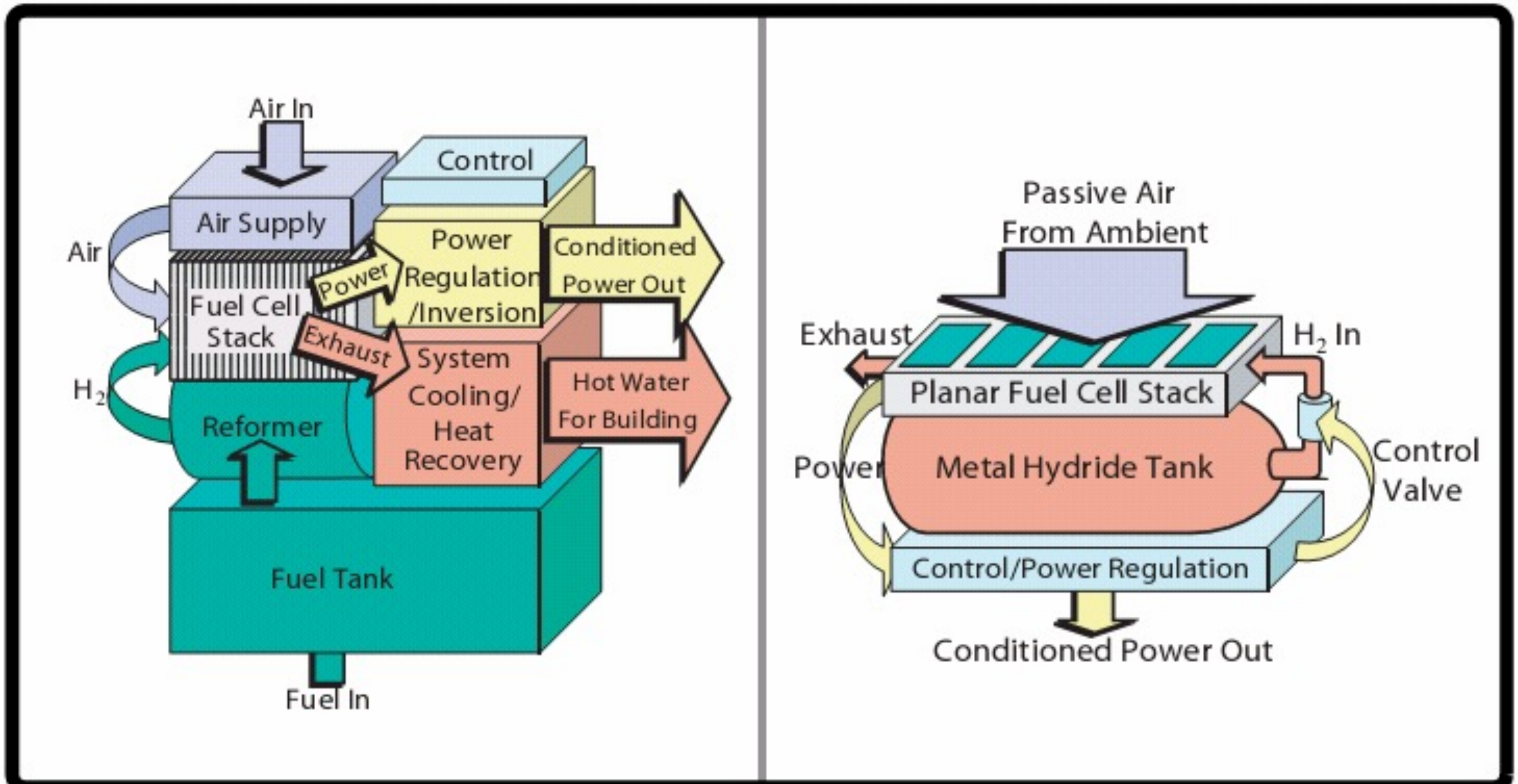
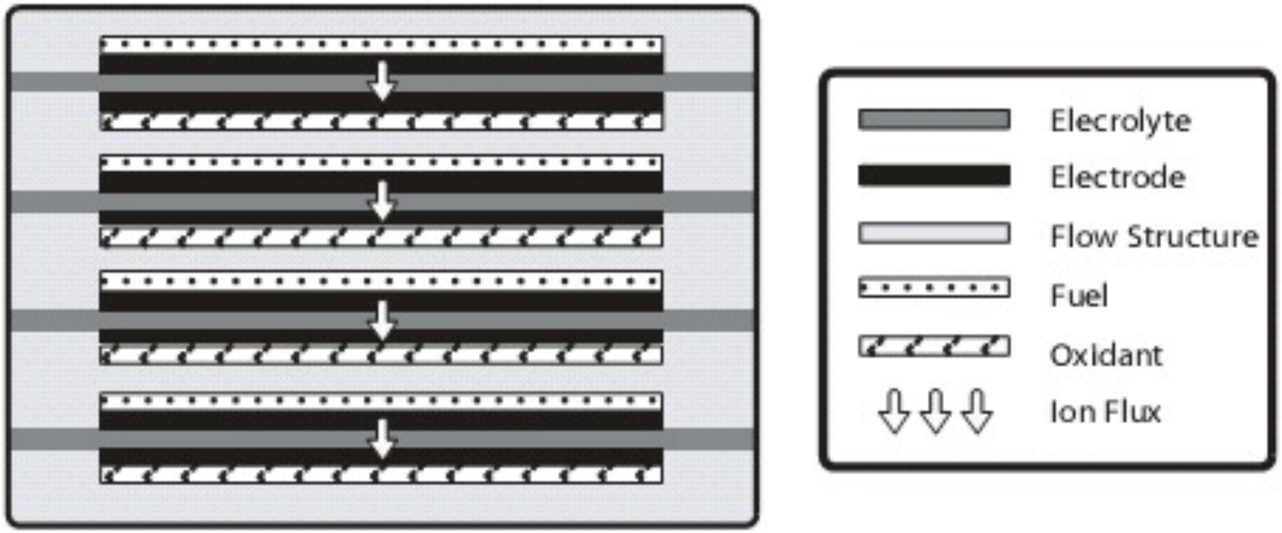
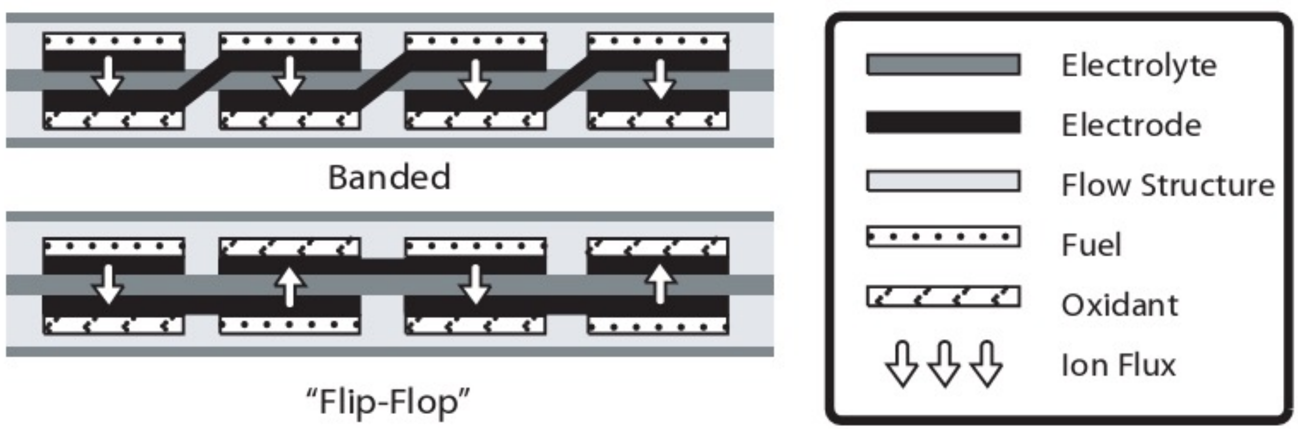
Fuel Cell Systems Overview

