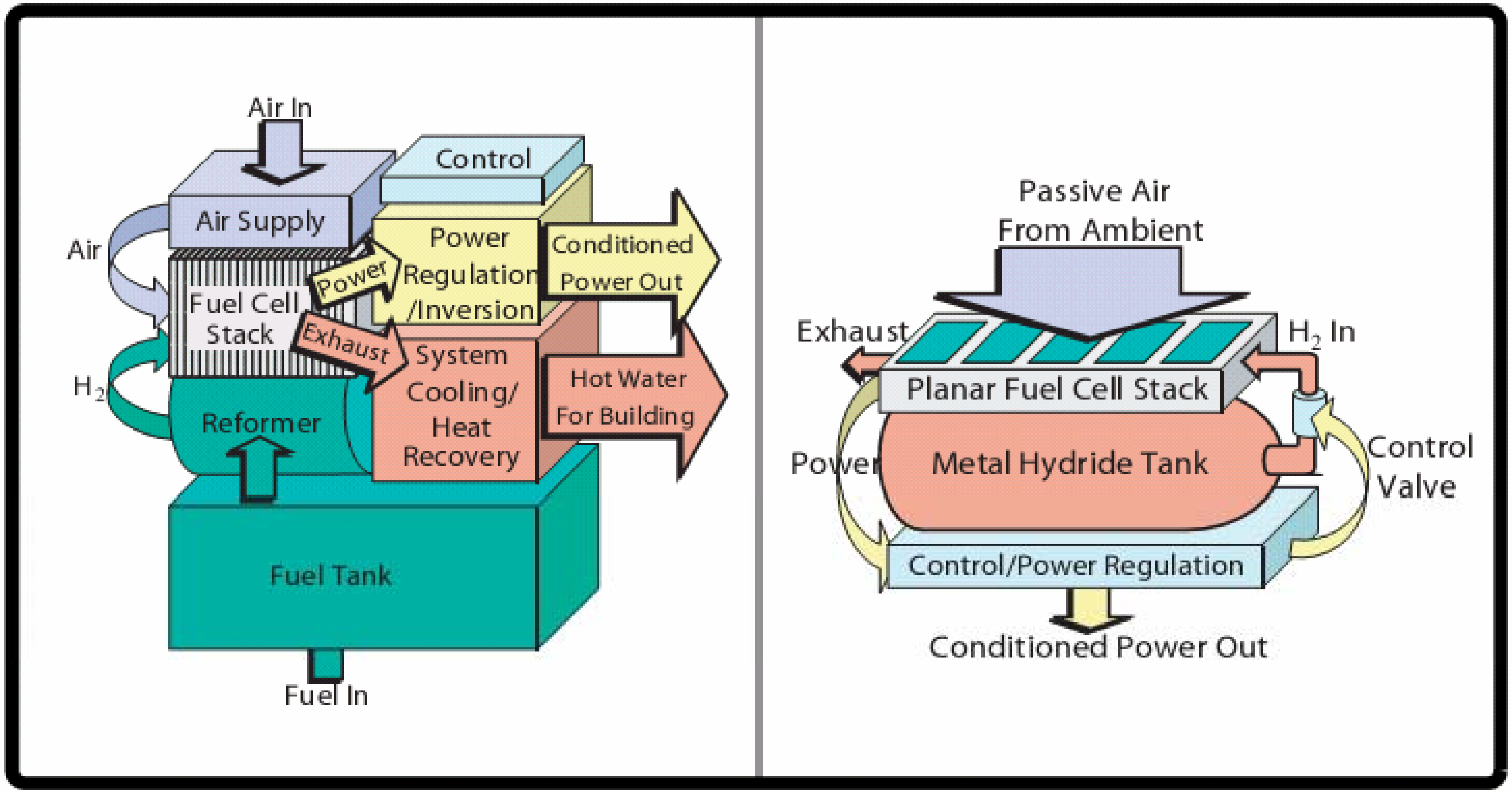
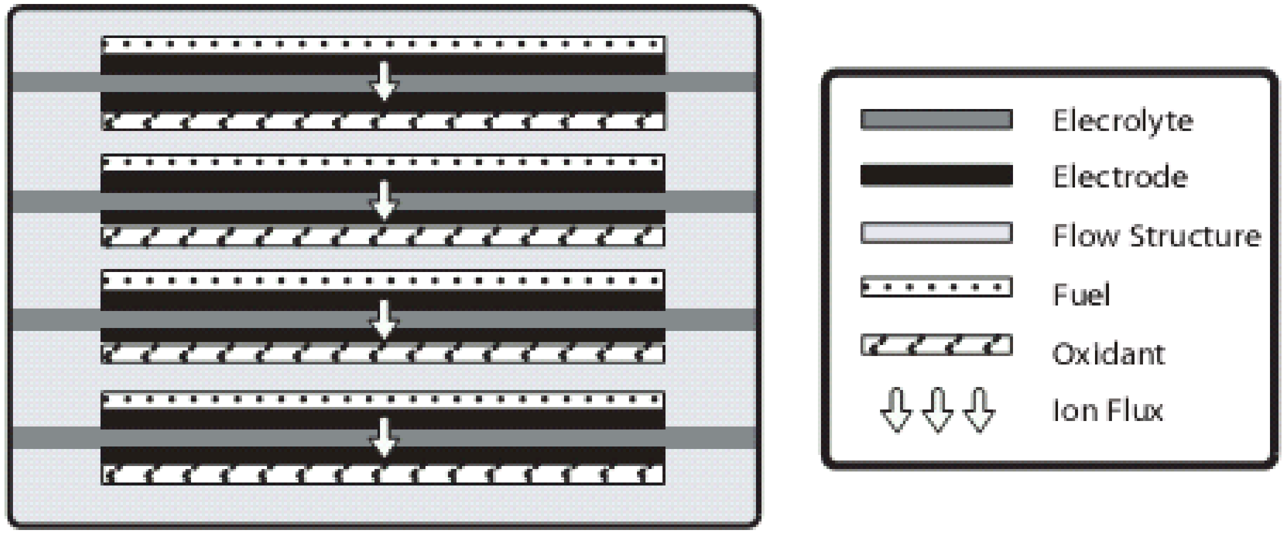
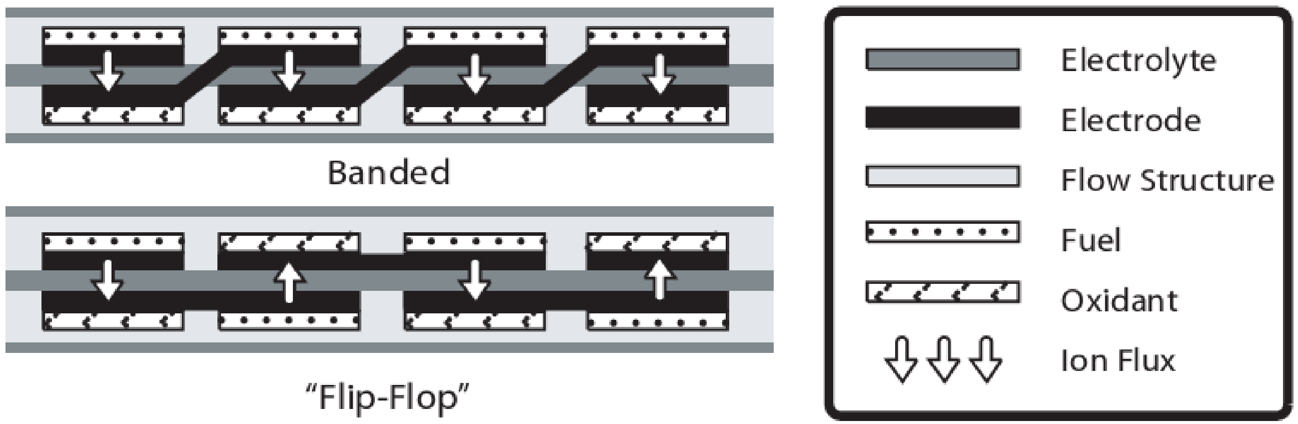
Fuel Cell Systems Overview

