SOLID OXIDE FUEL CELLS:

FUNDAMENTALS TO SYSTEMS
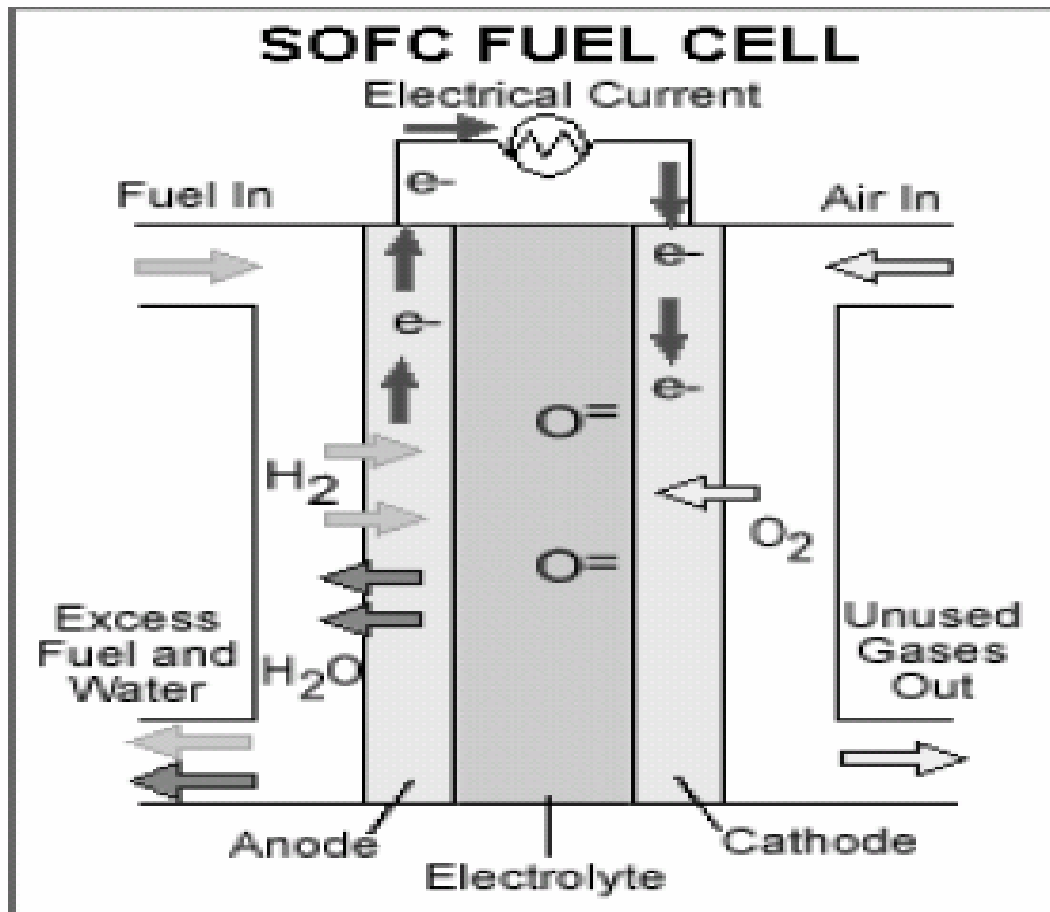
Fig. 1 Basic SOFC.

Solid oxide fuel cells have an electrolyte that is a solid, non-porous metal oxide, usually Y_2O_3-stablilized ZrO_2. The cell operates at 600–1,000 °C where ionic conduction by oxygen ions takes place. Typically, the anode is a Ni-ZrO_2 cermet and the cathode is Sr-doped $LaMnO_3$. There is no liquid electrolyte with its attendant material corrosion or electrolyte management problems. The high temperature of the SOFC, however, places stringent requirements on its materials. The development of suitable low cost materials and the low-cost fabrication of ceramic structures are presently the key technical challenges facing SOFCs.

The cell is constructed with two porous electrodes that sandwich an electrolyte. Air flows along the cathode. When an oxygen molecule contacts the cathode/electrolyte interface, it acquires electrons from the cathode. The oxygen ions diffuse into the electrolyte material and migrate to the other side of the cell where they contact the anode. The oxygen ions encounter the fuel at the anode/electrolyte interface and react catalytically, giving off water, carbon dioxide, heat, and electrons. The electrons transport through the external circuit, providing electrical energy.

SOFCs use a ceramic electrolyte that results in a solid state unit, an important aspect. The conduction mechanism is solid state conduction of O^{2-} ions. The reaction is completed by the reaction of oxygen ions and hydrogen to form water. As indicated by their name, SOFCs use solid oxide ceramics, typically perovskites, as the electrolyte. Nernst realized in the 1890s that certain perovskites, stabilized zirconias, conducted ions in a certain temperature range. Baur and Preis demonstrated in 1943 that such electrolytes could be used as (oxygen) ion conductors in fuel cells. Currently, yttrium stablilized zirconia (3, 8, or 10% yttria, abbreviated to YSZ) is the most commonly used electrolyte for SOFC. YSZ provides high conductivity at temperatures above 700 °C, while exhibiting negligible electronic conductivity at these temperatures.

Although a wide range of materials has been considered as anode materials for SOFC, most developers today use a cermet of nickel and YSZ. The composition of the anode, particle sizes of the powders, and the manufacturing method are key to achieving high electrical conductivity, adequate ionic conductivity, and high activity for electrochemical reactions and reforming and shift reactions. Reduction of the NiO powder in the virgin anode mixture to Ni results in the desired porosity. For the more recent anode-supported cells, it also achieves good mechanical properties and maintains geometric stability during manufacture and operation. For example, by also achieving the desired contact between the Ni phase and the YSZ phase.

Most cathode materials are lanthanum based perovskite (ABO3) materials – doped lanthanum maganites in the high temperature strontium doped $LaMnO_3$ (LSM)
For low temperature operation ($<700^0C$) other materials are being pursued.

NCCR

Low temperature operation (700^{0}C) cost of material will come down – small scale stationary power (2 kW) for mobile generators for civilian and military applications – possible as prime power sources in vehicles.

To develop robust high performance stack technologies based on suitable low cost materials and fabrication methods – less prone to CO poisoning catalyst based on nickel less expensive compared to Pt- 55% efficiency and over 80% if waste heat is used for cogeneration- conventional fuels can be used and hydrogen in future.

-    Less expensive materials
-   simplified stack and system designs
- high volume markets

high electrical efficiency superior environmental performance; flexibility, both stationary and transportation applications.