Fuel Cell Systems

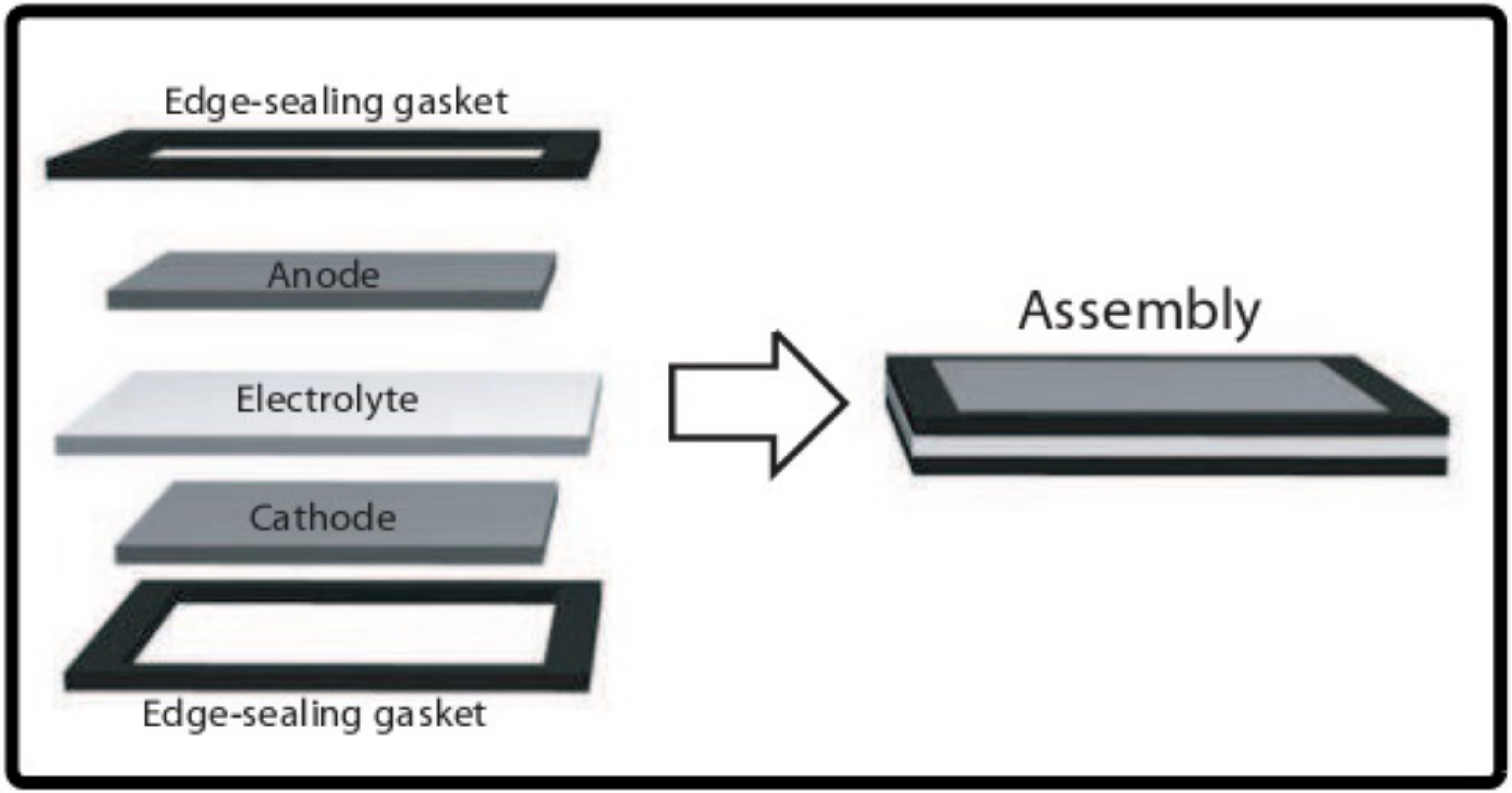


Fuel Cell Stacks





Fuel Cell Stacks



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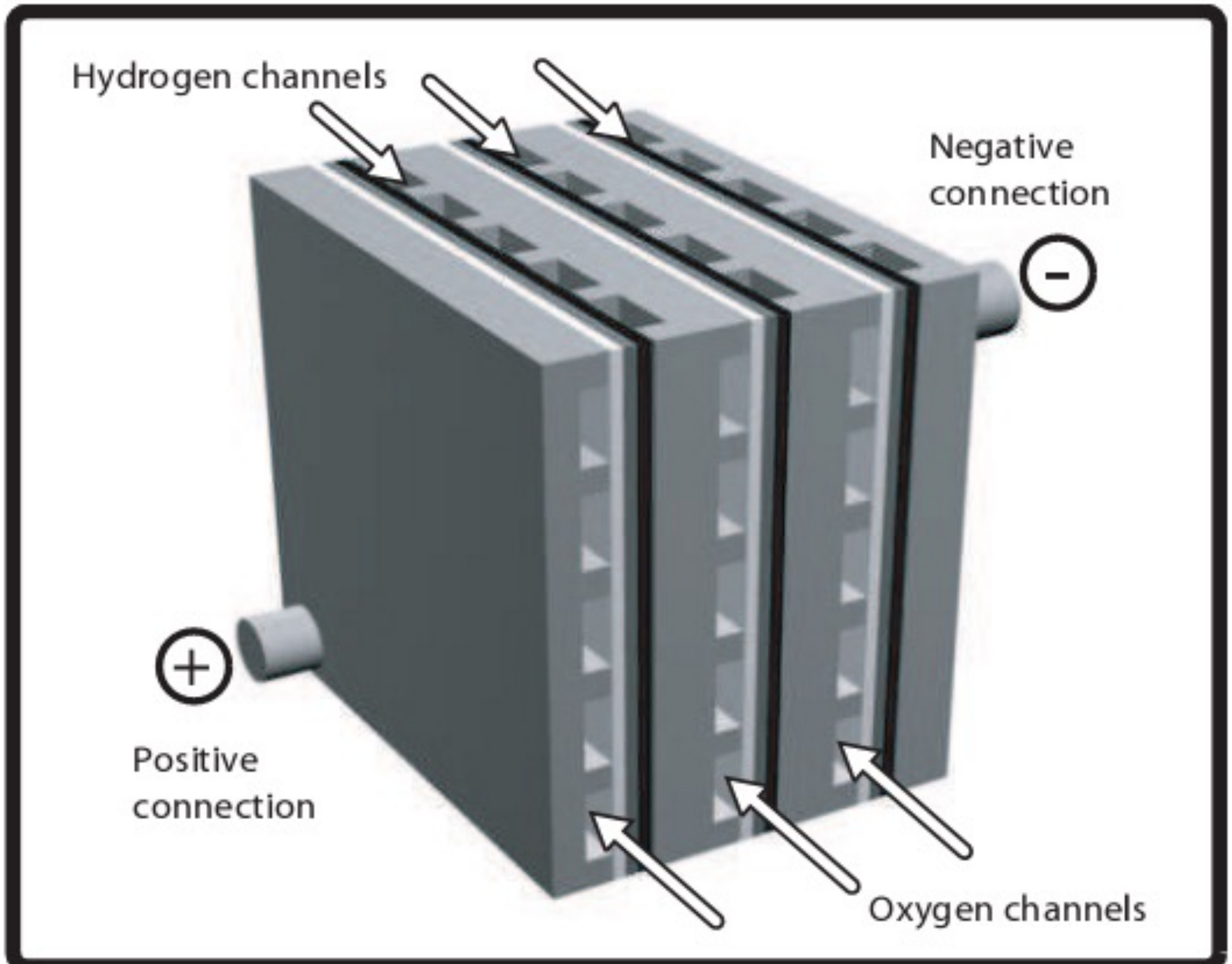
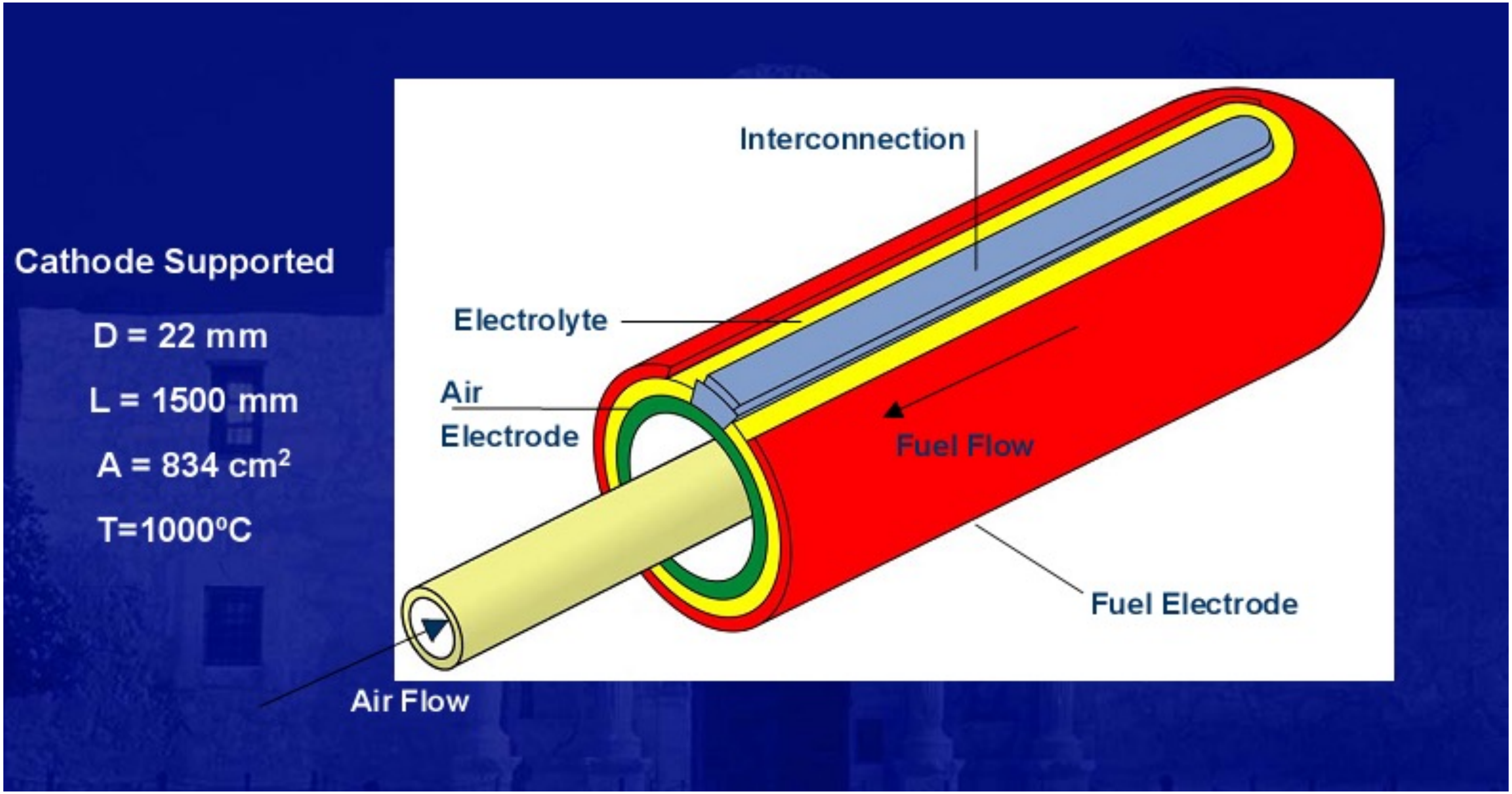