Fuel Cell Systems

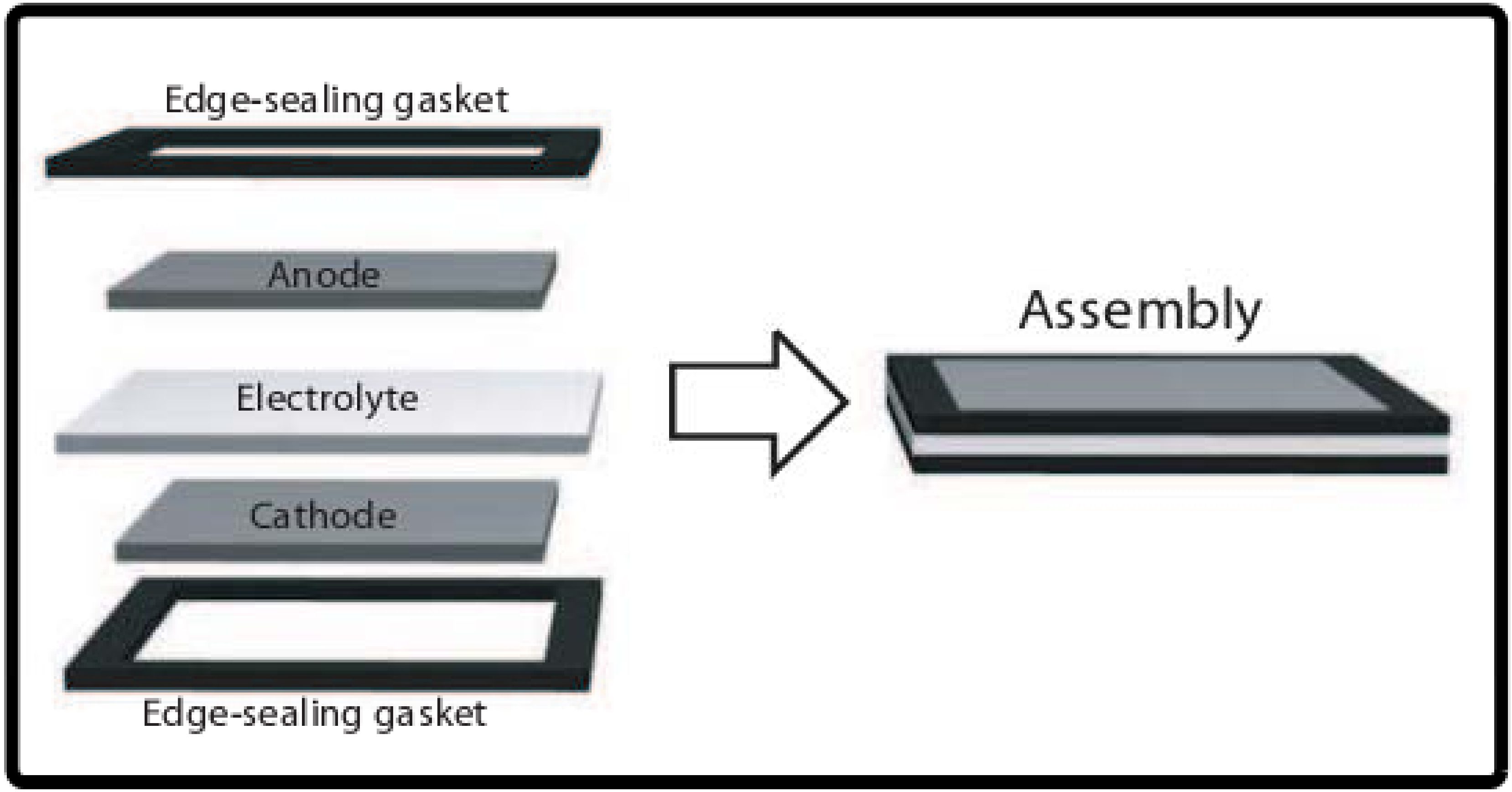


Fuel Cell Stacks

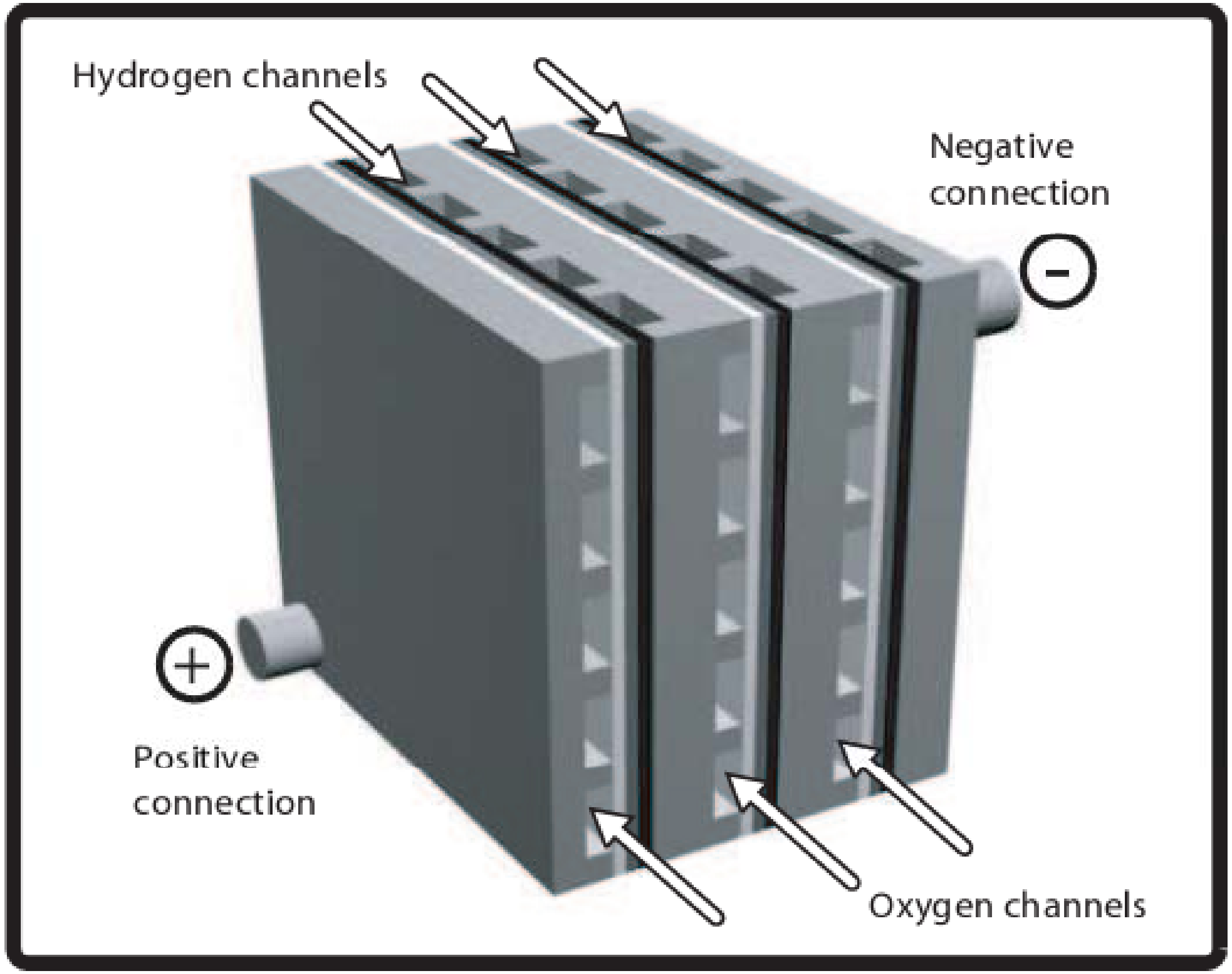




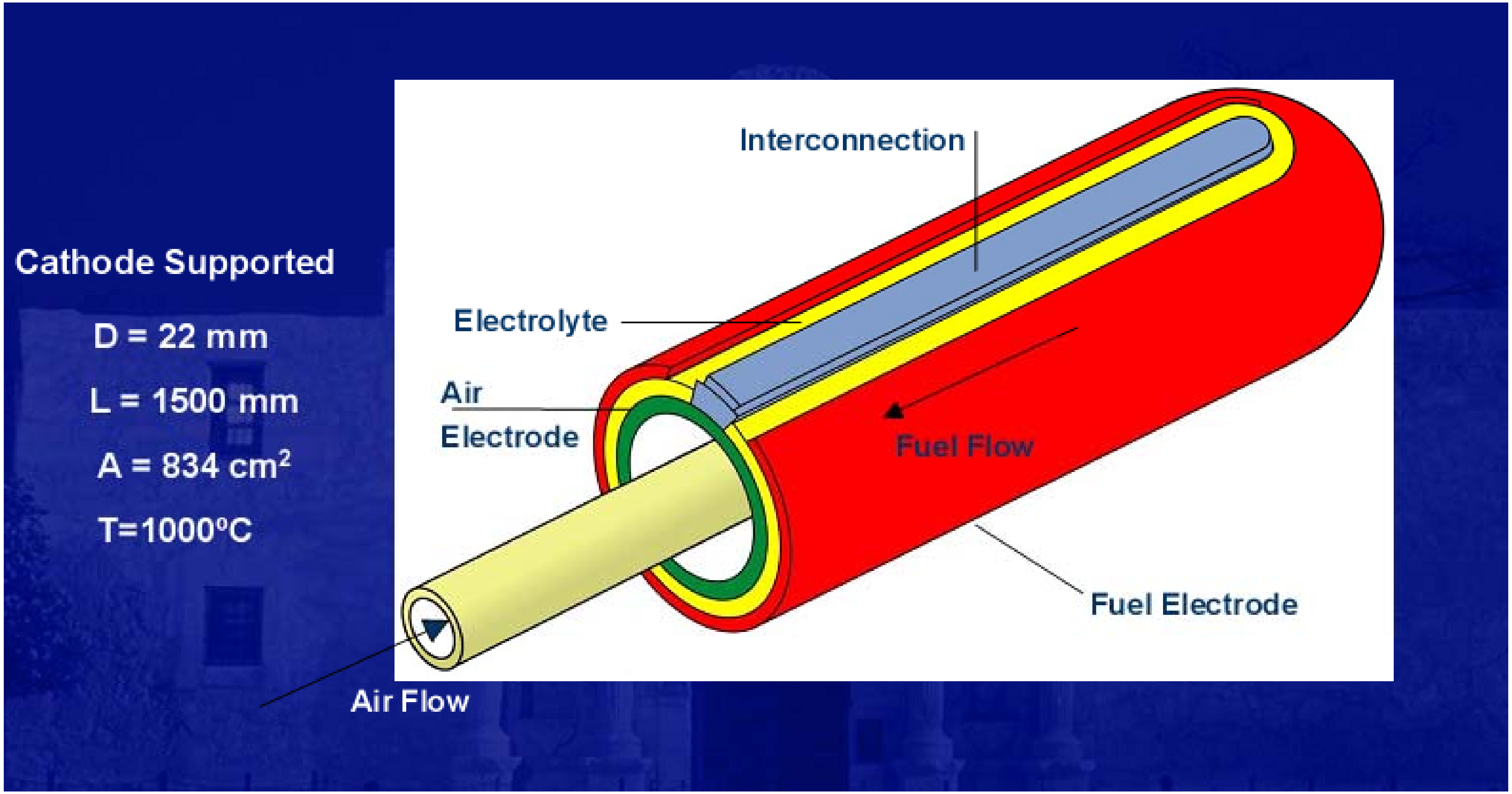
Fuel Cell Stacks



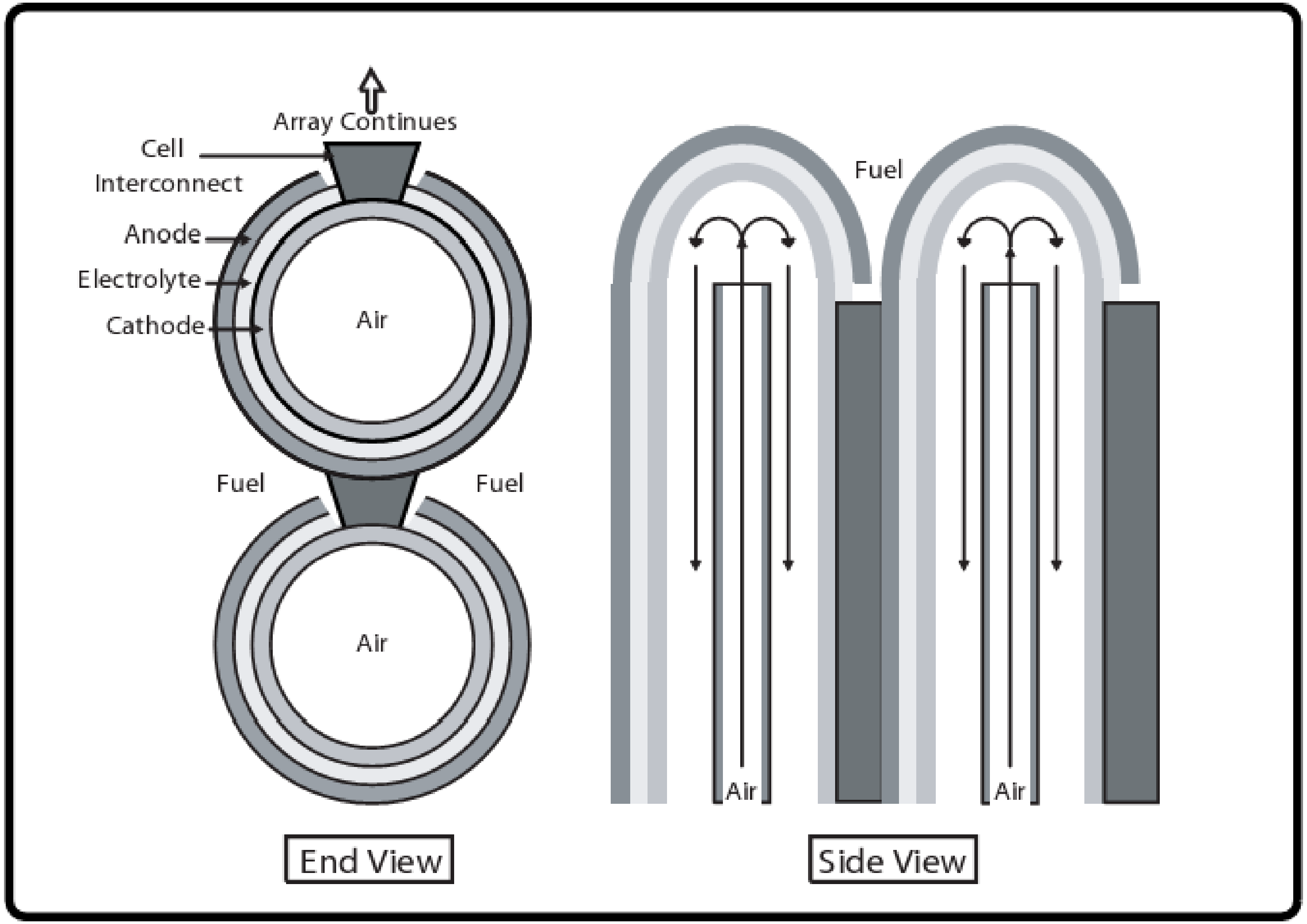
Fuel Cell Stacks



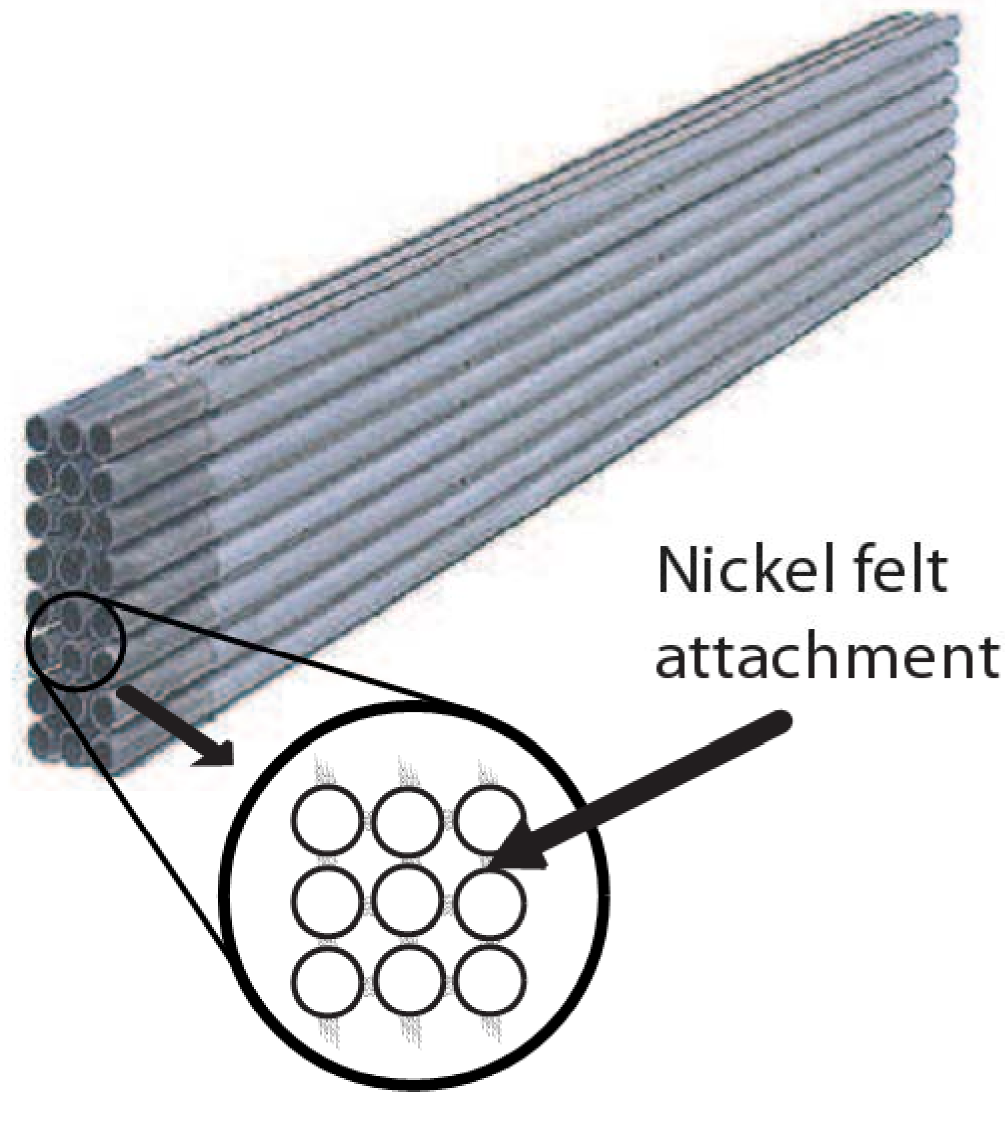
Tubular SOFC



Tubular SOFC