SOLID OXIDE FUEL CELLS ATTRIBUTES

HIGH ELECTRIC CONVERSION EFFICIENCIES (ONLY CA VALUES POSSIBLE	Demonstrated 47%, Achievable 55% Hybrid 65%, CHP 80%
Superior environmental performance	NO NOx, quiet no vibrations
Cogeneration CHP	High quality exhaust heat for heating and cooling hybrid power generation and industrial use of co-production of hydrogen with electricity compatible with steam turbine, gas turbine, renewable technologies and other heat engines for increased efficiency.
Fuel flexibility	Low or high pure hydrogen liquified natural gas, pipeline natural gas, diesel, coal synthesis gas fuel oil, gasoline biogases
Size and siting flexibility	Modularity permits wide range of system sizes rapid siting for distributed power
Transport and stationary applications	Watts to megawatts

Table 5.1 Institutions involved in SOFC technology development programmes

Country	Institutions involved
USA	Department of Energy (DOE) Electric Power Research Institute (EPRI) Gas Research Institute (GRI) Pacific Northwest National Laboratory Westinghouse Electrical Corporation Allied Signal Argonne National Laboratory University of Missouri – Rolla[12]
Japan	New Energy Development Organisation (NEDO)[13]
EU	European Community
Germany	Simens and Dornier
The Netherlands	ECN
UK	GEC
Ex-USSR	Institute of Electrochemistry in Sverdlovsk[14]
Australia	Ceramic Fuel Cell Company[15]

in Table 5.2. SOFCs advantages are: they can be modular, they can be distributed to eliminate the need for transmission lines, they operate quietly and they are vibration free. SOFCs could provide higher system efficiency, higher power density and simpler designs than fuel cells based on liquid electrolytes. At low costs, they could compete with combined cycle gas turbines for distributed applications. The high cell operating temperature enables high reactant activity and therefore, facilitates fast electrode kinetics (large exchange currents) and reduced activation polarization. This is especially advantageous as precious platinum electrocatalysts are not required and the electrodes cannot be poisoned by carbon monoxide. As a result, carbon monoxide is a potential fuel in SOFCs. Moreover, the operating temperatures are sufficiently elevated, so performance issues are not related to kinetics (activation over-potentials) but to ohmic losses due to charge transport across components and component interfaces. The benefits of SOFCs also include:
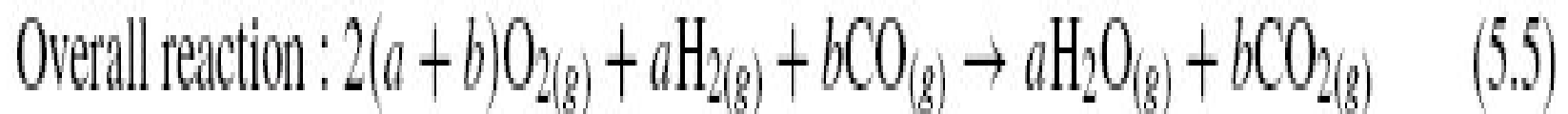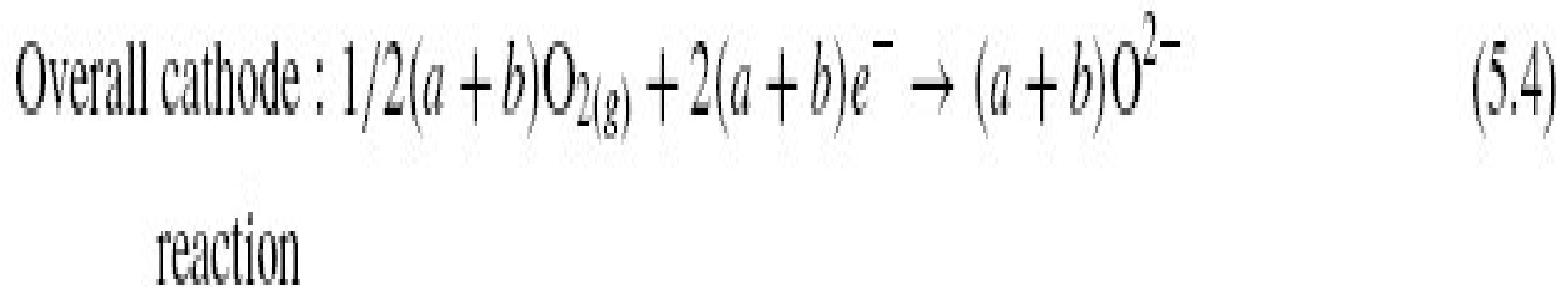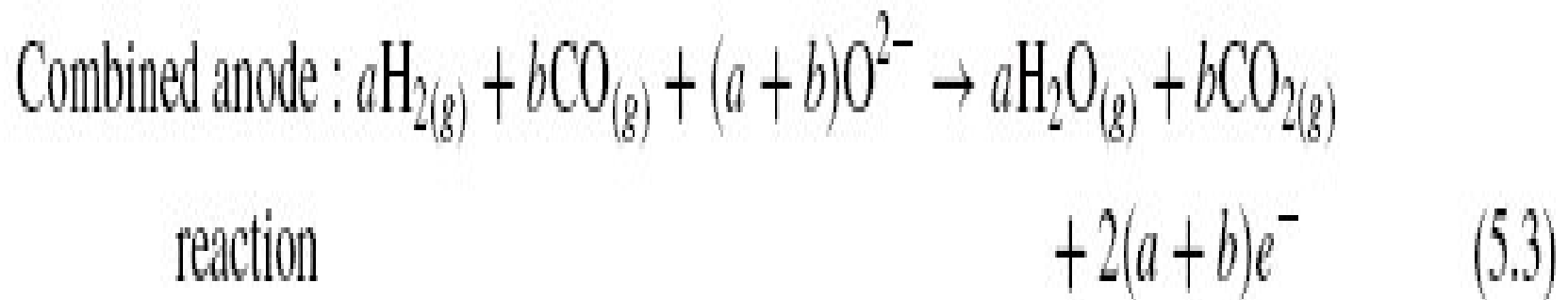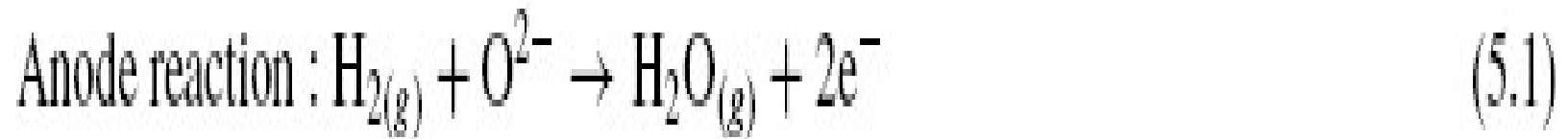
- *Energy security*: reduce oil consumption, cut oil imports, and increase the amount of the country's available electricity supply.

- *Reliability*: achieve operating times in excess of 90% and power available 99.99% of the time.

- *Low operating and maintenance cost*: the efficiency of the SOFC system will drastically reduce the energy bill (mass production) and have lower maintenance costs than their alternatives.

- *Constant power production*: generate power continuously unlike backup generators, diesel engines or Uninterrupted Power Supply (UPS).

- *Choice of fuel*: allow fuel selection: hydrogen may be extracted from natural gas, propane, butane, methanol or diesel fuel.

