PEM Fuel Cell Technology Status and Applicability for Propulsion of Autonomous Underwater Vehicles

Frano Barbir
Proton Energy Systems
50 Inwood Road, Rocky Hill, CT 06067
www.protonenergy.com

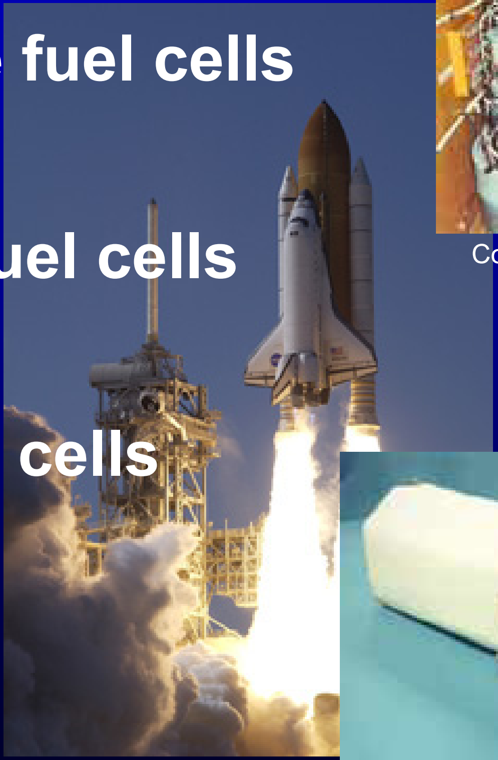
PEM Fuel Cell Applications

- Space
- Automotive
- Stationary Power
- Portable Power
- Battery Replacement
- (Sub)marine

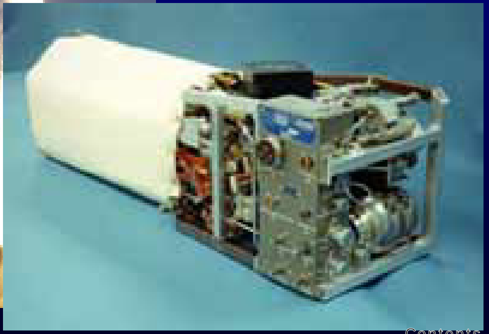
Space Applications

- PEM Fuel Cells used in Gemini program
- Apollo program used alkaline fuel cells
- Space Shuttle uses alkaline fuel cells
- Renewed interest in PEM fuel cells

Courtesy of UTC Fuel Cells



Courtesy of NASA



Courtesy of UTC Fuel C

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DAIMLERCHRYSLER

GM

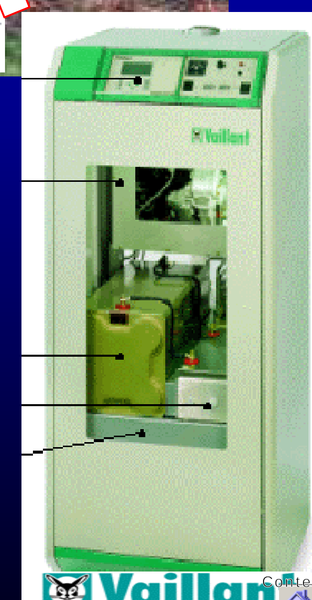
Every car manufacturer has already demonstrated a fuel cell vehicle

Fuel Cell Buses have already been demonstrated

Contents

Stationary fuel cells are in pilot programs!

Residential fuel cells are being developed



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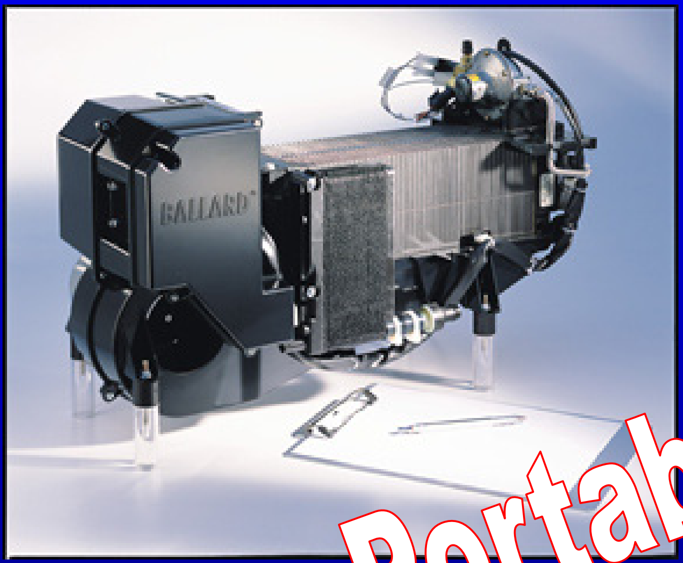
Portable power - first commercial fuel cells?