Tubular SOFC



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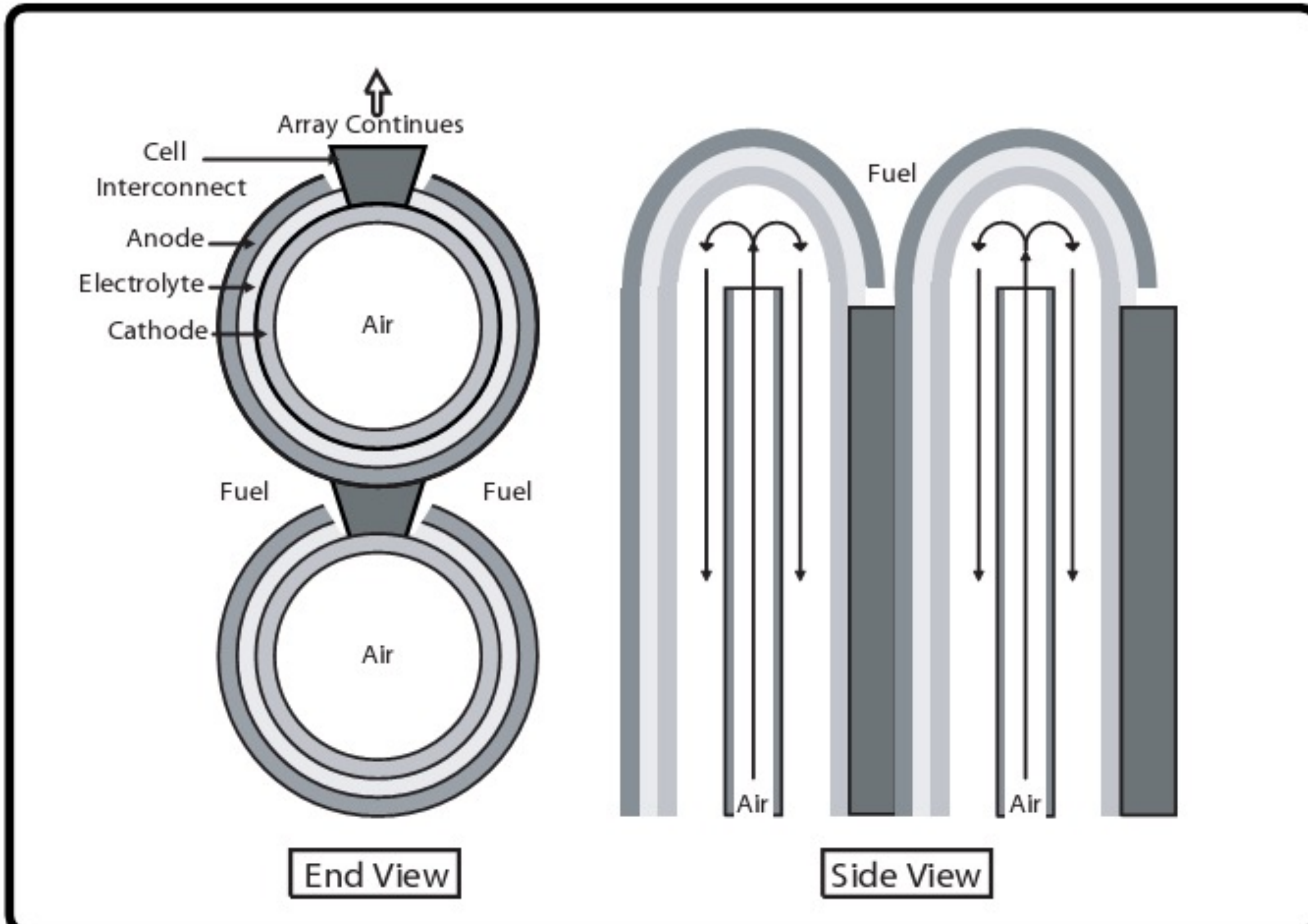
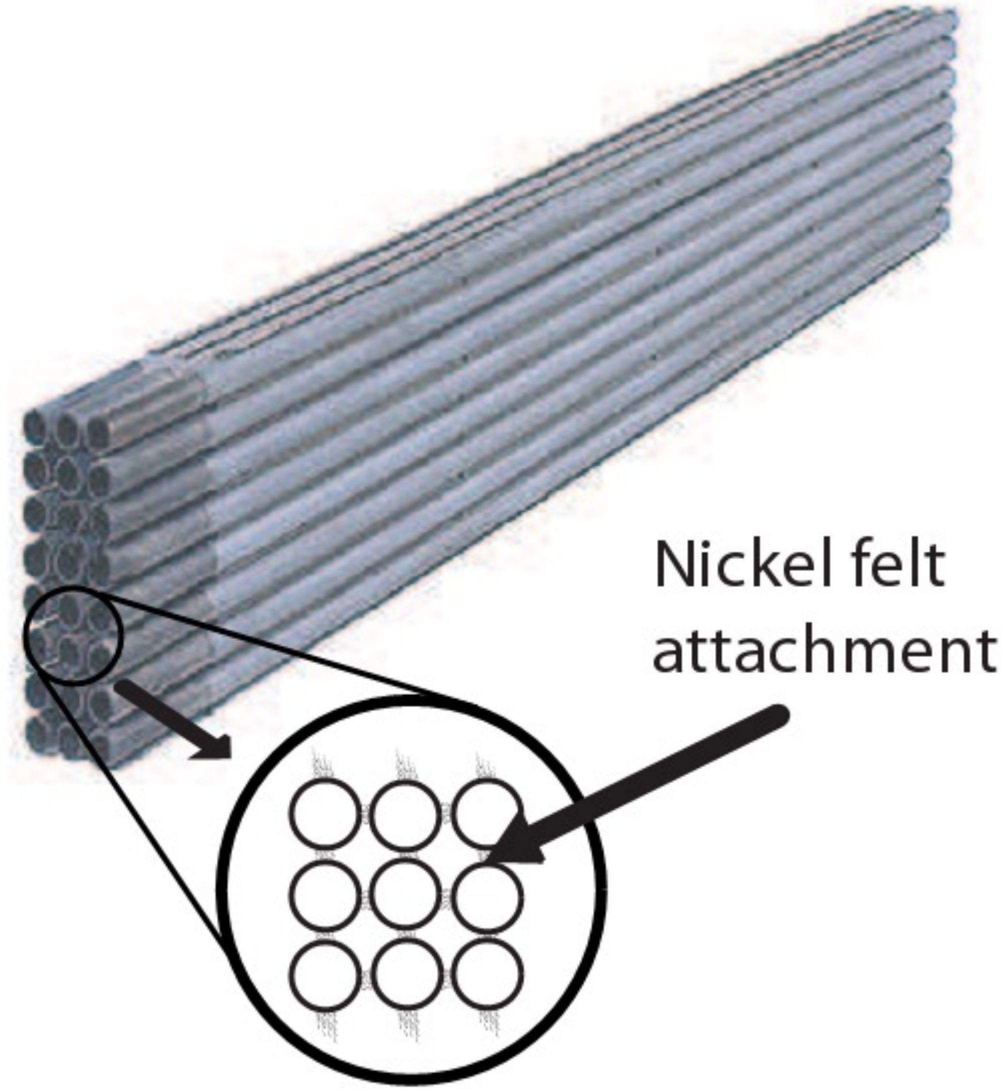
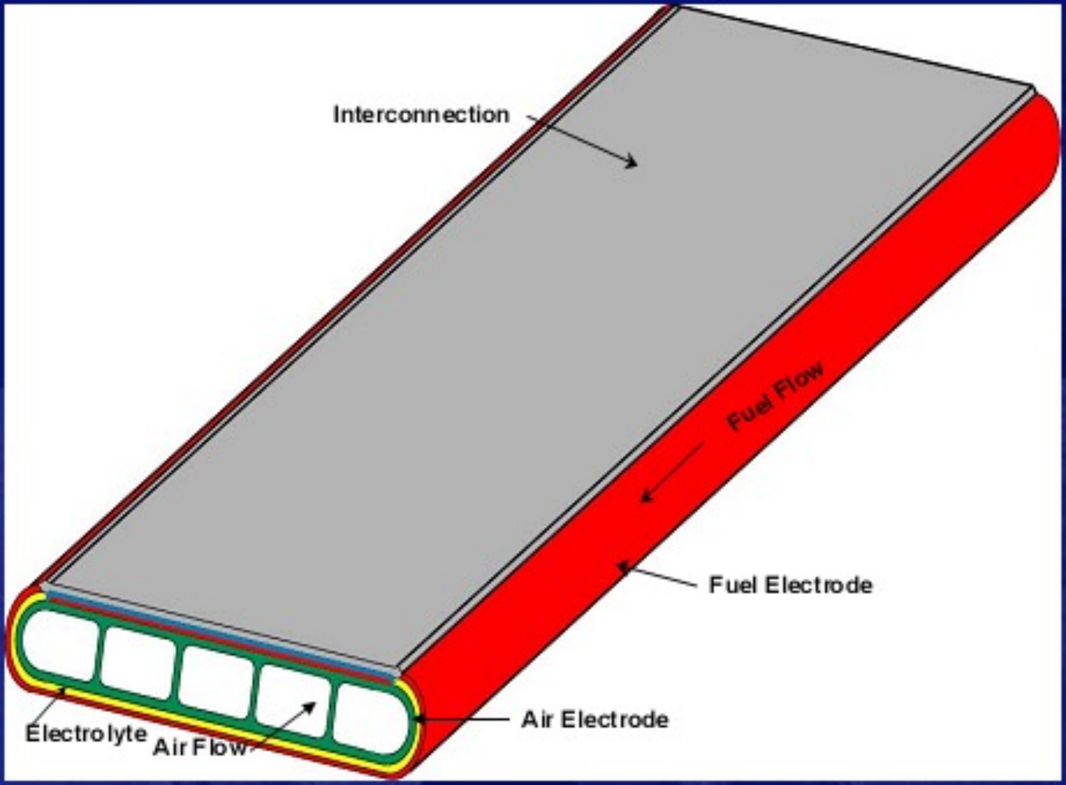


