**Outline**

- Basics of electrochemistry
- Polymer electrolyte membrane (PEM) fuel cells
- Solid oxide fuel cells (SOFCs)
- Hydrogen production and storage
- Coal-fired plants and integrated gasifier fuel cell (IGFC) systems

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**History of Fuel Cells**

1839 Sir William Grove discovers the principle of the fuel cell
1889 Mond and Langer uses air and coal gas reactants and phosphoric acid as electrolyte in a “stack”
1959 Francis Bacon demonstrates an alkaline 5kW system
1960’s NASA begins alkaline fuel cell utilization on space flights - Mercury through current shuttle missions
1970’s UTC 250kW phosphoric acid technology developed and employed
1990’s – Present Stationary and automotive PEM-based field service demos

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**Polymer Electrolyte Membrane Fuel Cells**

(PEMFCs)

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**Fuel Cell**

Fuel Cell is a device that converts chemical energy of fuel and oxygen into electricity. It usually consists of anode, electrolyte, cathode and interconnect.

- **Anode side:** $2H_2 \rightarrow 4H^+ + 4e^-$
- **Cathode side:** $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
- **Net reaction:** $2H_2 + O_2 \rightarrow 2H_2O$
- **Operating temp:** around 80 °C

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**Configuration of PEM fuel cell**

Source: Ajay K. Prasad
Polymer electrolyte membrane fuel cells

PEM fuel cell components:

Anode and cathode: Carbon supported Pt particles – as the electro-catalysts

Electrolyte: Nafion manufactured by DuPont
- Fuel (H₂) and oxidant (O₂) are separated by the electrolyte
- Only ions transports in the electrolyte
- No electrons migrate in the electrolyte

Fuel cell thermodynamics

The energy conversion of a fuel cell is described as:

Chemical energy of fuel = Electrical energy + Heat energy

The fuel cell system can be considered as a control volume

Hydrogen → Fuel cell → Oxygen

Energy = Electricity Energy = V·I·t

Ejected Heat
Water (byproduct)

The first law of thermodynamics for a control volume:

\[ \dot{Q} - \dot{W} = \int \left( h_f - h_i + \frac{V_f^2 - V_i^2}{2} + g(z_f - z_i) \right) \]

For a stationary control volume (i.e. the kinetic and potential energies are constant in time, then

\[ \Delta H = Q - W \]

Thus, the enthalpy is the difference between the heat and the work involved in a system

Fuel cell thermodynamics

The maximum possible efficiency for an ideal, reversible fuel cell is:

\[ \eta_{\text{max}} = \frac{W}{\Delta H} = 1 - \frac{Q_{\text{net}}}{\Delta H} = \frac{\Delta H - T \Delta S}{\Delta H} \]

An alternative derivation involves using “Gibbs Free Energy”

Fuel cell thermodynamics

The enthalpy change of reaction (\(\Delta H\)) captures the notion of energy changes for chemical reactions.

the change in Gibbs energy (\(\Delta G\)) of reaction discounts the change of entropy, retaining only the usable energy.

The two are related by the following equation:

\[ \Delta G = \Delta H - T \Delta S \]

where \(T\) is the temperature in Kelvin and \(\Delta S\) is the change in entropy.

Because absolute temperature is always positive and entropy increases with every reaction, the above equation tells us that the change in Gibbs energy is always less than the change in enthalpy, which is precisely what we would expect.
The maximum possible efficiency for an ideal, reversible fuel cell is:

\[
\eta_{\text{max}} = \frac{\Delta G}{\Delta H}
\]

For the reaction in the fuel cells:

\[
\begin{align*}
\text{In the anode:} & \quad H_2 \rightarrow 2H^+ + 2e^- \quad \Delta H = 0 \text{ kJ} \\
\text{In the cathode:} & \quad 1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad \Delta H = -285.8 \text{ kJ}
\end{align*}
\]

Thus, the maximum possible efficiency for an ideal, reversible fuel cell is:

\[
\eta_{\text{max}} = \frac{\Delta G}{\Delta H} = \frac{237.2}{285.8} = 0.83
\]

The Nernst equation

\[
\Delta G^\circ = \Delta G + RT \ln Q
\]

\(\Delta G^\circ\) for a redox reaction that is reversible

\[
\Delta G^\circ = -nFE_0
\]

where \(n\) is the number of moles of electrons transferred, and \(F\) is a constant, the Faraday.