Table 5.2   Merits and demerits of SOFCs

Merits	Demerits
• SOFCs do not contain noble metals that could be problematic in resource availability and price issue in high volume manufacture. Expensive catalysts such as Pt or Ru are not necessary.	• Electrolyte resistivity and electrode polarization are still too high.
• High quality of exhaust heat (1,073–1,173 K) is useful for co-generation applications in industries.	• Formation of low conducting phases by solid state reactions at cathode/electrolyte interface must be reduced/avoided.
• High efficiency for electricity production (50%) can be achieved in combined cycles.	• Brittleness of ceramic components makes it difficult to use cell sizes $> 0.2\,m^2$. This limitation is a problem for scaling up SOFC power plants to megawatt size.
• Internal reforming of natural gas may considerably reduce costs.	• High capital cost-to-performance ratio prevents its introduction in the energy market.
• SOFCs do not have problems with electrolyte management. For example, in the case of liquid electrolytes, they are corrosive and difficult to handle. Electrolyte loss maintenance as well as electrode corrosions are eliminated.	• Electrolyte preparation and homogeneity of material have to be improved.
• SOFCs are flexible in the choice of fuel such as carbon-based fuels, like natural gas	• Compact cell designs have to be evolved.
• SOFCs have a modular and solid state construction and do not present any moving parts, thereby they are quiet enough to be installed indoors.	
• SOFC technology is most suited to applications in the distributed generation (that is, stationary power) market because its high conversion efficiency provides the greatest benefit when fuel costs are higher, due to long fuel delivery systems to customer premises.	
• Life of cell is increased due to higher tolerance to impurities such as sulphur in the fuel. SOFCs have a potential long life expectancy of more than 40,000–80,000 h.	
• SOFCs have extremely low emissions by eliminating the danger of carbon monoxide in exhaust gases, as any CO produced is converted to CO_2 at the high operating temperature. CO_2 emission is also considerably reduced.	

Table 5.2 *(continued)*

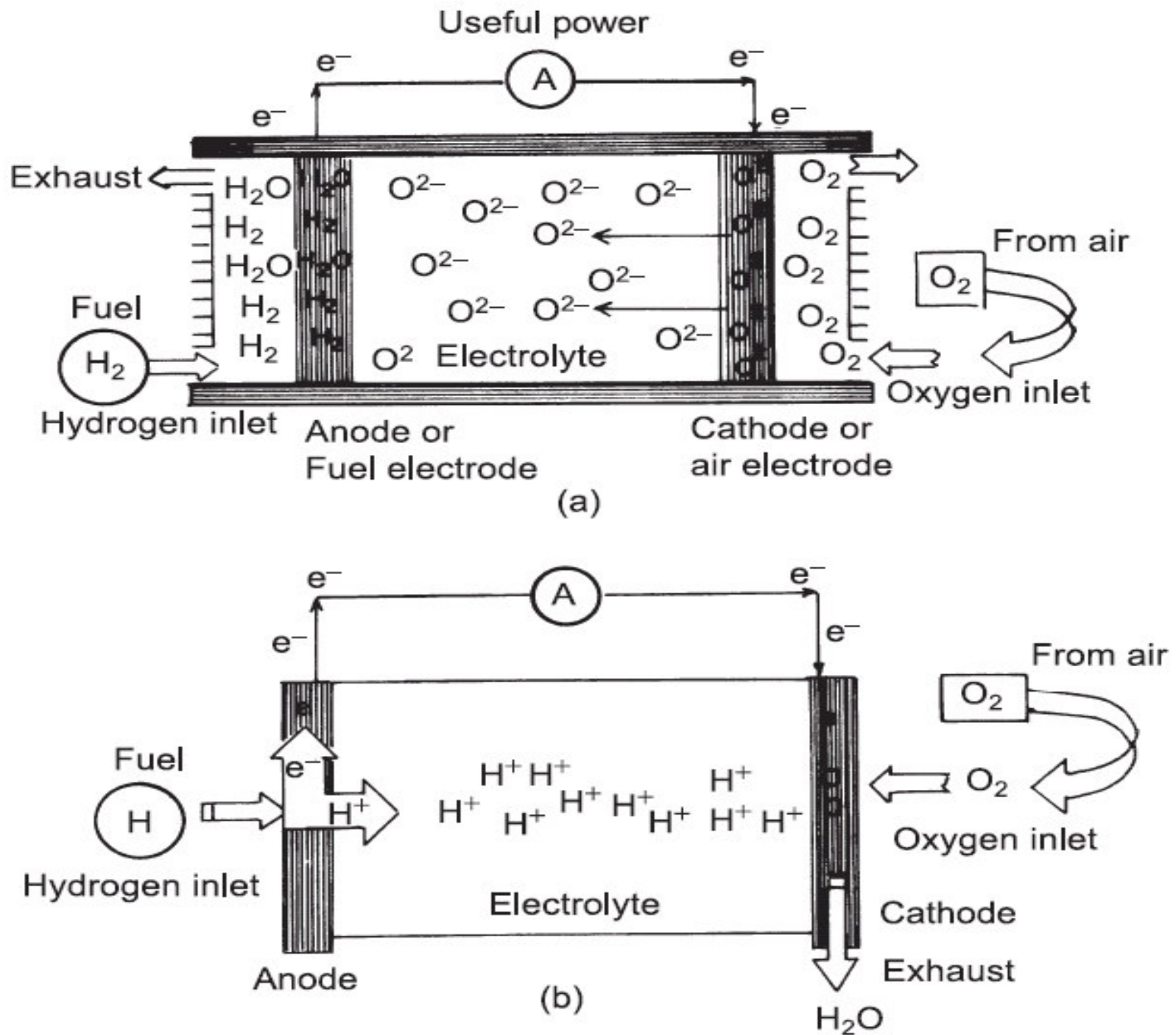| Merits	Demerits
• Appropriate electrocatalytic anodes may lead to co-generation of electricity and chemical compounds. • SOFCs can be used as high-temperature water electrolyzers without major modifications. • SOFCs offer flexibility in planning and setting up of power generation capacity as a consequence of their modular nature.	

Anode reaction : $H_{2(g)} + O^{2-} \rightarrow H_2O_{(g)} + 2e^-$ (5.1)

Anode reaction : $CO_{(g)} + O^{2-} \rightarrow CO_{2(g)} + 2e^-$ (5.2)

Combined anode : $aH_{2(g)} + bCO_{(g)} + (a+b)O^{2-} \rightarrow aH_2O_{(g)} + bCO_{2(g)}$

reaction $+ 2(a+b)e^-$ (5.3)

Overall cathode : $1/2(a+b)O_{2(g)} + 2(a+b)e^- \rightarrow (a+b)O^{2-}$ (5.4)

reaction

Overall reaction : $2(a+b)O_{2(g)} + aH_{2(g)} + bCO_{(g)} \rightarrow aH_2O_{(g)} + bCO_{2(g)}$ (5.5)

Figure 5.1 Concept diagram of SOFC based on (a) oxygen-ion conductors, and (b) proton conductors

The desirable characteristics of each of the components of the SOFC are listed below.

- Good stability (chemical, phase, morphological and dimensional),
- Appropriate conductivity,
- Chemical compatibility with other components of the cell,
- Similar thermal expansion coefficient to avoid cracking during the cell operation,
- Dense electrolyte to prevent gas mixing,
- Porous anode and cathode to allow gas transport to the reaction sites,
- High strength and toughness properties,
- Fabricability,
- Amenable to particular fabrication conditions,
- Compatibility at higher temperatures at which the ceramic structures are fabricated,
- Low cost.

