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

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REDOX

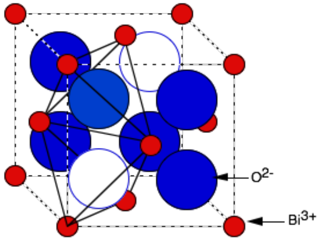
25 Years of Persistence

Fundamentals

Commercialization

1988

2014



From one “Cube” to another

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

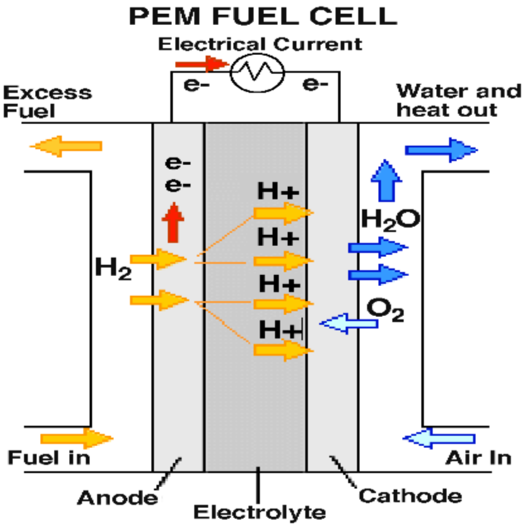
2002 to 2009 - *Leveraged multiple related funding sources to continue cell development*

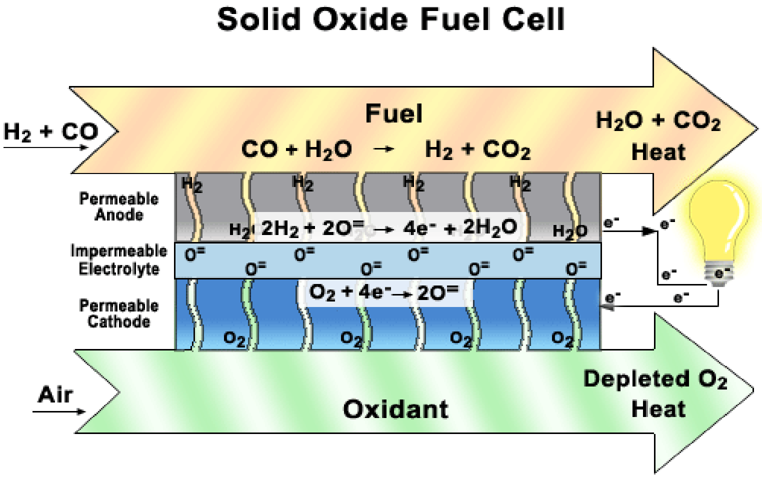
2009 - Demonstrated record high power density 2 W/cm^2 at 650°C with bilayer electrolyte SOFC

2009 to 2012 - *Tried to obtain funding to advance development of bilayer electrolyte SOFCs*

2012 - Redox Power Systems formed

Solid State Fuel Cell Technologies





Temperature

~80°C 200°C ←——————→ 600°C ~800°C

Fuel C/H Ratio

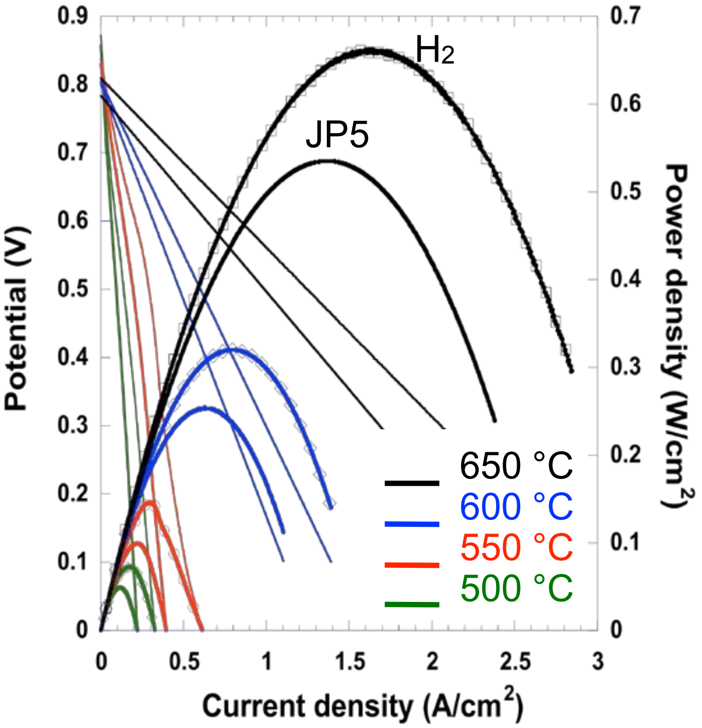
H_2 Natural Gas Biofuel Gasoline Diesel Coal Gas

DOE – EERE's
H_2 & Fuel Cell Program

?

