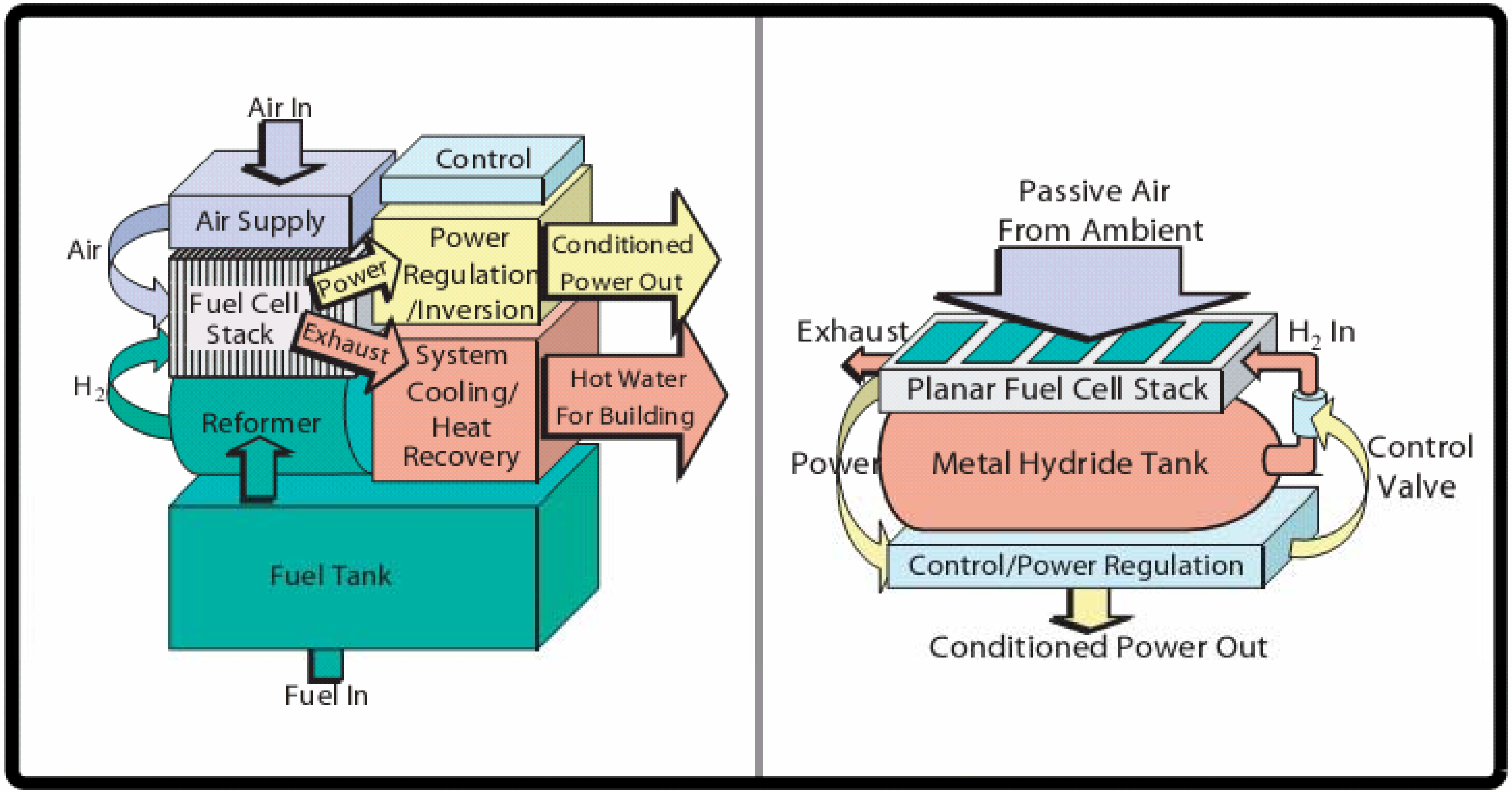
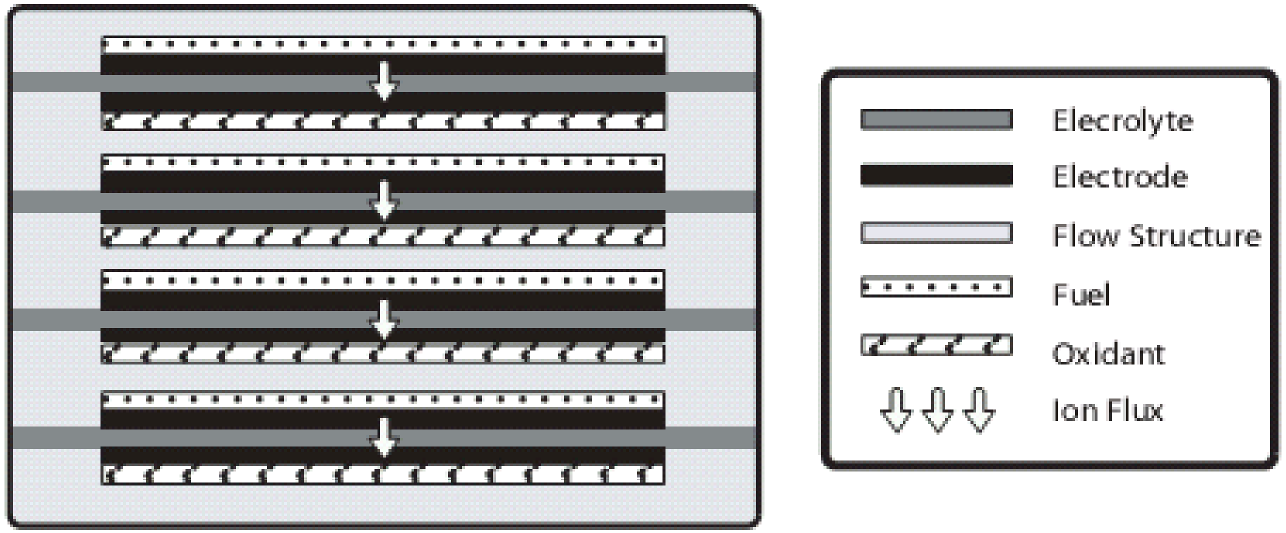
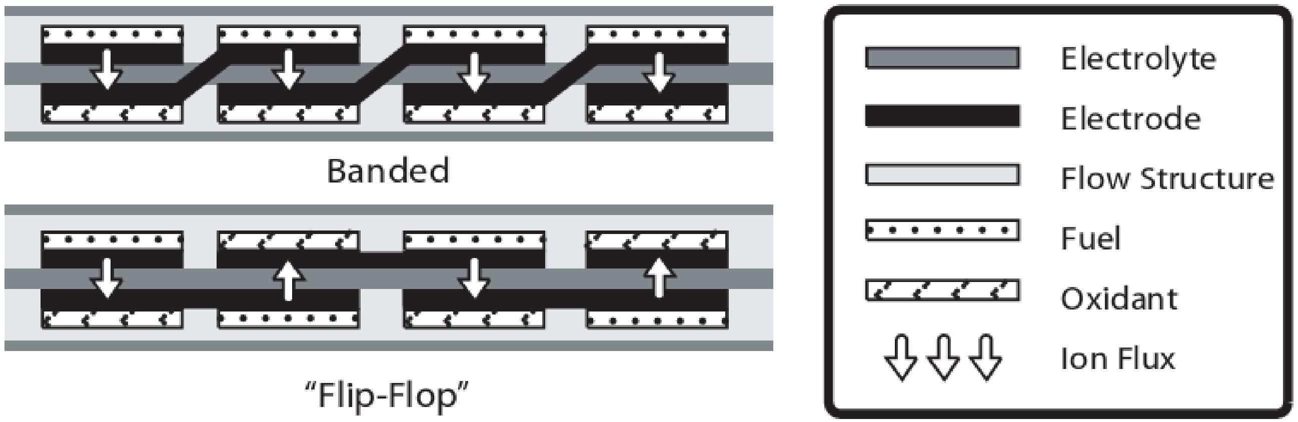
Fuel Cell Systems Overview

