

The Carbon Fuel Cell

Background

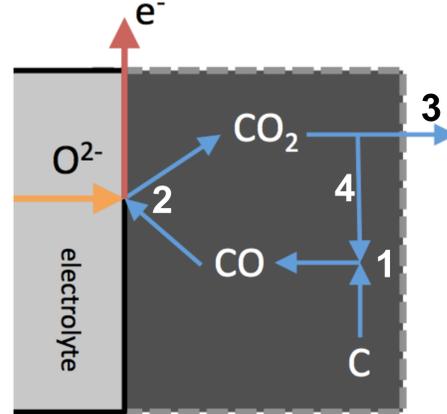
Carbon fuel cells (CFCs) can electrochemically oxidize solid carbonaceous fuels such as coal to directly produce work. Research in the Mitchell lab focuses on solid-oxide-based CFCs that offer:

- High efficiency (not Carnot limited)
- Fuel flexibility (coals, biomasses, other wastes)
- Product flexibility (electricity and hydrogen)
- Solid-state design (no moving parts)
- Purified CO₂ product (near-capture ready)

Principle of Operation

Solid-oxide CFC devices operate through a multistep oxidation process known as the “shuttle mechanism”¹

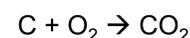
1. C + CO₂ → 2 CO (Boudouard reaction)
2. CO + O²⁻ → CO₂ + 2e⁻
3. Some CO₂ leaves system
4. Remaining CO₂ reacts with C through step 1



Above 973 K, Boudouard reaction is favorable. The cell self-generates needed CO₂ to gasify the fuel. The conversion process results in four electrons traversing external circuit per carbon, directly producing highly efficient electrical work. CO₂ product is purified and near-capture ready, as it is not diluted with N₂.

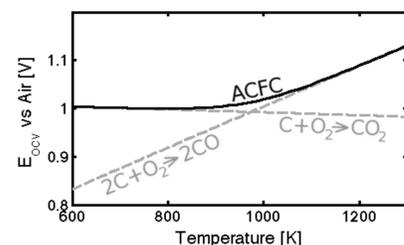
Air-Carbon Fuel Cell (ACFC)

ACFC devices employ oxygen (from air) as the oxidizer at the cell cathode. The overall reaction is:

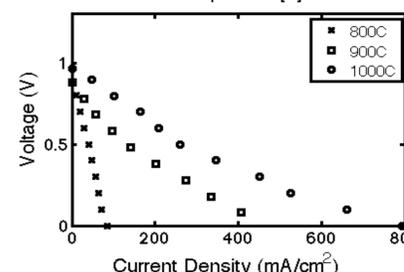


This is the same reaction as combustion, but here **electricity is directly generated** from its completion. The **exothermic** cell reactions are large enough to overcome the endothermic Boudouard reaction in the fuel bed.

- Theoretical cell open circuit potential is 1 volt below 900 K, and then rises steadily above 1000 K. Shift in slope follows from Boudouard equilibrium shift from CO₂ to CO product around 950 K

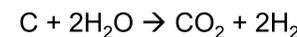


- Experimental devices running on biomass fuels have demonstrated current densities approaching 800 mA/cm² and power densities approaching 150 mW/cm²



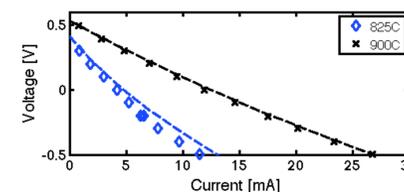
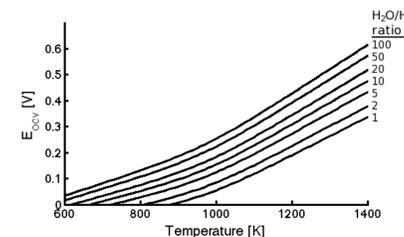
Steam-Carbon Fuel Cell (SCFC)

SCFC devices employ steam as the oxidizer at the cell cathode. The overall reaction is:



This reaction is similar to steam reforming with an added water-gas shift step. Its completion results in the generation of both **hydrogen and electricity**, however the overall cell reaction is **endothermic**.

- Theoretical cell open circuit potential is dependent on cathode steam to hydrogen ratio and is between 0.3 and 0.5 at normal operating conditions
- Experimental devices running on biomass fuels have demonstrated the co-production of electricity and hydrogen from a single cell with external heat input

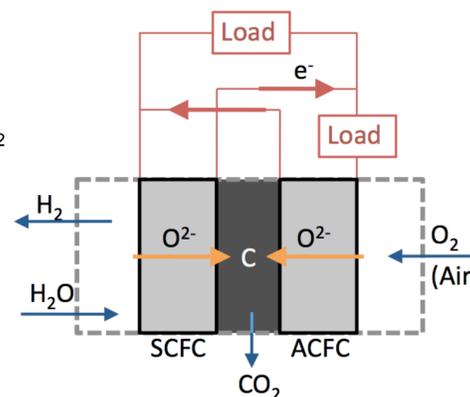


Steam-Carbon-Air Fuel Cell (SCAFC)

ACFC devices are **exothermic**, and it is desirable to utilize the rejected heat to increase efficiency. SCFC devices are **endothermic**, and to maximize H₂ production it is further desirable to overdrive an SCFC by pushing electricity into the cell to increase the cell current density. These two devices are therefore highly complementary, as the ACFC can provide the heat and work a SCFC needs. A SCAFC device takes advantage of this fact by combining an ACFC and SCFC through a shared carbon bed. This puts the devices in physical and thermal communication. Excess heat and electrical power from the ACFC half is used to overdrive and warm the SCFC half, producing more H₂ per unit area of cell.