DOE – FE's
SECA Program

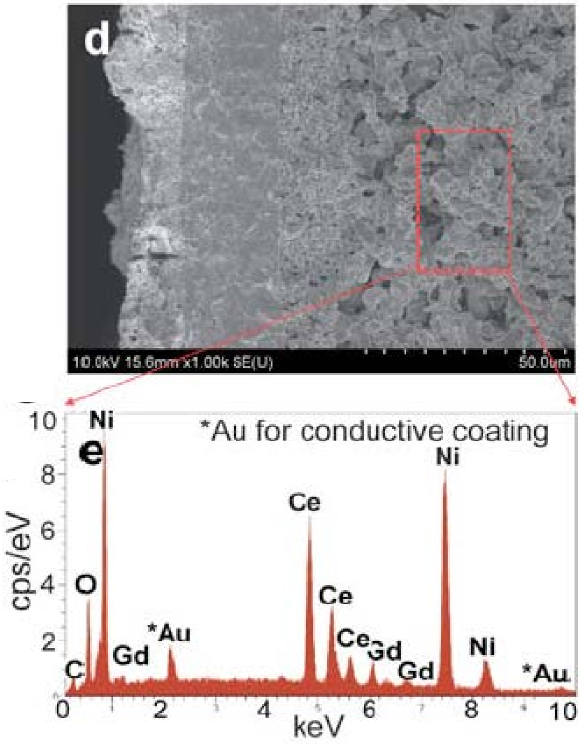
Anodes and Fuel Flexibility



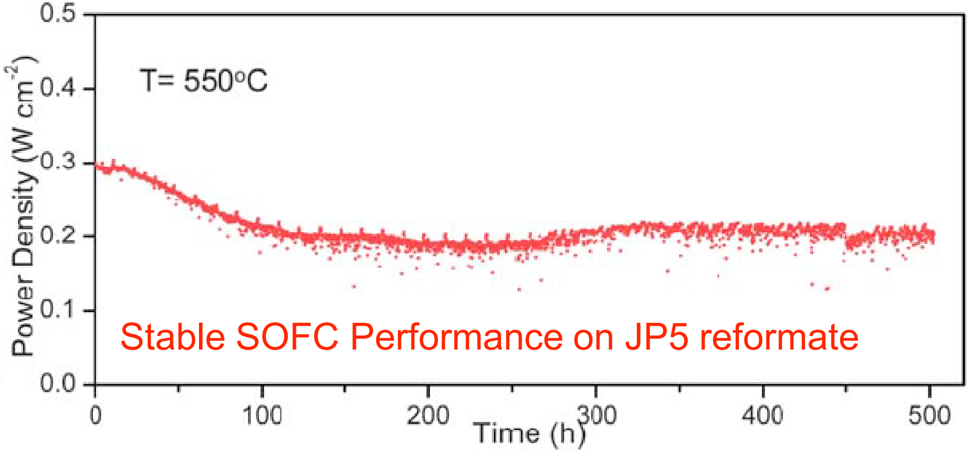
SOFC with H_2 and JP5 reformate

(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



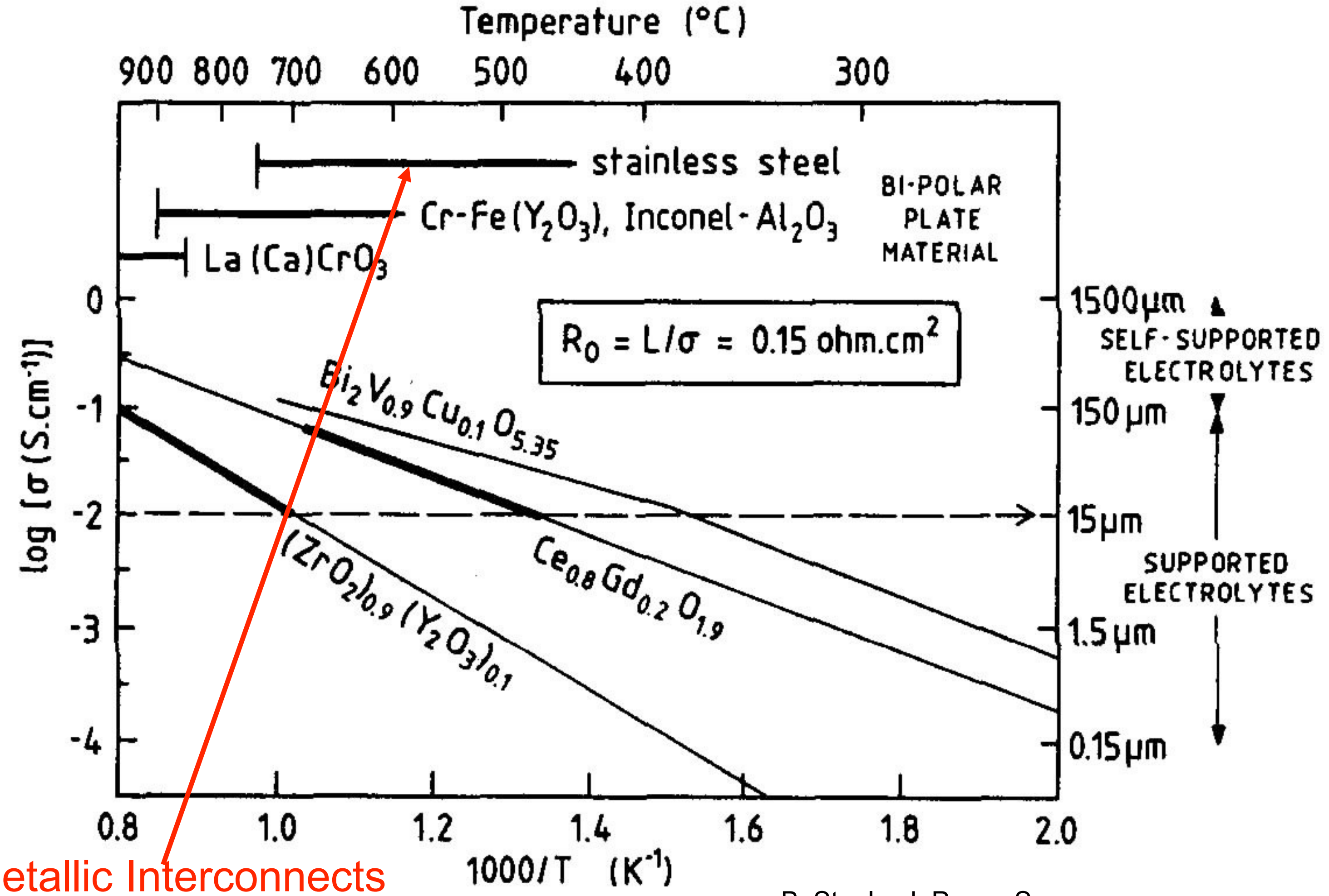
No Carbon deposition at 550°C



Stable SOFC Performance on JP5 reformate

Kang Tack Lee, Colin M. Gore, and Eric D. Wachsman, Feasibility of low temperature solid fuel cells operating on reformed hydrocarbon fuels, Journal of Materials Chemistry, 10.1036/c2jm35590f, www.rsc.org/materials

Intermediate Temperature SOFCs (< 800 ºC)

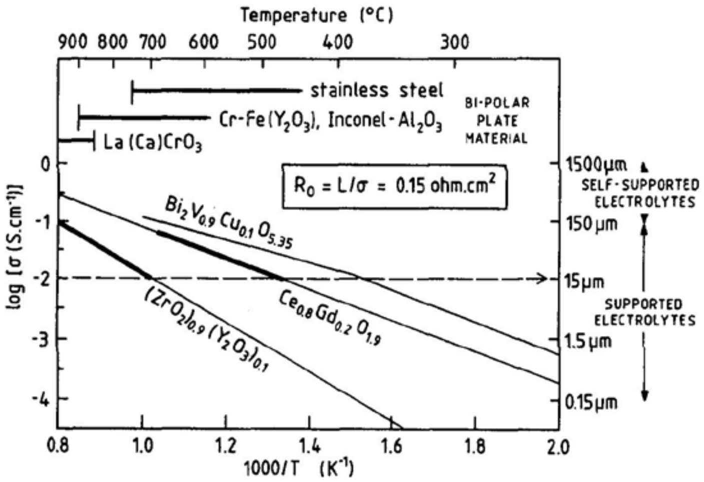


Metallic Interconnects

Lower cost and greater reliability

B. Steele, J. Power Sources

Why Lower Temperature SOFCs ($\leq$ 600 ºC)?



Metallic Interconnects

Lower cost and greater reliability

Easier Sealing

Lower cost and greater reliability

Smaller Thermal Mismatch

Greater reliability

Less Insulation

Lower cost

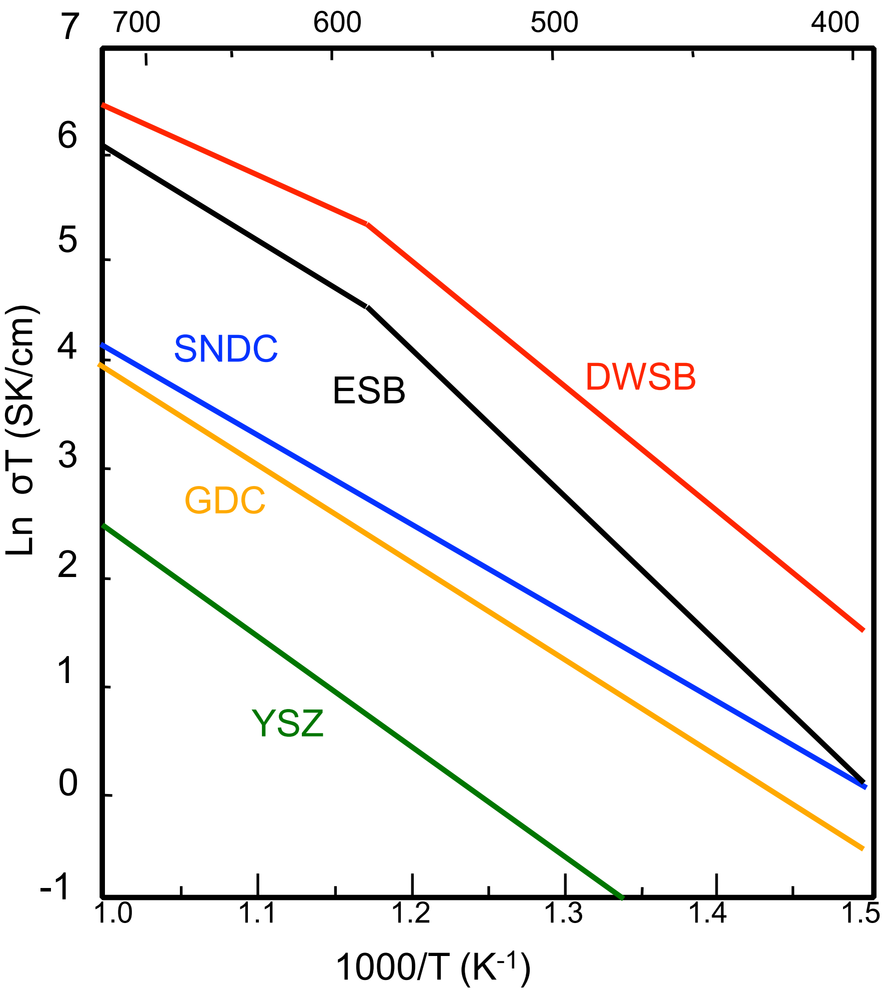
Rapid Startup with Less Energy Consumption