Table 5.3   Constraints imposed by the electrolytes in SOFC due to high operating temperatures

Types of constraints	Properties of electrolytes
Electrochemical constraint	High ionic conductivity (≥ 0.1 Scm^{-1} at $1,000\,^\circ$C), low electronic transference number ($< 10^{-3}$) and large electrolytic domain.
Chemical constraint	Electrolyte must be stable with respect to electrode materials, oxygen and fuel gas
Thermal constraint	Phase stability and a good match of thermal expansion coefficient (TEC) with other cell components
Mechanical constraint	Fracture toughness (> 400 MPa at room temperature) and gas tightness.

- Cerium oxide doped with samarium (SDC), $(Ce_{0.85}Sm_{0.15})O_{1.925}$
- Cerium oxide doped with gadolinium (GDC), $(Ce_{0.90}Gd_{0.10})O_{1.95}$
- Cerium oxide doped with yttrium (YDC), $(Ce_{0.85}Y_{0.15})O_{1.925}$
- Cerium doped with calcium (CDC), $(Ce_{0.88}Ca_{0.12})O_{1.88}$
- Lanthanum gallate ceramic that include lanthanum strontium gallium magnesium (LSGM),

$$(La_{0.80}Sr_{0.20})(Ga_{0.90}Mg_{0.10})O_{2.85} \quad or \quad (La_{0.80}Sr_{0.20})(Ga_{0.80}Mg_{0.20})O_{2.80}$$
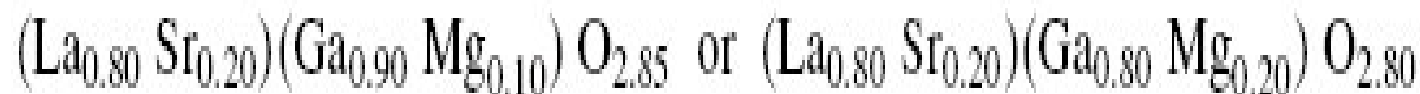
- Bismuth yttrium oxide (BYO), $(Bi_{0.75}Y_{0.25})_2O_3$
- Barium Cerate (BCN), $Ba(Ce_{0.90}Nd_{0.10})O_3$
- Strontium Cerate (SYC), $Sr(Ce_{0.95}Yb_{0.05})O_3$
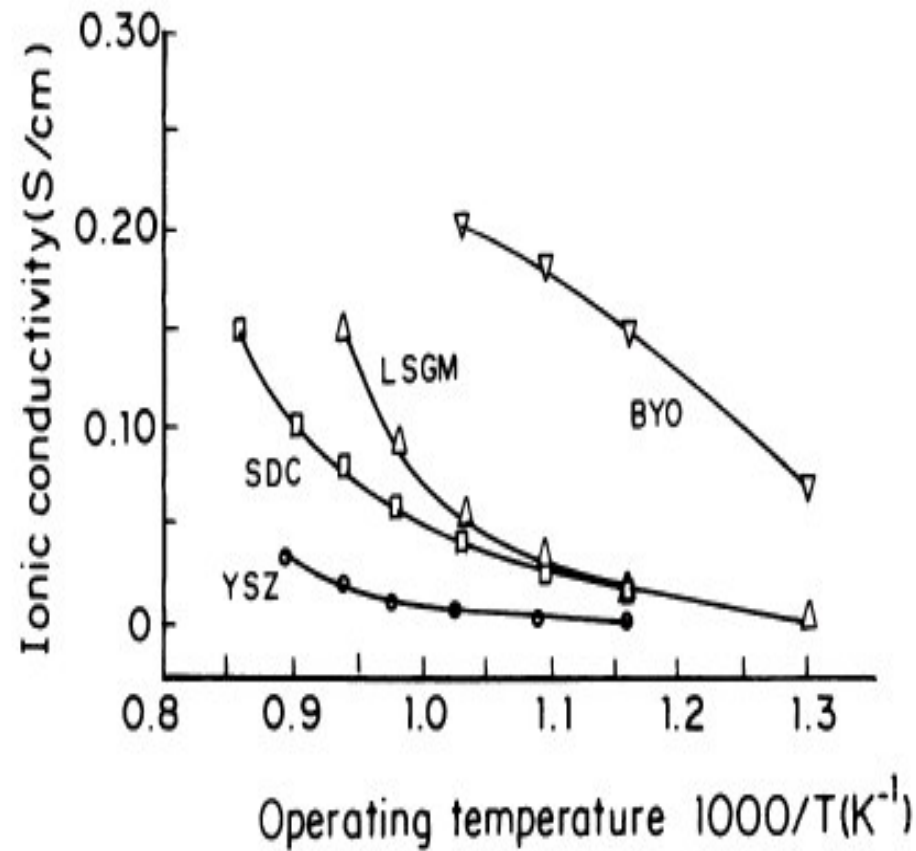
Figure 5.2   Typical ionic conductivity of some electrolyte materials as a function of operating temperature [Reproduced from *Fuel cell materials* by Nextech materials, August 2001]

- Isothermal variation of conductivity shows a maximum at 9 mol% of dopant for ZrO_2–M_2O_3 systems.[24]
- The activation energy is close to 0.8 eV for the composition of maximum conductivity.

- For a particular composition, the conductivity increases as the radius of the dopant cation approaches that of Zr^{4+}. Thus, the best conductivity in Zr-based system is obtained with ZrO_2–Sc_2O_3 system ($R_{Zr}^{4+} = 0.80$Å and $R_{Sc^{3+}} = 0.81$Å).
- In the working temperature range of SOFCs, a decrease in ionic conductivity with time is observed.[25]
- Electrolytic domain extends over several orders of magnitude of oxygen partial pressures with a significant influence of temperature. In highly reducing media, n-type electronic conductivity predominates.

  In spite of these limitations, yettria stabilized zirconia (YSZ) with the composition $(ZrO_2)_{0.92}$ $(Y_2O_3)_{0.08}$ is employed still as a solid electrolyte.

