovative high porosity/high surface area binderless SWCNTs cathode electrode sheet material, paired with a high O_2 solubility electrolyte, enable both high specific energy density and high-power density of LOBs.
  - ✓ Storage Capacity: >10,000 mAh/g, >18 mAh/cm^2
  - ✓ Power Density: Up to 5 mA/cm^2
- Demonstrated electrochemical performance of lab scale LOB prototypes with both single and doble sided SWCNT cathode electrodes.
- Gas activated reserve LOB configurations are possible with integrated chemical oxygen generation (COG) or from compressed O_2 storage.

Thank You For Your Attention
Any Questions?

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