Fuel Cell Systems



Fuel Cell Stacks





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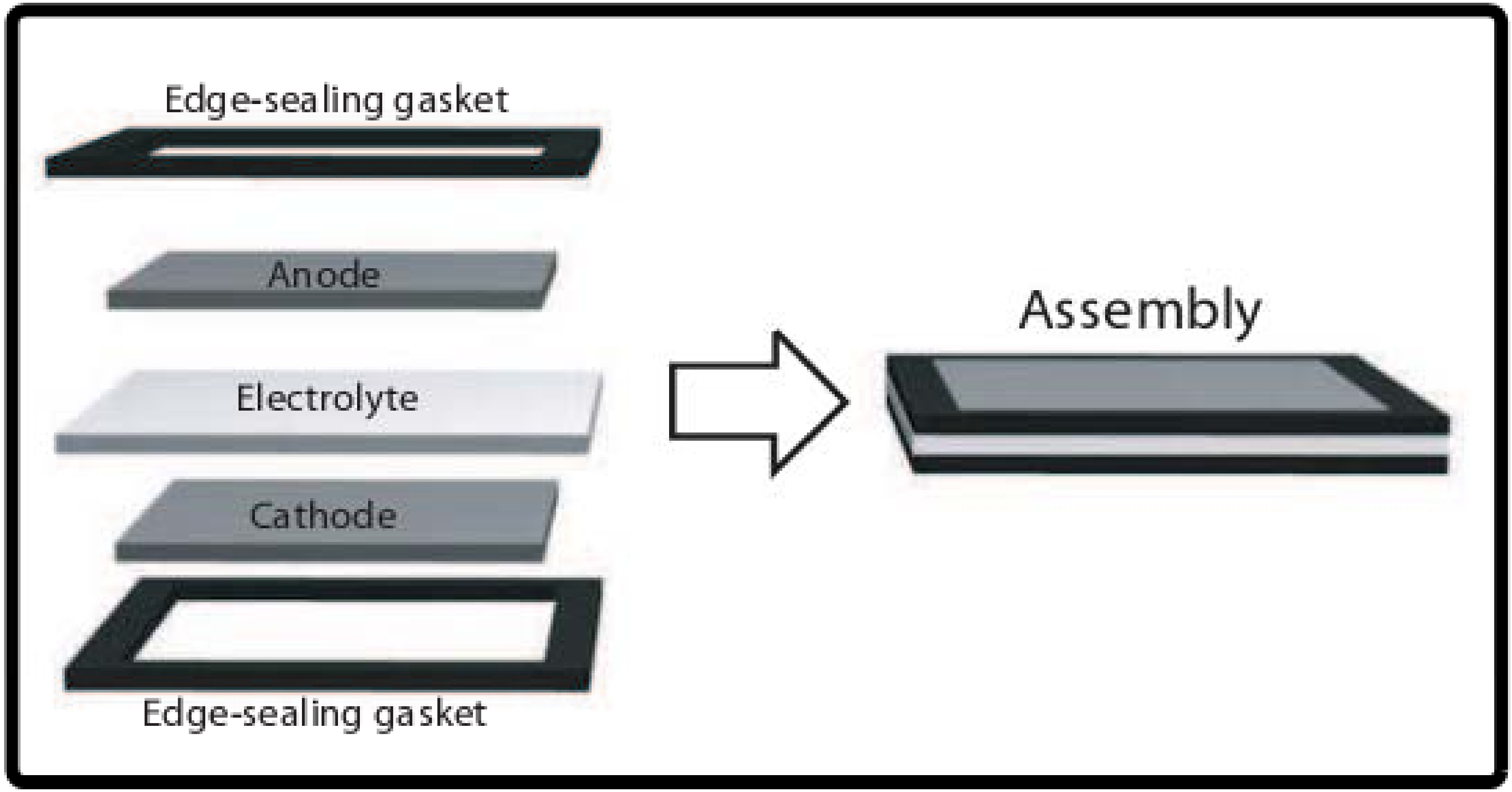

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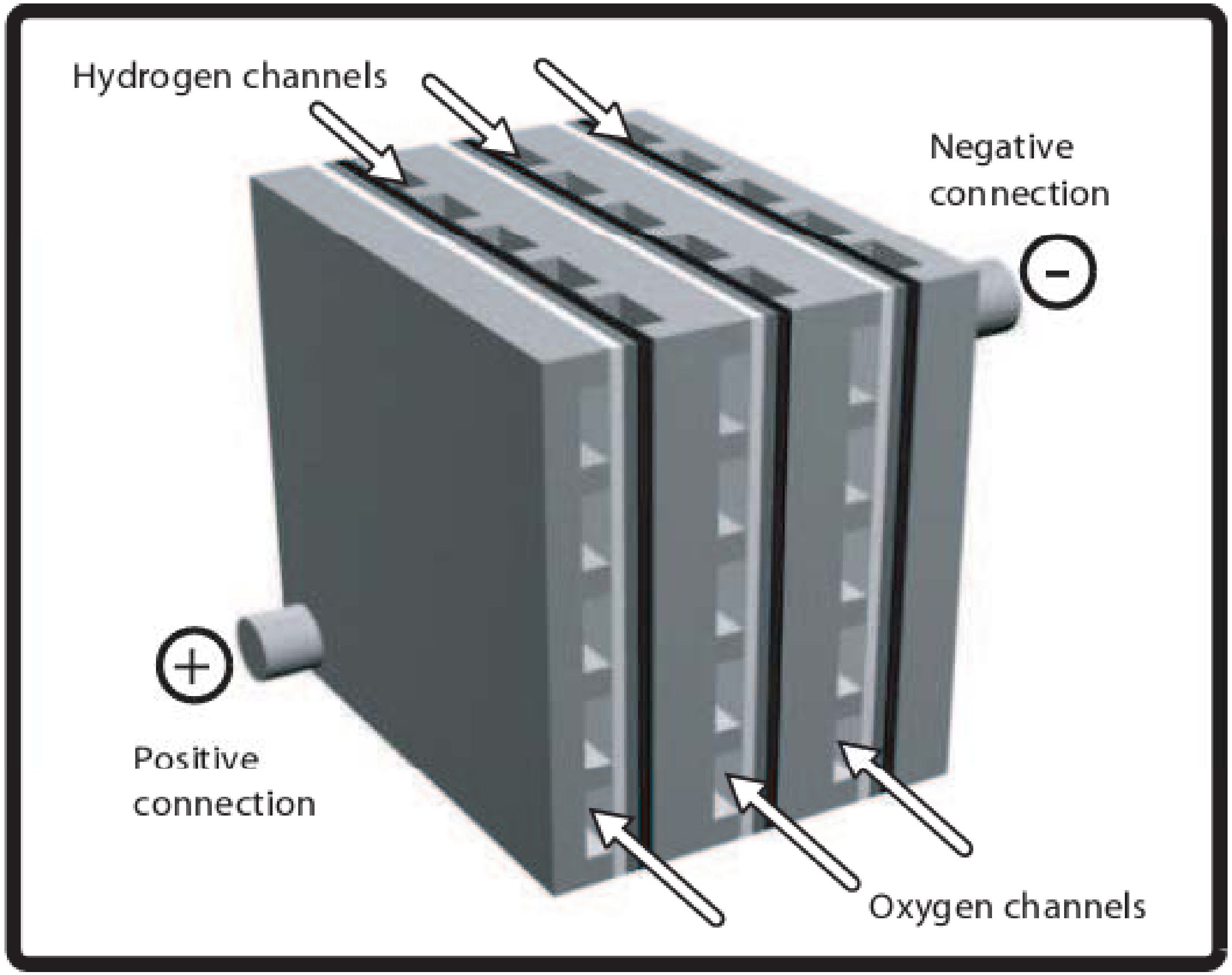
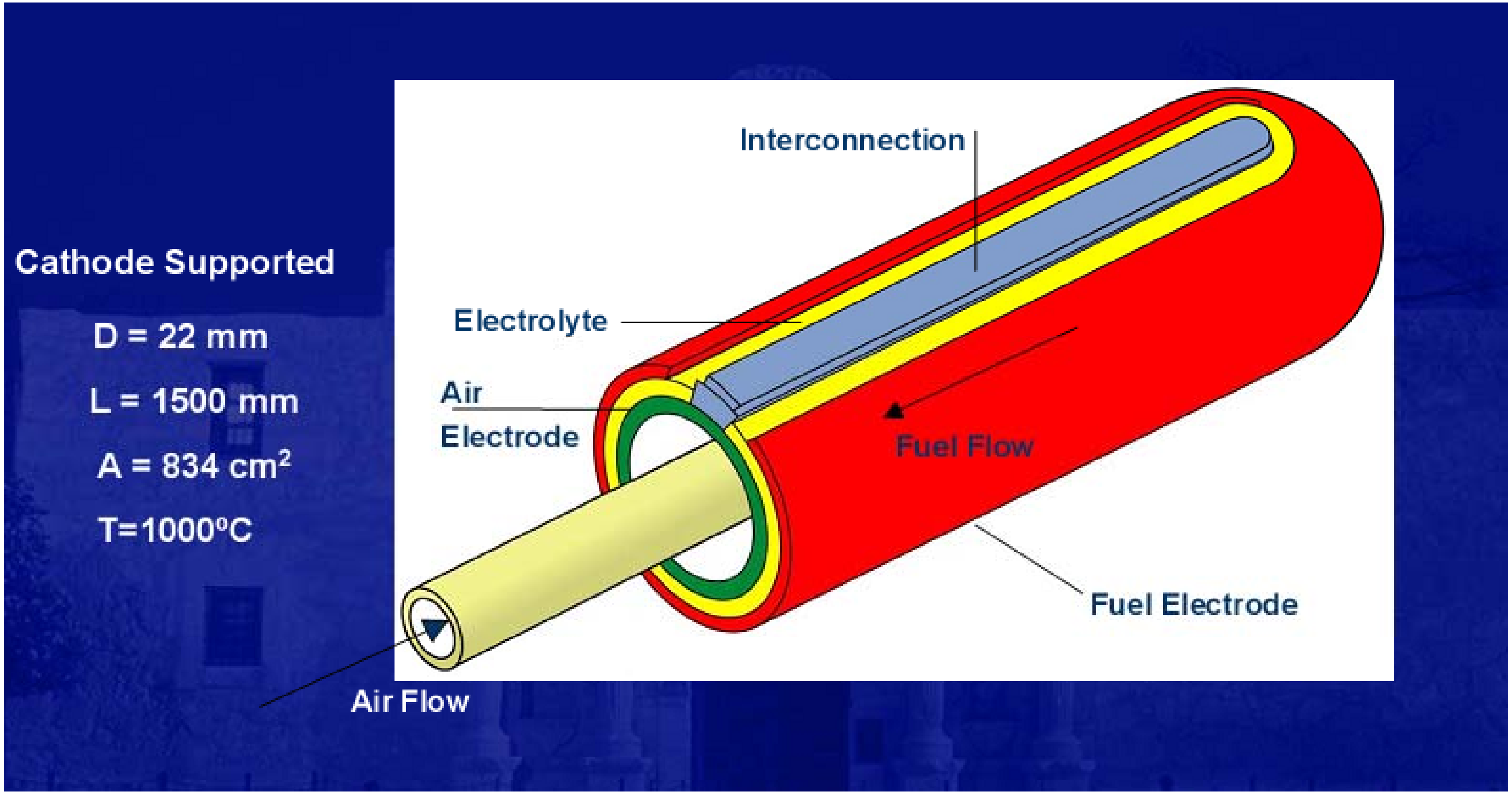