Table 5.4 Radii of cations A and B for ABO_3-type perovskites

Dodecahedral A-site				Octahedral B-site			
Na^+	1.06	1.32	(IX)	Li^+		0.68	0.74
K^+	1.45	1.60		Cu^{+2}		0.72	0.73
Rb^+	1.61	1.73		Mg^{+2}		0.66	0.72
Ag^+	1.40	1.30	(VIII)	Ti^{+3}		0.76	0.67
Ca^{+2}	1.08	1.35		V^{+3}		0.74	0.64
Sr^{+2}	1.23	1.44		Cr^{+3}		0.70	0.62
Ba^{+2}	1.46	1.60		Mn^{+3}		0.66	0.65
Pb^{+2}	1.29	1.49		Fe^{+3}		0.64	0.64
La^{+3}	1.22	1.32		Co^{+3}	(LS)	-	0.52
Pr^{+3}	1.10	1.14	(VIII)	Co^{+3}	(HS)	0.63	0.61
Nd^{+3}	1.09	1.12	(VIII)	Ni^{+3}	(LS)	-	0.56
Bi^{+3}	1.07	1.11	(VIII)	Ni^{+3}	(HS)	0.62	0.60
Ce^{+4}	1.02	0.97	(VIII)	Rh^{+3}		0.68	0.66
Th^{+4}	1.09	1.06	(VIII)	Ti^{+4}		0.68	0.60
				Mn^{+4}		0.56	0.54
				Ru^{+4}		0.67	0.62
				Pt^{+4}		0.65	0.63
				Nb^{+5}		0.69	0.64
				Ta^{+5}		0.69	0.64
				Mo^{+6}		0.62	0.60
				W^{+6}		0.62	0.58

* The coordination number is in parentheses if the radii given are not for 12-coordination. HS and LS represent the spin states.[46]

Table 5.5 Electrical conductivities at 1,000 K of oxygen ion conductors with the perovskite-related structure [Reproduced from Ref. 59]

	$\log(\sigma/S\ cm^{-1})$	Ref.		$\log(\sigma/S\ cm^{-1})$	Ref.
a) Series of the smaller specific free volume			b) Series of the larger specific free volume		
$Nd_{0.9}Sr_{0.1}AlO_{2.95}$	−3.35	[62]	$BaZrO_3$	−6.08	[63]
$Nd_{0.9}Ba_{0.1}AlO_{2.95}$	−4.09	[62]	$BaZr_{0.9}In_{0.1}O_{2.95}$	−4.08	[63]
$Nd_{0.9}Ca_{0.1}AlO_{2.95}$	−2.93	[62]	$BaZr_{0.8}In_{0.2}O_{2.9}$	−3.49	[63]
$Nd_{0.9}Sr_{0.1}GaO_{2.95}$	−2.73	[65]	$BaZr_{0.7}In_{0.3}O_{2.85}$	−3.13	[63]
$Nd_{0.9}Ca_{0.1}GaO_{2.95}$	−2.38	[65]	$BaZr_{0.5}In_{0.5}O_{2.75}$	−3.10	[63]
$Nd_{0.9}Ba_{0.1}GaO_{2.95}$	−3.63	[65]	$BaZr_{0.4}In_{0.6}O_{2.7}$	−2.15	[63]
$NdGa_{0.9}Mg_{0.1}O_{2.95}$	−1.70	[72]	$BaZr_{0.3}In_{0.7}O_{0.65} \rightarrow O_{2.65}$	−2.45	[63]
$Nd_{0.9}Ca_{0.1}Al_{0.5}Ga_{0.5}O_{2.95}$	−2.14	[61,62]	$BaZr_{0.2}In_{0.8}O_{2.6}$	−2.68	[63]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Ga_{0.1}O_{2.95}$	−2.83	[61,62]	$BaZr_{0.1}In_{0.9}O_{2.55}$	−2.74	[63]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Ni_{0.1}O_{2.9}$	−3.13	[61,62]	$BaInAl_{0.5} \rightarrow O_{2.5}$	−2.45	[63]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Be_{0.1}O_{2.9}$	−3.23	[61,62]	$BaGd_{0.5}In_{0.4}Ga_{0.1} \rightarrow O_{2.5}$	−2.39	[63]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Zr_{0.1}O_3$	−3.44	[61,62]	$BaGd_{0.5}In_{0.3}Ga_{0.2} \rightarrow O_{2.5}$	−2.43	[71]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Mg_{0.1}O_{2.9}$	−3.52	[61,62]	$BaIn_{0.8}Ca_{0.1}Zr_{0.1}Al_{0.5} \rightarrow O_{2.5}$	−2.23	[71]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Si_{0.1}O_3$	−4.25	[61,62]	$BaIn_{0.9}Ca_{0.05}Zr_{0.05}Al_{0.5} \rightarrow O_{2.5}$	−2.24	[70]
$Nd_{0.9}Ca_{0.1}Al_{0.9}Zn_{0.1}O_{2.9}$	−3.72	[61,62]	$BaIn_{0.9}Ca_{0.1}O_{2.45}$	−2.38	[70]
$Nd_{0.9}Ca_{0.1}Ga_{0.9}Mg_{0.1}O_{2.9}$	−2.08	[65]	$SrTiO_3$	−2.32	[70]
$La_{0.9}Sr_{0.1}AlO_{2.95}$	−2.61	[59]	$SrTi_{0.9}Al_{0.1}O_{2.95}$	−3.15	[64]
$La_{0.9}Sr_{0.1}GaO_{2.95}$	−1.80	[48,59,68]	$SrTi_{0.5}Al_{0.5} \rightarrow O_{2.5}$	−2.47	[64]
$La_{0.9}Sr_{0.1}ScO_{2.95}$	−1.90	[59]	$SrSc_{0.55}Al_{0.45} \rightarrow O_{2.5}$	−4.72	[66]
$La_{0.9}Sr_{0.1}InO_{2.95}$	−2.03	[59]	$SrSc_{0.6}Al_{0.4}Al_{0.5} \rightarrow O_{2.5}$	−3.93	[66]
$La_{0.9}Sr_{0.1}LuO_{2.95}$	−2.56	[59]		−3.32	[66]

The optimum conditions to obtain high ionic conductivity of perovskite-type oxides are summarized as below.

1. The $A^{III}B^{III}O_3$-type perovskites are preferred for high oxygen ionic conductivities. $A^{II}B^{IV}O_3$-type perovskites are not good for use as oxygen ion conductor.

2. The optimum tolerance factor is near unity from the viewpoint of lattice stability and equivalency in the oxygen site. A larger specific free volume is desirable in view of the mobility of the oxygen ion. The specific free volume increases linearly with decrease in the tolerance factor for each series with fixed A-site cation. The optimum tolerance factor for $A^{III}B^{III}O_3$-type perovskites to obtain the maximum electrical conductivity exists around 0.96 due to the balance between the specific free volume and the tolerance factor.

3. The appropriate dopants are Sr^{2+} for La^{3+}, Ca^{2+} for Nd^{3+} and Mg^{2+} for Ga^{3+}. However, no such choice is available for Al^{3+} at the B site. From these considerations, $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ systems appear to be the ideal available choices.

4. The optimum oxygen deficiency δ to obtain the maximum electrical conductivity is around 0.2. When δ is considerably larger than 0.2, the electrical conductivity decreases, probably due to short-range interaction among vacancies.

At the cathodic side of SOFC, as a consequence of high operating temperatures, the problems of ohmic and polarization losses persist.

The desirabilities of cathode materials are:

- High electronic conductivity ($> 100 \, S \, cm^{-1}$),
- Non-negligible anionic (oxide) conductivity ($\sim 10^{-1} S \, cm^{-1}$),
- High catalytic activity for oxygen molecule dissociation or reduction,
- Chemical stability with regard to electrolytes and interconnects,
- Match of thermal expansion coefficient (TEC) with other cell components,
- Good processability (ability to form films with desired microstructure, and good adherence to adjacent components).