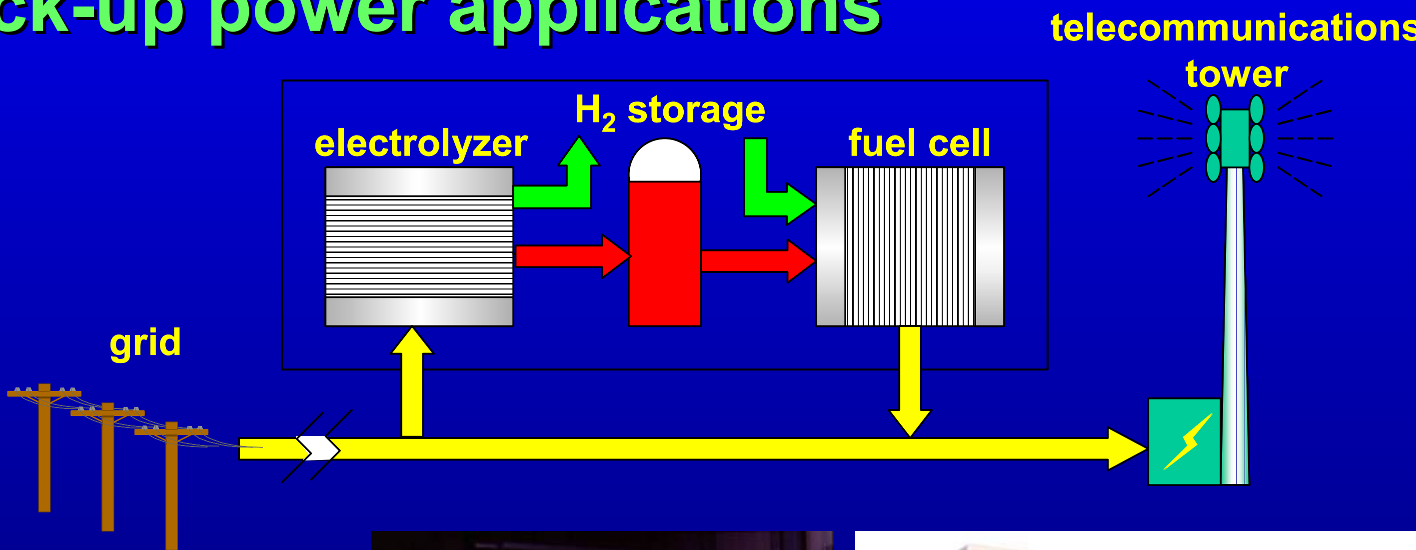
Ballard 1 kW Nexa Fuel Cell Power Module

Coleman 1 kW Fuel Cell Generator
with Ballard Nexa power module inside

H-Power 500 W stackable module

PROTON ENERGY SYSTEMS

Regenerative fuel cells for back-up power applications



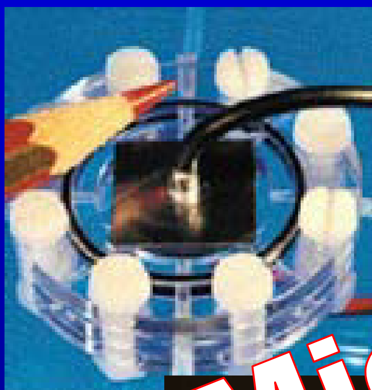
PROTON ENERGY SYSTEMS

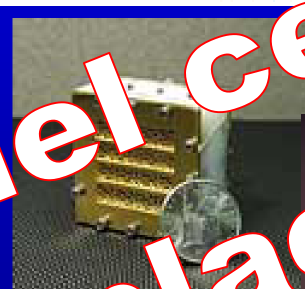
Micro-fuel cells - battery replacement

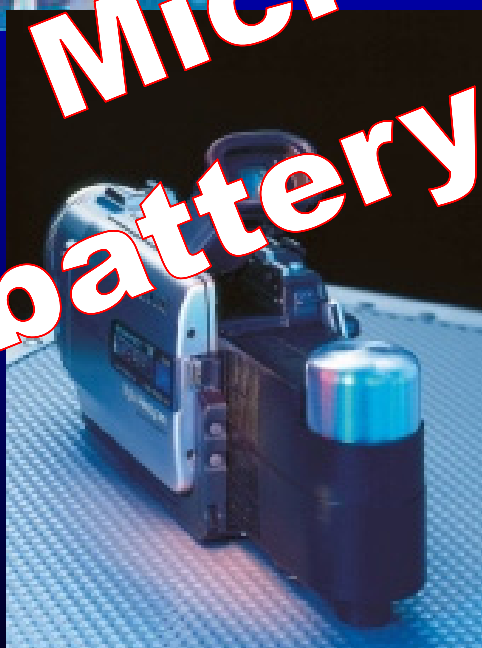
ISE
Fraunhofer Institut
Institut
Solare Energiesysteme