Tubular SOFC



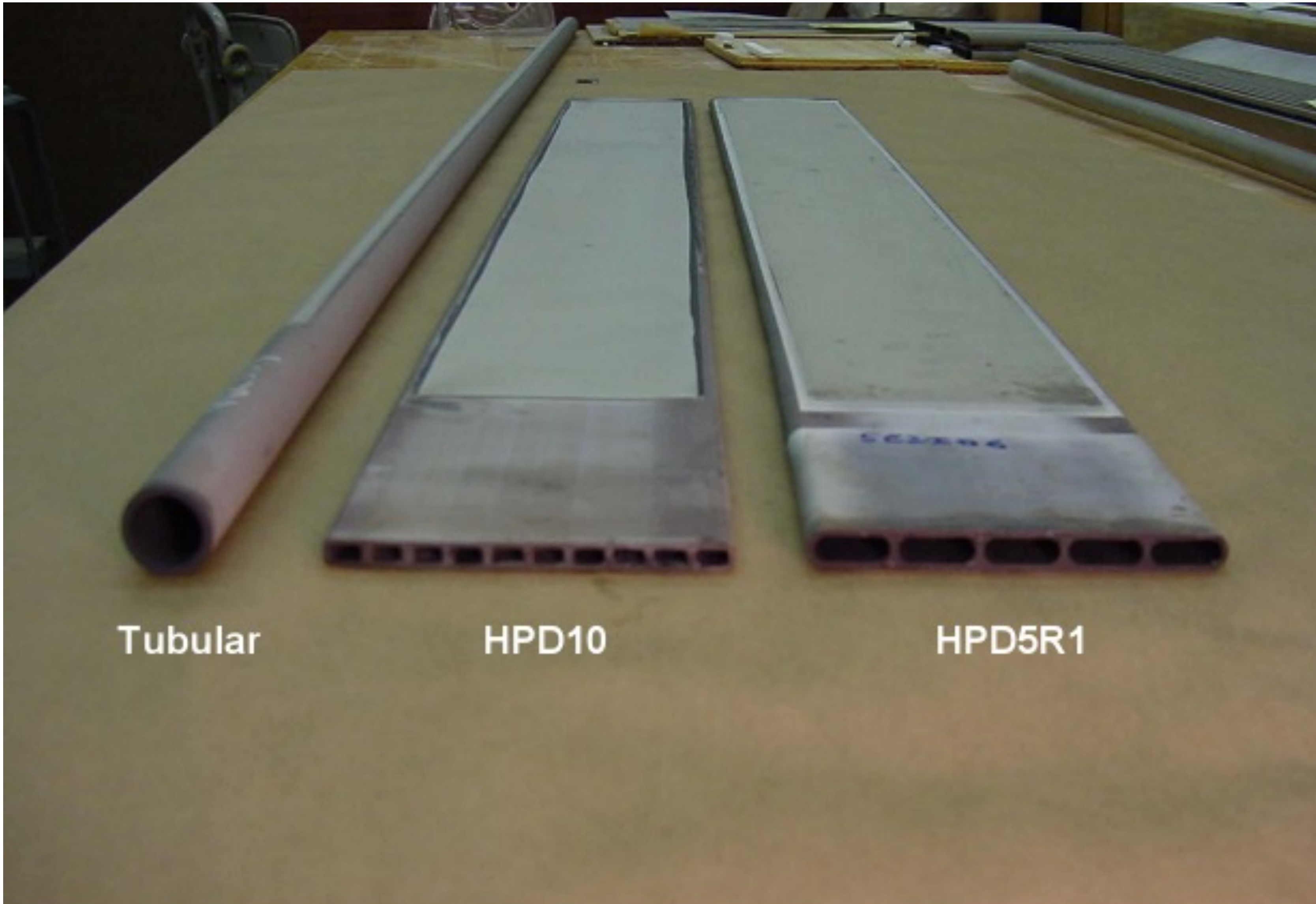
Flat Tubular SOFC

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

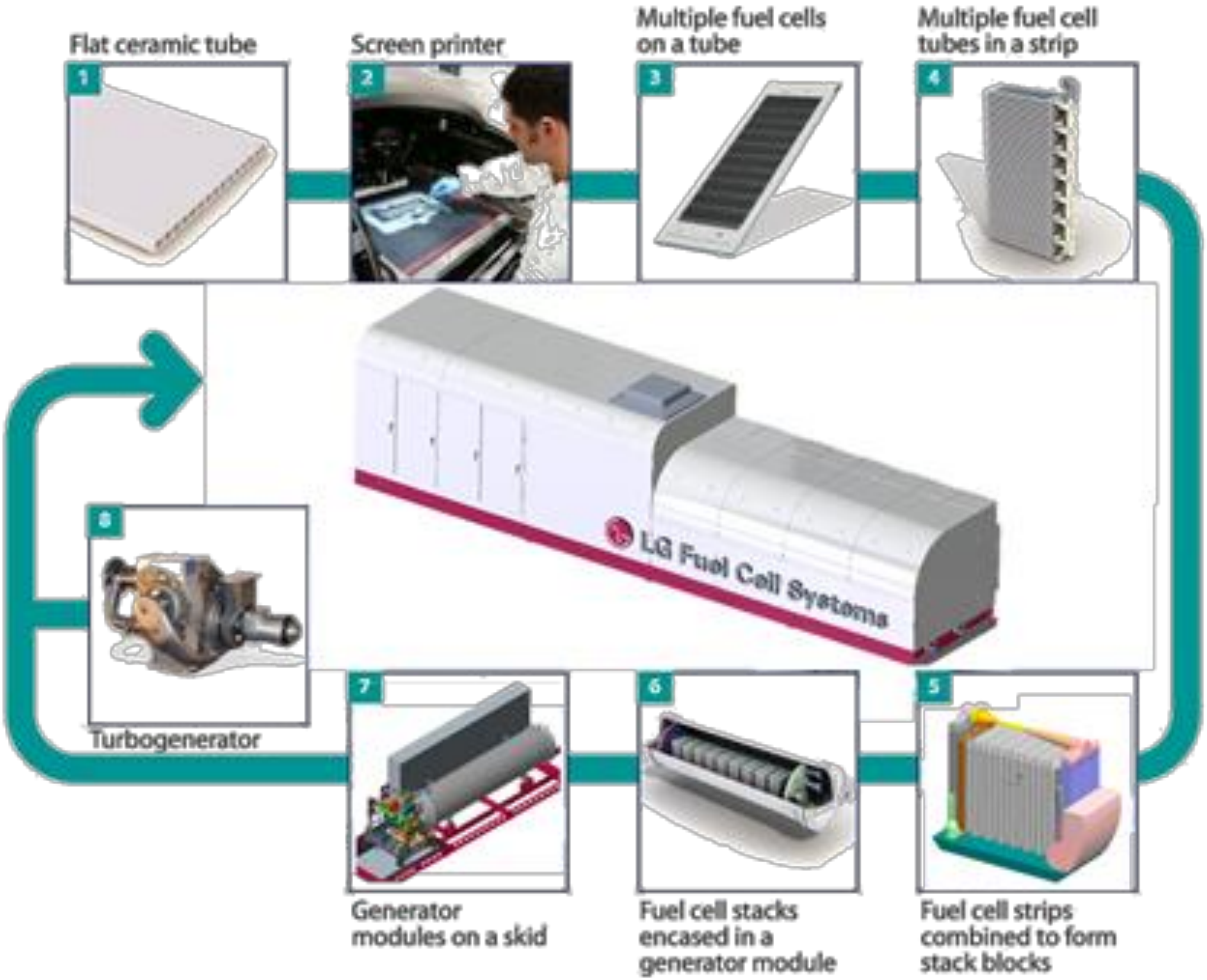


- Maintains seal-less design
- Reduction in cell resistance
- Increase in cell power density
- Eliminates air feed tubes