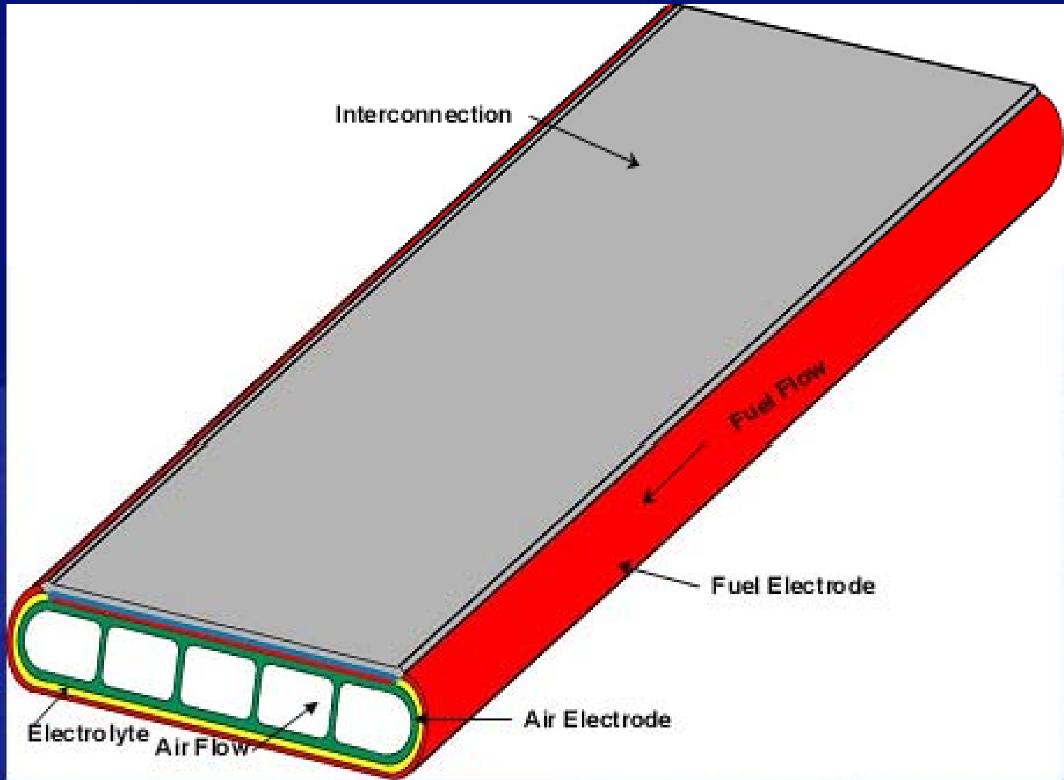


Tubular SOFC



Flat Tubular SOFC

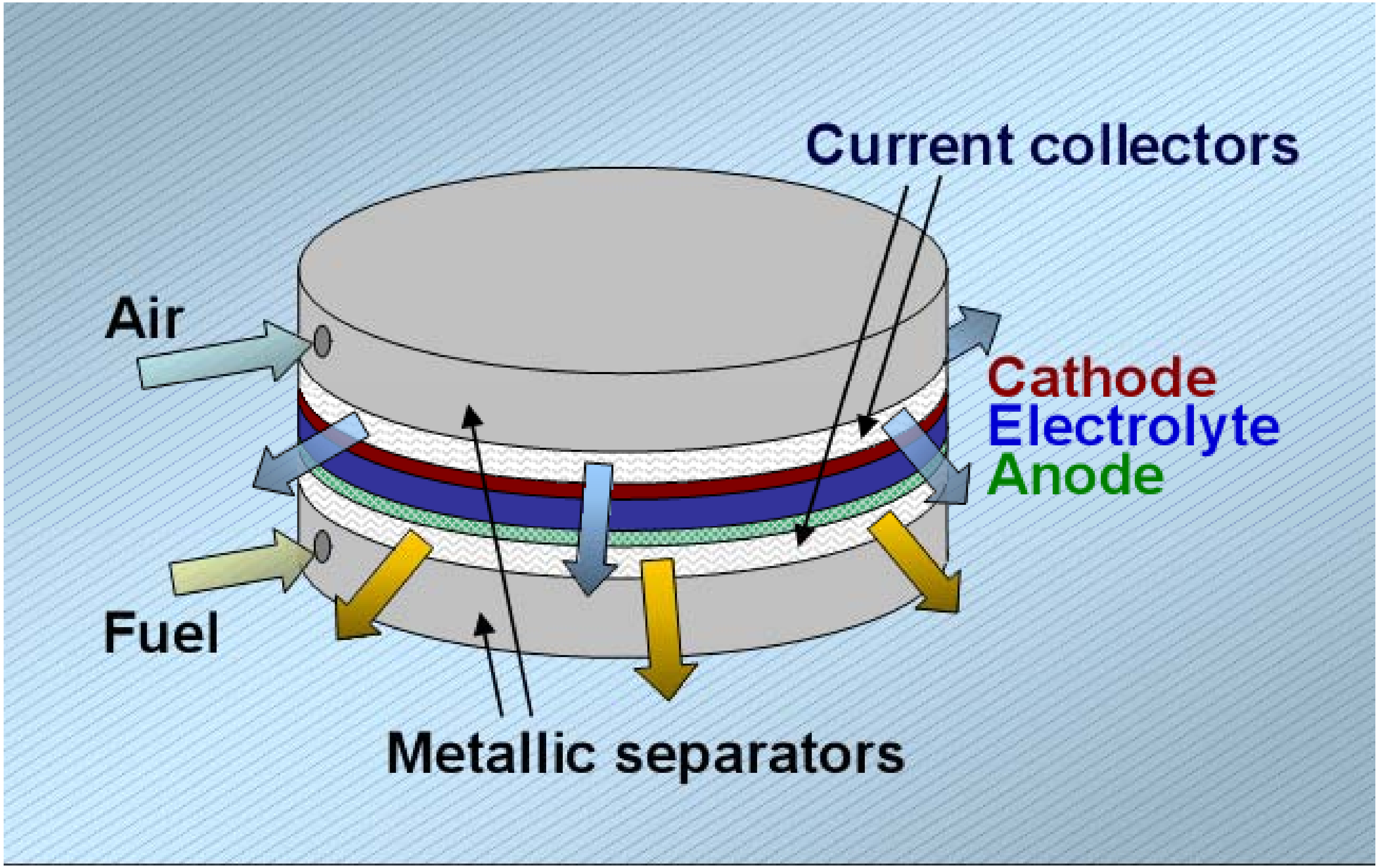
Development of HPD cell is carried out under the DOE SECA program



- Maintains seal-less design
- Reduction in cell resistance
- Increase in cell power density
- Eliminates air feed tubes

Flat Tubular SOFC

