Vanadium-Bromine Redox Flow Battery

Flow Batterie Kolloquium in Karlsruhe am 27. September 2017

H. Frank Gibbard, Ph.D.
CEO WattJoule Corporation
Devens, Massachusetts USA

Stationary Energy Storage – Why Now?

WattJoule

In the past few years the demand for large-scale energy storage has increased for several applications

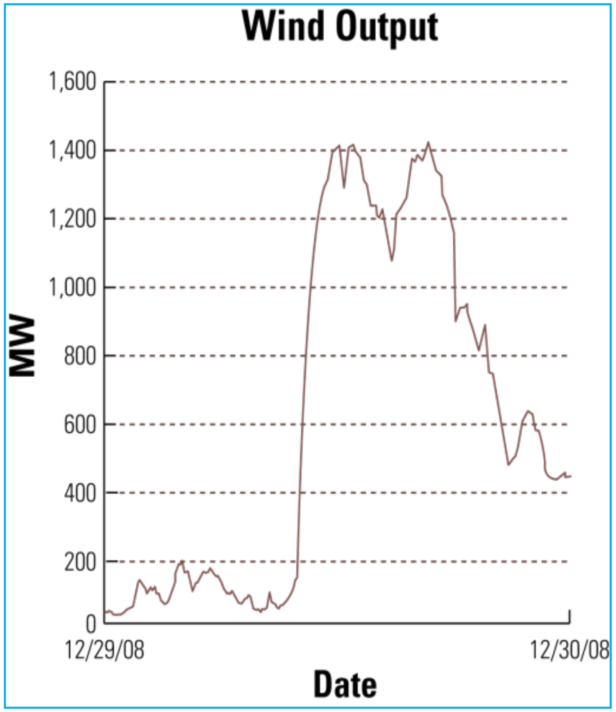
- **Renewables integration**
- Ancillary services
- Arbitrage
- Grid asset optimization
- T&D deferral
- Telecommunications – substitute for diesel