Flat Tubular SOFC



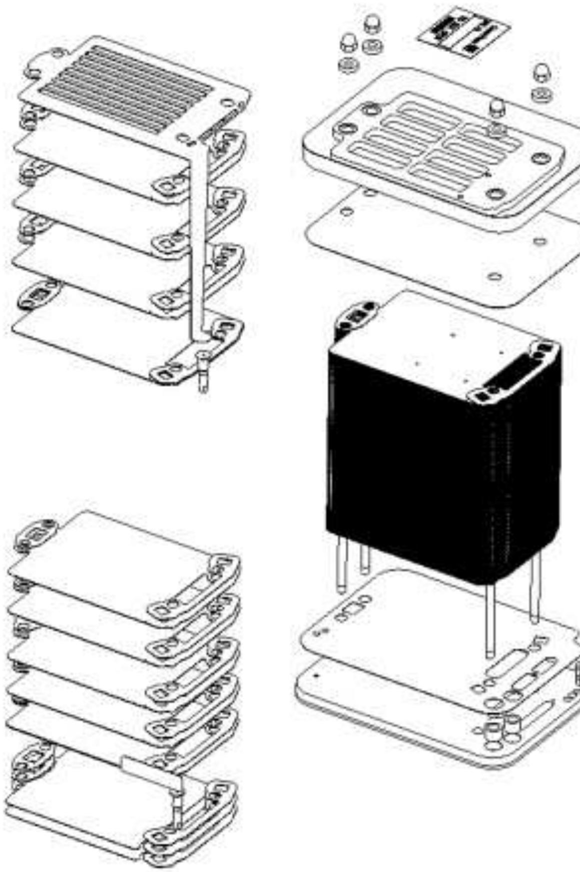
Flat Tubular SOFC

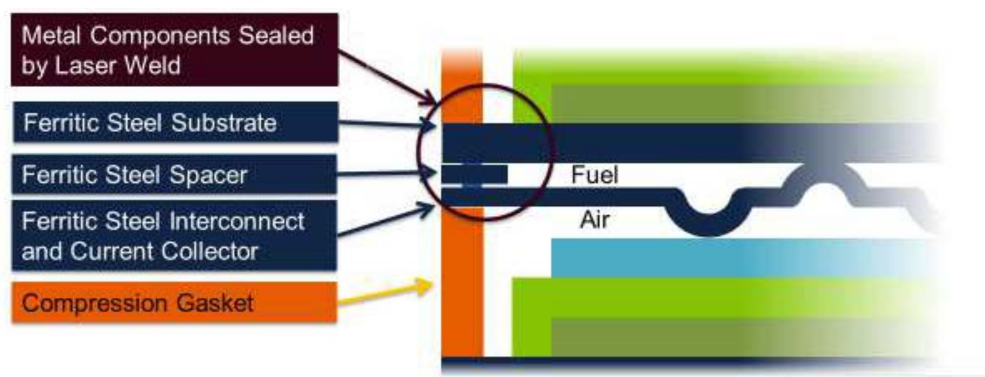


Planar SOFC's

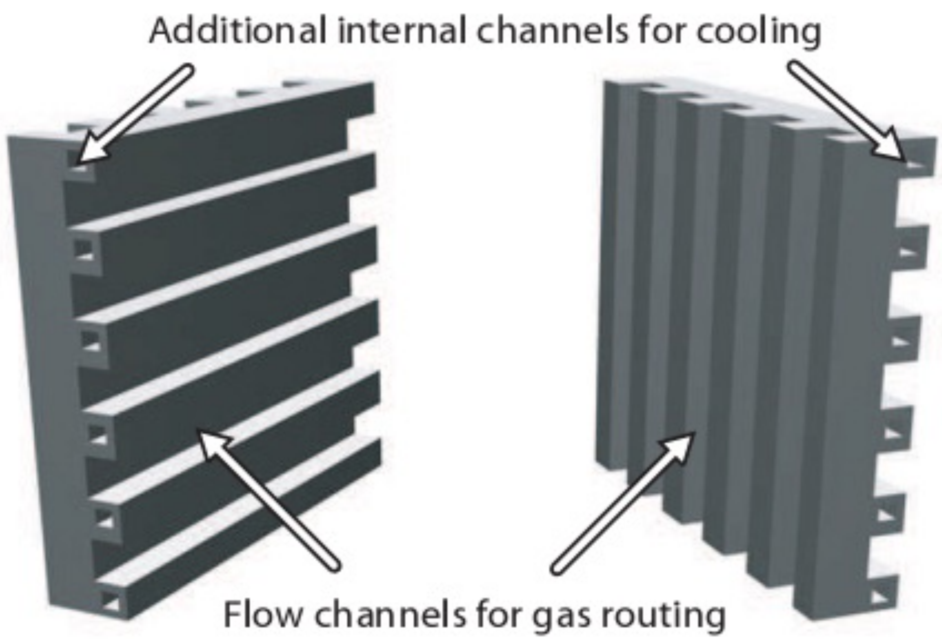
Ceres Power – Metal supported SOFC

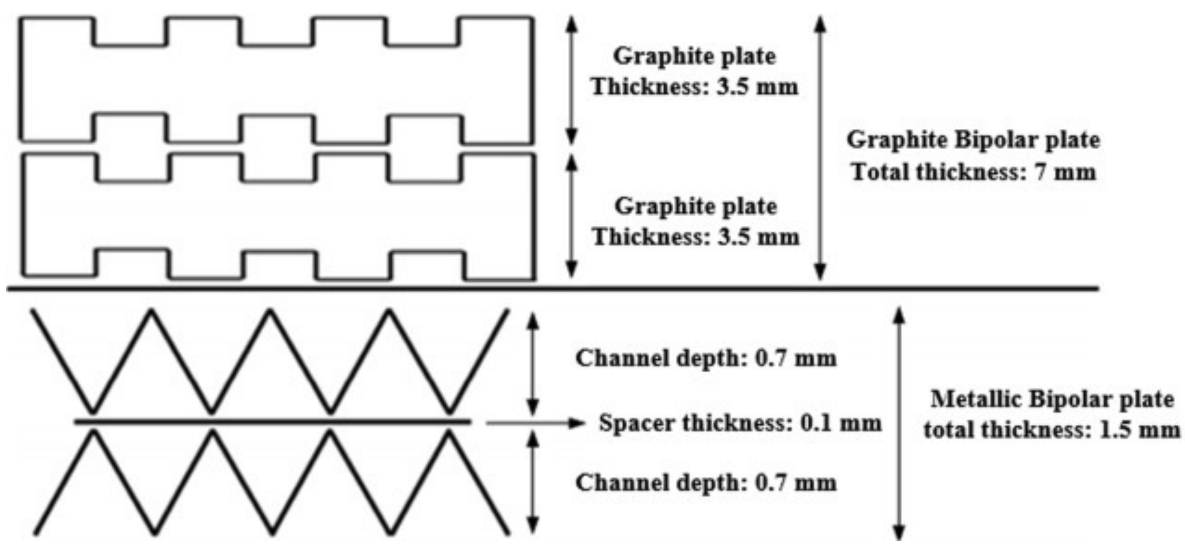
CeresPower limited



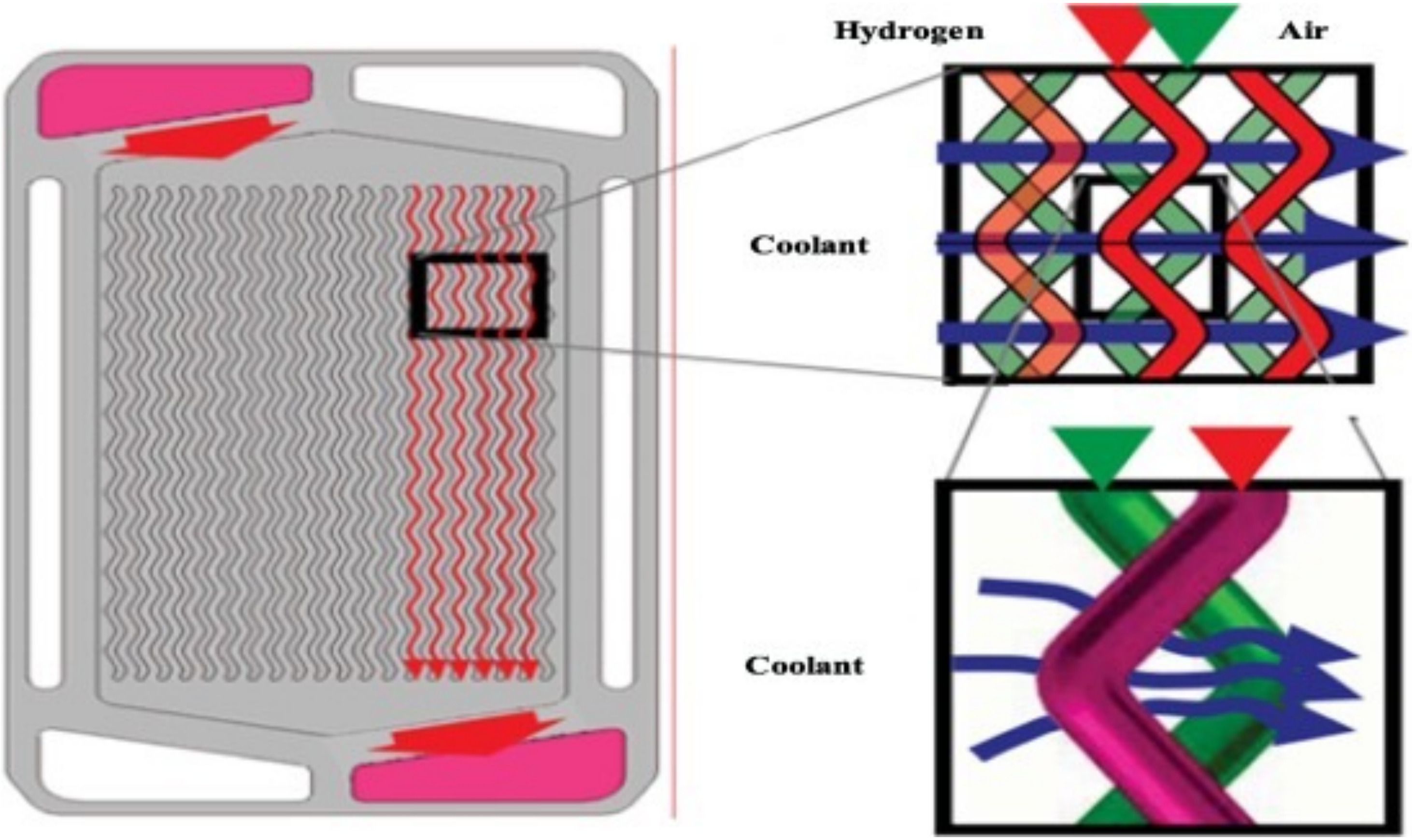


Thermal Management





Thermal Management



Honda's cooling channel design

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

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