1 \(F = 96,485 \text{ C/mol} = 96,485 \text{ J/V-mol}\)

\(\Delta G = -237.2 \text{ kJ/mole}\)

\(n = 2\)

The maximum output voltage of an ideal fuel cell:

\[
E_0 = \frac{(-237200)}{2 \times 96485} = 1.229 \approx 1.23 \text{ V}
\]

However, additional energy losing mechanisms further reduce this voltage.

---

**PEM Fuel Cells**

**Energy loss in the PEM fuel cells:**

**Activation Polarization:** These losses are caused by the slowness of the reaction taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons.

**Ohmic Polarization:** The voltage drop due to the resistance to the flow of electrons through the material of the electrodes. This loss varies linearly with current density.

**Concentration Polarization:** Losses that result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used.

Therefore,

**Actual Efficiency of PEM fuel cells:** ~ 0.5

---

**PEM Fuel Cells**

The actual output voltage:

\[
\Delta V = E - (i - i_a)r - A \ln \left( \frac{i + i_a}{i_a} \right) + B \ln \left( 1 - \frac{i + i_a}{i} \right)
\]

**Activation loss**

**Mass diffusion loss**

**Ohmic drop**

Maximum output at the ideal, reversible case
Comparison of two engines for vehicles

**Internal-combustion engine**
- Only <33% efficient at best 80-90% efficient
- Air emissions Zero direct emissions
- Peaky torque-rpm curve Broad torque-rpm curve
- (needs a transmission) (does not need a transmission)
- Power loss in idle No idle
- Irreversible energy conversion Regenerative braking
- Big and heavy Small and light
- (250 hp in 600 lbs = 0.7 kW/kg) (75 kW in 13 kg = 5.8 kW/kg)
- Noisy Quiet

**Electric motor**

**why don’t we have electric motors in our automobiles today?**

We do not have an electric power supply source

PEM fuel cell is the option for supply electric power in a vehicle

Vehicles Driven by Ideal Engines

The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.

The maximum efficiency of Carnot heat engine

\[ \eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} \]

Therefore, a Carnot engine would have to have a high temperature of 1753 K, with a corresponding low temperature of 298 K, to achieve an efficiency of 83%, which is comparable to the maximum efficiency of fuel cells.
Why Fuel Cells?

Vehicles driven by actual Engines

<table>
<thead>
<tr>
<th>Combustion engine: 20-28%</th>
<th>PEMFC combined with motor: 50%</th>
</tr>
</thead>
</table>

Comparison of two engines for vehicles

Environmental Impacts

<table>
<thead>
<tr>
<th>Internal-combustion engine</th>
<th>PEM fuel cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unburned hydrocarbons</td>
<td>Water is the only emission and exhaust product</td>
</tr>
<tr>
<td>Ozone formation</td>
<td></td>
</tr>
<tr>
<td>CO (incomplete combustion)</td>
<td></td>
</tr>
<tr>
<td>NOx (both from fuel and air combustion)</td>
<td></td>
</tr>
<tr>
<td>SOx (from sulfur in fuel)</td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td></td>
</tr>
<tr>
<td>Sulfate aerosols, carbonaceous</td>
<td></td>
</tr>
</tbody>
</table>

Fuel cell/internal combustion engine hybrid vehicles

Hybrid increase the fuel economy and horsepower

PEM fuel cell applications

Portable

Military applications

PEM fuel cell applications

Ballard fuel cell buses, Chicago

Ford F-1500 hydrogen fuel cell car

Asia-Pacific Fuel Cell Technologies’s zero emission scooter

Pacifica Fuel Cell Company’s fuel cell bicycle

Fuel Cells

Summary of fuel cell value points:

- Reduced weight
- Extended run times
- Reduced size
- Lower cost of ownership
- Greater efficiency
- Reduced emissions
- Low noise level
- Lower heat signatures
**Advantages of PEM Fuel Cells:**

- Higher Power density → Fewer cells needed in stack
- No electrolyte corrosion or safety concerns
- Lower operating temperature, 50 – 120 °C → In a car, it allows for instant start-up.