ICL Industrial Products
Where needs take us

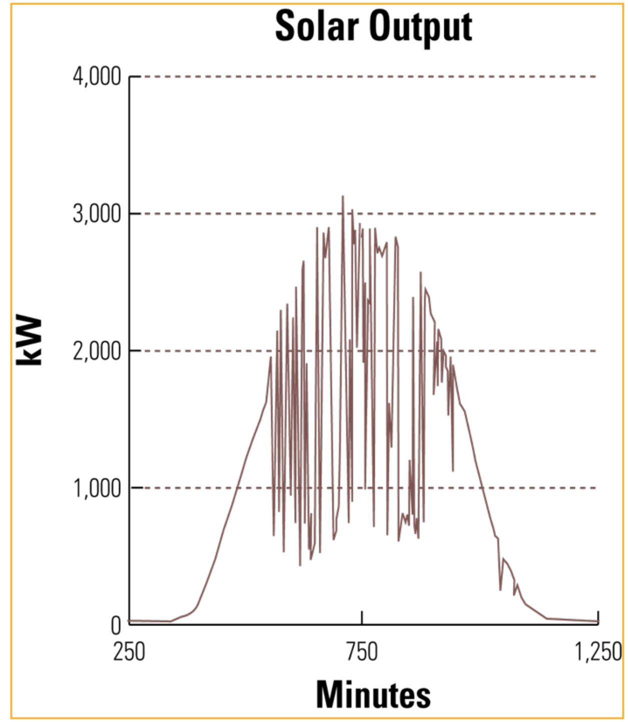
Renewables Integration

WattJoule

Wind & Solar Variability Problem



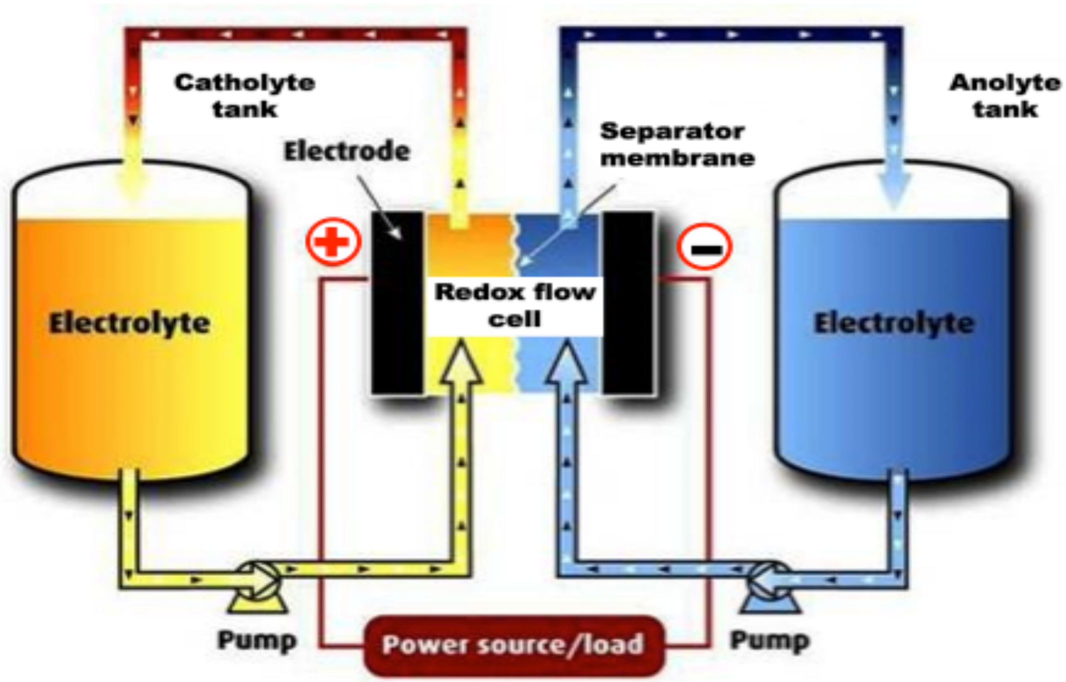
Oregon Wind Farm
10 - 100% in 1 hour



Arizona Solar Farm
10 - 80% in 5 min

ICL Industrial Products
Where needs take us

Why Redox Flow Batteries?



- Separation of POWER and ENERGY
- More POWER = larger stack
- More ENERGY = larger tank
- Competitive energy efficiency

- Highly durable: 10,000+ cycles
- Safe, non-flammable liquid
- Lowest CapEx & OpEx
- Large application space

Product Development Approach

WattJoule

- Start with a proven chemistry to lower risk: **vanadium redox**
- Engineer a next-gen OEM platform: **quantum improvement**
- Identify key barriers preventing full commercialization
- Utilize open innovation approach to secure best IP
- Leverage the best expertise wherever it is
- Develop a multi-generational pipeline of product improvements

ICL Industrial Products
Where needs take us

Building a Superior Product

WattJoule

CURRENT PROBLEM SET	WATTJOULE IMPROVEMENT
Electrochemical stacks are large and use expensive materials	New breakthroughs now allow major reductions in stack size
Electrolyte energy density is low and requires large tanks	We have technology that increases the energy we can store in every liter
System needs refrigerated cooling thereby increasing costs and lowering efficiency	We can now eliminate AC and chiller equipment with our platform
Lifetime system efficiency needs improvement	We now add major efficiency improvements with no added cost
Need for costly, high purity active materials like vanadium	We have a pathway to utilizing less and then no vanadium over time
Relatively high cost vs. attractive economics	**All of the above improvements translate to significantly lower cost**