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

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

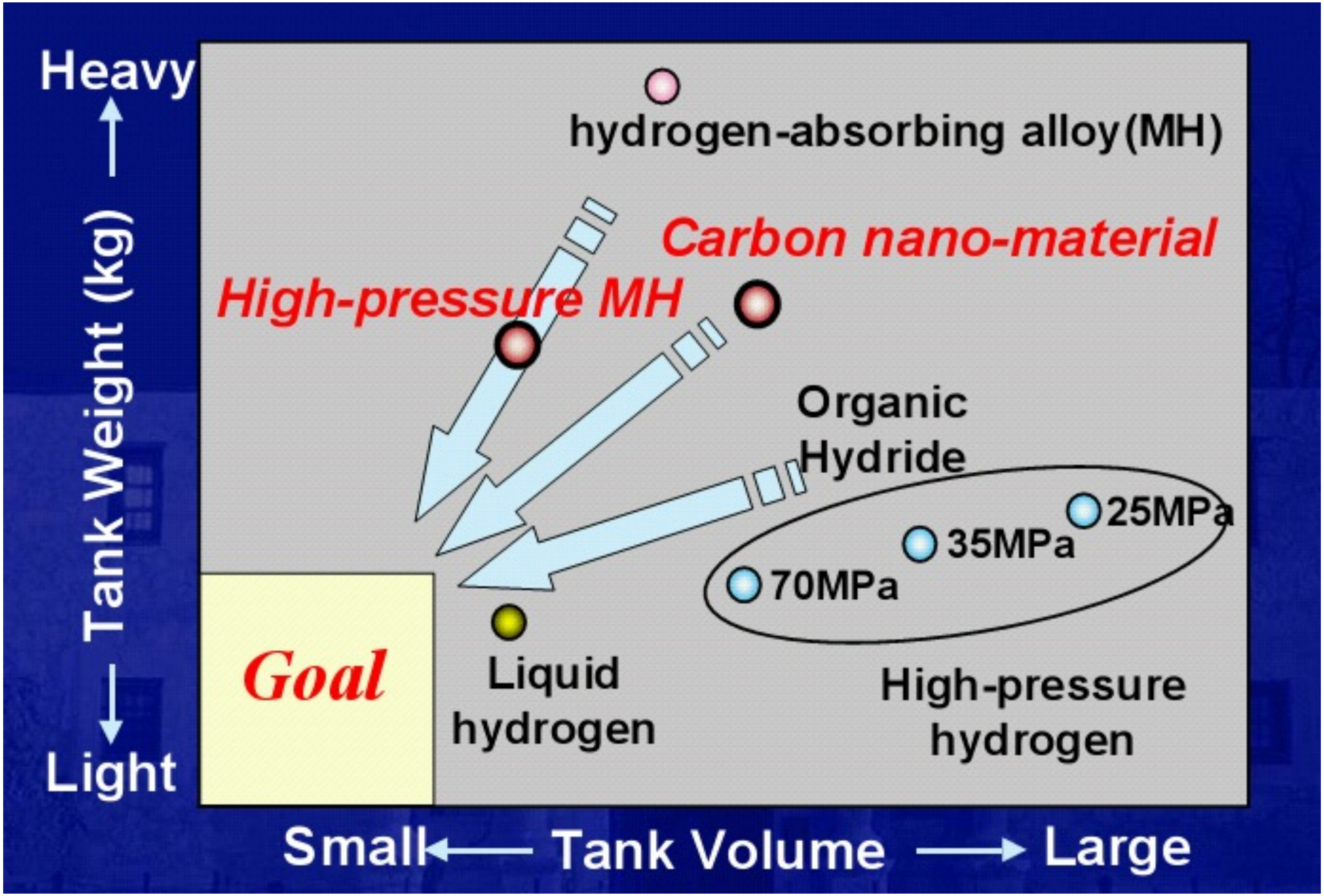
Hydrogen Storage

- 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

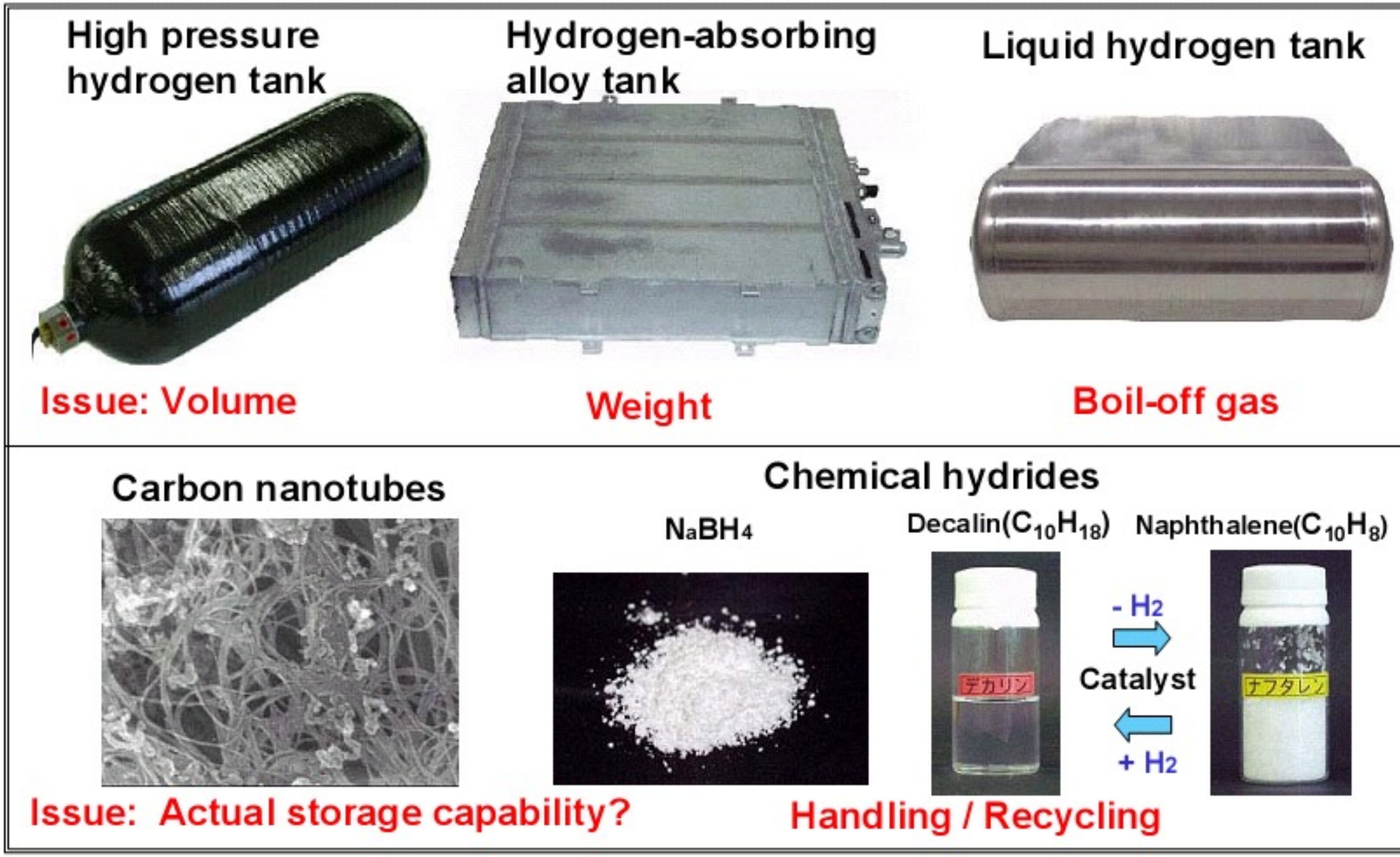
Hydrogen Storage

- 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



Hydrogen Carrier

- Hydrocarbon
  - -Methane(CH_4), ethane(C_2H_6), propane(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

