Redox Power System’s Revolutionary SOFC Technology; 25 Years of Persistence

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25 Years of Persistence

Fundamentals

1988 - Discovered ordering mechanism in bismuth oxide electrolytes
1989 - Identified reduction stability issue in bismuth oxide electrolytes
   - Developed bilayer electrolyte concept to address stability issue
1989 to 1993 - Tried to obtain funding to demonstrate bilayer electrolyte concept
1993 - Demonstrated bilayer electrolyte under GRI support and prepared patent applications
1994 to 1999 - Tried to obtain funding to develop bilayer electrolyte SOFC
1999 to 2002 - DE-AC26-99FT40712: Stable High Conductivity Electrolytes for Low Temperature SOFCs
   - Determined effect of local structure on conductivity
   - Developed record highest conductivity oxide-ion electrolyte DWSB
   - Demonstrated relative bilayer thickness effect on OCP
   - Achieved near theoretical OCP with bilayer electrolyte SOFCs
2002 to 2009 - Leveraged multiple related funding sources to continue cell development
2009 - Demonstrated record high power density 2 W/cm² at 650°C with bilayer electrolyte SOFC
2009 to 2012 - Tried to obtain funding to advance development of bilayer electrolyte SOFCs
2012 - Redox Power Systems formed

Commercialization

2014
Solid State Fuel Cell Technologies

~80°C ~800°C

Temperature

~80°C 200°C 600°C ~800°C

Fuel C/H Ratio

H₂ Natural Gas Biofuel Gasoline Diesel Coal Gas

DOE – EERE’s H₂ & Fuel Cell Program

DOE – FE’s SECA Program
Anodes and Fuel Flexibility

SOFC with $H_2$ and JP5 reformate

($H_2$ 0.306, $H_2O$ 0.244, $CH_4$ 0.008, CO 0.093, CO$_2$ 0.093, N$_2$ 0.255)

Only ~20% drop in power with JP5

Stable SOFC Performance on JP5 reformate

No Carbon deposition at 550°C

Intermediate Temperature SOFCs (< 800 ºC)

B. Steele, J. Power Sources

Metallic Interconnects
Lower cost and greater reliability

B. Steele, J. Power Sources
Why Lower Temperature SOFCs ($\leq 600 \, ^\circ C$)?

- **Metallic Interconnects**
  - Lower cost and greater reliability

- **Easier Sealing**
  - Lower cost and greater reliability

- **Smaller Thermal Mismatch**
  - Greater reliability

- **Less Insulation**
  - Lower cost

- **Rapid Startup with Less Energy Consumption**
  - Lower cost and better performance

*Transportation applications*

Need higher conductivity electrolytes
Higher Conductivity Electrolytes

- Fundamentals of oxide transport
- Conductivity of 8Dy4WSB is
  - 0.57 S/cm at 700°C
  - 0.10 S/cm at 500°C
- Highest conductivity of any stabilized Fluorite oxide
  - 3X that of ESB
  - 10X that of GDC
  - 100X that of YSZ
- Optimized DWSB composition for 650°, 500° & 300°C operation
- Demonstrated co-doping enhancement of conductivity with SNDC
Weak M-O bonds lead to high conductivity but also low thermodynamic stability.
**Bilayer Electrolyte**

![Diagram showing the interfacial oxygen pressure (PO2) and the ratio of SDC to ESB thicknesses (LSDC/L_ESB).]

\[ \frac{L_{SDC}}{L_{ESB}} < \frac{1}{optimal} \quad \text{ESB decomposes} \]

\[ \frac{L_{SDC}}{L_{ESB}} > \frac{1}{optimal} \quad \text{ESB is stable} \]

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Near theoretical OCP achieved with anode supported thin bilayer electrolytes

Need to optimize both GDC and ESB thicknesses
Bilayer Electrolytes for LT-SOFC

Integrating new materials and microstructures to achieve world record performance

Volumetric Power Density

2 W/cm\(^2\) = 10 W/cm\(^3\)

Steel Interconnect/gas channels

~0.05 cm

~0.15 cm
Volumetric Power Density

Stack Power (kW)

Stack Size (liter)

10 W/cm³

10 cm 10 cm 10 cm

10 cm 10 cm 10 cm

10 cm 0.2 cm

0.1 0.1 1 10 100
Gravimetric Power Density

Electrochemical capacitors

- Anode
- Cathode
- Electrolyte

Electrodes ~30% porous

Steel Interconnect/gas channels ~70% porous

\[ 0.7 \times 7\text{g/cc} \times 0.05\text{cm} + 0.3 \times 8\text{g/cc} \times 0.15\text{cm} = \sim 0.6 \text{ g/cm}^2 \]

\[ \sim 2 \text{ W/cm}^2 / 0.6 \text{ g/cm}^2 = \sim 3 \text{ kW/kg} \]
Energy Storage Figure of Merit

V. Srinivasan, Batteries for Vehicular Applications,

Low Temperature Solid Oxide Fuel Cells

Lowering the Temperature of Solid Oxide Fuel Cells
– Science (2011)

Role of Solid Oxide Fuel Cells in a Balanced Energy Strategy
– Energy & Environmental Science (2012)

Next-Generation Flex-Fuel Cells Ready to Hit the Market – Scientific American (2011)

  • Picked up by numerous news papers and websites around the world
  • A highlight of The Year in Energy – Technology Review (2011)

2012 Fuel Cell Seminar & Energy Expo Award
Next Generation Solid Oxide Fuel Cells

Redox Power Systems
Launched in 2012 to commercialize this next generation SOFC technology
Next Generation Solid Oxide Fuel Cells
Next Generation Solid Oxide Fuel Cells


Avoiding the Power Grid – Technology Review (2013)

Could This Be the Fuel Cell to Beat All Fuel Cells?
– GreentechMedia (2013)

Redox Power Plans to Roll Out Dishwasher-Sized Fuel Cells that Cost 90% Less than Currently Available Fuel Cells
– Forbes (2013)

The Navy Has Fuel-Cell Generators; Will You Have Them Soon, Too?
– The Atlantic (2013)

At Redox Power Systems, the Future of Electricity Lies in Fuel Cells

Sir William Grove Award
- International Association for Hydrogen Energy (2014)
SOFC Cost

- Anode Support/Advanced Cathode, Seal & Interconnect
- Low Cost Manufacturing
- Increased Power Density, Voltage & Cell Size

- Atmospheric or Pressurized Fuel Cell
- Separate Fuel to Oxy-Combustion
- 25% Dry Methane/Catalytic, Methanation or NG Pipeline

Transition to Coal Applications

Time line (year)


-$1500/kW (2000)

$275/kW

$175/kW

$51/kW

$44/kW

EEERE/PEMFC

SECA/SOFC
Increasing Performance & Driving Down Temperature

- ~4.5 kW/kg
- ~350°C operation
Scale-Up and Stack Development

• Developed repeatable and manufacturable 10 cm x 10 cm cell fabrication processes

• Transferred UMD fabrication technology to Industry Partners

• Fabricating and testing multi-cell short stacks

• Negligible difference in multi 10x10 cell stack performance between H₂ and 100% CH₄ Slip
Scale-Up and Stack Development

Initial 1 kW short stacks

Then 10 kW stacks

25 kW nominal
32 kW peak system

250 kW nominal
320 kW peak system
Redox Core Technology Enables

- Bilayer Cell ~200 W
- Commercial & Industrial Power 25 kW to 250 kW
- Residential Combined Heat & Power 1 to 10 kWₑ
- Datacenter Embedded Power 10 kW
- 1 to 10 kW Stacks

24 kW to 250 kW

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