ICL Industrial Products
Where needs take us

Quantum Improvement Factors

Pathway to Better VRB Metrics

Key Metric	SOA[1]	Gen 1	Gen 2 V-Br	Core Benefit
Converter Stack Power Density	1X	6X	7X	Lower material cost
Electrolyte Energy Density	1X	2X	3X	Less liquid required
Electrolyte Temperature Range	1X	3X	3.2X	No active cooling needed
Roundtrip Efficiency	1X	1.1X	1.2X	Lower life cycle cost
Vanadium Cost Reduction	1X	1.4X	2.2X	Lower vanadium cost
DC System Capital Cost ($/kWh)	600	200	150	Significantly lower CapEx

[1] State-of-the-Art Redox Flow Battery

Industrial Products

Where needs take us

ElectriStor™ ES10 Test System

WattJoule

2kW, 10kWh Engineering Prototype II, DC Only

1,000-fold increase in power and energy from 2014-2016

AICL Industrial Products
Where needs take us

So…What's Next?

WattJoule

- We believe that the improvements made in the chemistry, materials and design of our Gen 1 all-vanadium redox flow battery have pushed this system nearly to its maximum performance and minimum cost limits.
- Further improvements in our RFB platform will require a change in the basic system chemistry.
- With financial and technical support from ICL, we have chosen the vanadium-bromine redox flow battery for further development.

ICL Industrial Products
Where needs take us

V-Br Redox Flow Battery

WattJoule

Performance

- Electrolyte energy density of ≥ 50 Wh/kg
- Operating electrode current density of ≥ 200 mA/cm^2
- Maximum power density of ≥ 1000 mW/cm^2
- Standard operating temperature of 45°C
- Round-trip DC electrical efficiency of 80%

Cost

- $150/kWh for DC energy storage system

ICL Industrial Products
Where needs take us

V-Br Redox Flow Battery

WattJoule

Electrode reactions for charge:

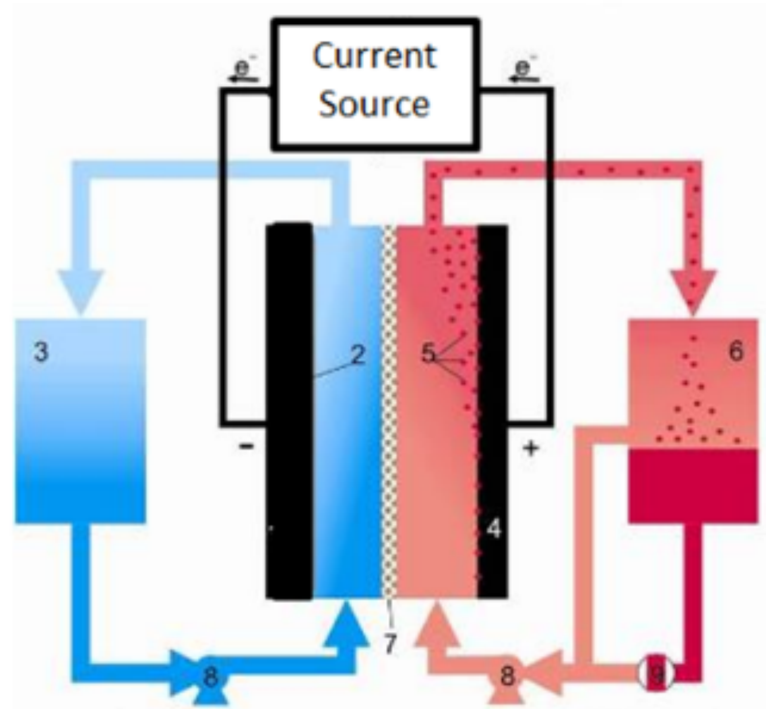
Negative electrode reaction:

$$2V^{3+} + 2e^{-} \rightarrow 2V^{2+}$$

Positive electrode reaction:

$$2Br^{-} + QBr_{n} \rightarrow QBr_{n+2} + 2e^{-}$$

Insoluble bromine oil falls to the bottom of the catholyte tank

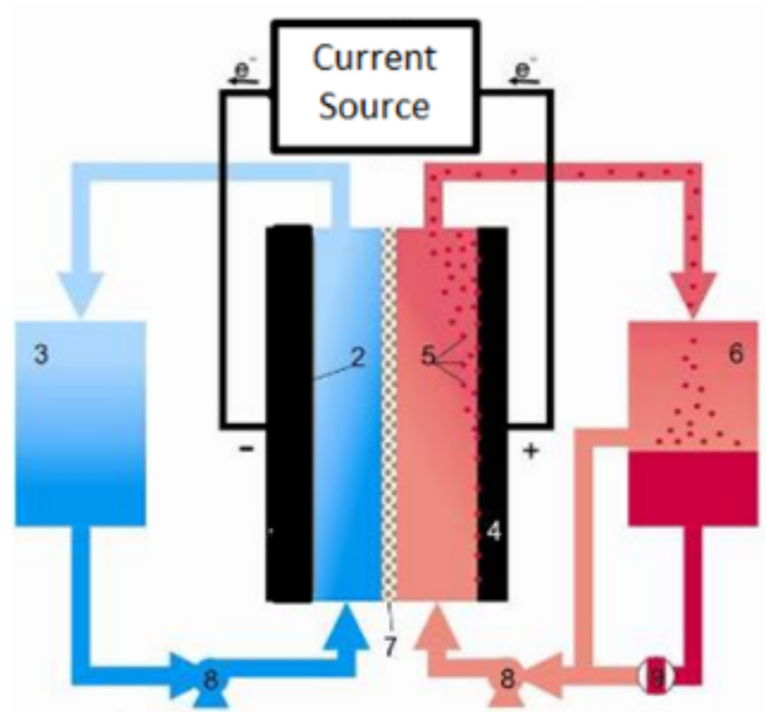


2 Negative electrode
3 Anolyte tank
4 Positive electrode
5 Polybromide
6 Catholyte tank
7 Separator
8 Pumps
9 Valve

ICL Industrial Products
Where needs take us

V-Br Redox Flow Battery Advantages Over All-Vanadium

- Decrease amount of Vanadium by nearly 50%
- Increased electrolyte energy density
- Technology demonstrated in lab-scale hardware
- Utilizes Gen 1 high-power density cell technology
- Proprietary complexing agent provides multiple system benefits
- Strong WattJoule IP position