A range of alternative perovskite-structured ceramic electrode materials are available. These include:

- Lanthanum strontium ferrite (LSF), $(LaSr)(Fe)O_3$
- Lanthanum strontium cobaltite (LSC), $(LaSr)CoO_3$
- Lanthanum strontium cobaltite ferrite (LSCF), $(LaSr)(CoFe)O_3$
- Lanthanum strontium manganite ferrite (LSMF), $(LaSr)(MnFe)O_3$
- Samarium strontium cobaltite (SSC), $(SmSr)CoO_3$
- Lanthanum calcium cobaltite ferrite (LCCF), $(LaCa)(CoFe)O_3$
- Praseodymium strontium manganite (PSM), $(PrSr)MnO_3$ and
- Praseodymium strontium manganite ferrite (PSMF), $(PrSr)(MnFe)O_3$

Interconnects are necessary to combine single cells to form stacks by connecting the cathode material of one cell to the anode material of the adjacent one. By this function, they are in contact with an oxidizing and a reducing medium at the two electrodes. The essential required features of interconnects are:

- High electronic conductivity (> 1 S cm^{-1}) with a small variation within the oxygen partial pressure range from air to fuel gas,

- Chemical and phase stability in both air and fuel atmospheres during fabrication and operation,

- TEC close to that of zirconia and other cell components,

- Resistance to thermal shock,

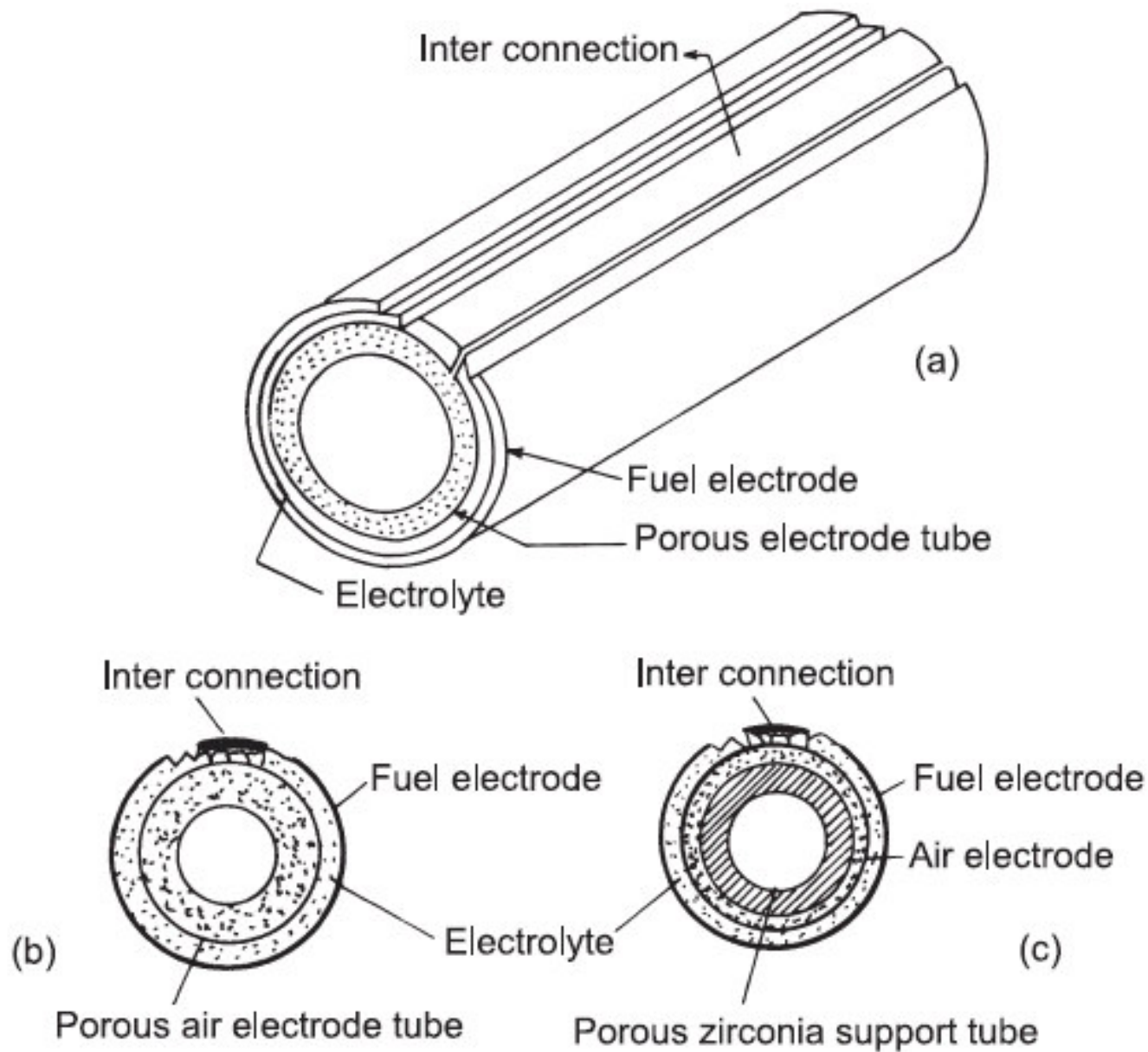- Physical and electrochemical gas tightness.

Figure 5.5 (a) Siemens–Westinghouse tubular design, and the difference between (b) Self-supported structure and (c) Substrate-supported structure

Table 5.6 Cell components, materials, and fabrication processes for the tubular configuration of SOFC (Westinghouse)* [Reproduced from Ref. 151]