mti micro fuel cells

MOTOROLA
intelligence everywhere



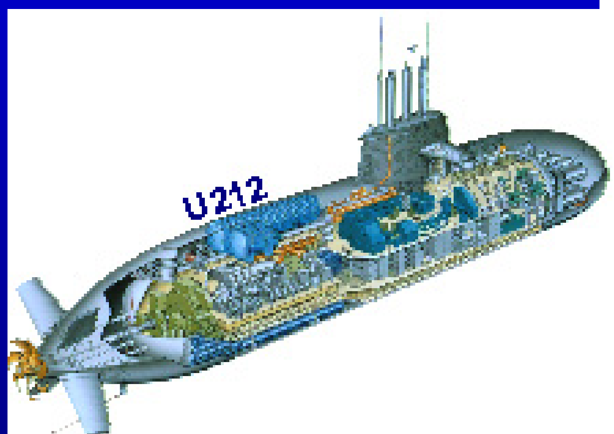


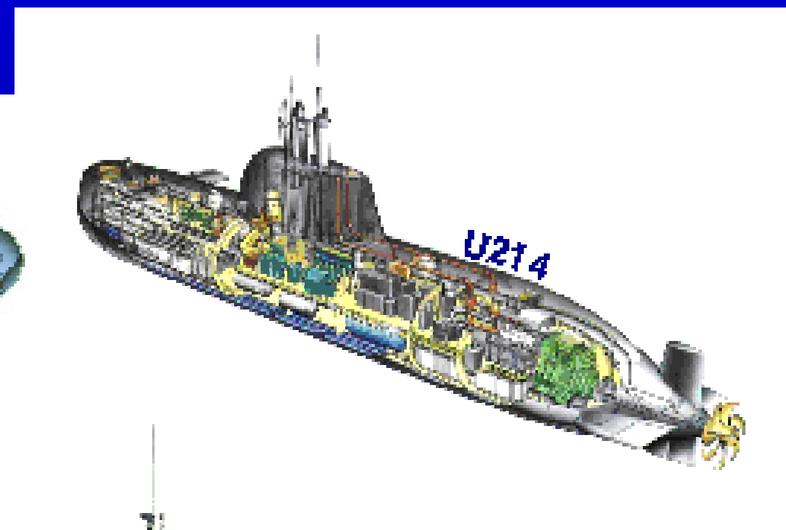


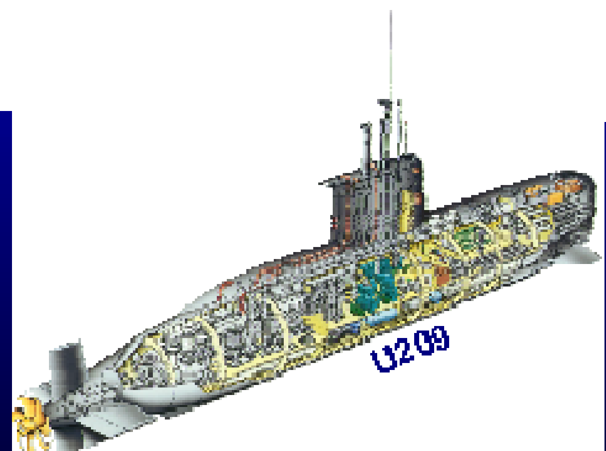
PEM Fuel Cells Technology Status

- **Power output:** from several Watts up to 250 kW
- **Performance**
  - **Power density:** up to 1 W/cm^2 = 10 kW/m^2
  - **Efficiency:** <0.4
  - **Size:** >10 kg/m^2; 6 lit/m^2 (stack)
- **Weight&Volume:** 1 kW/kg; <1 kW/l (stack)
- **Durability:** <5,000 hours
- **System issues:** fuel choice, operating pressure; operating temperature; heat rejection; water management; operation at extreme conditions; load following; hybridization