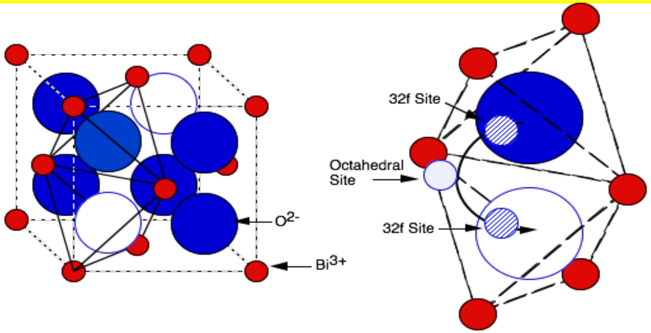
Lower cost and better performance

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

Stability of High Conductivity Electrolytes in Reducing Conditions

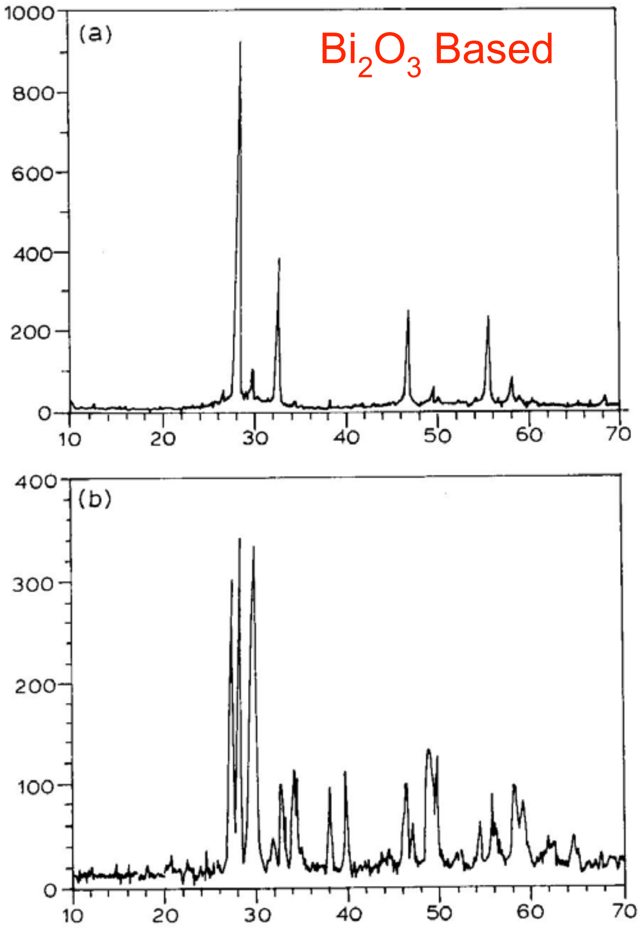


Fig. 4. X-ray diffraction of 20 mol% ESB: (a) as received; (b) annealed 4 h at 700 °C in H_2/H_2O $P_{O_2} = 10^{-21}$ atm).

Wachsman, et al., *Solid State Ionics,* **52**, 216 (1992)

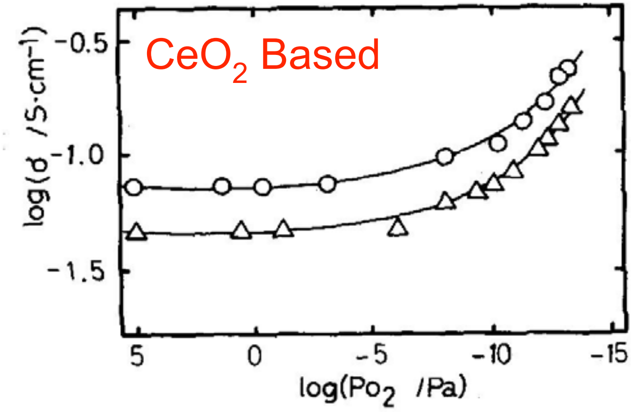
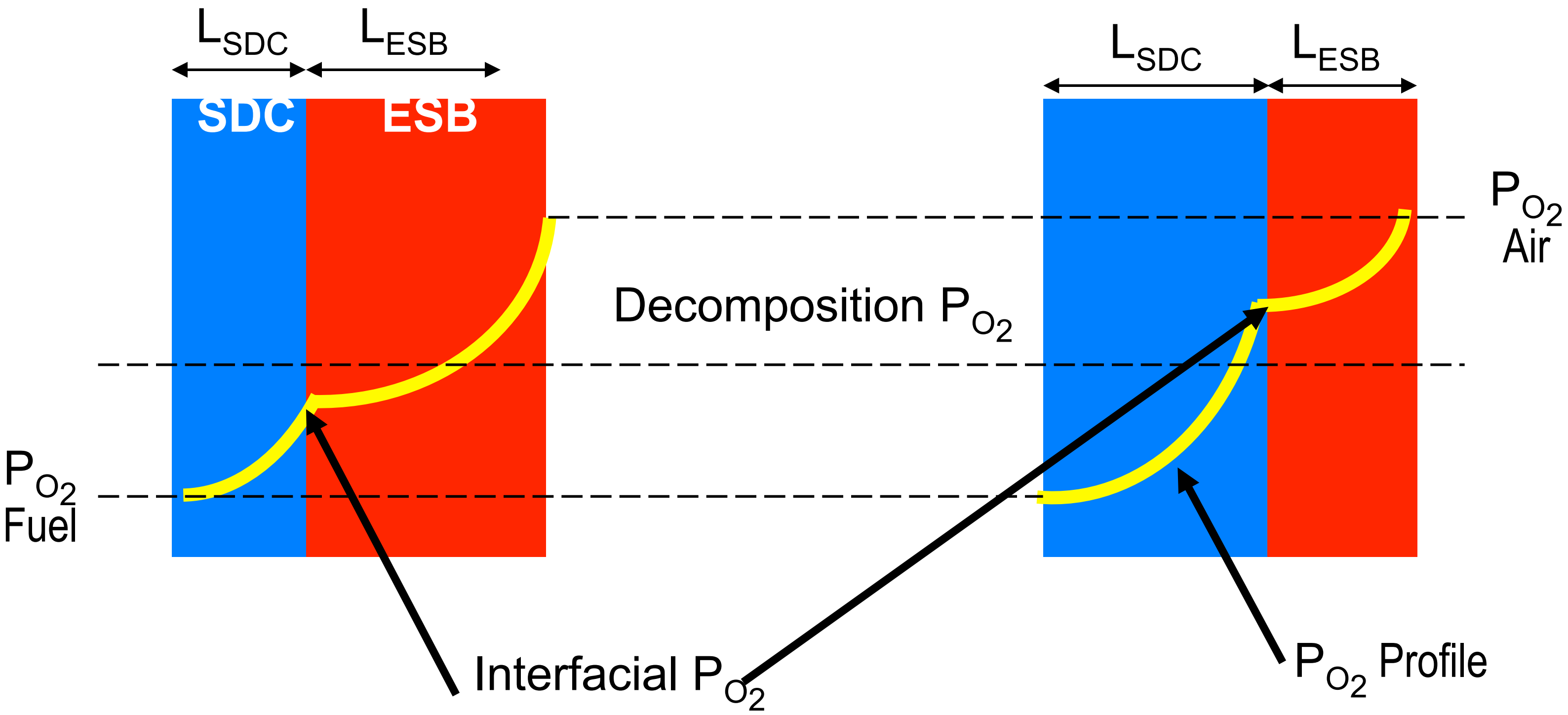


Fig. 6. Electrical conductivities as a function of oxygen partial pressure at 800°C: (○) $(CeO_2)_{0.8}(SmO_{1.5})_{0.2}$; (△) $(CeO_2)_{0.8}(GdO_{1.5})_{0.2}$.