Tubular SOFC



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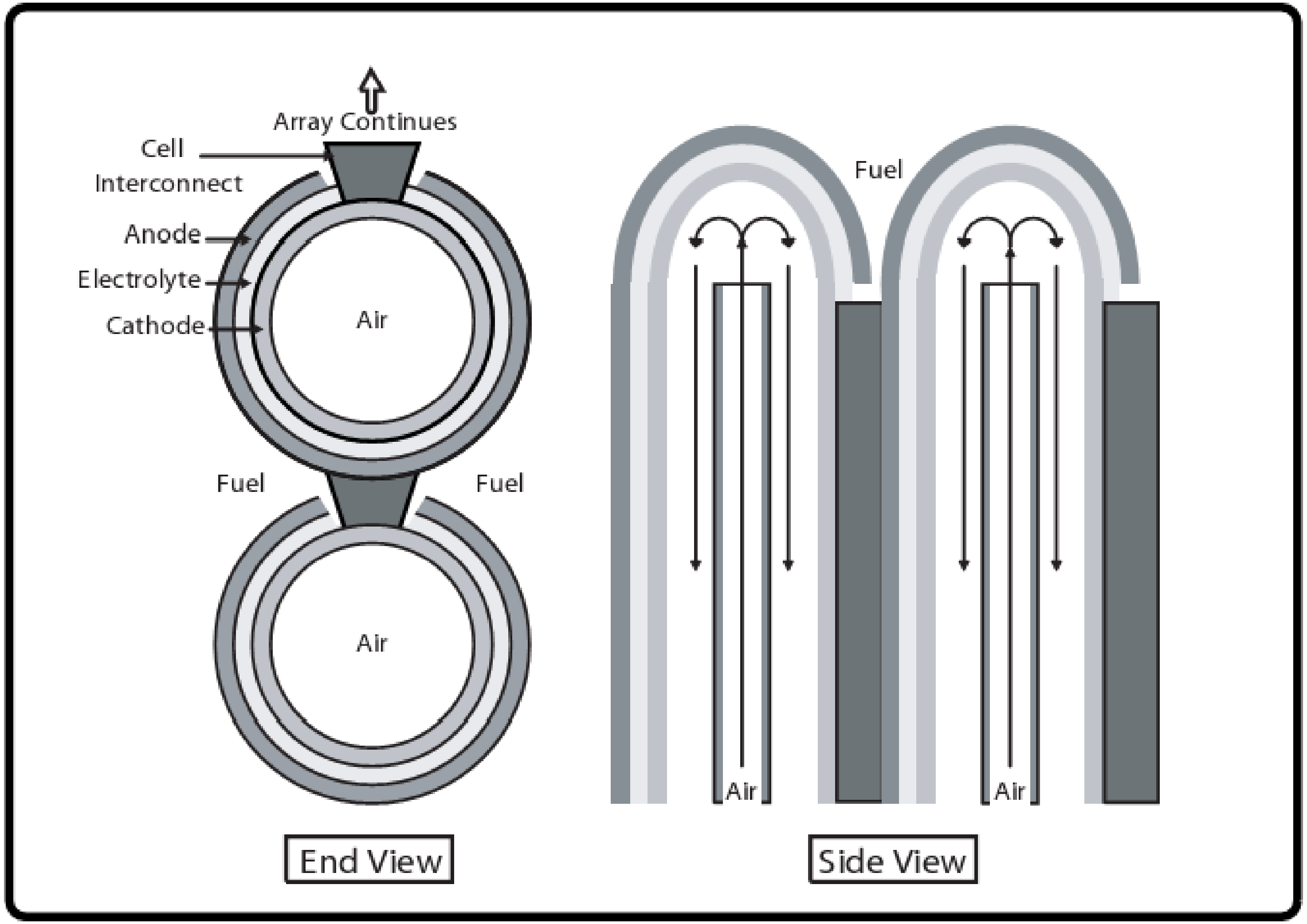