German Fuel Cell Submarine Program

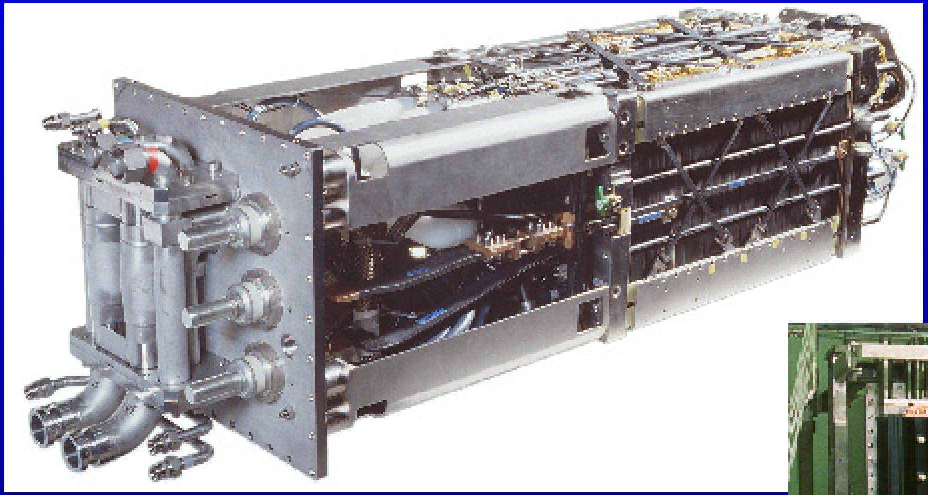




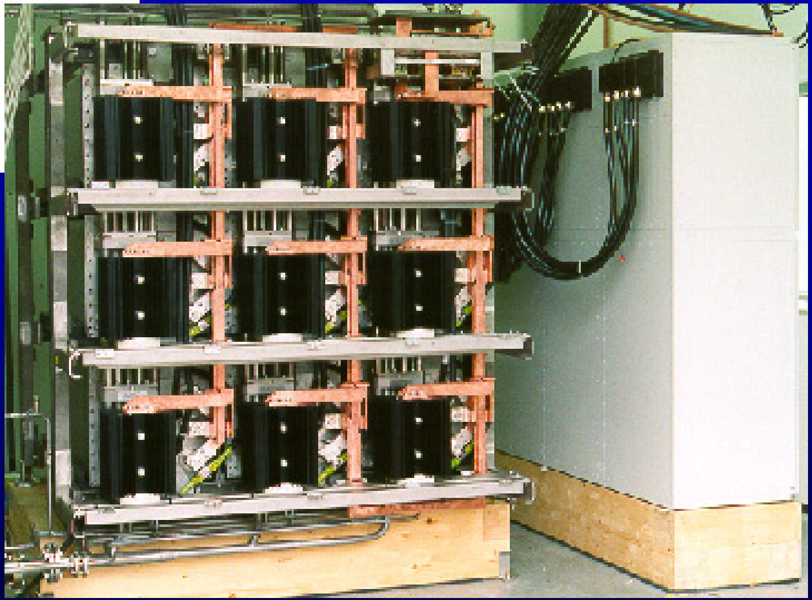


German Fuel Cell Submarine Program

Siemens Fuel Cells