Eguchi, et al., *Solid State Ionics,* **52**, 168 (1992)

Weak M-O bonds lead to high conductivity but also low thermodynamic stability

Bilayer Electrolyte



$L_{SDC}/L_{ESB} < |_{optimal}$

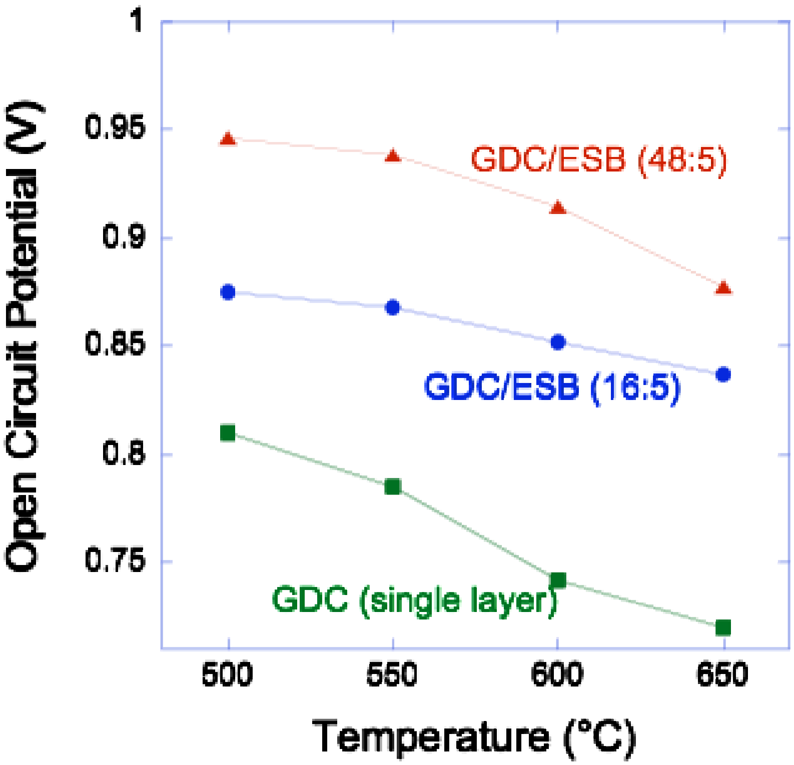
ESB decomposes

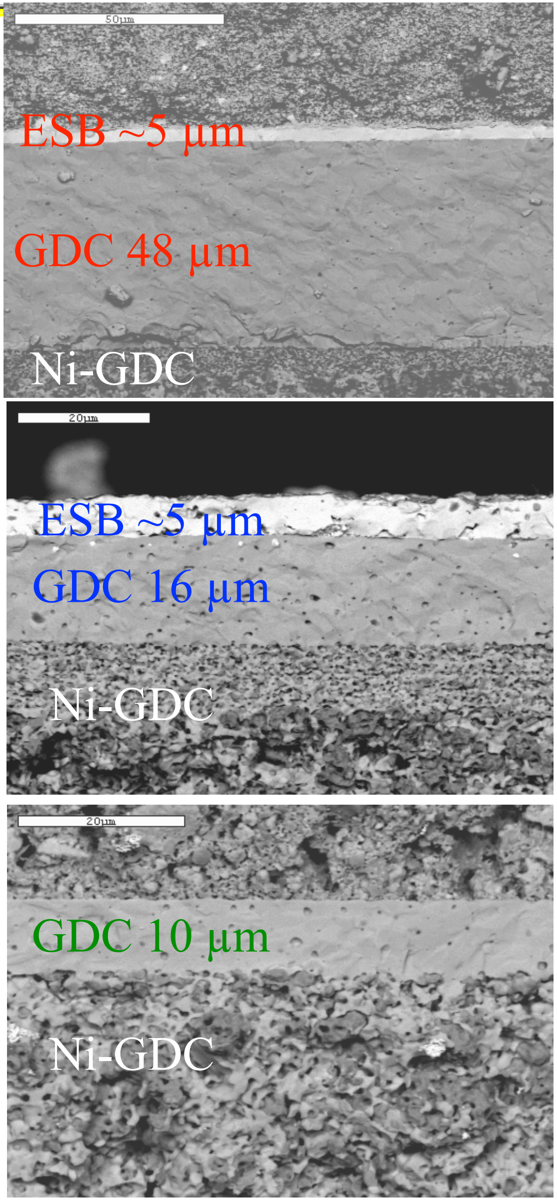
$L_{SDC}/L_{ESB} > |_{optimal}$

ESB is stable

E. D. Wachsman, P. Jayaweera, N. Jiang, D. M. Lowe, and B.G. Pound, *J. Electrochem. Soci.*, **144**, 233 (1997).

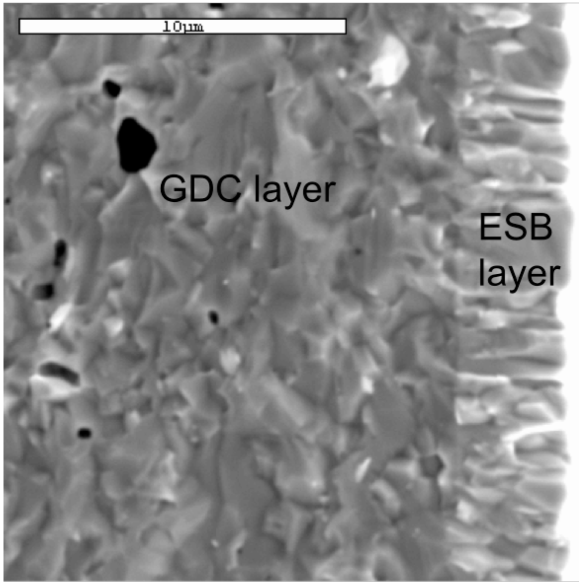
Thin Bilayer Electrolyte OCP

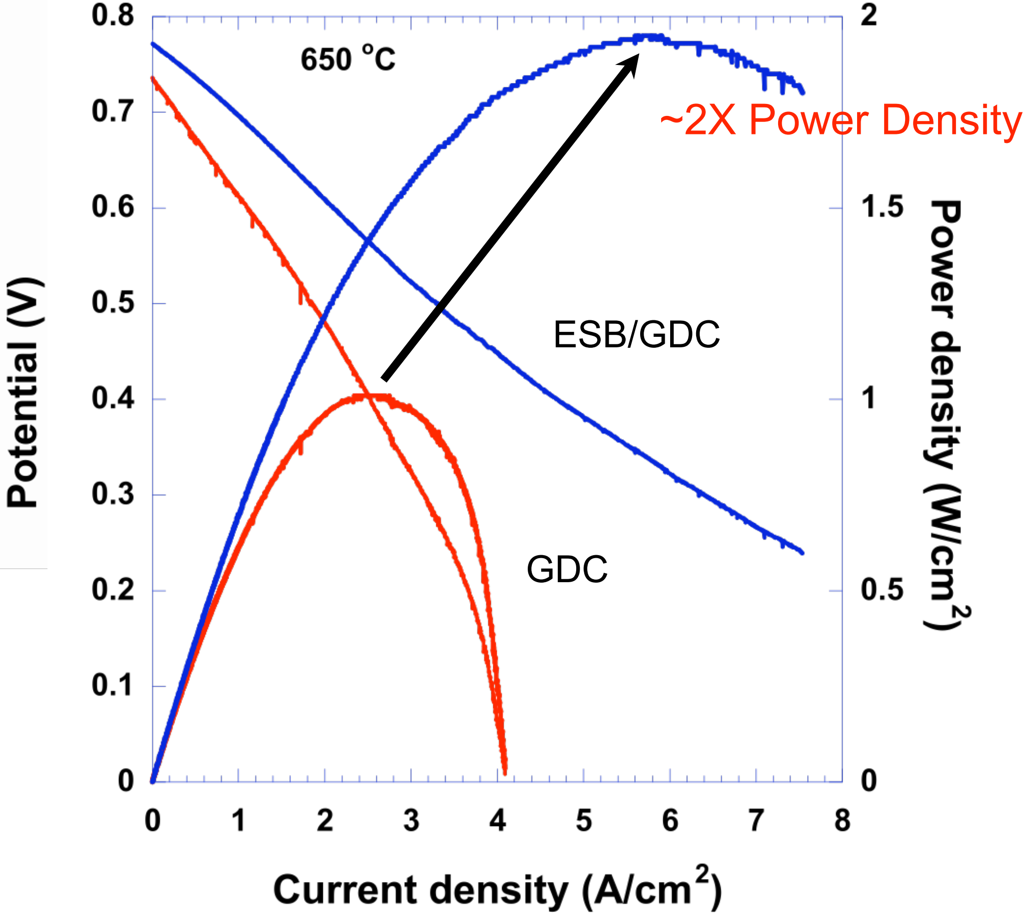




- Near theoretical OCP achieved with anode supported thin bilayer electrolytes
- Need to optimize *both* GDC and ESB thicknesses