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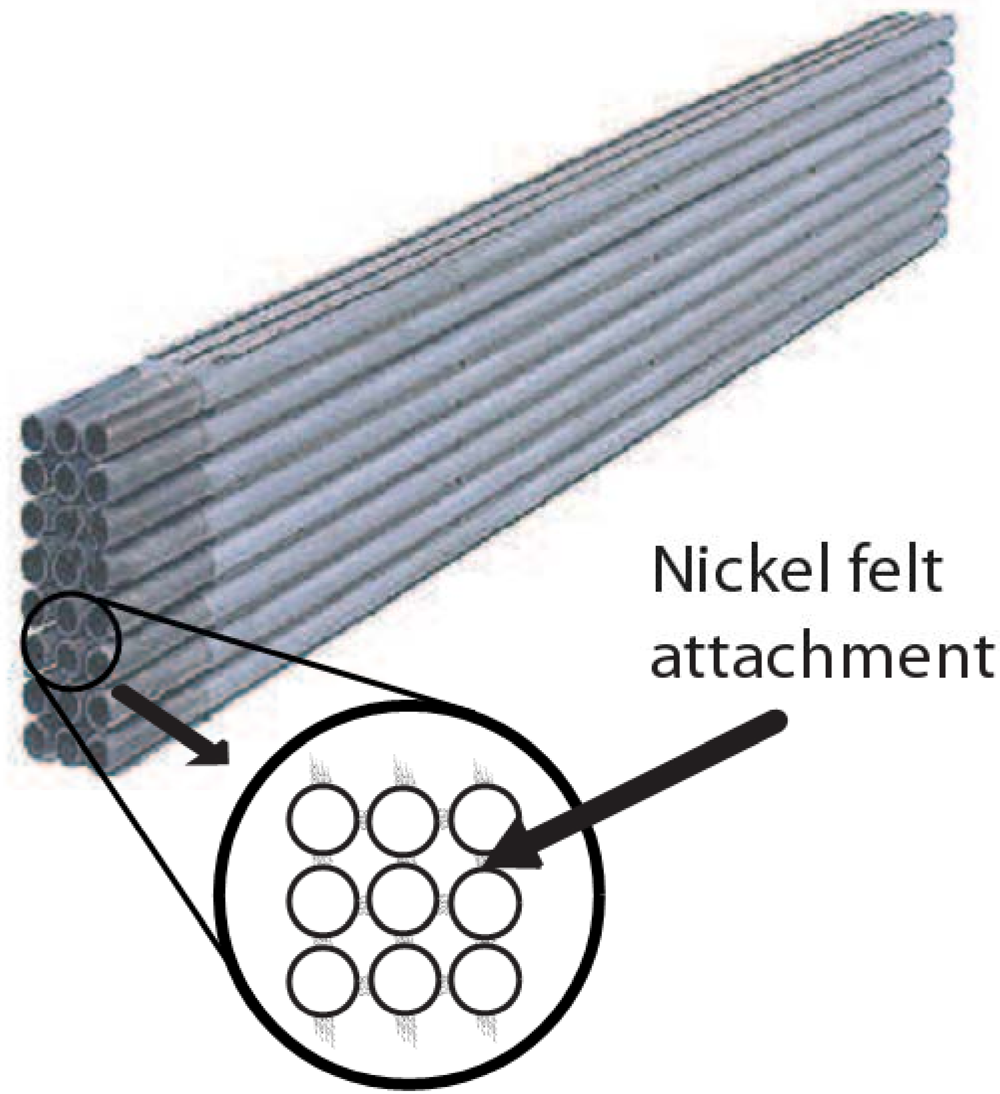
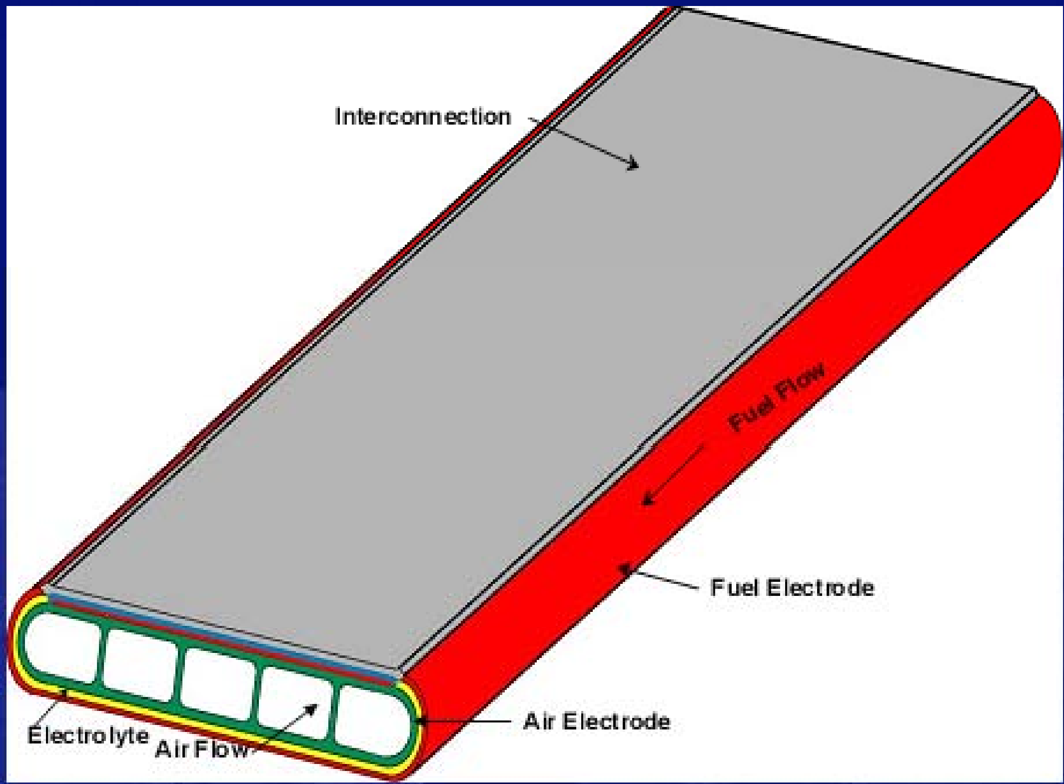


Flat Tubular SOFC

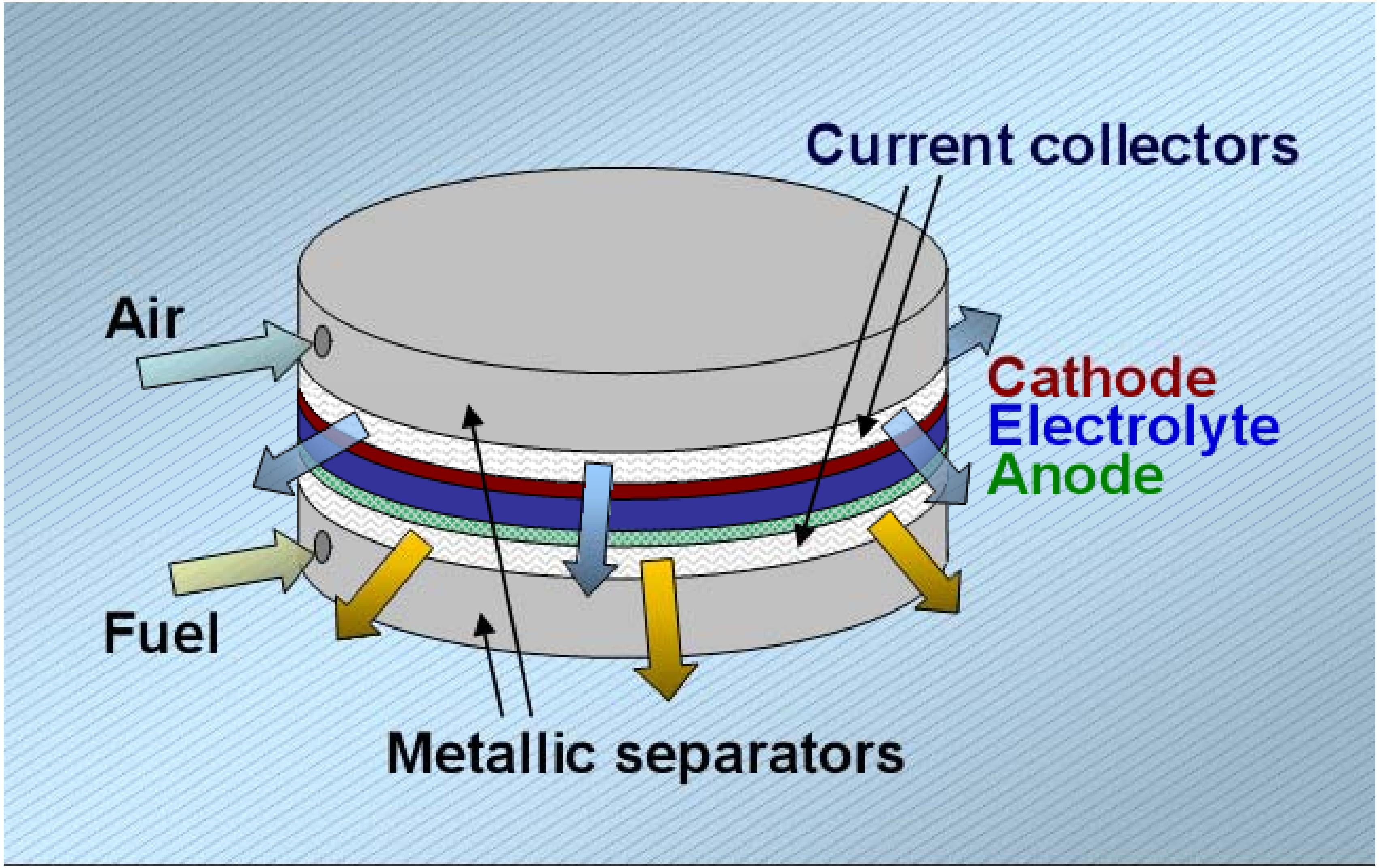
Development of HPD cell is carried out under the DOE SECA program