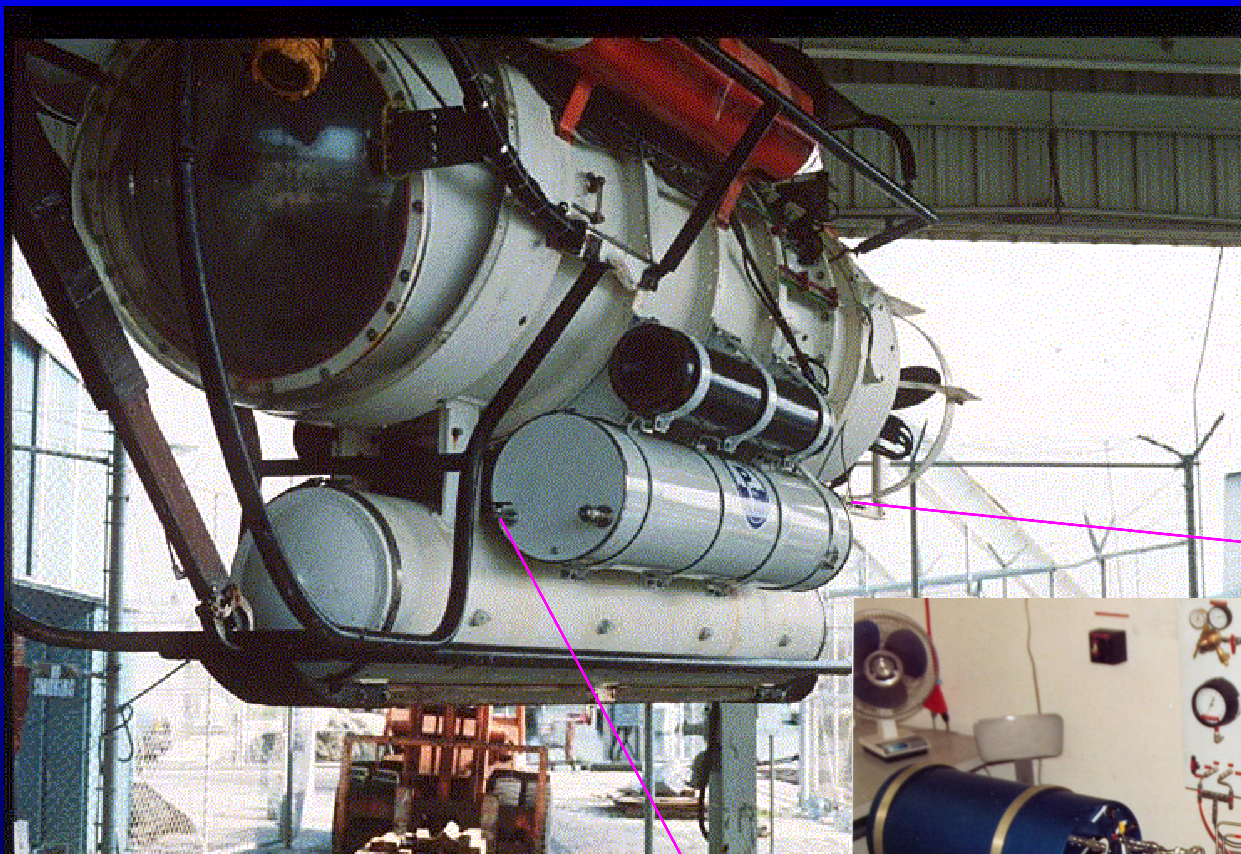


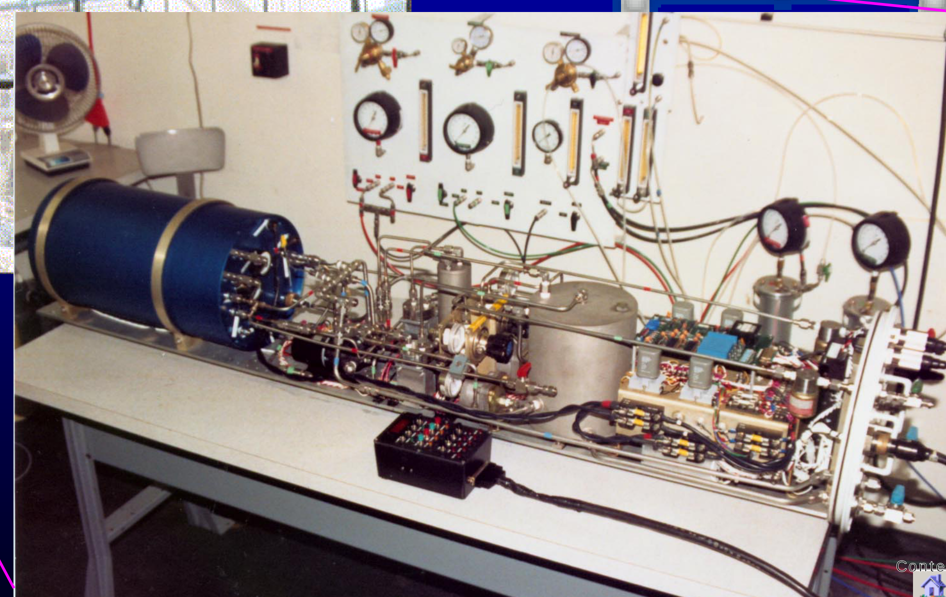
120 kW PEM Fuel Cell Module



Fuel Cell Battery for U212
including switchboard

First PEM Fuel Cell Powered Submarine (1989)