Sealess SOFC



Sealess SOFC

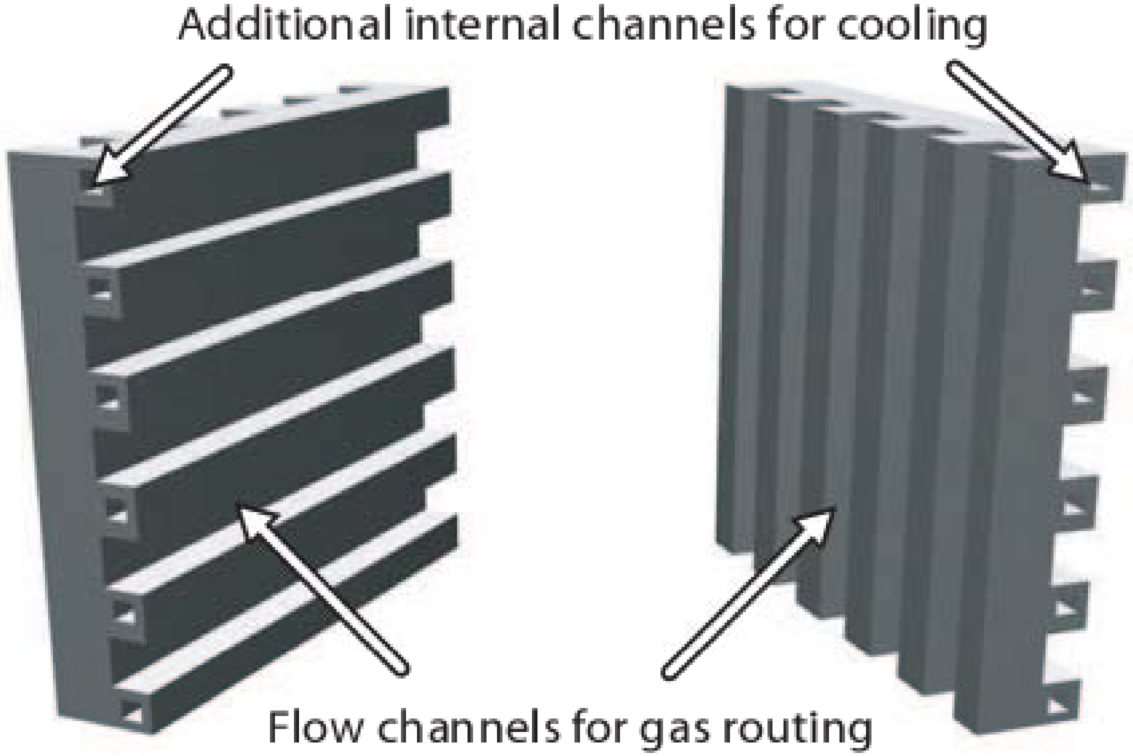
The 1 kW SOFC Module#1

Module

Cell stack

Module contains a stack of 25 old standard cells with 154 mm in diameter

Thermal Management



$$\text{Effectiveness} = \frac{\text{heat removal rate}}{\text{electrical power consumed by fan, blower, or pump}}$$