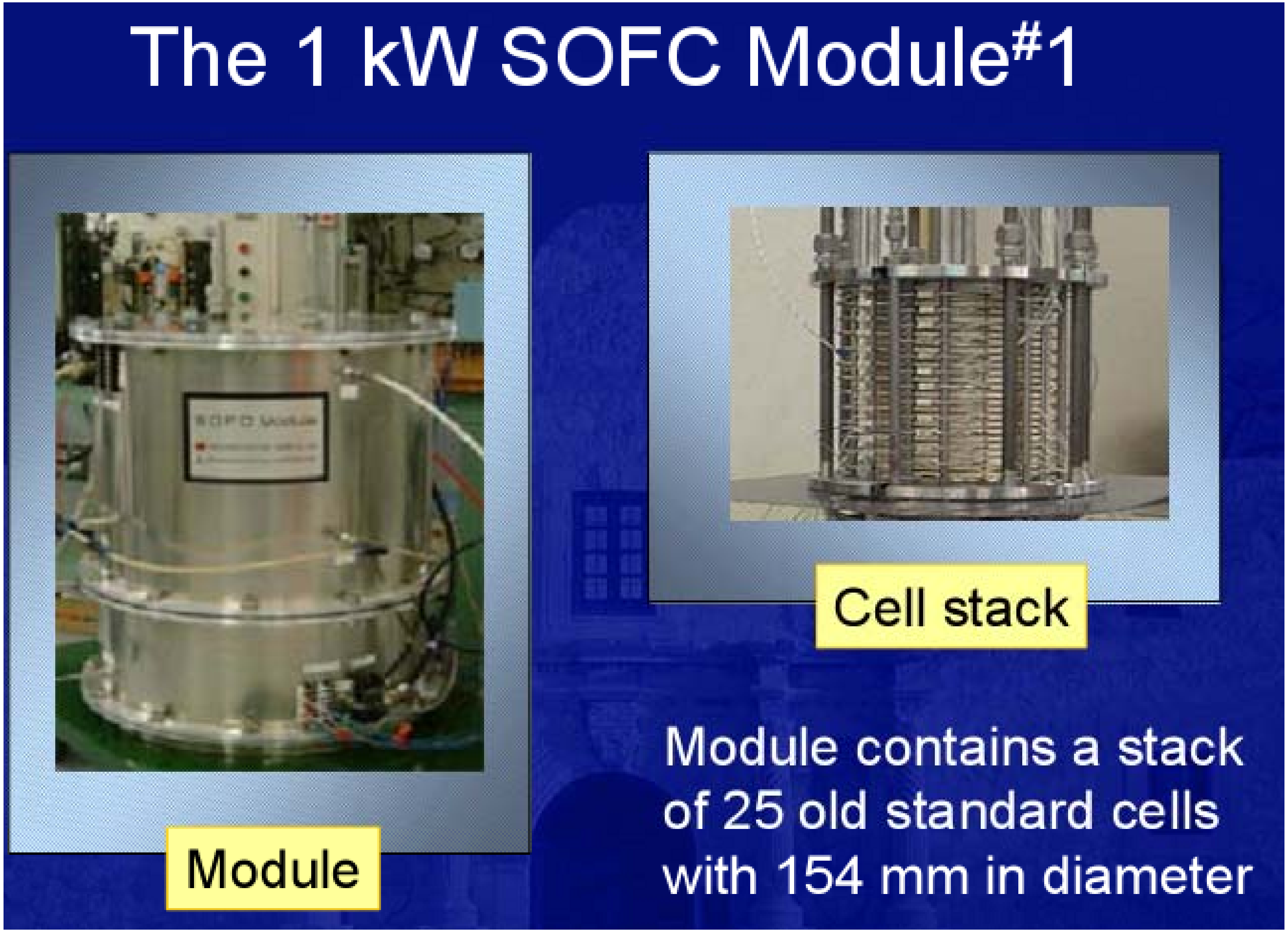
- Maintains seal-less design
- Reduction in cell resistance
- Increase in cell power density
- Eliminates air feed tubes

