SCALE-UP, OPERATION AND MANUFACTURE OF REDOX FLOW BATTERIES

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Why Redox?

- **Low cost**
  - Modules can be made from HDPE and low cost
  - Need to design for manufacture
  - Electrolytes fully soluble
- **Very large arrays possible,**
  - All modules in the array have the same electrolytes
  - Long storage (inventory) time
  - Efficiency of numbers
- **Separation of power /energy**
  - Power / energy optimisation for both capital costs
  - Operational optimisation possible
RFC energy storage system

- Power and energy are separable
- Modules capable of mass production
- Operates at ambient temperature and pressure
- Two moving parts
- Environmentally benign

Diagram of RFC energy storage system:

- Electrolyte tank
- Electrode
- Regenerative fuel cell
- Ion-selective membrane
- Electrolyte tank
- Power source/load
- Pump
Bipolar Stack
RFC System

Transformer
AC breaker

Inverter/rectifier

Control system

Regenerative fuel cell modules

Process plant

Electrolyte storage tanks

Auxiliary systems

Electrolyte
Flow Battery Benefits

- Energy storage capacities are independent of their power rating.
- The same electrolytes are used in all the cells of the module providing a common state of charge. Moreover, measurement of the state of charge of the electrolyte is equivalent to measuring the state of charge of the entire system.
- Overcharging and fully discharging does not usually cause permanent damage to the electrodes or electrolytes.
- The flowing electrolyte provides a convenient means to thermally manage flow batteries – in contrast to conventional battery systems.
- The flowing electrolyte provides a means to chemically manage the electrolyte(s) for the entire battery.
Flow battery system also presents a number of challenges:

- The pipe work carrying the flowing electrolyte provides a parallel shunt current path between the cells and the modules. The power for the pumps represents a parasitic load, which reduces efficiency.
- Flow batteries have a tendency to leak and leave salt tracks from the high concentrated electrolytes unless designed and built extremely carefully.
- The cycle life of cells is expected to be relatively long. Cycle lives perhaps up to 3500-4500 cycles is a reasonable expectation. Lifetime limitations can generally be split into materials issues leading to the physical breakdown of key structural components and chemical imbalance of electrolytes during extensive cycling.
RFC – Bromine/Polysulphide - Charge

\[ 2\text{Na}_2\text{S}_2 + \text{NaBr}_3 \rightarrow 3\text{NaBr} + \text{Na}_2\text{S}_4 + \text{electrical energy} \]

\[ E^\circ = 1.54 \text{ V} \]
Regenerative Fuel Cell - discharging

\[ 2\text{Na}_2\text{S}_2 + \text{NaBr}_3 \]

\[ 3\text{NaBr} + \text{Na}_2\text{S}_4 + \text{electrical energy} \]

\[ E^o = 1.54 \text{ V} \]
Sodium Flux - Discharging

\[
\begin{align*}
\text{Source or Load} & \quad \text{Source or Load} \\
\text{Br}_3^- & \quad \text{2S}_{2}^2^- \\
3\text{Br}^- & \quad \text{Na}^+ \\
\end{align*}
\]
Bench scale
## Module Progress

<table>
<thead>
<tr>
<th>Module</th>
<th>Nominal Power rating (kW)</th>
<th>Electrode area per bipole (m²)</th>
<th>Number of bipoles</th>
<th>OCV (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L series</td>
<td>20 kW</td>
<td>0.2</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>XL series</td>
<td>100 kW</td>
<td>0.7</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

First generation test stack, 0.1 m² electrode, 5kW
5 and 20 kW modules
The Regenesys power module

XL200 module
Nominal power 100 kW
200 bipoles
No load voltage 300 V
Voltage range 150 - 360 V
Operating temperature 20 - 40 °C
200 Bipole Module Design

The development of a 200 cell bipolar module was based on the following:

- Simple plate-and-frame filter press design
- Designed for ease of manufacture and low cost
- Injection moulded HDPE frames
- Carbon composite electrodes – carbon/HDPE _activate carbon/PVDF
- Internally manifolds with manifold shunt current reducer.
- Integral seals (instead of O rings) to prevent electrolyte leakage and cross over
- Ease of installation to electrolyte pipe work and electrical connections
- Reduction in shunt current losses by design of the module’s internal manifolds and plant layout.
Development stack designs