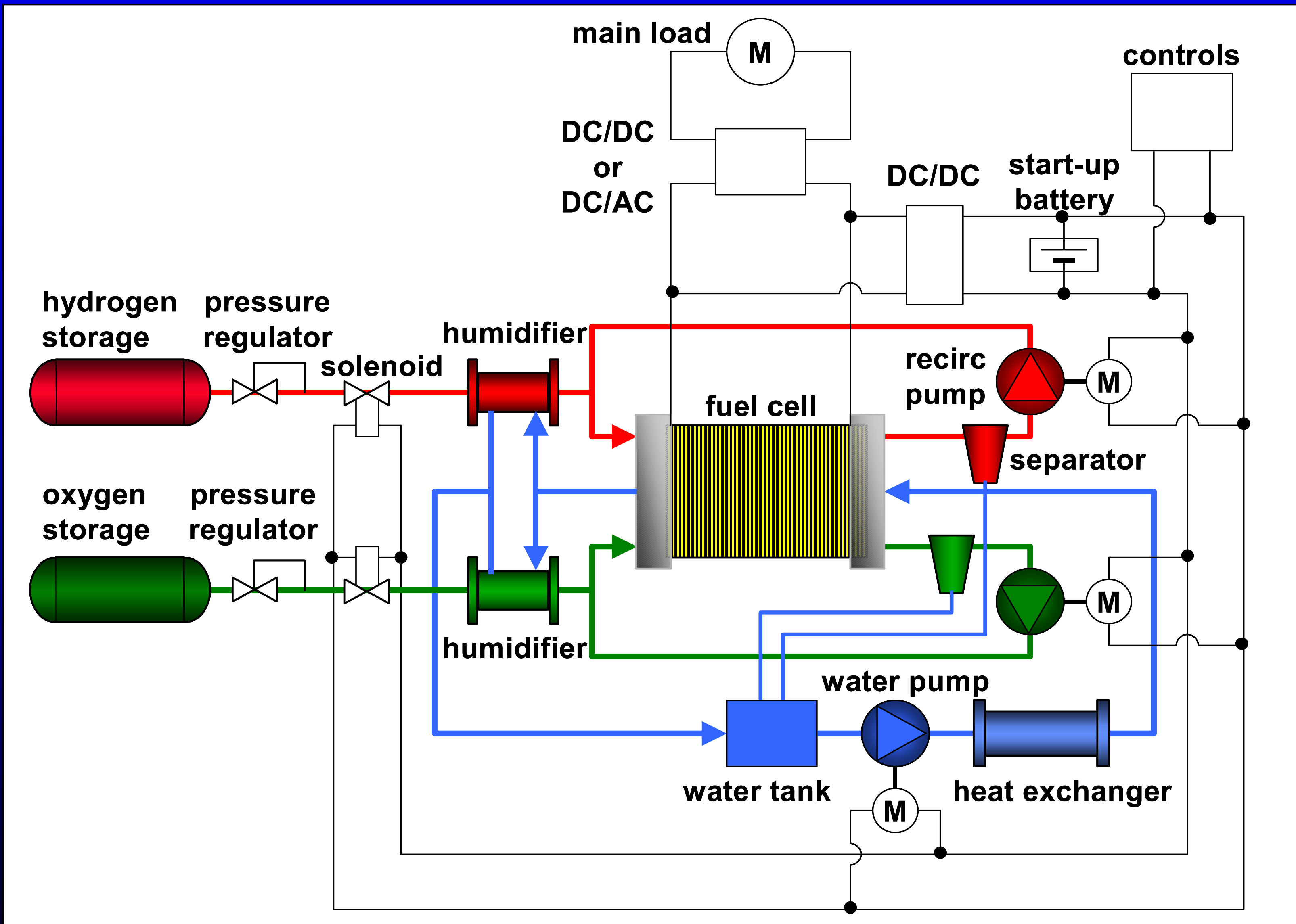
PC1401 by Perry Group

Contents

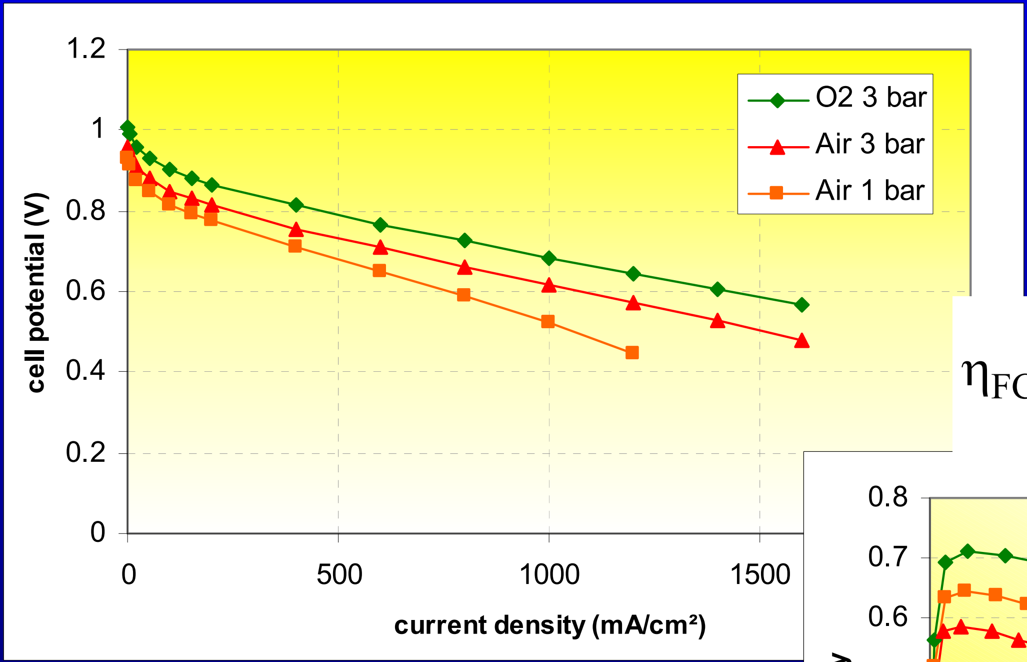
Specific requirements for submarine applications

Power output:	?
Oxidant:	oxygen
Fuel:	hydrogen, methanol, diesel?
Efficiency:	the higher the better (but limited by size)
Size:	the smaller the better
Weight:	? (ballast)
Load following:	yes (fuel cell only) and no (hybrid)
Refueling time:	?
Reliability:	extremely important