**Challenges for PEMFC Applications**

- Lack of H₂ fuel infrastructure
- H₂ safety concern
- Complex bulky H₂ storage system (DOE requirement: 6.5 w/t)
- High-pressure containers (4 w/t)
- High cost: NEED to obtain higher catalytic activity than the standard carbon-supported Pt particle catalysts
- CO poisoning of Pt catalysts

**Hot research fields:**

- Hydrogen storage in carbon nanotubes
  - 1-8 wt% reversible storage
- Hydrogen storage by metal hydrides:
  - LaNi₅Hₓ (1.37 m/l, 2 bar, 298K)³⁻¹
  - Mg₂NiH₄ (3.59 m/l, 1 bar, 555K)
  - Zr₂V₂H₅.₅ (3.01 m/l, 10⁻⁸ bar, 323K)
- Low Pt catalyst loading

**Fuel Cells**

**Fuel Cell Types:**

- Solid Oxide Fuel Cell (SOFC)
- Molten Carbonate (MCFC)
- Phosphoric Acid (PAFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Alkaline Fuel Cell (AFC)

**Characteristics and applications of common types of fuel cells**

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Proton Exchange Membrane (PEM)</th>
<th>Phosphoric Acid Fuel Cell (PAFC)</th>
<th>Molten Carbonate Fuel Cell (MCFC)</th>
<th>Solid Oxide Fuel Cell (SOFC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>80°C (200°F)</td>
<td>200°C (400°F)</td>
<td>650°C (1200°F)</td>
<td>600-1000°C (1100-1800°F)</td>
</tr>
<tr>
<td>System Efficiency Ranges (kW/°C)</td>
<td>20-45%</td>
<td>35-40%</td>
<td>40-60%</td>
<td>30-70%</td>
</tr>
<tr>
<td>Size Range</td>
<td>0.1 – 250 kW</td>
<td>200-400 kW</td>
<td>250 kW – 3 MW</td>
<td>1 kW – 1 MW</td>
</tr>
<tr>
<td>Cost (est.) Cost Target</td>
<td>$1,500-4,000/kW</td>
<td>$25-50/kW</td>
<td>$1,800/kW</td>
<td>$400-500/kW</td>
</tr>
<tr>
<td>Applications</td>
<td>Stationary/Portable</td>
<td>Stationary/Stationary/Stationary/Stationary/Portable</td>
<td>Stationary/Stationary/Stationary/Portable</td>
<td></td>
</tr>
</tbody>
</table>
Solid Oxide Fuel Cells (SOFCs)

Advantages of SOFCs:

- High efficiency: Theoretical efficiency reaches 70%. Currently 51% (Mitsubishi) and 54% (Kyocera) have reported as compared to 36% for gas turbines.
- Utilization of ejected heat: The high operating temperature makes it utilize the high-temp steam, which could be coupled to gas turbines system. The SOFC/gas turbine hybrid system can achieve an efficiency of 70%.
- Fuel flexibility: directly reform hydrocarbon fuels at the anode side.
- No precious metal

Operating Mechanism of SOFC

Cathode reaction
\[ O_2 + 4e^- \rightarrow 2O^{2-} \]

Anode reaction
\[ 2O^{2-} - 4e^- + 2H_2 \rightarrow 2H_2O \]

Overall reaction
\[ 2H_2 + O_2 \rightarrow 2H_2O \]

Cathode reaction
\[ O_2 + 4e^- \rightarrow 2O^{2-} \]

Anode reaction
\[ 4O^{2-} - 8e^- + CH_4 \rightarrow 2H_2O + CO_2 \]

Overall reaction
\[ CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \]

SOFC Configuration

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Electrolyte-supported</th>
<th>Anode-supported</th>
<th>Cathode-supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000°C</td>
<td>59 μm</td>
<td>50 μm</td>
<td>50 - 2000 μm</td>
</tr>
<tr>
<td>700-800°C</td>
<td>50 μm</td>
<td>&gt;150 μm</td>
<td>&lt;20 μm</td>
</tr>
<tr>
<td>700-800°C</td>
<td>50 μm</td>
<td>500 - 1500 μm</td>
<td>20 - 50 μm</td>
</tr>
</tbody>
</table>