- Frames machined to allow design development
- O-ring seals for assembly/disassembly and post mortem analysis
- Compression moulded carbon/HDPE composite electrodes
- Compression secondary bonded active surface activated carbon/PVDF “tile”
- Voltage probes per cell for bipole stack voltage monitoring and shunt current measurement
- Flexible flow distributor sections
- Flexible design of manifold/shunt current management
- Polymer electrodes for welding
Key manufactured Module Components

- Injection moulded HDPE frame design – one piece with “clip-fit” seal and membrane pinch
- Flexible “pop-in” flow distributor
- Conducting extruded base electrode core pressure/temp bonded to secondary porous carbon/polymer tile
- Automated laser welded electrode/frame
- Fully stack assembly
- Minimal components
- Minimize cost
Scale-up issues

• 2-dimensional changes
  – Wider channel (flow dispersion)
  – Longer channel (conversion per pass)
  – Electrode material consistency (resistivity)

• 3-dimensional changes
  – Longer stack (flow distribution)
  – Shunt current optimisation
  – Reproducibility of channel gap
  – Module stack mechanics
Economies of scale and manufacture

• Modules designed for mass production
• low cost materials
• Increased module size decreases specific cost ($ / kW) and reduces on site costs (connections, installation etc)
• Detailed hydrodynamics for electrolyte flow distribution
• integrated process control and power conversion system
• advanced manufacturing cells capable of volume manufacture
• automated assembly
XL Frame Design

Inlet

Outlet
Flow distribution channel
Mechanical design issues:

- Hydrodynamic characterisation, understanding of…
  - Flow gaps
  - Mesh Impact
  - Manifold distribution
  - Side channel distribution effects
  - End bipole mechanics

Apply to full module design
Mid Reactor Assembly

- LT Outlet
- ST Outlet
- Outlet Plenum
- ST Inlet
- LT Inlet
- Electrode:
  Thickness ±0.2
  Plan ±1.0mm
  Laminated resistance
- Large Tile Side Channel:
  2.0 ±0.5mm
- Mesh either side of membrane
- Flow Gap 4h
- Section A-A
A End Schematic
Cell voltage components

Bromide channel

Membrane

Thin tile

Overvoltage / mV

IR

η_{Br}

η_{S}

Sulphide channel

Thick tile

Core
Composite Electrode

295 kg/cm²
Shunt Currents

• What are Shunt Currents?
  – Discharge through process electrolytes
  – Occur within modules & plant pipework

• Why are they important
  – Represent a loss in the system
  – Target < 1% nominal current loss
Shunt currents
Shunt currents

- Primary Control in module spiral
- length 500mm
- Provides 2200Ω shunt resistance
Manufacturing

Mass production of components

High quality achievable
Assembly can be automated
Plant Design Philosophy
Little Barford RFC

- First Demonstration RFC Design
- Peak rating 15 MW
- Energy storage 120 MWh
- 120 XL modules, 1800 m³ each electrolyte
- Arbitrage capability (6 hour storage)
- Black start capability (4 hours)
- High reliability/availability
- Design towards unmanned operation
Module power rating

DC Voltage (V)

Power (kW)

charging

discharging
RFC Module

Module stream

Bipolar construction

100 kW module = 200 bipoles
Shunt currents

Plant losses > 20%

Electrolyte Tank
Shunt currents

Plant Losses < 3%

Electrolyte Tank

dc bus (+)

dc bus (-)
Module supply pipework

- Black Start Tank
- Electrolyte Tank
- Electrolyte Pumps
- Electrolyte Supply
- Electrolyte Return
- Vent
- Modules
- Cross Header
Black start

415 Supplies

DC Bus-VE

+VE

PCS

Other Streams

415 Supplies

Rectifier

DC Link

Inverter

VSD

Selector

Control Enable

600 VDC

Process Pump

1

2

3

Modules

Streams 1 & 2

12