Flat Tubular SOFC

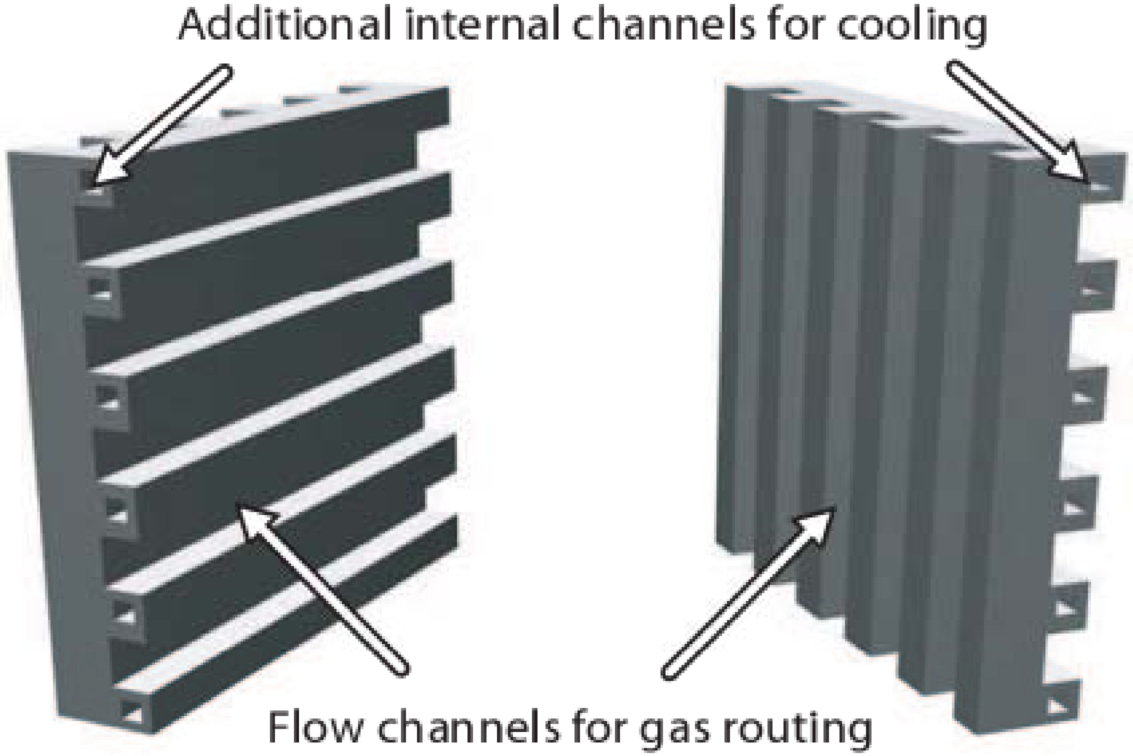
Sealess SOFC



Sealess SOFC



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

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

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

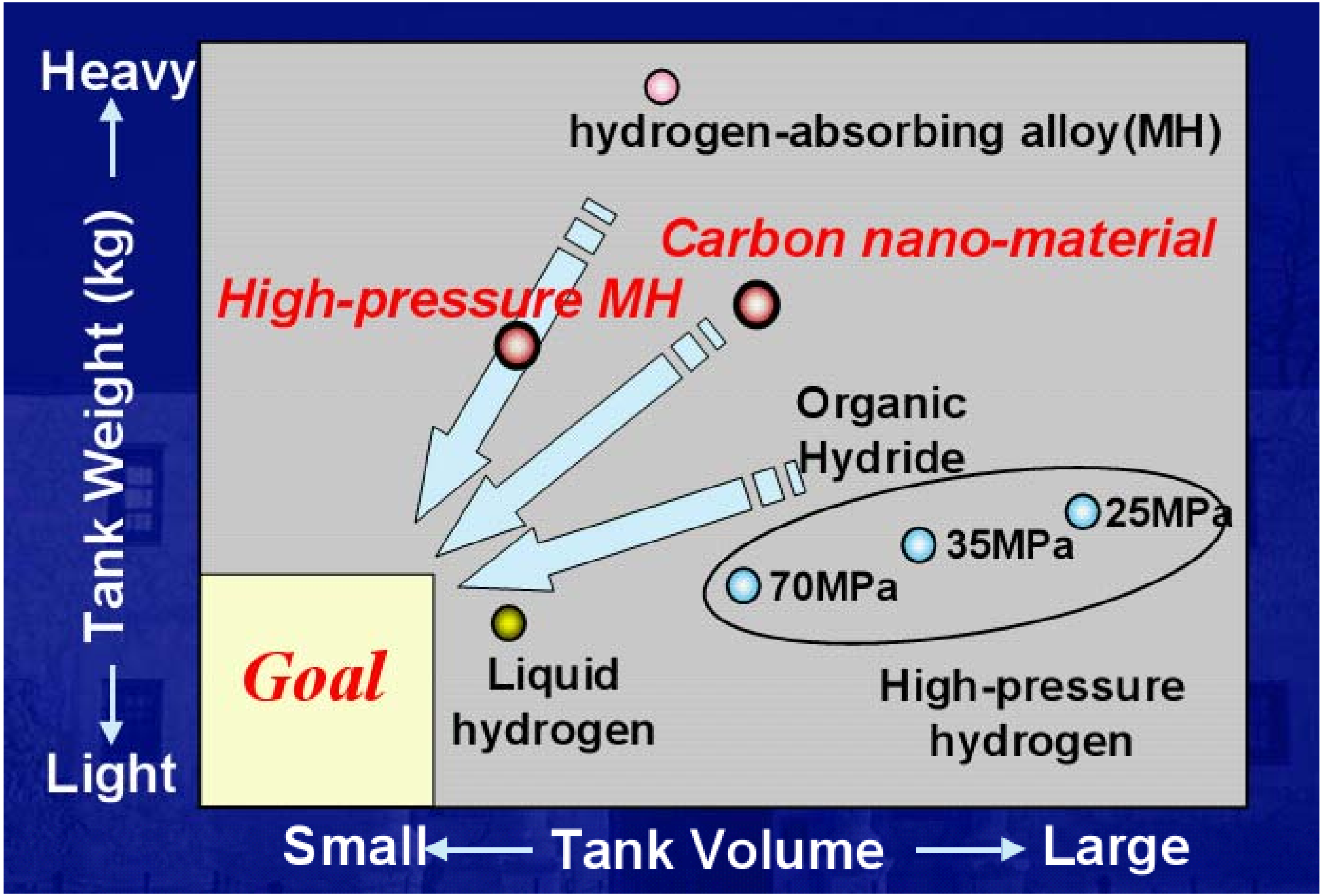
Hydrogen Storage

- 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



by Toyota corp.

Hydrogen Storage Technology

High pressure hydrogen tank

Issue: Volume

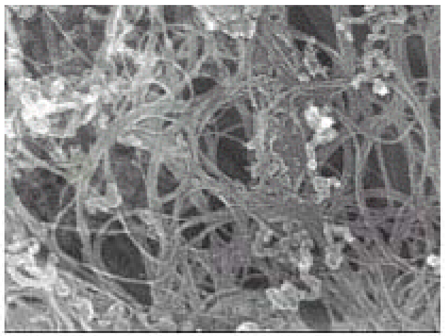
Hydrogen-absorbing alloy tank

Weight

Liquid hydrogen tank

Boil-off gas

Carbon nanotubes



Issue: Actual storage capability?

Chemical hydrides

$NaBH_4$

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

$- H_2$ →

Catalyst

← $+ H_2$

Naphthalene($C_{10}H_8$)

Handling / Recycling

by Toyota corp.

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: $CH_3OH + H_2O \Rightarrow CO_2 + 6H^+ + 6e^-$
Cathode: $1.5O_2 + 6H^+ + 6e \Rightarrow 3H_2O$

DBFC: Anode: $NaBH_4 + 8OH^- \Rightarrow NaBO_2 + 6H2O + 8e^-$
Cathode: $2O_2 + 4H_2O + 8e^- \Rightarrow 8OH^-$