Most popular

Anode-Supported SOFC

Micrograph of anode-supported thin electrolyte cell structure

On either side of the dense electrolyte is a fine-structured "functional layer" for the electrocatalytic promotion of the electrode reactions

Source: cool fuel cells by NASA

Source: http://people.bu.edu/pzink/sofc-1.html
SOFC Testing Rig

Key Elements in SOFCs

- Good ion conduction in the electrolyte
- Efficient electrocatalysts at the anode and the cathode
- High triple-phase interfacial contact

SOFC Electrolyte Materials

Requirements of electrolyte

- Stability in both reducing and oxidizing environments
- No chemical reaction with the electrodes
- High ionic conductivity and negligible electronic conductivity at operating temperature
- High mechanical strength
- Coefficient of thermal expansion (CTE) that matches to the electrode materials

SOFC Testing

Fluorite Structure of Electrolyte

Pure ZrO$_2$

$\begin{bmatrix} a = b = c = 5.12 \text{Å} \\ \text{space group} = \text{Fm\bar{3}m} \ (225) \\ \text{Zr}^{4+} = 0.0 \ 0.0 \ 0.0 \\ \text{O}^{2-} = (0.25 \ 0.25 \ 0.25) \end{bmatrix}$
Fluorite Structure

- This view focuses on the O sub-lattice (half a unit cell) and includes a substituted cation and a charge compensating O vacancy.

Fluorite Structure – Yttria Stabilized Zirconia (YSZ)

Pure ZrO₂: monoclinic at room temperature, tetragonal above 1170 °C and cubic fluorite above 2370 °C.

8 at.% Y₂O₃ can stabilize the fluorite structure down to room temperature.

Phase Diagram of ZrO₂


Ionic Conductivity of Doped ZrO₂

Sc doped ZrO₂ has the highest ionic conductivity because Sc³⁺ has similar ionic radius with Zr⁴⁺. But it has the problem of ageing:

\[ Y_2O_3(ZrO_2) \rightarrow 2Y_2O_3 + 3O_2 + 4Zr^{4+} \]

Conductivity of ZrO₂-M₂O₃ at 1000 °C

Y. Ando, et al, solid state ionic, 111 (1990), 115

Ionic Conductivity of Electrolyte

Doped ZrO₂ is widely used as SOFC electrolyte because of its stability in both reducing and oxidizing environments and compatibility with other components of fuel cell.

Other oxides have disadvantages such as electronic conductivity, high cost, or difficulties in processing.

The electronic conductivity is negligible at the normal SOFC operating range of 0.21-10⁻²⁰ atm

Temperature Dependence of Electrical Conductivity for Oxide Ion Conductors

S.P. Saw et al, Solid State Ionics, 32-33, 1992

Properties of Doped Zirconia

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Conductivity at 1000°C (S/cm)</th>
<th>Bending strength (MPa)</th>
<th>Thermal exp. coeff. (1/K x 10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As annealed</td>
<td>After annealing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.065</td>
<td>0.030</td>
<td>1200</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.063</td>
<td>0.09</td>
<td>230</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.13</td>
<td>0.09</td>
<td>300</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.12</td>
<td>0.12</td>
<td>350</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.15</td>
<td>0.15</td>
<td>270</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.15</td>
<td>0.12</td>
<td>255</td>
</tr>
<tr>
<td>( \text{ZrO}_2 )</td>
<td>0.20</td>
<td>0.15</td>
<td>250</td>
</tr>
</tbody>
</table>

The electronic conductivity is negligible at the normal SOFC operating range of 0.21-10⁻²⁰ atm

Fluorite Structure -- Doped Ceria

Concentration dependence of electrical conductivity for CeO$_2$-Sm$_2$O$_3$


Perovskite Phase

A cations
B cations
Oxygen anions

Total electrical conductivity of Ce$_{0.8}$Sm$_{0.2}$O$_{1.9-\delta}$

S.C. Singhal, K. Kendall, Book, "High Temperature Solid Oxide Fuel Cells"