Fuel Delievary/Processing

- Energy density of fuel

$$\text{gravimetric energy density} = \frac{\text{stored enthalpy of fuel}}{\text{total system mass}}$$

$$\text{volumetric energy density} = \frac{\text{stored enthalpy of fuel}}{\text{total system volume}}$$

- Hydrogen storage

$$\text{mass storage efficiency} = \frac{\text{mass of } H_2 \text{ stored}}{\text{total system mass}} \times 100\%$$

$$\text{volume storage density} = \frac{\text{mass of } H_2 \text{ stored}}{\text{total system volume}}$$

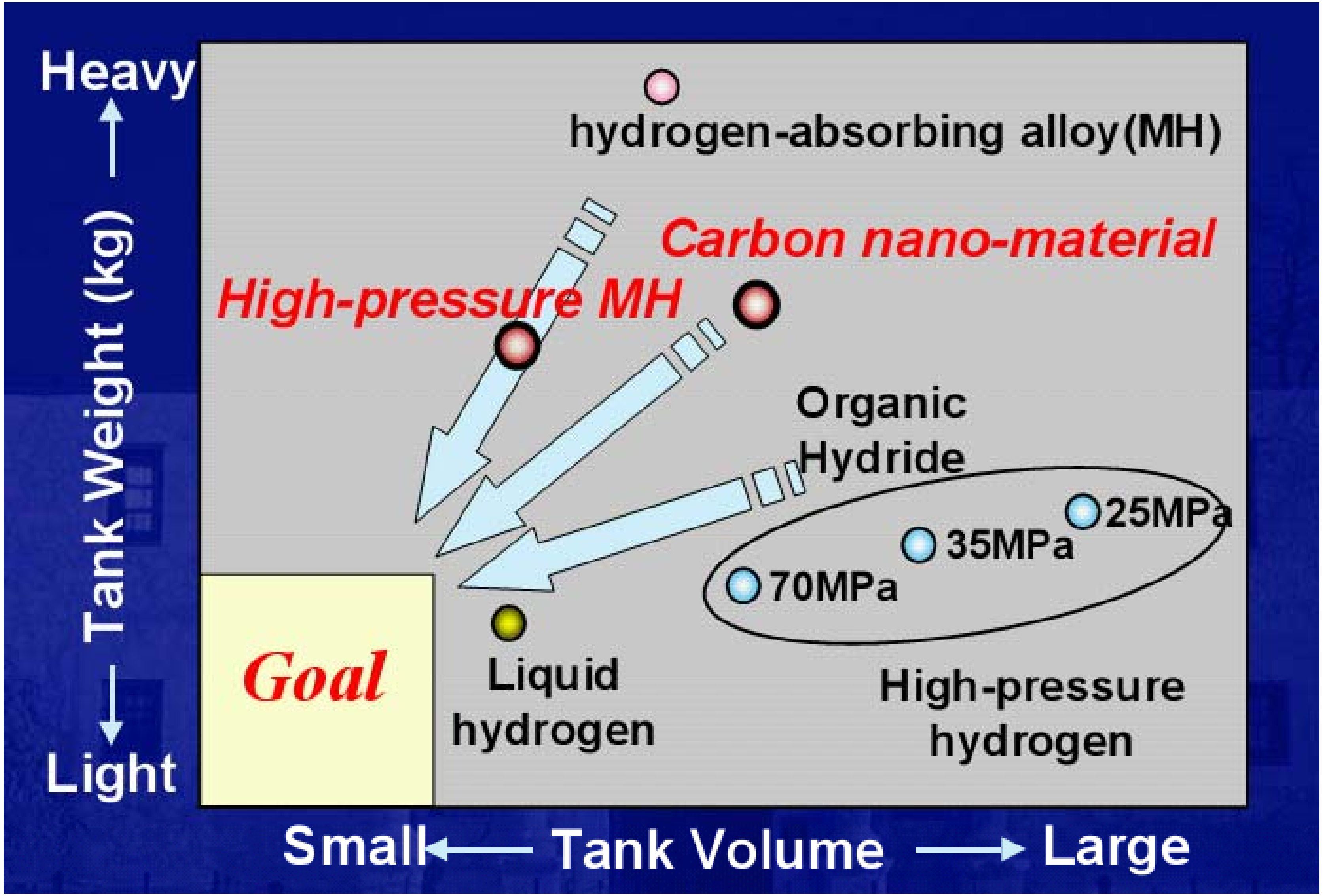
Hydrogen Storage

- Compressed hydrogen
  - Easy to store and retrieve
  - Safety issue
  - Additional energy to compress (10% loss for 300bar)
- Liquid hydrogen
  - High energy density
  - Additional energy to liquify (30% loss)
  - Boil off due to phase change

Hydrogen Storage

- Metal hydride
  - Excellent volumetric density
  - Poor gravimetric density
  - Expensive materials (e.g. Pd)
  - Hydrogen embrittlement
  - May Need cooling or heating during charging/discharging

Hydrogen Storage Technology



Hydrogen Storage Technology

High pressure hydrogen tank

Issue: Volume

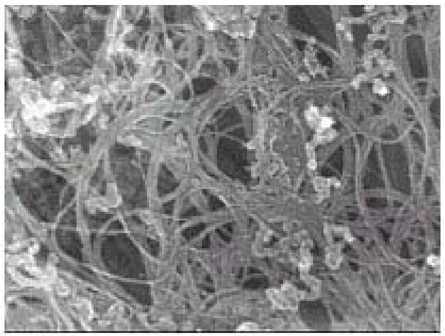
Hydrogen-absorbing alloy tank

Weight

Liquid hydrogen tank

Boil-off gas

Carbon nanotubes

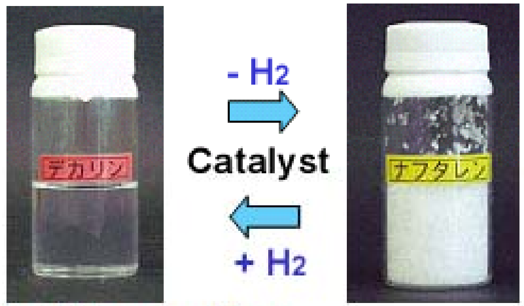


Issue: Actual storage capability?

Chemical hydrides

$NaBH_4$

Decalin($C_{10}H_{18}$) Naphthalene($C_{10}H_8$)



Handling / Recycling

Efficiency

Storage System	Mass Storage Efficiency (% H_2/kg)	Vol. Storage Density (kgH_2/L)	Grav. Storage Energy Density (kWh/kg)	Vol. Storage Energy Density (kWh/L)
Compressed H_2, 300bar	3.1	0.014	1.2	0.55
Compressed H_2, 700bar	4.8	0.033	1.9	1.30
Cryogenic Liquid H_2	14.2	0.043	5.57	1.68
Metal Hydride (Conservative)	0.65	0.028	0.26	1.12
Metal Hydride (Optimistic)	2.0	0.085	0.80	3.40

Storage System	Grav. Storage Energy Density (kWh/kg)	Vol. Storage Energy Density (kWh/L)	Carrier Effectiveness
Direct Methanol (50% molar mix with H_2O)	4	3.4	0.40
Reformed Methanol (50% molar mix with H_2O)	2	1.7	0.70
Reformed $NaBH_4$ (30% molar mix with H_2O)	1.5	1.5	0.90

Hydrogen Carrier

- Hydrocarbon
  - –Methane(CH_4), ethane(C_2H_6), butane(C_3H_8)...
  - –Methanol(CH_3OH), formic acid(HCOOH)
  - –Gasoline($C_nH_{1.87n}$), diesel...
- Chemical hydride
  - –Sodium borohydride($NaBH_4$), Ammonia(NH_3)..