Bilayer Electrolytes for LT-SOFC

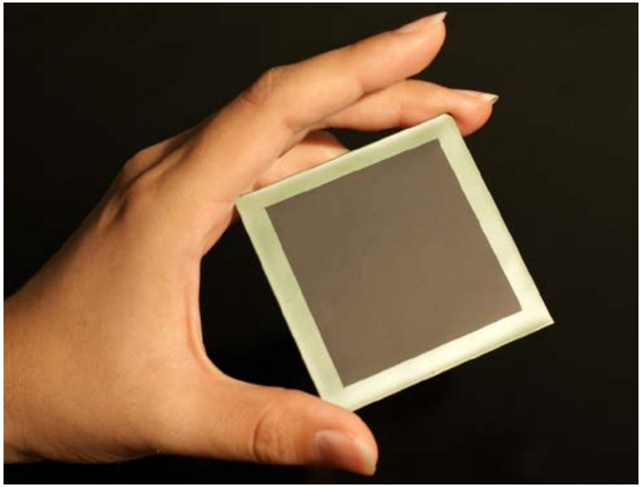




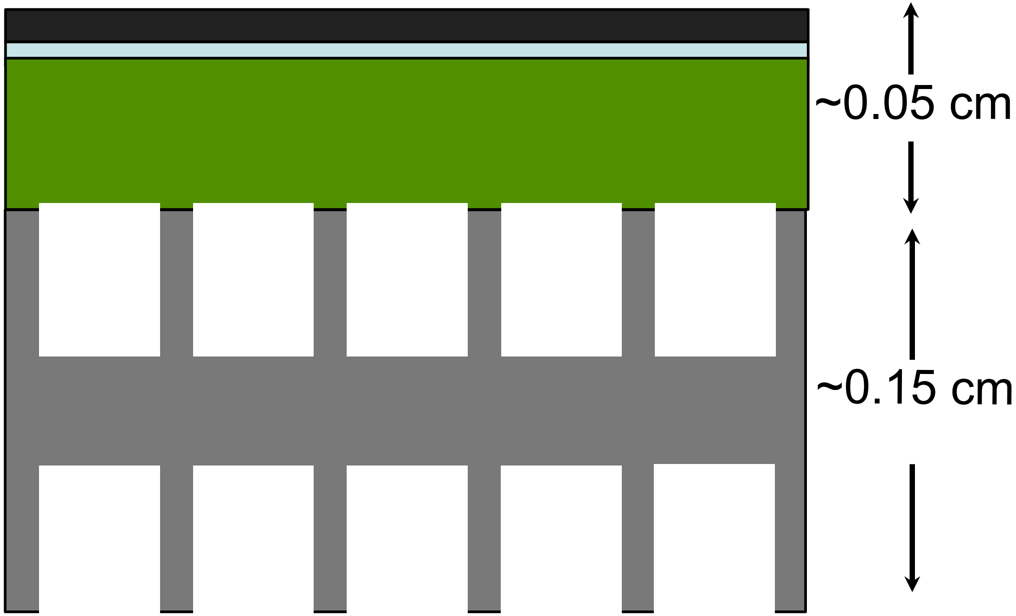
Integrating new materials and microstructures to achieve world record performance

J. S. Ahn, D. Pergolesi, M. A. Camaratta, H. Yoon, B. W. Lee, E. Traversa and E. D. Wachsman, *Electrochem. Comm.*, **11**, 1504 (2009).