Fluorite Structure -- Doped Ceria

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S.C. Singhal, K. Kendall, Book, "High Temperature Solid Oxide Fuel Cells"

Perovskite-Structured Electrolyte

Lanthanum Gallate, LaGaO$_3$

The highest ionic conductivity of doped LaGaO$_3$ was found at composition of La$_{0.8}$Sr$_{0.2}$Ga$_{0.85}$Mg$_{0.15}$O$_3$

S.C. Singhal, K. Kendall, Book, "High Temperature Solid Oxide Fuel Cells"

Lanthanum Gallate Electrolyte

Conductivity: doped LaGaO$_3$ > doped ceria > YSZ

Disadvantages
- Weaker mechanical strength of LaGaO$_3$ than YSZ
- Electronic conductivity under low Po$_2$ because of the partial reduction of Ce$^{4+}$ ions
- LaGaO$_3$ can be a mixed proton/oxide ion conductor

H$_2$O + V$_{O}^{+}$ + Q$_{O}^{2+}$ → 2H$_2$

S.C. Singhal, K. Kendall, Book, "High Temperature Solid Oxide Fuel Cells"

Anode of SOFC

Requirements for anode
- High electrical conductivity
- High catalytic activity for fuel oxidation
- Close CTE match with the electrolyte
- Stability in reducing environment at high temperature
- Chemical compatibility with the other cell components
- Corrosion resistance to the fuel and impurities

Fabrication of anode cerments

Typical anode material: Ni + YSZ

Where YSZ stands for yttria-stabilized zirconia

S.C. Singhal, K. Kendall, Book, "High Temperature Solid Oxide Fuel Cells"
Anode Reaction & Materials

Electrodes are a composite because reaction occurs only at the Three-Phase Boundary (TPB):

“Line” where 1) Gas phase, 2) Electrons, & 3) Ions meet.

Anode Reaction & Materials

Anode reaction

\[ \begin{align*}
    H_2 + O_2 & \rightarrow H_2O + V^{\ast\ast}_o + 2e^- \\
    2O^{2-} - 4e + 2H_2 & \rightarrow 2H_2O \\
    4O^{2-} - 8e + CH_4 & \rightarrow 2H_2O + CO_2
\end{align*} \]

Necessary conditions

- Catalytic properties
- Ionic conductivity
- Electronic conductivity
- Porosity

Anode materials

- Pt, Au (peeling off problem)
- Ni (aggregation)
- Ni+YSZ, sensitive to S impurity

Anodes for Hydrocarbon Fuels

Ni-based anodes cannot be exposed to hydrocarbons: 

\( Ni \) catalyzes carbon formation

Ni in methane for 3 hrs. 800°C
Ni in toluene for 3 hrs. 700°C

This can be avoided with other metals

Cu in methane for 3 hrs. 800°C
Cu in toluene for 3 hrs. 700°C

Anodes for Hydrocarbon Fuels

Carbon formation is \( in \), not \( on \), Ni:

Note: Fe, Co, and Ru will all form catalyze carbon formation

Current-potential characteristics of copper cerments at 800 °C showing effect of hydrocarbon fuel and electrocatalysis by ceria

Triangle: Ceria
Circle: Cu/YSZ

Stability of ceria-catalyzed copper cement under different fuel conditions contrasts with rapid irreversible deactivation of nickel cement.


**Anodes for Hydrocarbon Fuels**

![Graph showing current density vs time for various fuels at 800°C.](image)

**Cathode of SOFC**

Requirements for cathode material

- High electrical conductivity
- High catalytic activity for oxygen reduction
- Close CTE match with electrolyte
- Stability in oxidizing environment at high temperature
- Chemical compatibility with other cell components

**Cathode Materials**

**Typical cathode materials**

- Doped LaMnO₃, Doped LaCoO₃, LaFeO₃, Doped SmCoO₃

**Active sites for electrochemical reactions**

**Metallic Electrode: TPR**

\[ 2e^{-}(\text{electrode}) + V_d^+(\text{electrode}) + \frac{1}{2}O_2(g) \rightarrow O_2^2+ \]