2 Negative electrode
3 Anolyte tank
4 Positive electrode
5 Polybromide
6 Catholyte tank
7 Separator
8 Pumps
9 Valve

ICL Industrial Products
Where needs take us

V-Br Redox Flow Battery
Advantages Over Other Chemistries

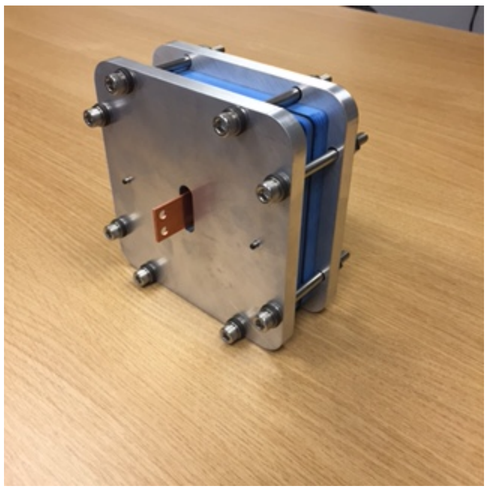
WattJoule

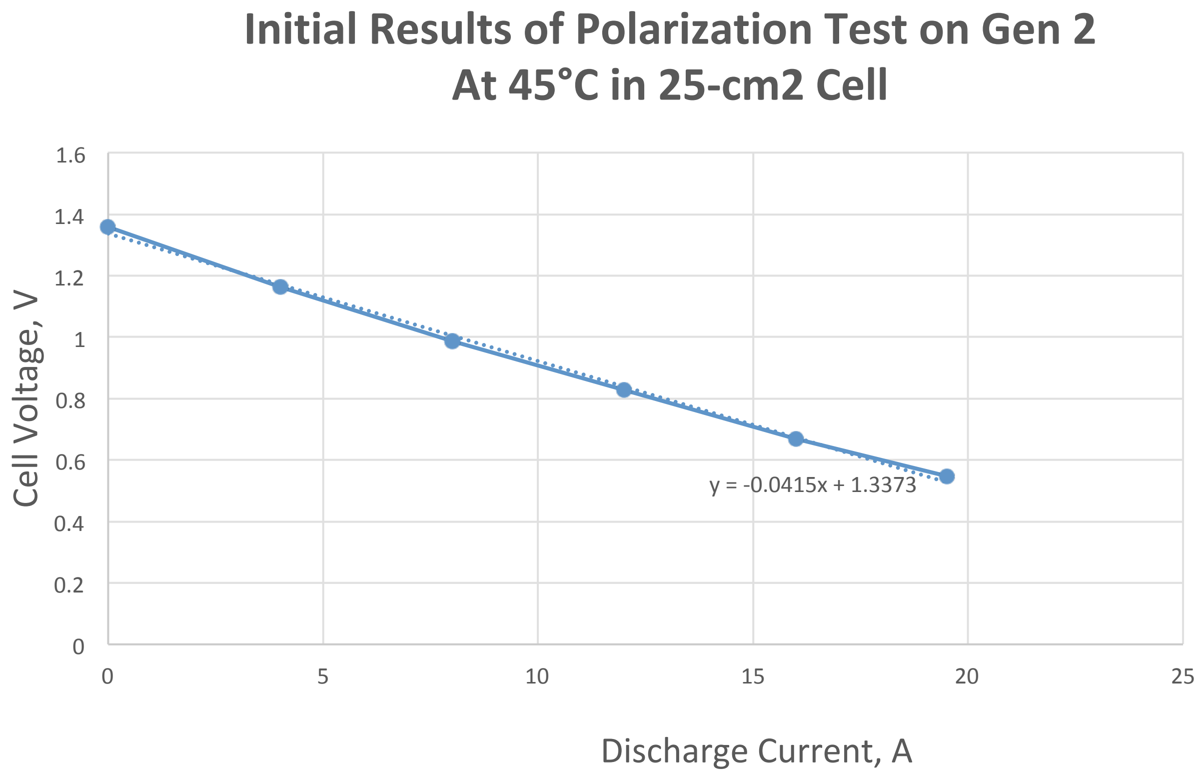
ALTERNATIVE FLOW CHEMISTRIES	VANADIUM BROMINE
Hydrogen bromine requires large high pressure tanks to store flammable and explosive gaseous hydrogen, and needs expensive catalyst that degrades over time	Requires no catalyst and all the energy is safely stored in liquid form. Electrolyte contains over 60% water and cannot burn or explode.
Zinc bromine has dendrite problems on electrodes that require stripping and have durability issues. Power and energy coupled since hybrid flow. Low power density.	True redox flow battery that requires no plating and therefore has no dendrite problems. Power and energy capability completely uncoupled.
Iron chromium has a significant hydrogen and chlorine gassing problem under normal operation and has low energy density.	Virtually no gassing potential due to electrochemical operating mode. Much higher energy density can be achieved.
Vanadium-vanadium requires large stacks and tanks and the higher cost of vanadium, also has a limited temperature range.	Much higher power and energy density can be achieved while cutting vanadium use by 50%. Temperature range not an issue.