The SCAFC allows:

- Direct, tunable production of H₂ and electricity from carbon
- H₂ product free of any CO traces (a poison for PEM cells)
- No external heat inputs
- No external work inputs
- Capture ready exhaust stream



By controlling system parameters, the ratio of electric power produced to hydrogen produced can be controlled.

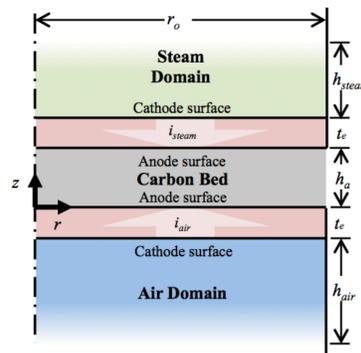
Recent Publications

1. B. Alexander, R. Mitchell, T. Gür. **Experimental and Modeling Study of Biomass Conversion in a Solid Carbon Fuel Cell.** *Journal of the Electrochemical Society*, 159, B347-B354 (2012).
3. B. Alexander, R. Mitchell, and T. Gür. **Viability of Coupled Steam-Carbon-Air Fuel Cell Concept for Spontaneous Co-production of Hydrogen and Electrical Power.** *Journal of the Electrochemical Society*, 159, B810-B818 (2012).
4. B. Alexander, R. Mitchell, and T. Gür. **Steam-Carbon Fuel Cell Concept for Cogeneration of Hydrogen and Electrical Power.** *Journal of the Electrochemical Society*, 158, B505-B513 (2011).

Predicting Performance: The SCAFC Model

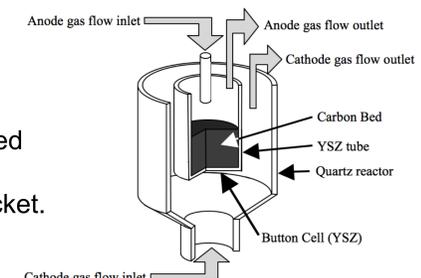
In order to predict SCAFC performance and understand the tradeoffs between maximizing system efficiency and system output, a coupled model of a SCAFC was developed that includes:

- Boudouard reaction kinetics (7-step reduced mechanism)
- Transport (convection and diffusion) of CO and CO₂ through the fuel bed
- O₂/N₂ transport in the ACFC cathode
- H₂/H₂O transport in the SCFC cathode
- Electrochemical kinetics of the cell half reactions based on three reduced surface reaction mechanisms
- Oxygen ion transport through YSZ
- Heat generation and transport in the cathode chambers, electrolytes, and anode chamber



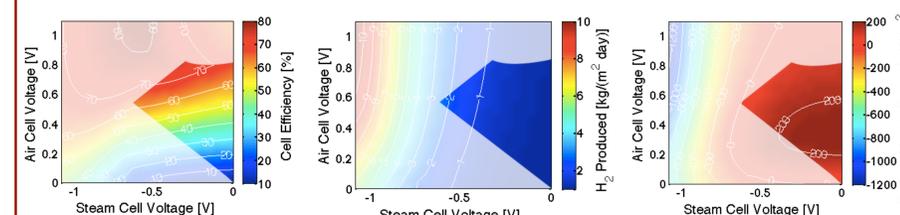
The model domain was taken as two axisymmetric button cells sandwiching a fuel bed, as shown above and to the right.

Experimental measurements were performed in button cell devices affixed to the end of a YSZ support tube and suspended within a quartz reactor jacket. A schematic of the experimental setup is shown at right.

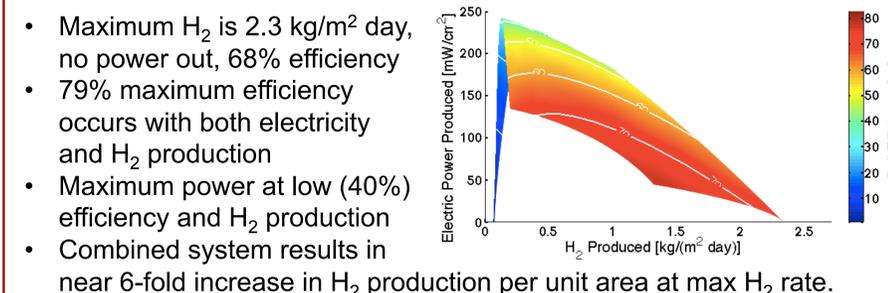


SCAFC Model Results

The model was exercised for a SCAFC device at 1173 K by predicting efficiency and power output as a function of ACFC and SCFC voltages:



Lighter areas indicate undesirable operational regions where external heat or work has to be added to the system. Results show maximizing efficiency, power, and H₂ output are all mutually exclusive. These results (excluding the undesirable modes) can be combined into a single plot:



- Maximum H₂ is 2.3 kg/m² day, no power out, 68% efficiency
- 79% maximum efficiency occurs with both electricity and H₂ production
- Maximum power at low (40%) efficiency and H₂ production
- Combined system results in near 6-fold increase in H₂ production per unit area at max H₂ rate.