**Elementary Steps**

- Ionization of \( O_d \)
- Adsorption
- Diffusion
- Oxidation
- Surface diffusion

**Cathode Materials**

**Active sites for electrochemical reactions**

**Solid/Gas Interface**

\[ 2e^{-}(\text{electrode}) + V_d^+(\text{electrode}) + \frac{1}{2}O_2(g) \rightarrow O_2^2+ \]

**Source:** Georgia Tech

**Typical cathode materials**

- \( \text{LaMnO}_x \rightarrow \text{La}^{3+} \text{Sr}^{2+} \text{Mn}^{4+} \text{O}_3 \)
- \( \text{Doped LaMnO}_3, \text{Doped LaCoO}_3, \text{LaFeO}_3, \text{Doped SmCoO}_3 \)
### Mechanism of Cathode Reaction

\[
\begin{align*}
\frac{1}{2} O_2 + x_{LSM} & \Leftrightarrow O_{ad,x,LSM} \\
O_{ad,x,LSM} & \Leftrightarrow O_{ad,x,TPB} \\
O_{ad,x,TPB} + V_{a,(TPB)} & + 2e \Leftrightarrow O_{a,(TPB)} + x_{YSZ} \\
O_{a,(TPB)} + V_{a,(YSZ)} & \Leftrightarrow O_{a,(YSZ)} + V_{a,(TPB)} \\
\frac{1}{2} O_2 + x_{LSM} & \Leftrightarrow O_{ad,x,LSM} \\
O_{ad,x,LSM} + 2e & \Leftrightarrow O_{a,(LSM)} + x
\end{align*}
\]

### Interconnect for SOFC

**Requirements of Interconnect**

- High electronic conductivity and negligible ionic conductivity
- High density/negligible gas leakage
- Close Coefficient of thermal expansion (CTE) match to other cell elements
- Stability in both oxidizing and reducing environments
- Chemical compatibility with other cell components

### Ceramic Interconnect

So far, only LaCrO₃ is found to satisfy the requirements at high temperature from 850-1000 C.

### Thermal Expansion of Doped LaCrO₃

<table>
<thead>
<tr>
<th>Composition (nominal)</th>
<th>Thermal expansion coefficient (x 10⁻⁶/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaCrO₃</td>
<td>9.5</td>
</tr>
<tr>
<td>La₀.₉Sr₀.₁Cr₂O₄</td>
<td>9.5</td>
</tr>
<tr>
<td>La₀.₈Sr₀.₂Cr₂O₄</td>
<td>10.7</td>
</tr>
<tr>
<td>La₀.₇Sr₀.₃Cr₂O₄</td>
<td>11.1</td>
</tr>
<tr>
<td>La₀.₆Sr₀.₄Cr₂O₄</td>
<td>10.8</td>
</tr>
<tr>
<td>La₀.₅Sr₀.₅Cr₂O₄</td>
<td>13.1</td>
</tr>
<tr>
<td>La₀.₄Sr₀.₆Cr₂O₄</td>
<td>11.1</td>
</tr>
<tr>
<td>La₀.₃Sr₀.₇Cr₂O₄</td>
<td>7.8</td>
</tr>
<tr>
<td>La₀.₂Sr₀.₈Cr₂O₄</td>
<td>8.9</td>
</tr>
<tr>
<td>La₀.₁Sr₀.₉Cr₂O₄</td>
<td>9.6</td>
</tr>
<tr>
<td>YSZ</td>
<td>9.6-11</td>
</tr>
</tbody>
</table>

Close CTE match with YSZ
CTE increase with increasing doping content
Different CTE in reducing and oxidizing environment, which causes warping of the material.

### Ceramic Material - LaCrO₃

**Advantages**
- Relatively high electronic conductivity
- Stability at high temperatures
- Close CTE to that of YSZ electrolyte
- Good compatibility with cathode and anode

**Disadvantages**
- Different CTE in oxidizing and reducing environments
- High material and fabrication cost
- Low thermal conductivity
**Metallic Interconnect for Intermediate Temperature SOFC**

Ferritic steels are intensively studied because of its suitable CTE.
- Compared to ceramic materials, metals have the following advantages:
  - High thermal conductivity
  - High electronic conductivity
  - Ease to fabricate and machine—low cost

Alloys which have a self-protection mechanism can satisfy the requirements. Only alloys containing Al, Si or Cr have this property. Al and Si—oxides have too low electrical conductivity. Only Cr-containing alloys can be used for this purpose.