Hydrogen Carrier

- Direct electro-oxidation
  - DMFC, DFAFC, DBFC…
  - Complicated & slow kinetics: low efficiency

ex)
DMFC: Anode: $CH_3OH + H_2O => CO_2 + 6H^+ + 6e-$
Cathode: $1.5O_2 + 6H^+ + 6e => 3H_2O$

DBFC: Anode: $NaBH_4 + 8OH- => NaBO_2 + 6H2O + 8e-$
Cathode: $2O_2 + 4H_2O + 8e- => 8OH-$

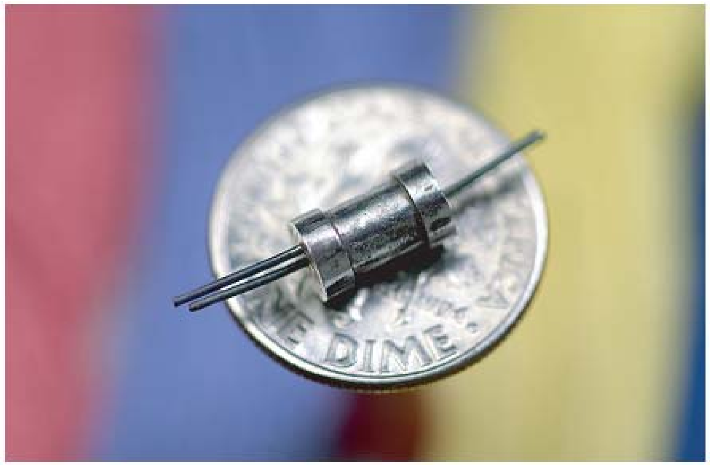
Hydrogen Carrier

- External reforming
  - High energy density of fuel
  - CO issue, hydrogen separation

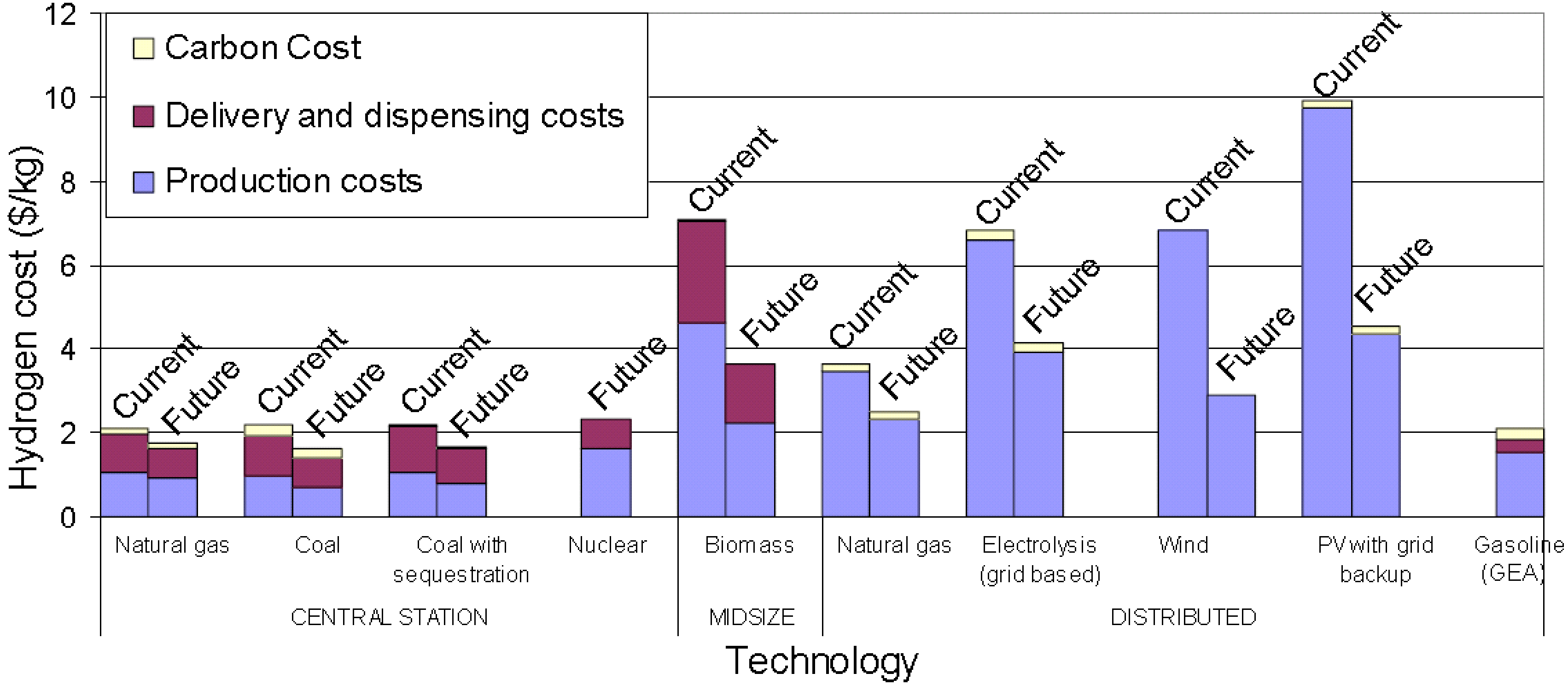
  Ex) steam reforming

  $CH_3OH + H_2O => CO_2 + 3H_2$

  $C \text{ (coal)} + 2H_2O => CO_2 + 2H_2$



Delivered Hydrogen Cost



• *GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency*

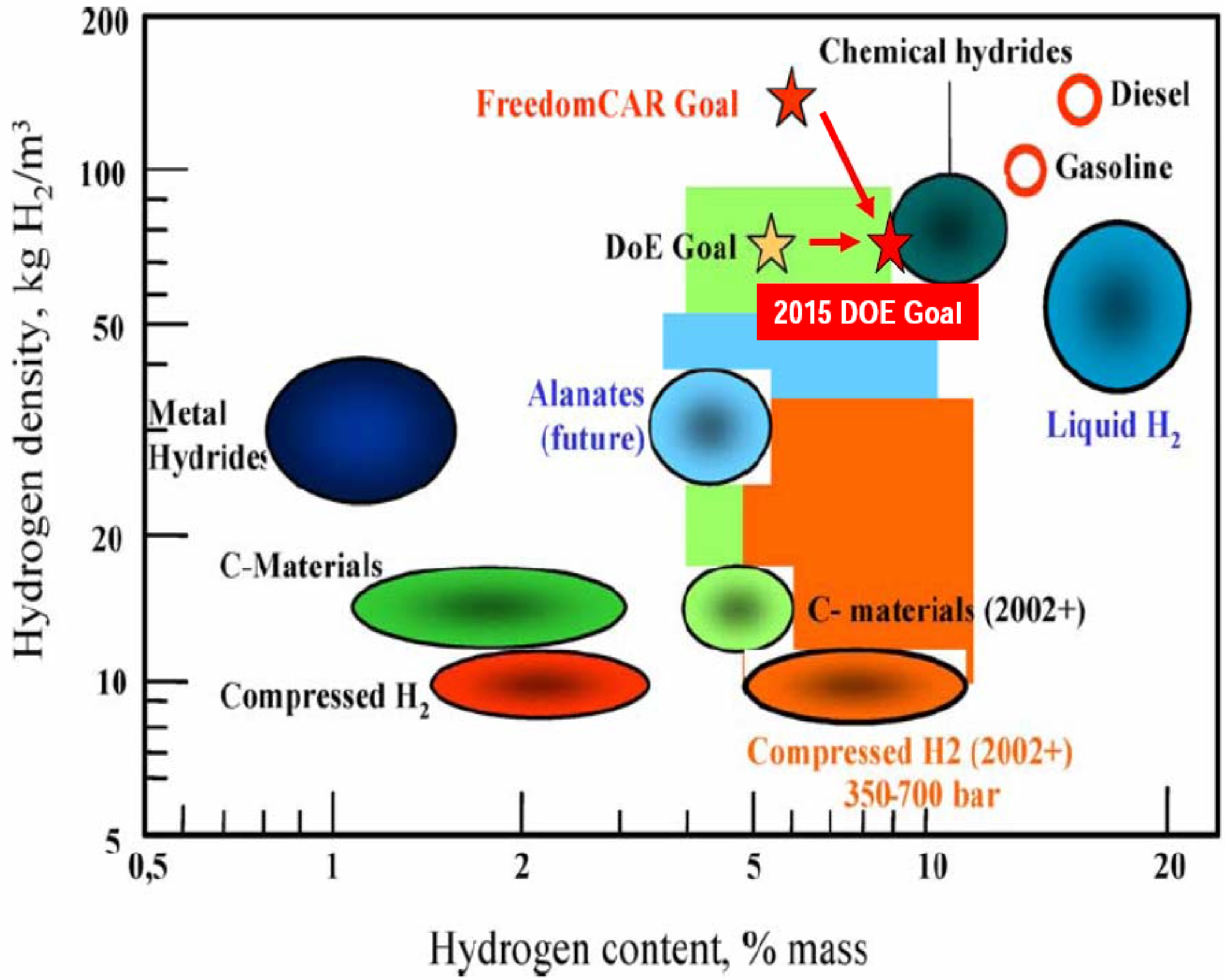
*The National Academies, 2004

Hydrogen Carrier

- Internal Reforming
  - Simple system
  - Appropriate for high temperature fuel cells
  - Careful on catalyst design

Fuel System	Grav. Storage Energy Density	Vol. Storage Energy Density	Fuel Availability	Fuel Suitability For Fuel Cell	Comments
Fuel Systems For Mobile Applications					
Compressed H_2	Moderate	Moderate	Low	High	For transportation
Cryogenic H_2	Moderate-High	Moderate	Low	High	Liquefaction is energy intensive
Metal Hydride	Low	Moderate-High	Low	High	Expensive, heavy
Direct Methanol	High	High	Moderate	Low-Moderate	For portable applications
Reformed Methanol	Moderate-High	Moderate-High	Moderate	Moderate	For transportation applications
Reformed Gasoline	Moderate-High	Moderate-High	High	Low	Expensive, hard to reform
Fuels For Stationary Generation Applications					
Neat Hydrogen	Low	Low	Low	High	Must have H_2 source!
Natural Gas	Low	Low	High	Moderate	Best for high-T FCs
Bio-gas	Low	Low	Low	Moderate	Best for high-T FCs