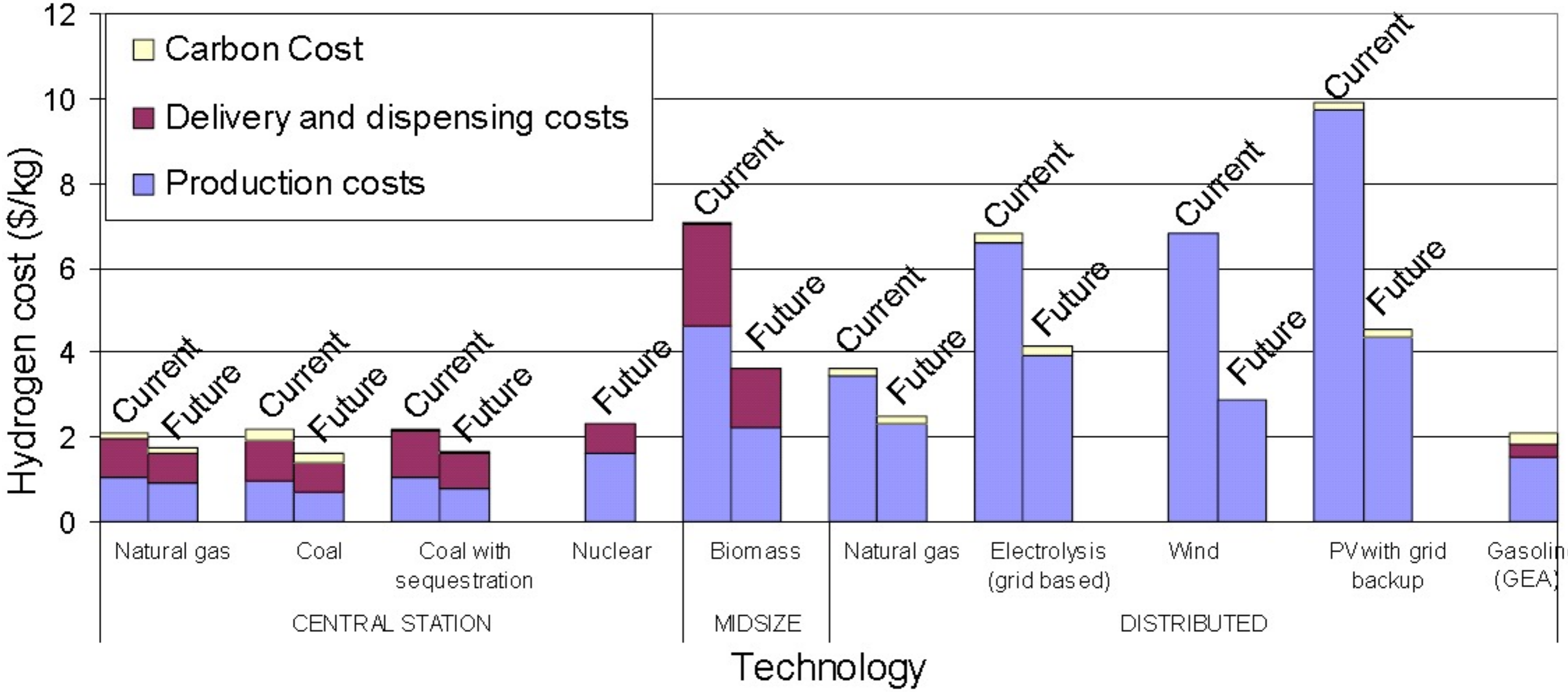
  -CO issue, hydrogen separation

  Ex) steam reforming

  $CH_3OH + H_2O => CO_2 + 3H_2$

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

Delivered Hydrogen Cost



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

*The National Academies, 2004

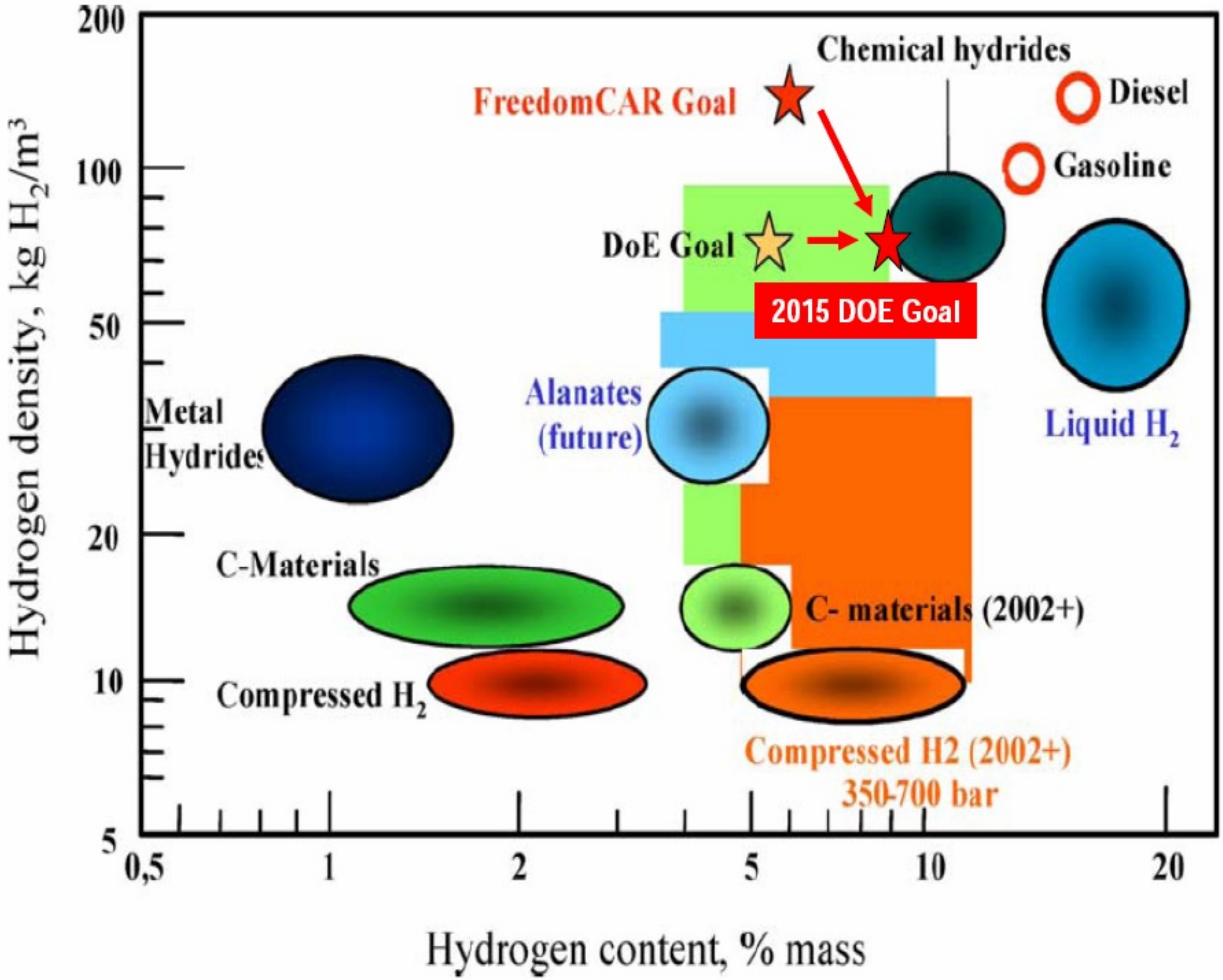
Hydrogen Carrier

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

TABLE 10.3. Qualitative Summary of Various Fuel/Fuel System Choices for Mobile and Stationary Fuel Cell Applications

Fuel System	Gravimetric Storage Energy Density	Volumetric 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	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	Low	Low	High	Low	Expensive, hard to reform
		Fuels for Stationary Generation Applications			
Neat hydrogen	Low	Low	Low	High	Must have H_2 source!
Methane	Moderate	Moderate	High	Moderate	Best for high-temperature fuel cells
Biogas	Low	Low	Low	Moderate	Best for high-temperature fuel cells

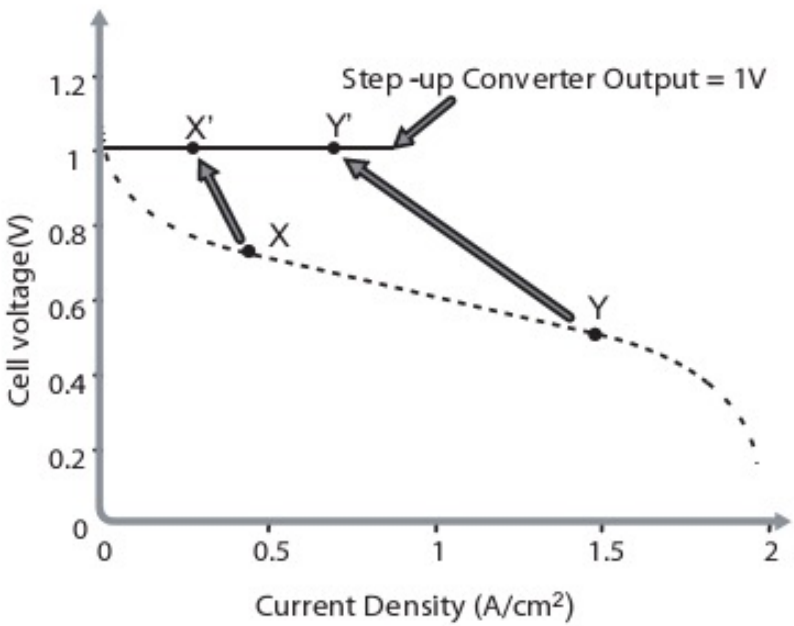
DOE Target

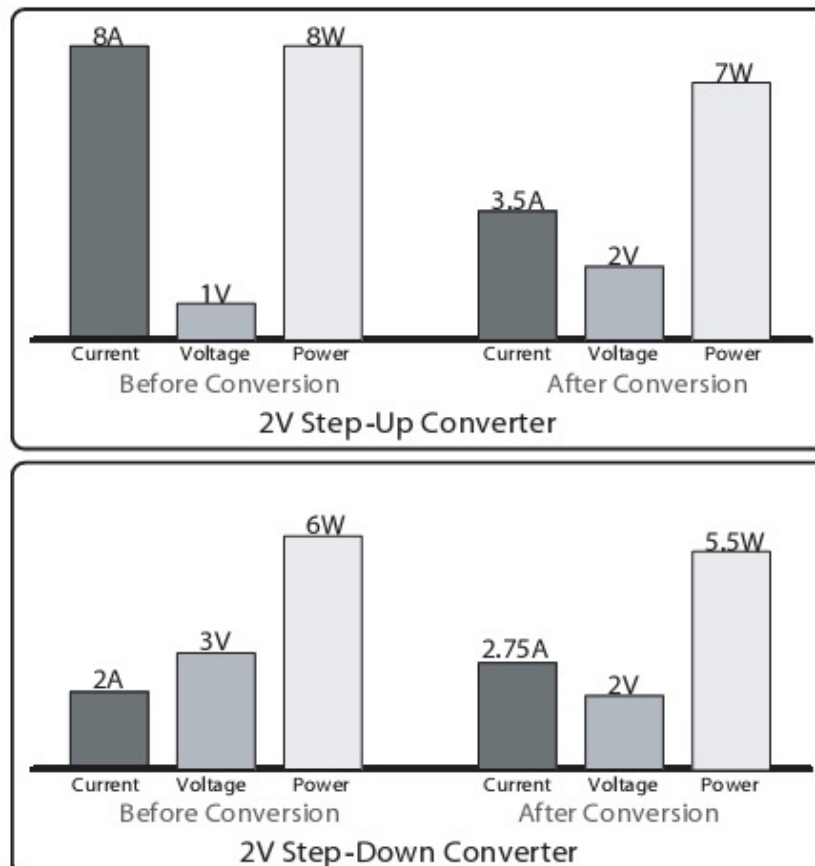


200
100
50
20
10
5
0,5
1
2
5
10
20
Hydrogen density, kg H_2/m^3
Hydrogen content, % mass
Chemical hydrides
FreedomCAR Goal
Diesel
Gasoline
DoE Goal
2015 DOE Goal
Metal Hydrides
Alanates (future)
Liquid H_2
C-Materials
C- materials (2002+)
Compressed H_2
Compressed H2 (2002+) 350-700 bar