**Problems of metallic interconnect**
- Oxidation
- Poisoning of cathode

**Coating on metallic interconnect**

LaCrO₃ Coating or Spinel Phase Formation on Alloy Surfaces will significantly reduce Cr evaporation

Two approaches are used to form a thin layer of oxide:
- Alloy design
- Coating

**Synthesizing LaCrO₃ Coatings**

**Step 1: Formation of Dense, Adherent Cr₂O₃ Template**
Hydrogen—Low Oxygen Partial Pressure Anneal

**Step 2: Deposition of La₂O₃ Layer**
- Physical Vapor Deposition

**Step 3: Reactive Formation of LaCrO₃**
- Post-Deposition Anneal in Air

**Ferritic Steel**

Cr₂O₃

LaCrO₃

La₂O₃

Ferritic Steel

Cr₂O₃

**As-sputtered**

LaCrO₃ Layer

Cr₂O₃ Layer

La-O Layer

444 Stainless Substrate

444 Stainless Substrate

2µm

**After interdiffusion (1000°Cx1hr)**

- A LaCrO₃ layer was formed after annealing of the two layers and some Kirkendall voids were present at the initial interface of the two layers due to interdiffusion

**Dip Coating**
SOFC Configuration

- Tubular
- Planar

http://www.msm.cam.ac.uk/doitpoms/tlplib/fuel-cells/high_temp_sofc.php

Solid Oxide Fuel Cell Structure

Typical Component Material
- Anode .............. Ni-YSZ Cermet
- Electrolyte ........ YSZ
- Cathode .............. LaMnO₃
- Interconnect ........ Doped-LaCrO₃ or Cr Alloys

SOFC for Stationary Power

UTC Fuel Cells: (PureCell™ 200) 200kW of electricity and 900,000 BTUs of usable heat. This system provides power at locations including a New York City police station, a major postal facility in Alaska, a credit-card processing system facility in Nebraska, and a science center in Japan.

UTC Fuel Cells: 5kW fuel cell power plants for backup power for telecommunications towers, power for small businesses, and residential use.

SOFC/Gas Turbine Hybrids

- Operational Basics
  - Air stream to SOFC pressurized by compressor and preheated by heat exchanger
  - High temperature SOFC exhaust expanded through turbine for power generation
  - Combustion of unutilized fuel in exhaust can boost power produced by turbine
SOFC/Gas Turbine Hybrids

- Benefits
  - High efficiency ($\eta > 60\%$)
  - Common combined cycle plants $\eta \sim 50\%$ maximum
  - Lowered emissions for criteria pollutants
  - Depending on fuel carbon dioxide can be eliminated or at least sequestered

Solid Oxide Fuel Cells

**Disadvantage of high-temp SOFCs:**

- Material costs are high, particularly for interconnect and construction materials. For high operating temperature SOFC (> 850 °C) the interconnect may be a ceramic such as lanthanum chromite. The interconnect represents a major proportion of the cost of the stack. Stack construction materials and balance of plant also need to be refractory enough.
- The use of chromium containing ceramics and alloys is the volatility of the material, leading to contamination of the stack components.
- High temperature cause the thermal instability of electrode/electrolyte interface.
- High temperature shorten the lifetime of SOFCs

Solid Oxide Fuel Cells

**DOE target of R&D:**

- 40,000 h of service for stationary fuel cell applications
- 5,000 h for transportation systems (fuel cell vehicles)
- Factory cost of $400/kW for a 10 kW coal-based system
- Overall degradation of 4.0% per 1,000 hs

Solid Oxide Fuel Cells

**SOFC market:**

Global Solid Oxide Fuel Cells (SOFCs) Market to Reach $240.6 Million by 2015, According to New Report by Global Industry Analysts, Inc.

Resources

One website that we recommend is:
http://www.fuelcells.org/ced/education.html