Volumetric Power Density

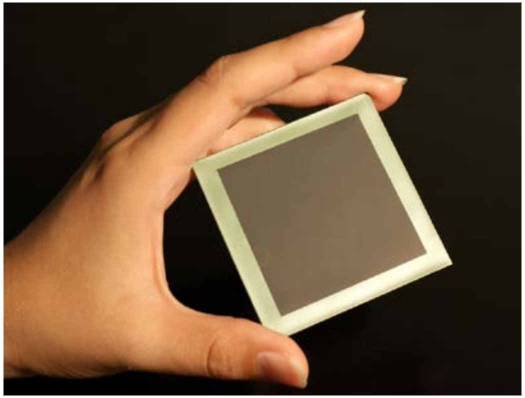


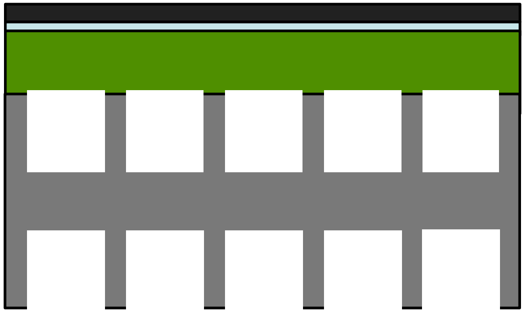
$2\ W/cm^2 = 10\ W/cm^3$

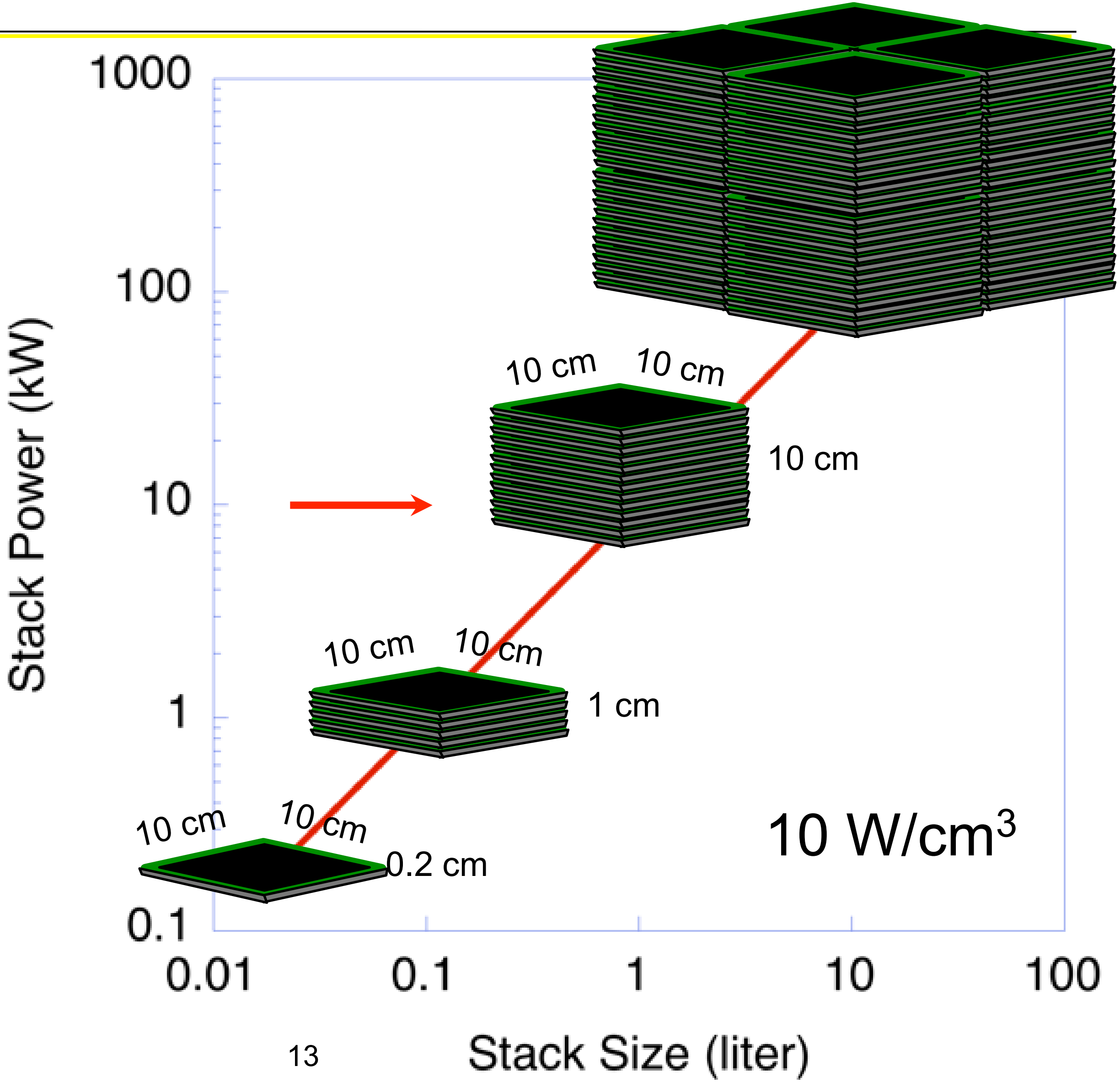


Steel Interconnect/gas channels

Volumetric Power Density

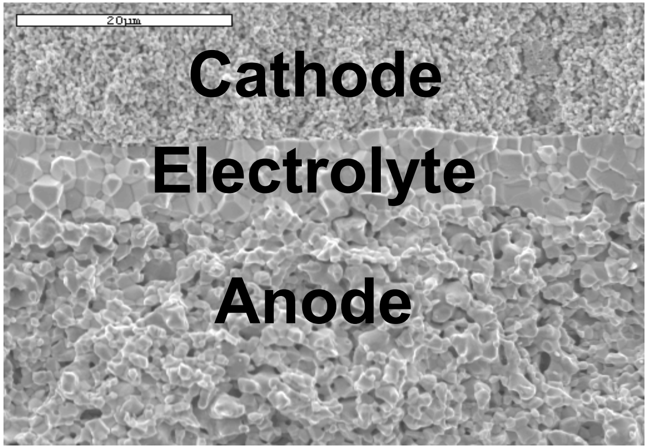




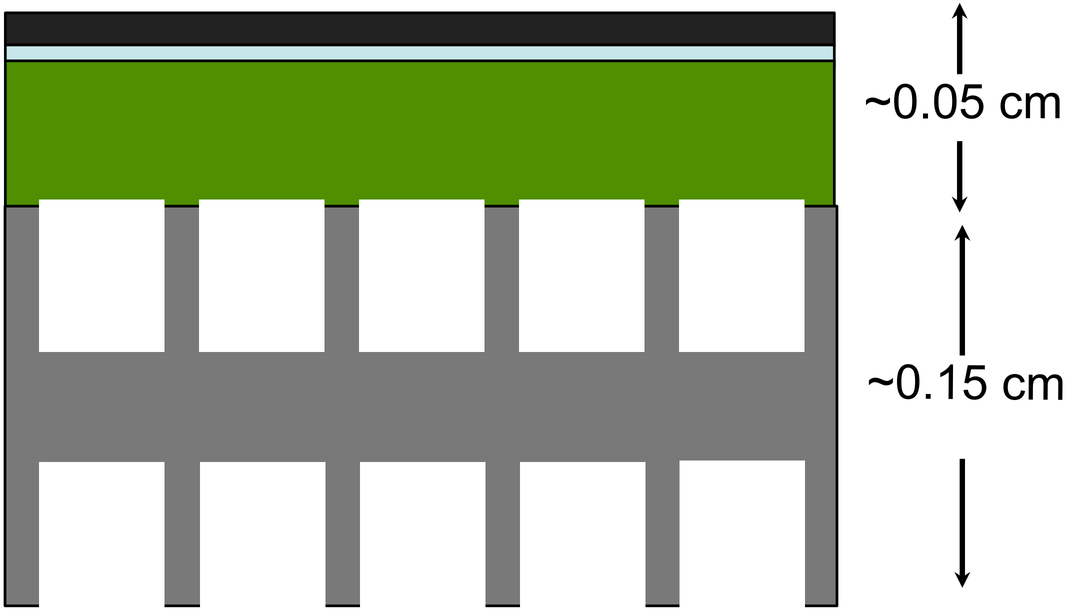


10 W/cm^3

Gravimetric Power Density



Electrodes ~30% porous

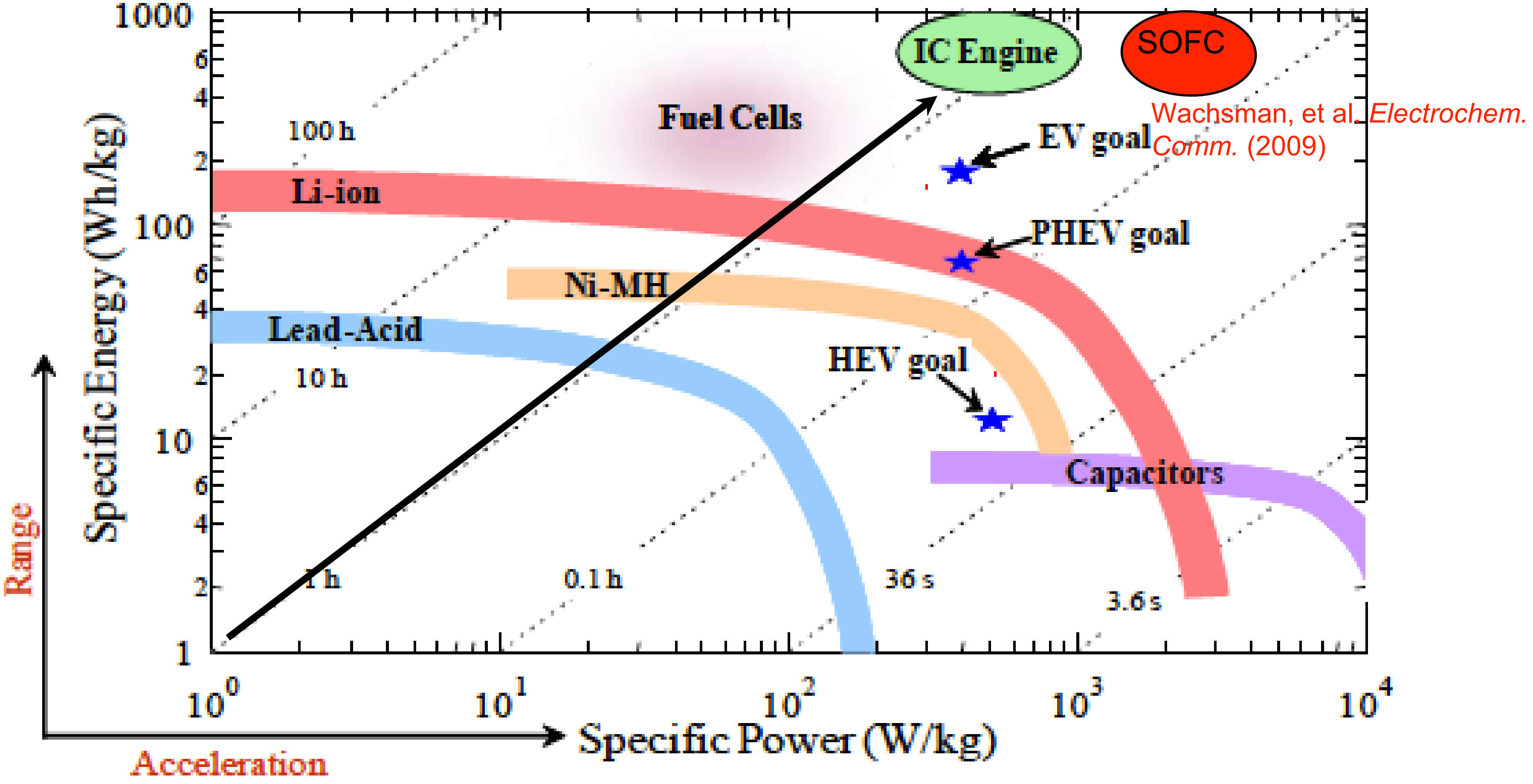


Steel Interconnect/gas channels ~70% porous

0.7 X 7g/cc X 0.05cm + 0.3 X 8g/cc X 0.15cm = ~0.6 g/cm^2

~2 W/cm^2 / 0.6 g/cm^2 = **~3 kW/kg**

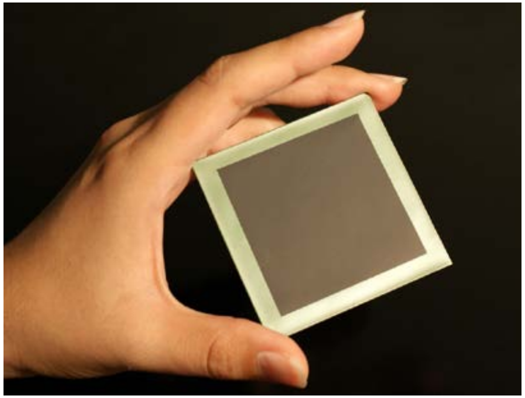
Energy Storage Figure of Merit



Wachsman, et al. *Electrochem. Comm.* (2009)

V. Srinivasan, Batteries for Vehicular Applications, http://berc.lbl.gov/venkat/files/batteries-for-vehicles.pdf