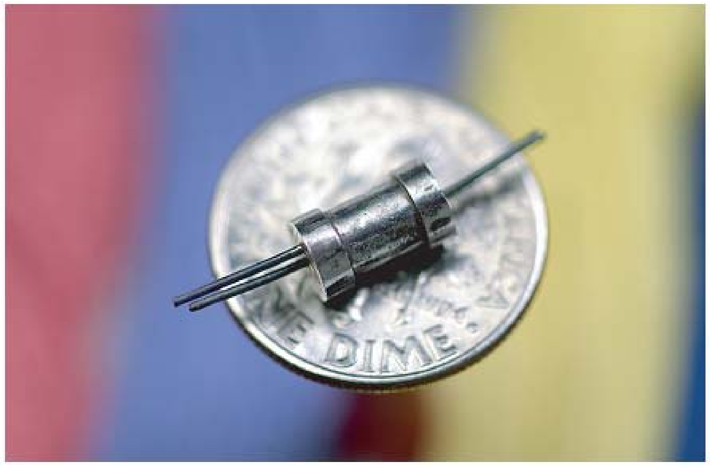
Hydrogen Carrier

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

  Ex) steam reforming

  $CH_3OH + H_2O => CO_2 + 3H_2$

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



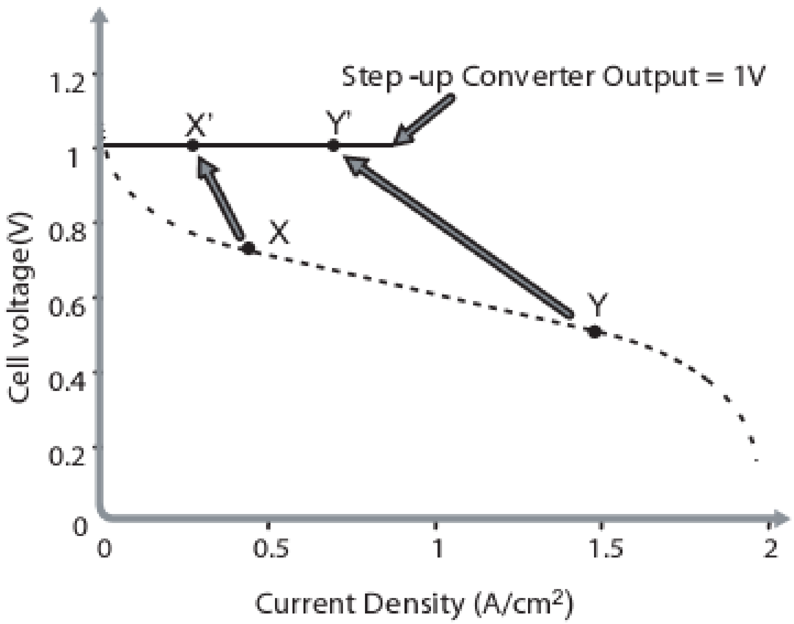
Hydrogen Carrier

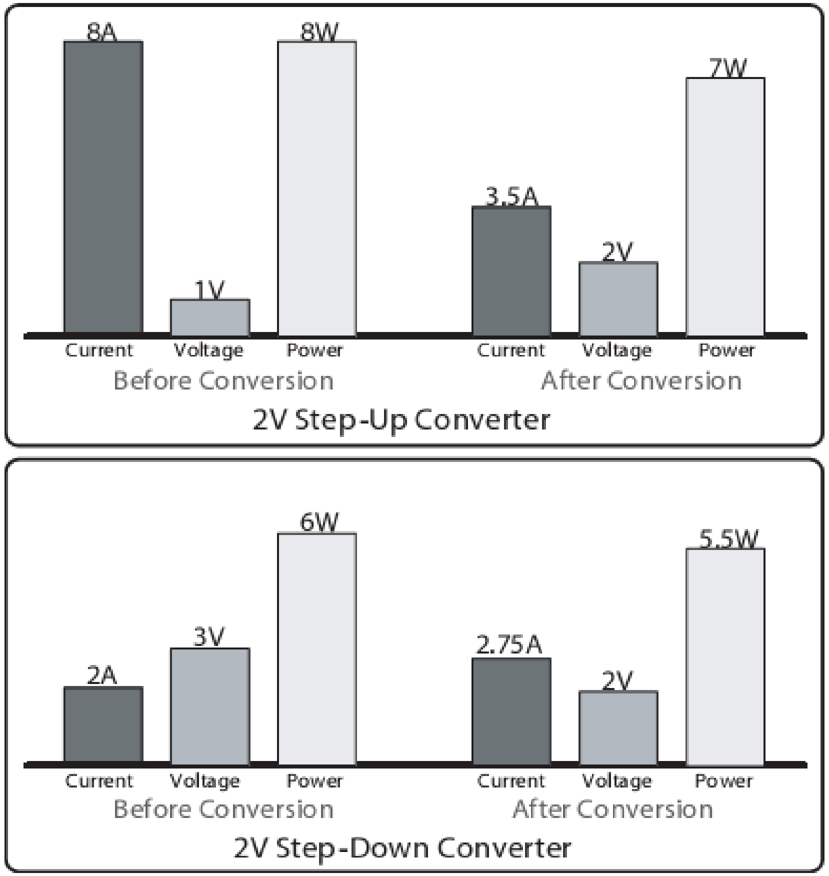
- Internal Reforming
  - Simple system
  - Appropriate for high temperature fuel cells
  - Careful on catalyst design