| Component	Materials	Thickness	Fabrication process
Support tube	$ZrO_2(CaO)$	1.2 mm	Extrusion sintering
Air electrode	$La(Sr)MnO_3$	1.4 mm	Slurry coat sintering
Electrolyte	$ZrO_2(Y_2O_3)$	40 μm	Electrochemical vapour deposition
Interconnection	$LaCr(Mg)O_3$	40 μm	Electrochemical vapour deposition
Fuel electrode	$Ni-ZrO_2(Y_2O_3)$	100 μm	Slurry coat electrochemical vapour deposition
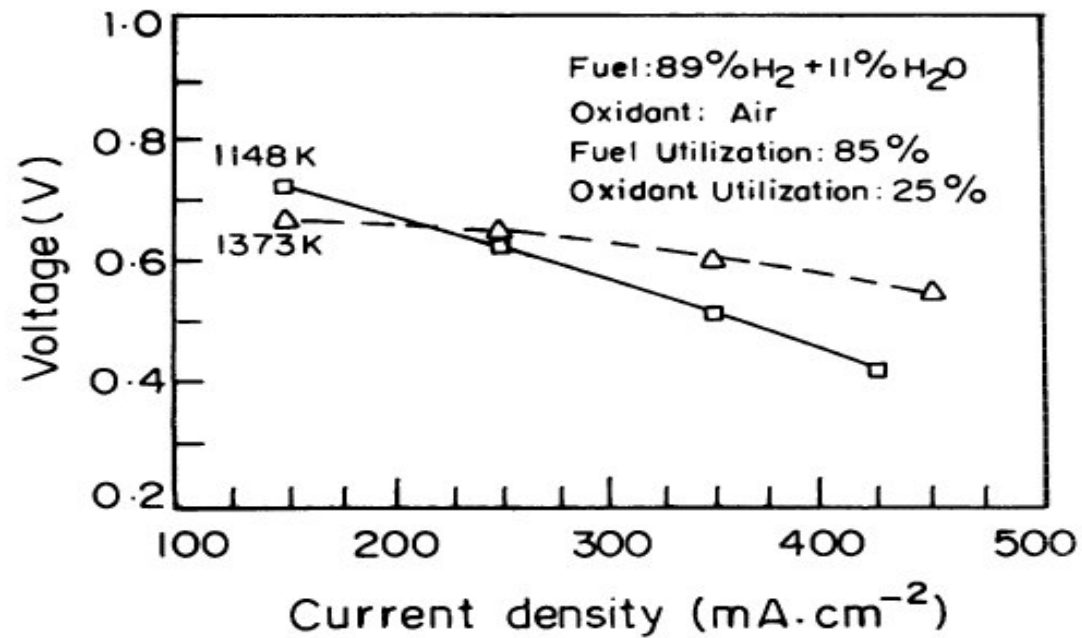
Figure 5.7 Current–voltage curve of a tubular solid oxide fuel cell at different temperatures [Reproduced from Ref. 151]
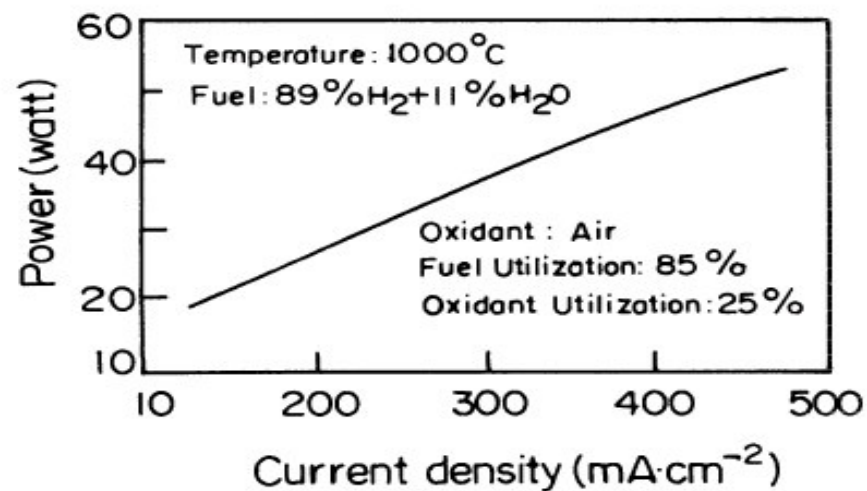

Figure 5.8 Power output dependence on current for a 50-cm active cell length [Reproduced from Ref. 151]
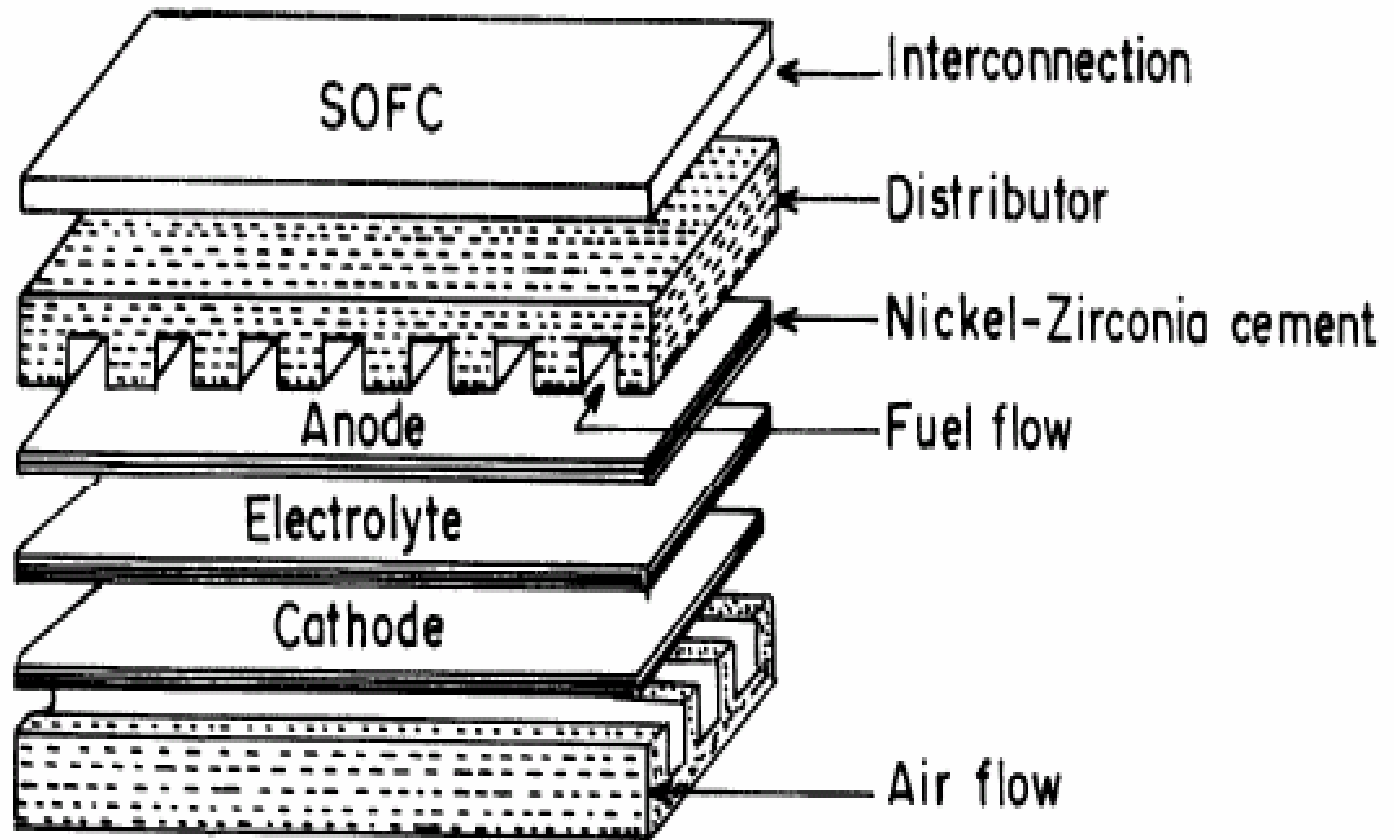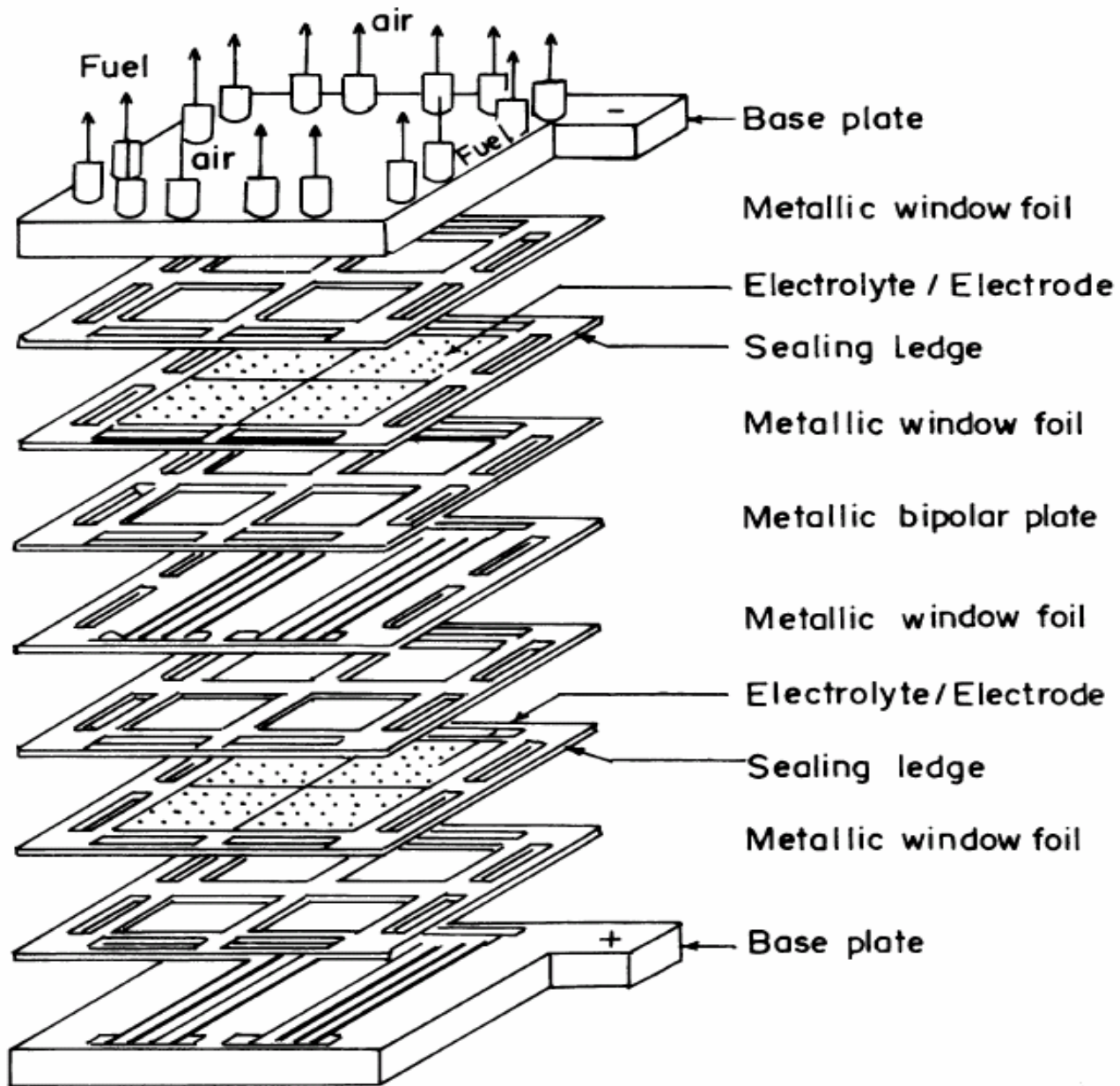
Figure 5.15   Planar design of SOFC