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)

Gasoline Fuel Cell Would Boost Electric Car Range – *Technology Review* (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

REDOX

Next Generation Solid Oxide Fuel Cells

Next Generation Solid Oxide Fuel Cells

An Inexpensive Fuel Cell Generator – *Technology Review* (2013)

Avoiding the Power Grid – *Technology Review* (2013)

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

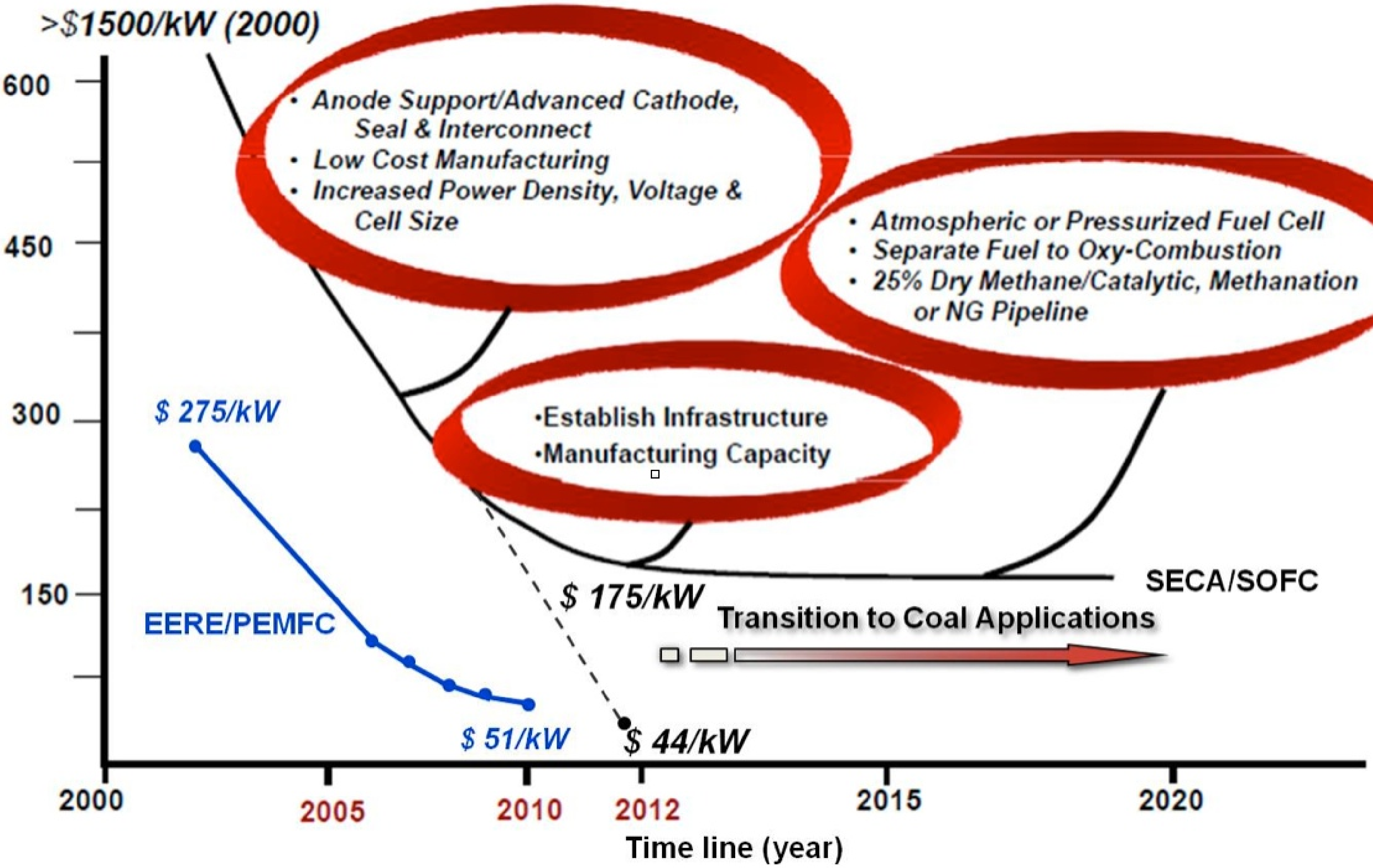
Redox Power Plans to Roll Out Dishwasher-Sized Fuel Cells that Cost 90% Less than Currently Available Fuel Cells
– *Forbes* (2013)

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

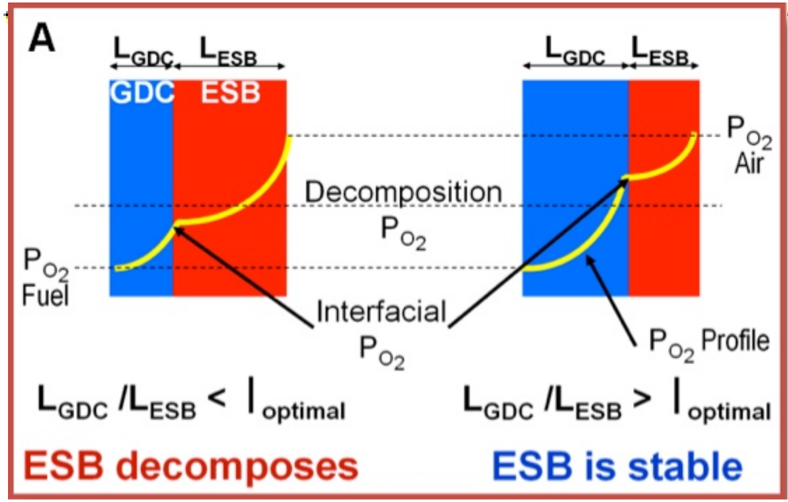
At Redox Power Systems, the Future of Electricity Lies in Fuel Cells
– *Washington Post* (2013)