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

Power Regulation

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

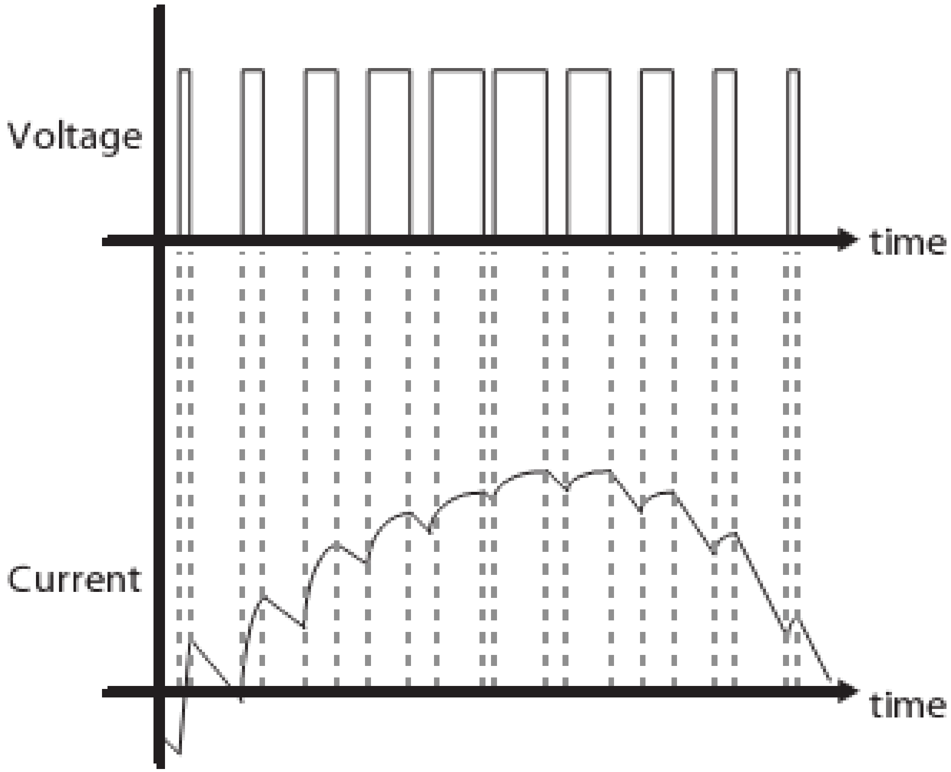




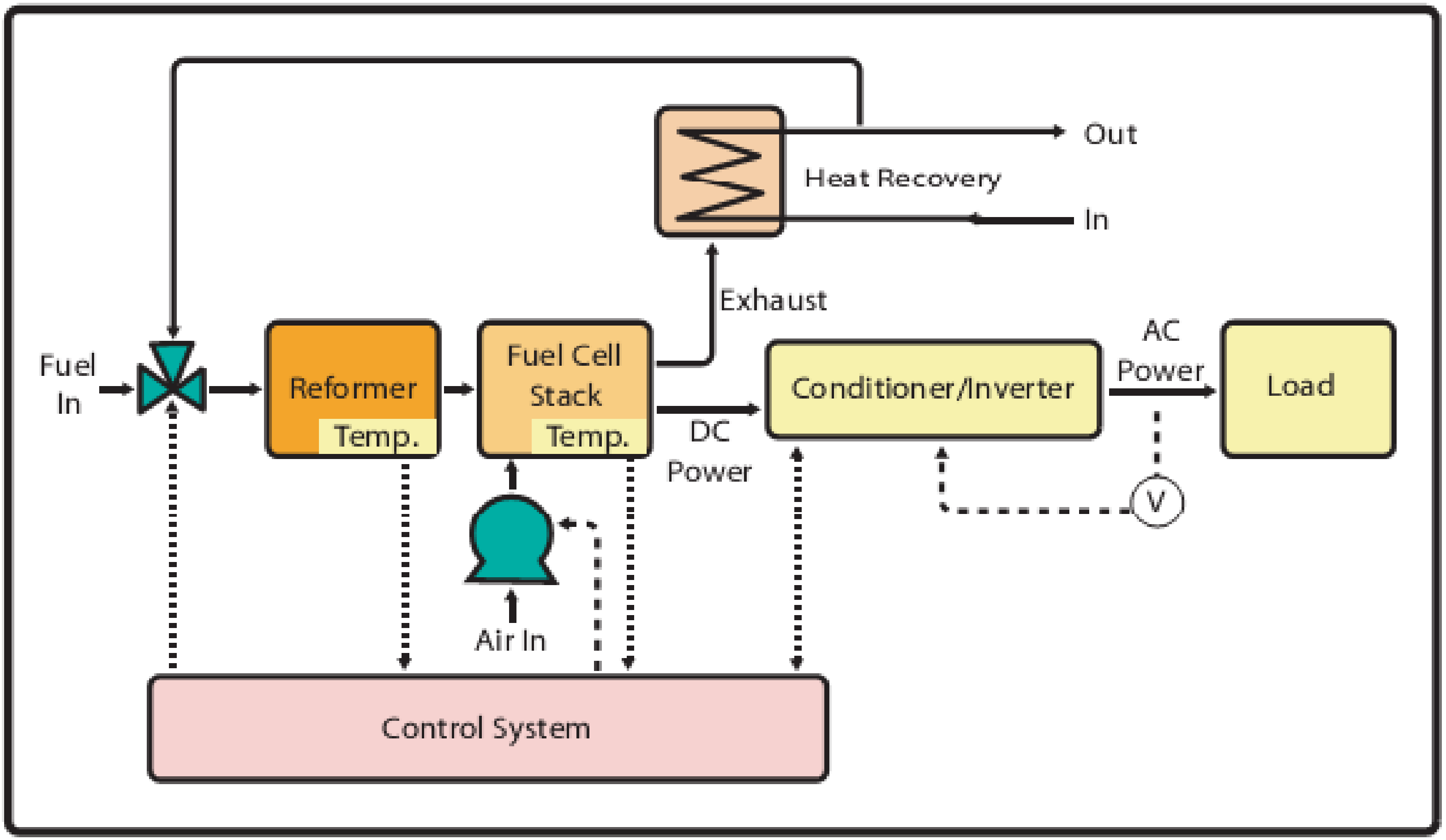
Power Inversion

- DC/AC conversion
- Appropriate stationary, automotive application

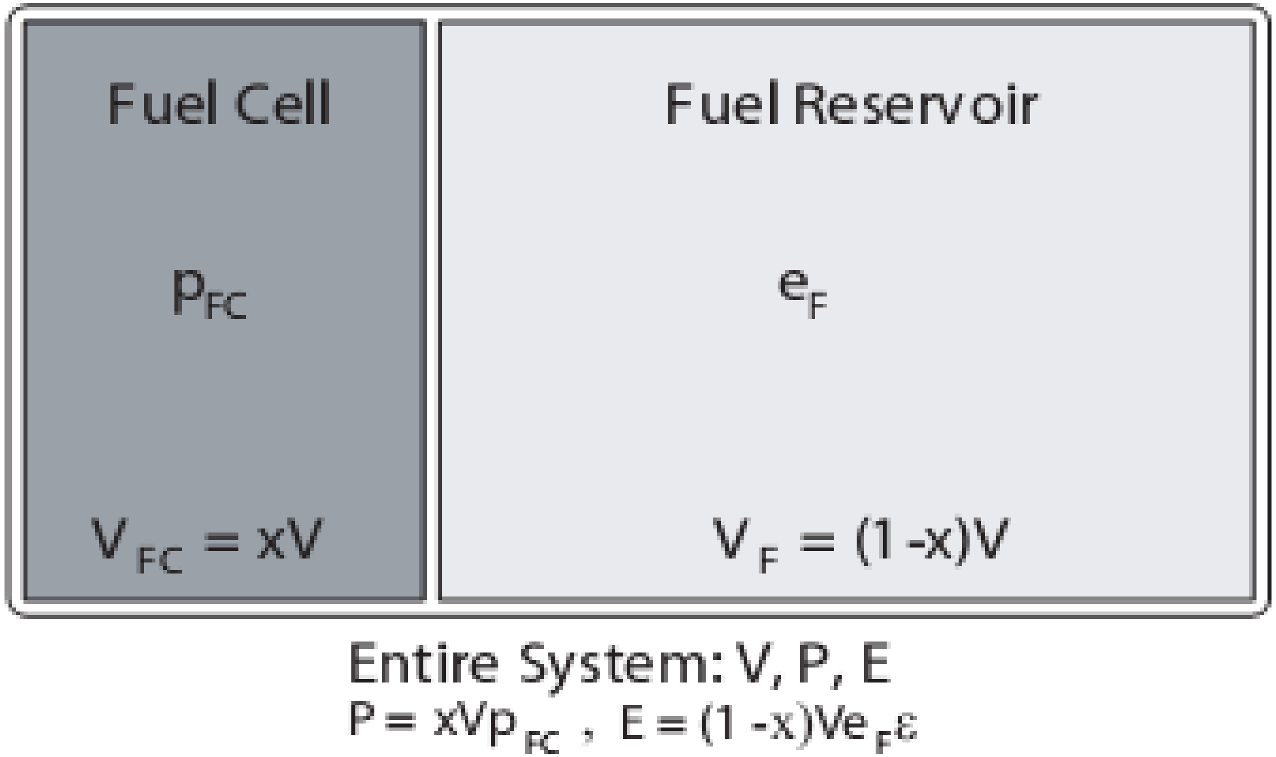
  Ex) Pulse width modulation



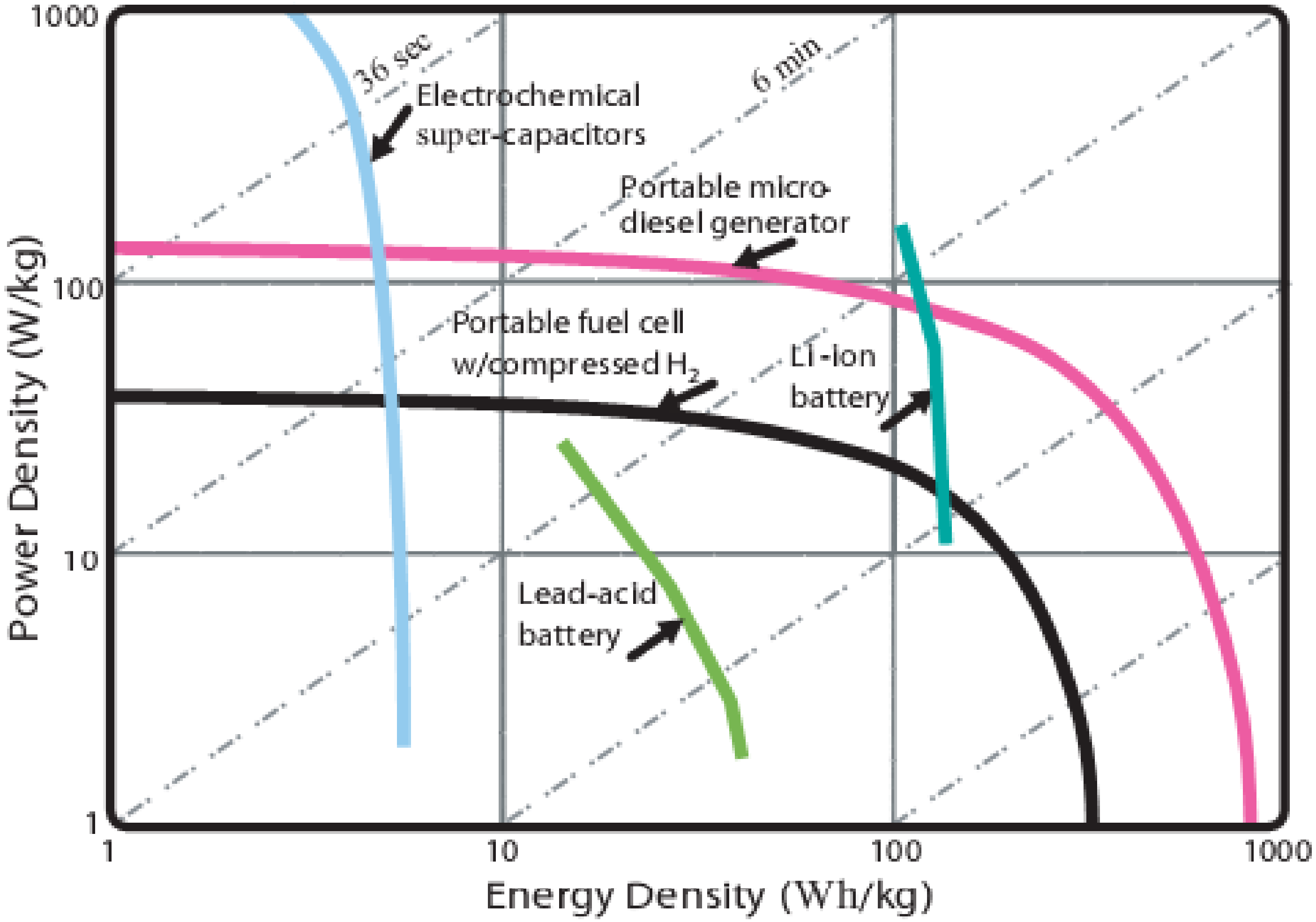
Monitoring/Control, Power Supply Management



Fuel Cell vs Fuel



Ragone Plot


1000
100
10
1
1
10
100
1000
Power Density (W/kg)
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