Figure 5.16 Multiple-cell array concept for solid oxide fuel cell reactor (Siemens)

Table 5.7   Potential cell performance of $400\,mS\,cm^{-2}$ at $1{,}273\,K$

Configuration	Cell voltage (V)	Power density $(W/cm)^2$	Cell efficiency %
Tubular	0.65	0.261	50
Monolithic	0.84	0.335	65
Planar	0.8	0.318	61

A comparison of the designs of SOFC is given below

Comparison of tubular vs planer cell designs of SOFC

Characteristics	Tubular design	Planar design
Specific power (w/cm)^2	Low (~ 0.25)	High (upto 2)
Volumetric power (W/cm)^3	Low	High
Manufacturing cost (Rs./kw)	High	Low
High temperature seals	Not needed	Required

Some of the essential characteristics of SOFC stack design are given below

Features	Design			
	Seal-less Tubular	Segmented cell in series	Monolithic	Flat-plate
Need for a structural support	Yes	Yes	No	No
Internal electrical resistance	High	High	Low	Medium
Gas sealing	No	Yes	No	Yes
Power density	Low	Low	High	Medium

Table 5.8 Typical SOFC air emissions from one year of operation [Data from The International Fuel Cells, a United Technology Company, Fuel Cells Review. 2000]

Air emissions[a]	SO_x	NO_x	CO	Particles	Organic compounds	CO_2
Fossil fuelled plant	12.740	18.850	12.797	228	213	1,840.020
SOFC system	0	0	32	0	0	846.300

[a] kgs of emissions per 1,650 MWh from one year of full operation

Table 5.9 Evolution of single SOFC performance measured in Watts/cm^2 at 0.7 V using H$_2$ as fuel [Source: Global Thermoelectric Inc. Annual report 2001]

Type & Year	Temperatures, K				
	873	923	973	1,023	1,073
G1-1998	–	–	–	0.150	0.250
G2-1999	0.156	0.318	0.487	0.528	0.594
G3-2000	0.197	0.382	0.635	0.900	1.093
G3-2000	0.200	0.416	0.723	1.093	1.216

Table 5.10 Materials cost per kilowatt [Source: Material Science & Research Inc. 2000, Fuel Cell Seminar, Portland, OR, USA, October 30 – November 02 2000]

Component	Material, (Cost/kg ($))	Thickness(μm)/ Weight (g)	Total cost[a]($) per kW & component
Electrolyte	YSZ (10)	10 / 12	0.12
Anode	Ni + YSZ (15)	1,500 / 1,365	20.50
Cathode	LSM	100 / 60	1.50
Interconnect	Metallic alloy	125 / 200	3.00
Total		1,735	25.12

[a] costs estimated are based on 0.5 W/cm^2 at an operating temperature of 1,073 K

Table 5.11 Desired performance targets and stretch goals for SOFC systems [California Energy Commission, November 2001]

Parameter	Target	Stretch goal	Remark
Capital cost, installed ($/kW)	800	400	year 2005–2010 at 50,000 units per year
Power degradation	< 1% per 1000 h	< 0.5% per 1,000 h	For year 2005–2010
Power density (mW/cm^2)	300	500	> 4 cell stack and > 25 cm^2 electrode

5.11 Perception

SOFCs provide highly efficient, pollution-free power generation. The state-of-the-art SOFC operates at 1,273 K, yielding high efficiency and low emissions with the opportunity for high-temperature heat recovery. As of today, tubular design fulfils the lifetime requirements. However, the high operating temperature is a serious problem in trying to reduce the capital cost of SOFCs and make them competitive with other power generators. If the operating temperature is reduced to 1,073 K, planar configurations can be used with metallic interconnects, with more efficient gas-tight seals and less costly ceramic processing techniques.