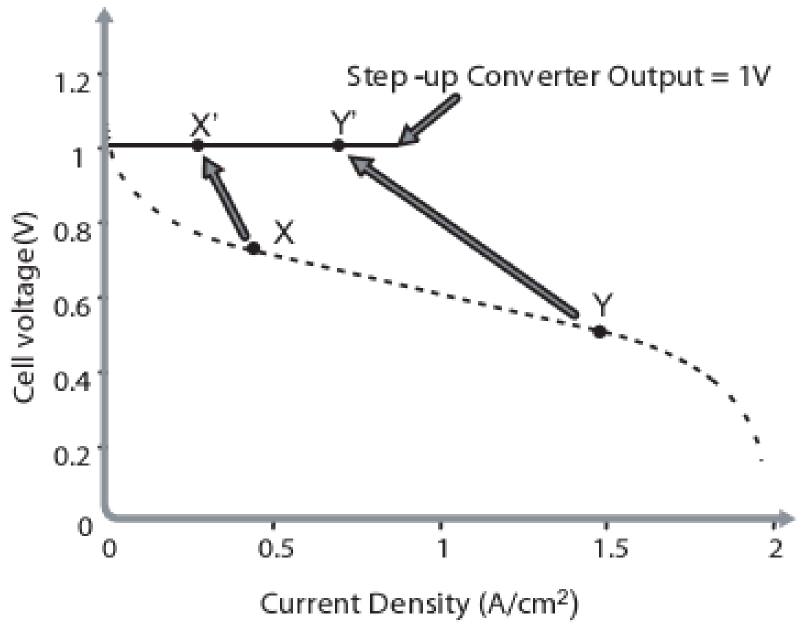
DOE Target

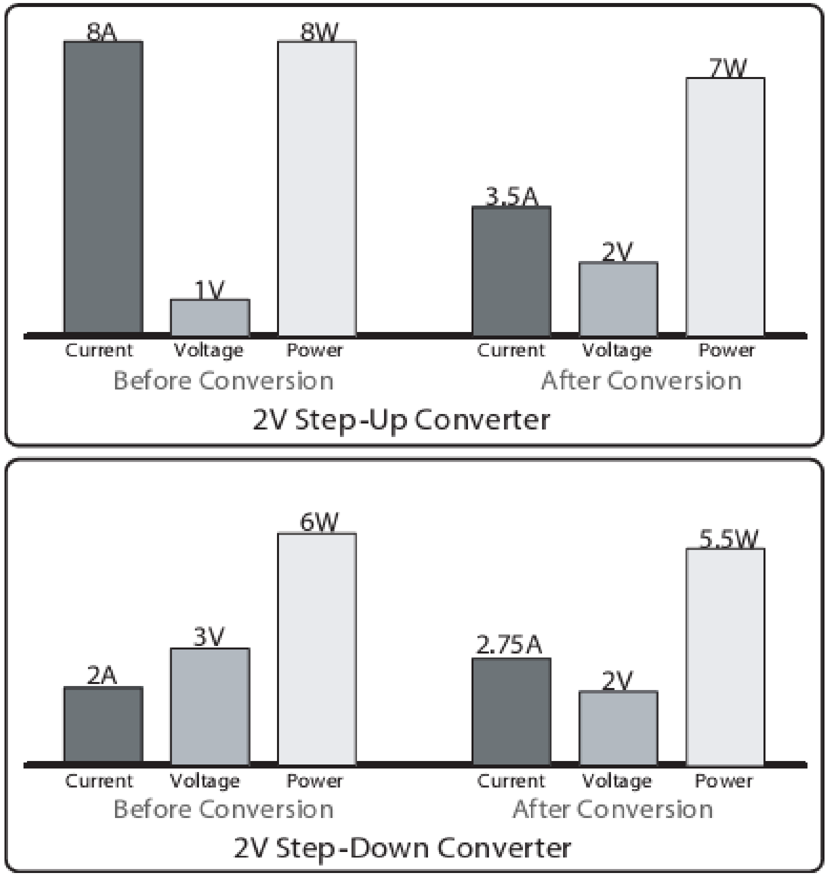


Chemical hydrides
FreedomCAR Goal
Diesel
Gasoline
DoE Goal
2015 DOE Goal
Liquid H2
Alanates
(future)
Metal
Hydrides
C-Materials
C- materials (2002+)
Compressed H2
Compressed H2 (2002+)
350-700 bar
Hydrogen density, kg H2/m3
200
100
50
20
10
5
0,5
1
2
5
10
20
Hydrogen content, % mass

Power Regulation

- Loading of fuel cells tend to change
- DC/DC conversion: 85~98% efficiency
- Step-up or step-down