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

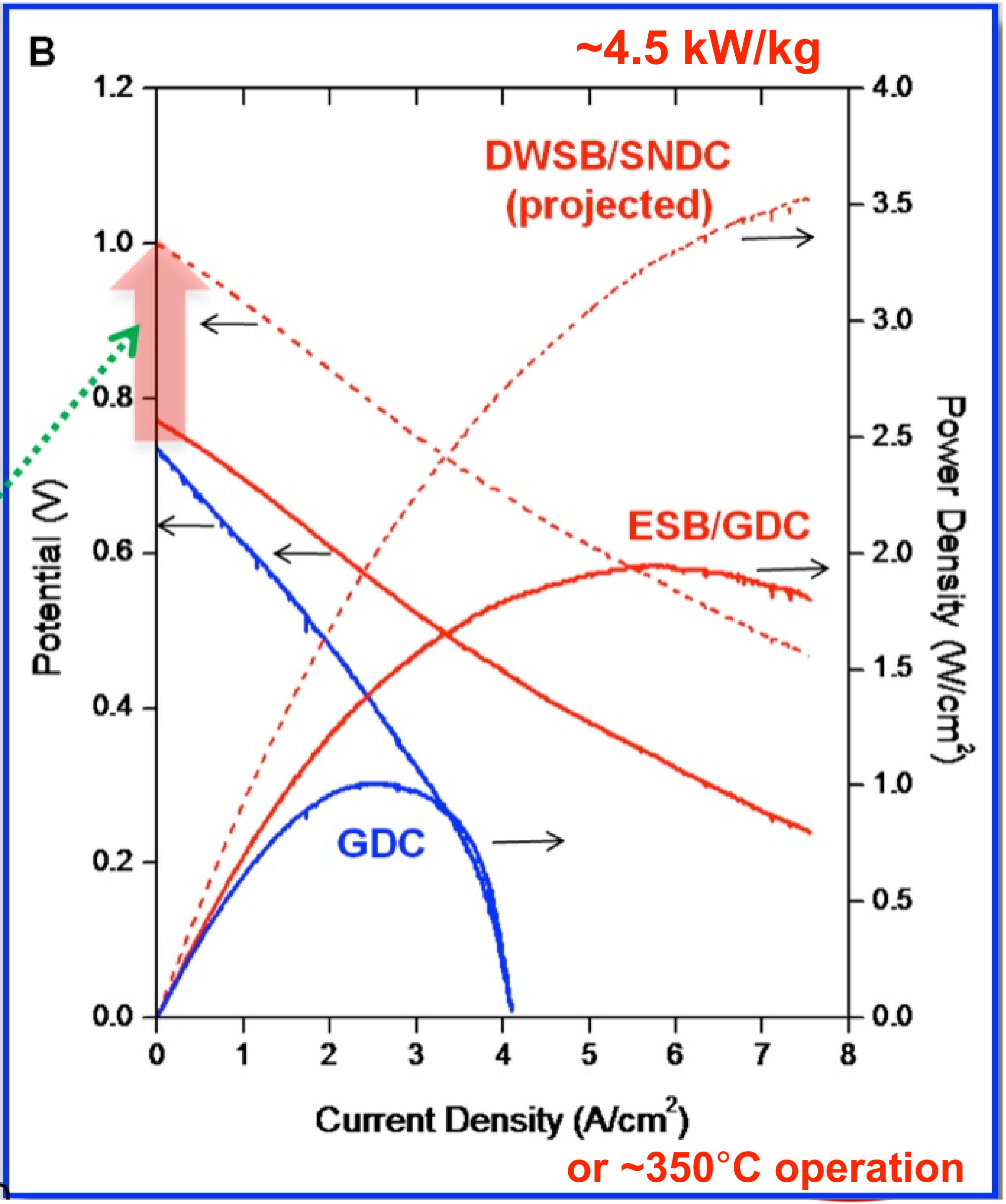
SOFC Cost


>$1500/kW (2000)
600
450
300
150
• 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
•Establish Infrastructure
•Manufacturing Capacity
$ 275/kW
EERE/PEMFC
$ 51/kW
$ 175/kW
$ 44/kW
SECA/SOFC
Transition to Coal Applications
2000
2005
2010
2012
2015
2020
Time line (year)

Increasing Performance & Driving Down Temperature

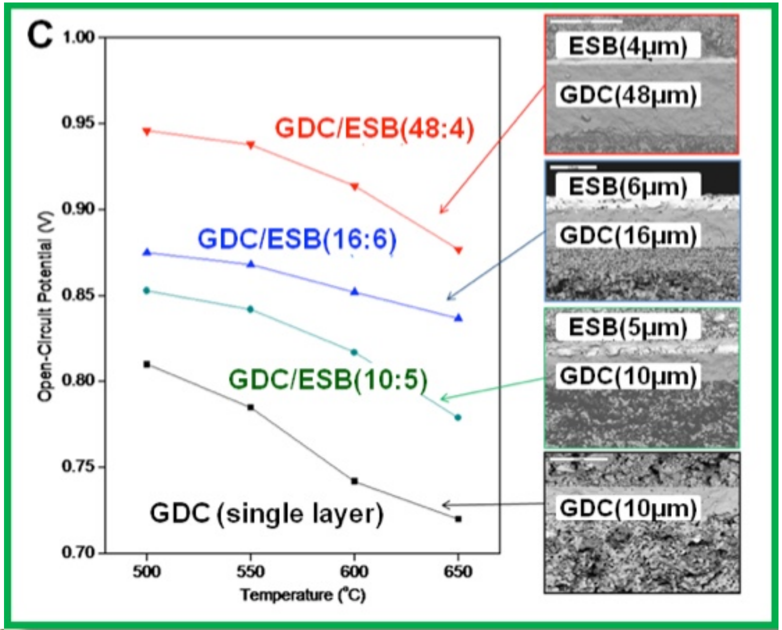


ESB decomposes **ESB is stable**

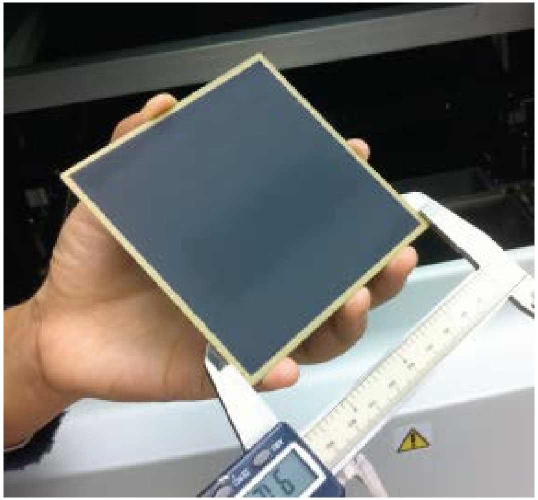


~4.5 kW/kg

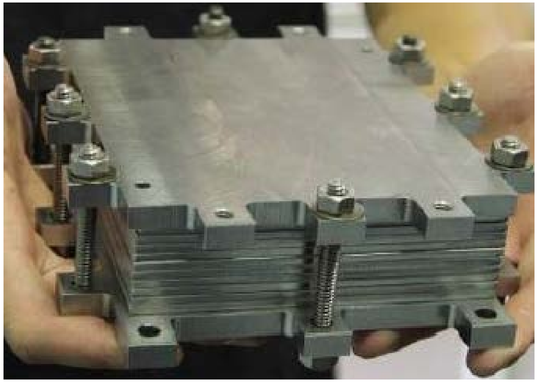
or ~350°C operation



Scale-Up and Stack Development

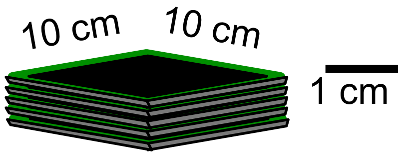


- Developed repeatable and manufacturable 10 cm x 10 cm cell fabrication processes
- Transferred UMD fabrication technology to Industry Partners

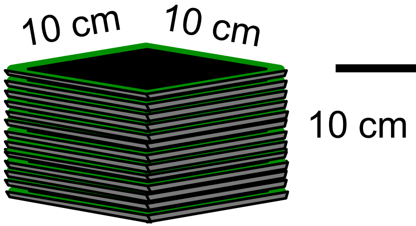


- Fabricating and testing multi-cell short stacks
- Negligible difference in multi 10x10 cell stack performance between H_2 and 100% CH_4 Slip

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

Commercial & Industrial Power 25 kW to 250 kW

REDOX

Bilayer Cell ~200 W

REDOX

1 to 10 kW Stacks

Datacenter Embedded Power 10 kW

[redacted]

[redacted]

Residential Combined Heat & Power 1 to 10 kW$_e$