ICL Industrial Products
Where needs take us

V-Br Test Results

WattJoule





ICL Industrial Products
Where needs take us

V-Br Test Results

WattJoule

Gen 2 Power Capability in 25-cm^2 cell at 45°C
Vanadium Concentration 2.0 Mol/L

Membrane	Pmax, mW/cm^2	Specific Resistance, Ωcm^2
Fluorinated Ion-Exchange	431	1.0375

Power Performance Similar to Gen 1 in First Experiments

ICL Industrial Products
Where needs take us

V-Br Test Results

WattJoule

Typical UNSW Cycling with Bromine Complexation
Current Density only 10 mA/cm^2

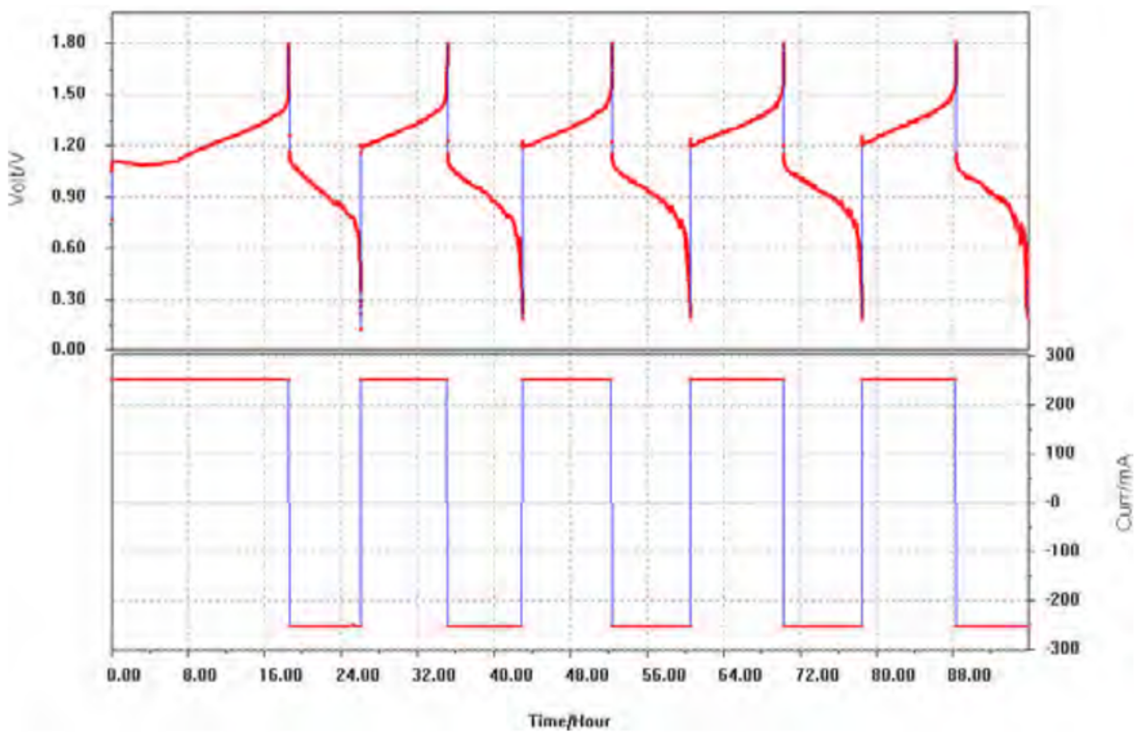
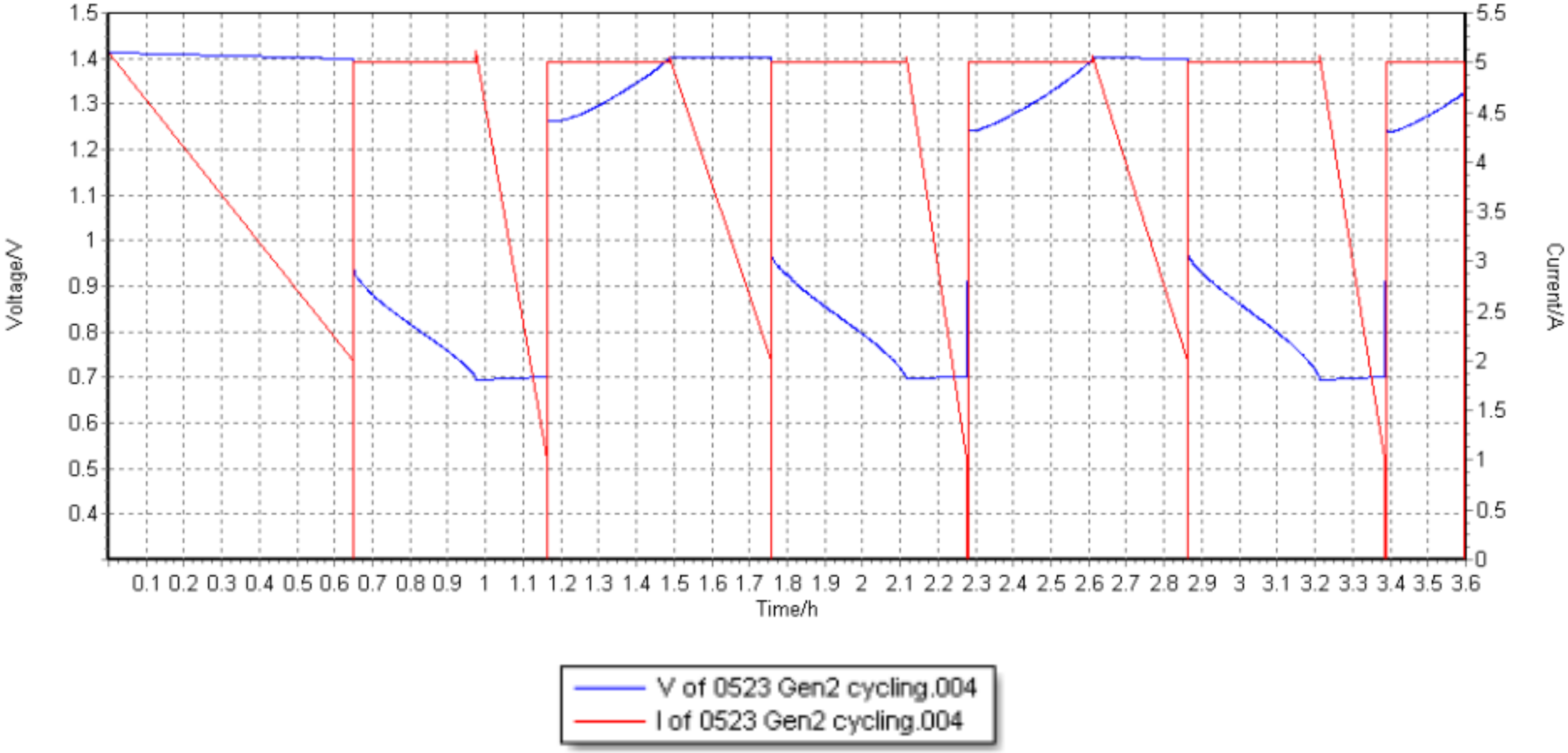


Figure H.23 Charge / discharge cycles of 2 M $V^{3.7+}$, 0.19 M MEM, 0.56 M MEP, 6.1 M HBr, 1.2 M HCl using ChiNafion membrane at 25°C (CY060929.cel; 50ml electrolytes; (+ve) 27°C (-ve) 26°C)

ICL Industrial Products
Where needs take us

V-Br Test Results

WattJoule Cycling Results at 200 mA/cm2
2M V at 45°C



Industrial Products

Where needs take us

Dr. Frank Gibbard

CEO & Founder

frank@wattjoule.com

603-502-3234

Greg Cipriano

VP Business Development & Founder

greg@wattjoule.com

508-942-8995

WattJoule expresses its sincere thanks to ICL for its financial and technical assistance in carrying out the work on the V-Br redox flow battery system.

ICL Industrial Products

Where needs take us