Power Regulation

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

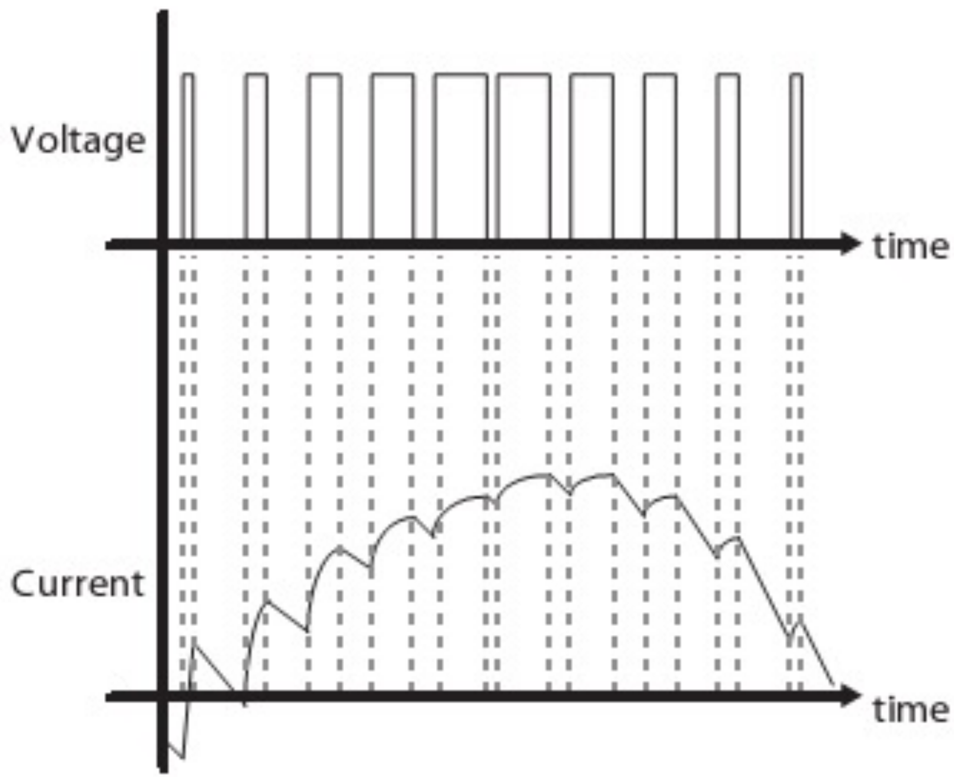




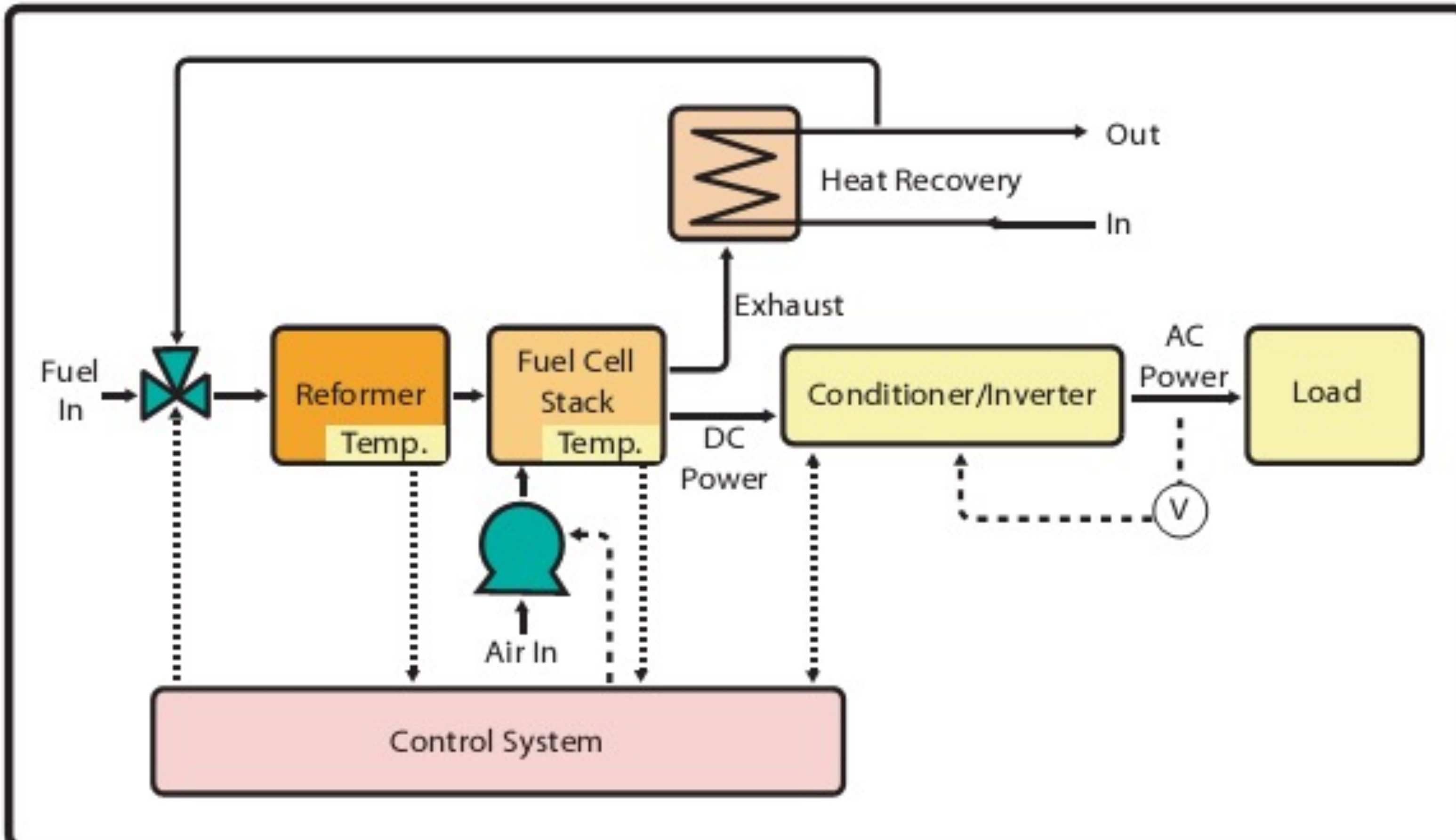
Power Inversion

- DC/AC conversion
- Appropriate stationary, automotive application

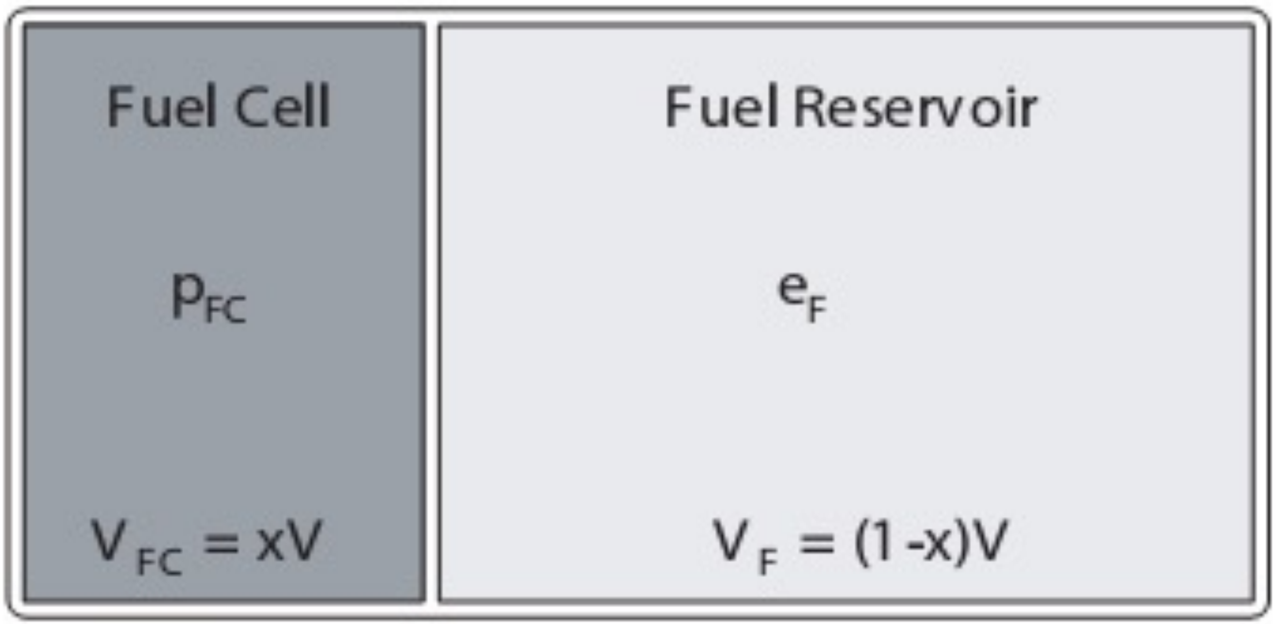
  Ex) Pulse width modulation



Monitoring/Control, Power Supply Management



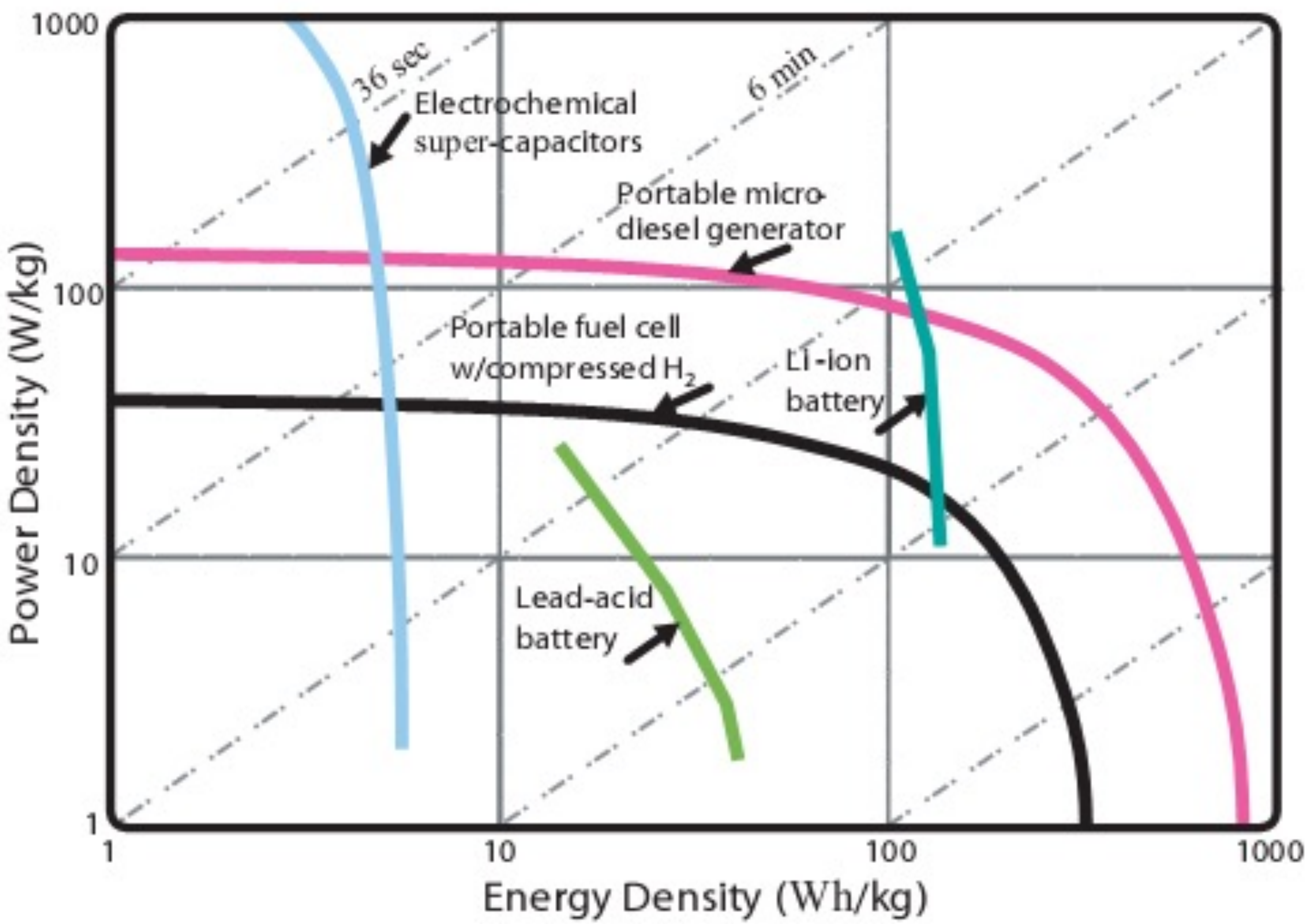
Fuel Cell vs Fuel



Entire System: V, P, E

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

Ragone Plot



1000
100
10
1
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