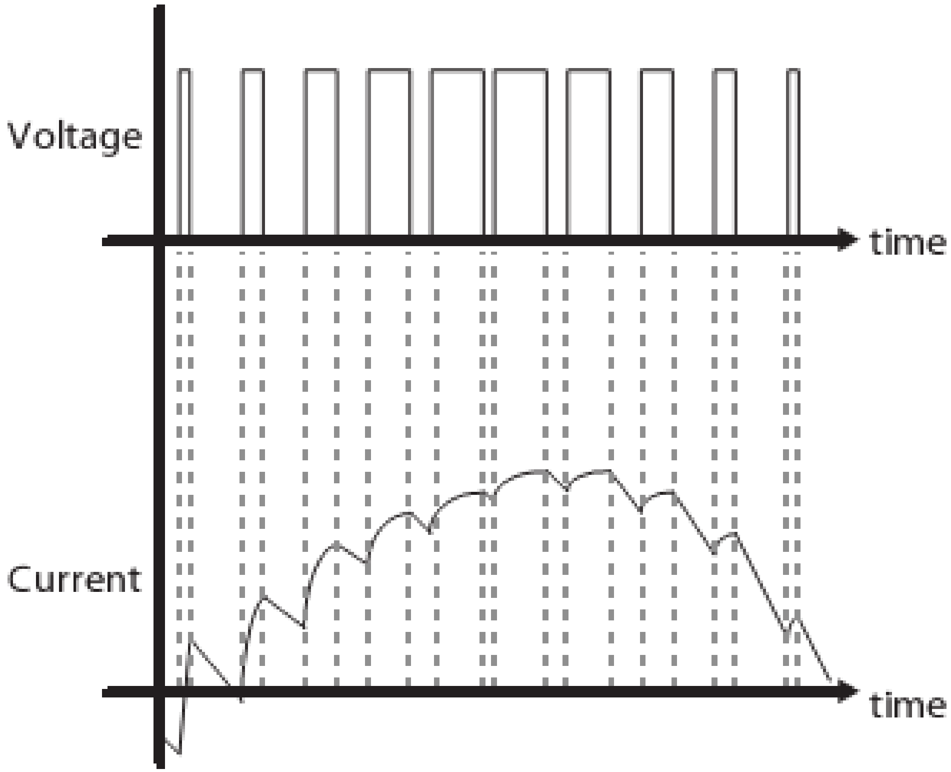




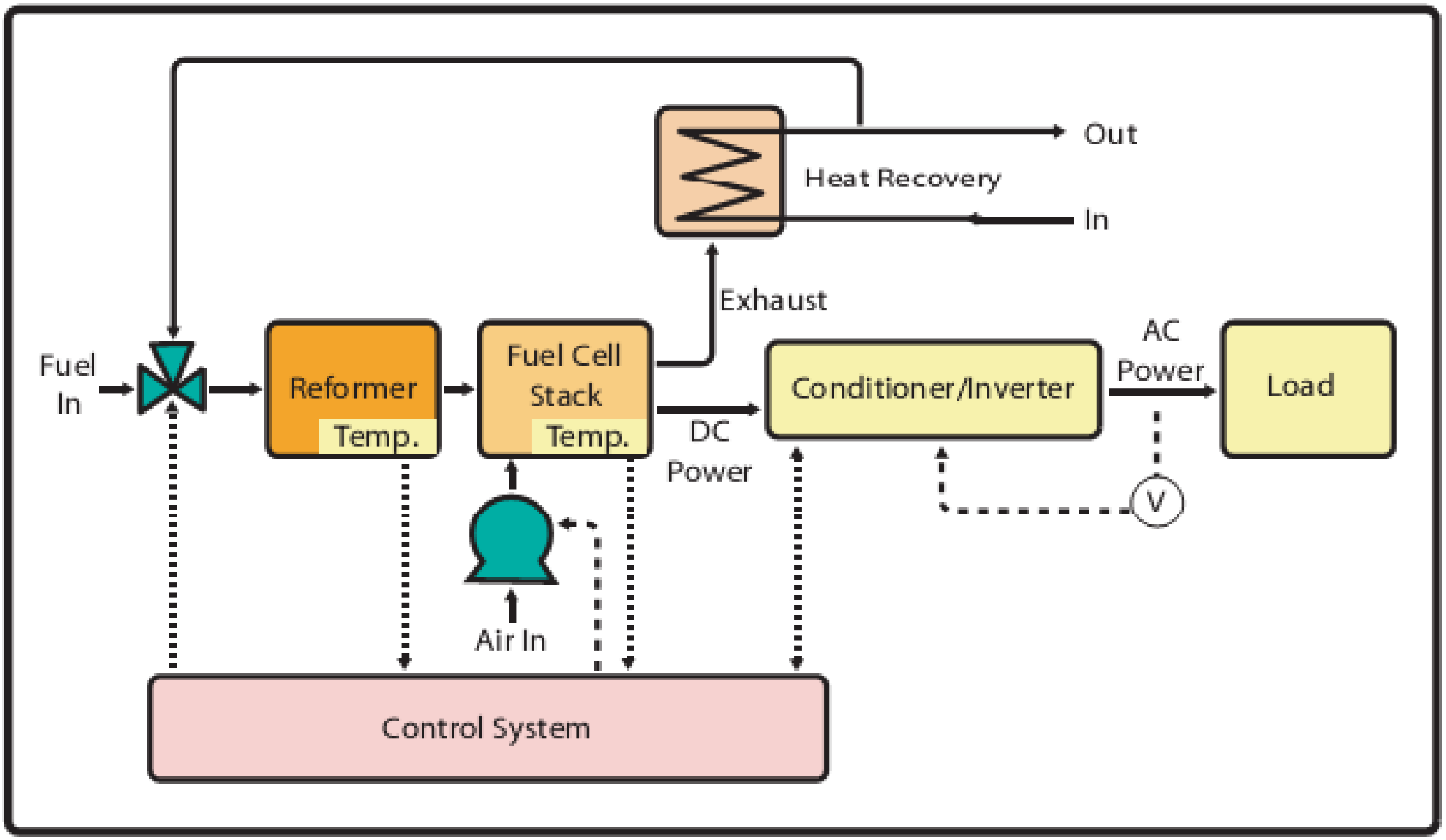
Power Inversion

- DC/AC conversion
- Appropriate stationary, automotive application

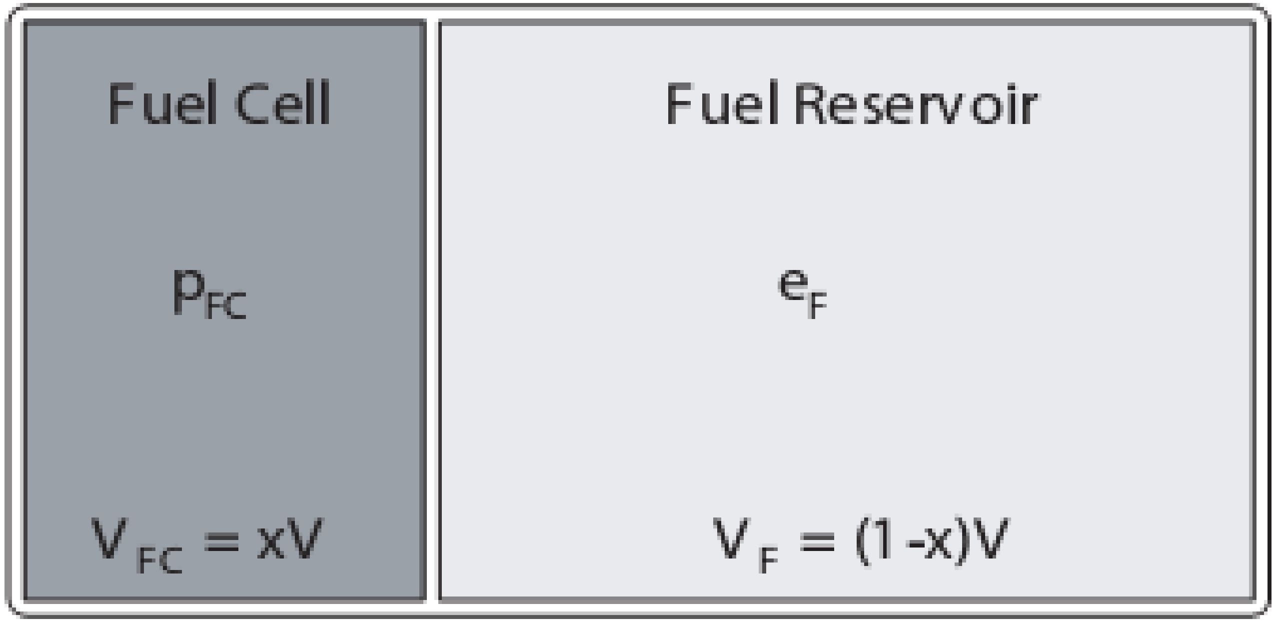
  Ex) Pulse width modulation



Monitoring/Control, Power Supply Management



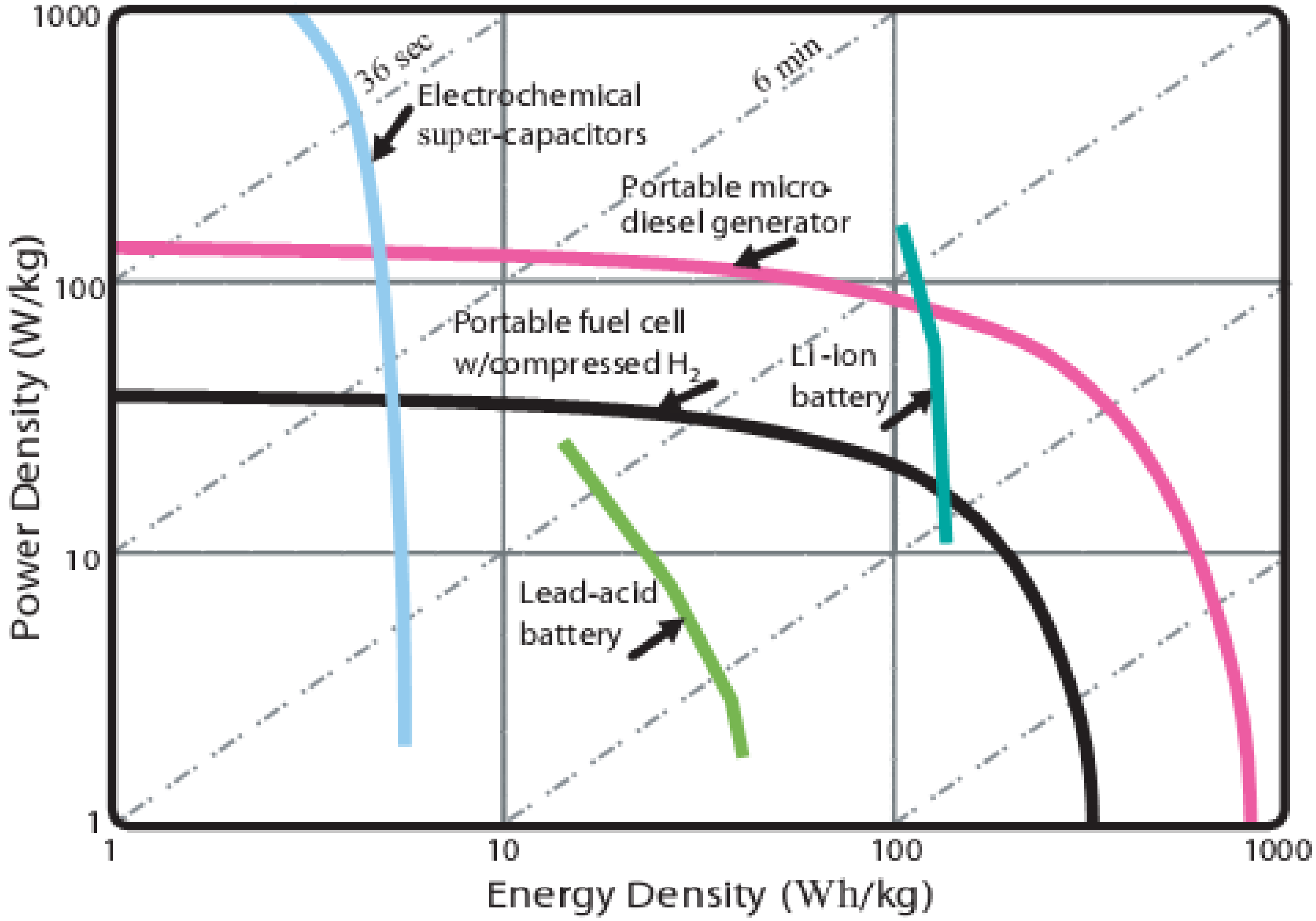
Fuel Cell vs Fuel



Entire System: V, P, E

$P = xVp_{FC}$, $E = (1 - x)Ve_F\varepsilon$

Ragone Plot



1000
100
10
1
Power Density (W/kg)
1
10
100
1000
Energy Density (Wh/kg)
36 sec
6 min
Electrochemical super-capacitors
Portable micro-diesel generator
Portable fuel cell w/compressed H_2
Li-ion battery
Lead-acid battery