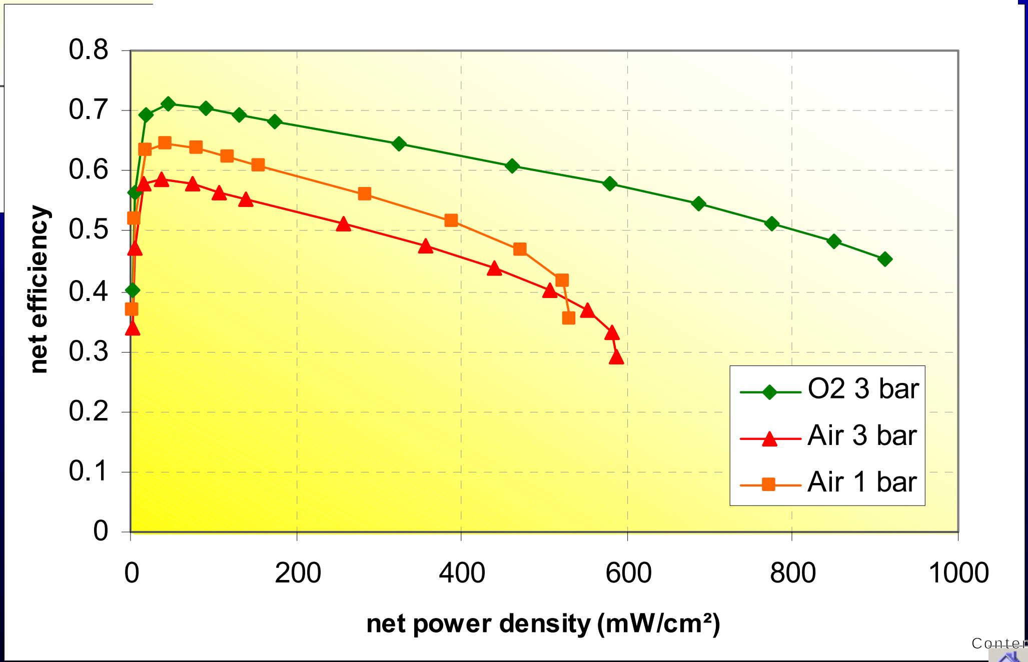
Generic “Closed Loop” Fuel Cell System



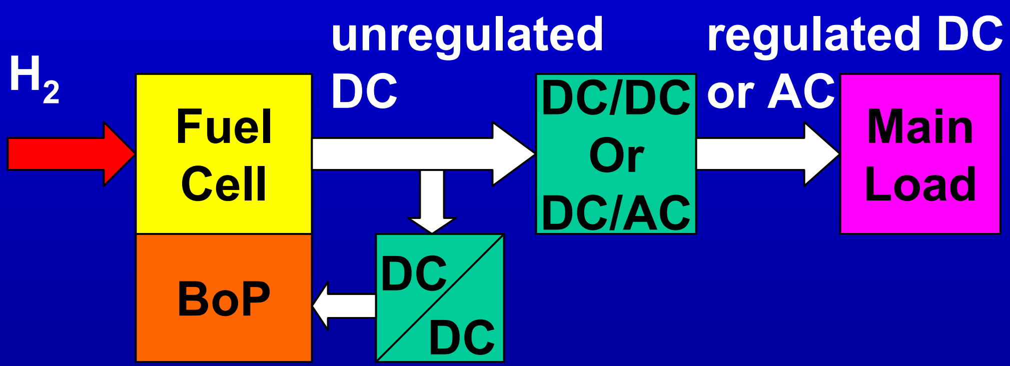
Fuel Cell Efficiency



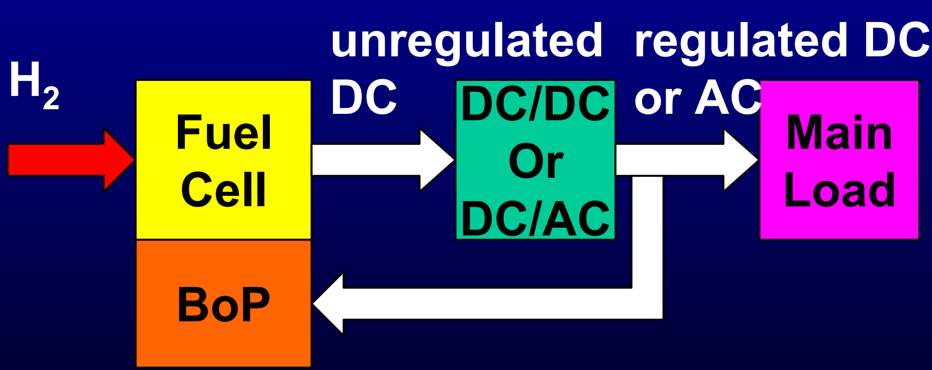
$$\eta_{FC} = \eta_I \cdot \eta_V = \frac{I}{I + I_{loss}} \frac{V_{cell}}{1.254} = \frac{1}{1+\varphi} \frac{V_{cell}}{1.254}$$



Fuel Cell System Efficiency

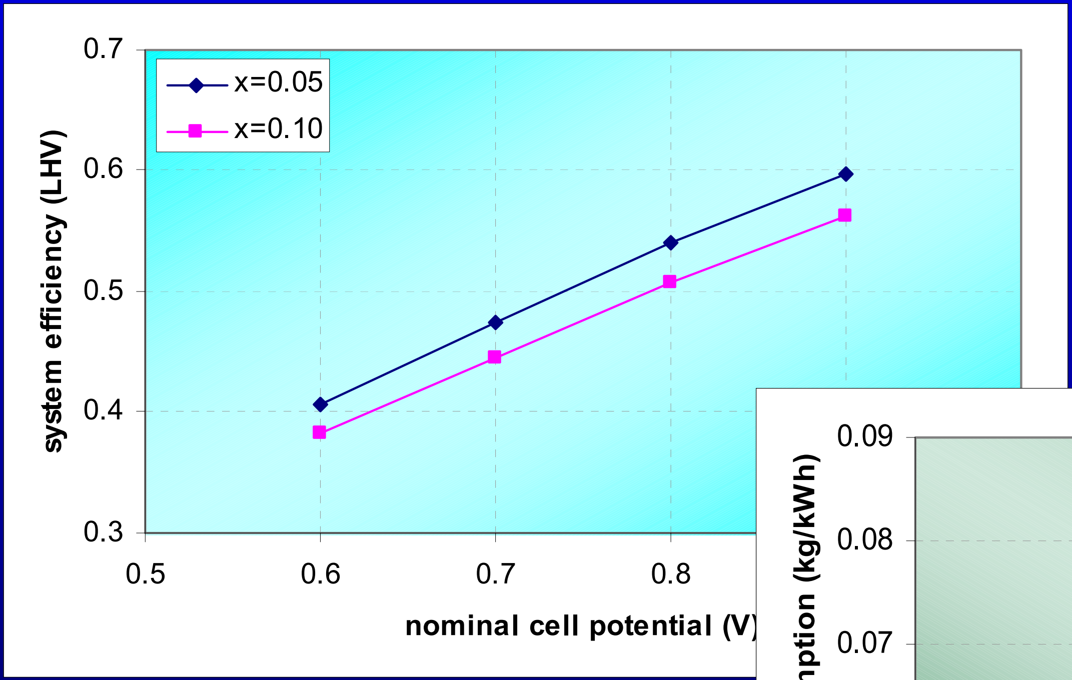


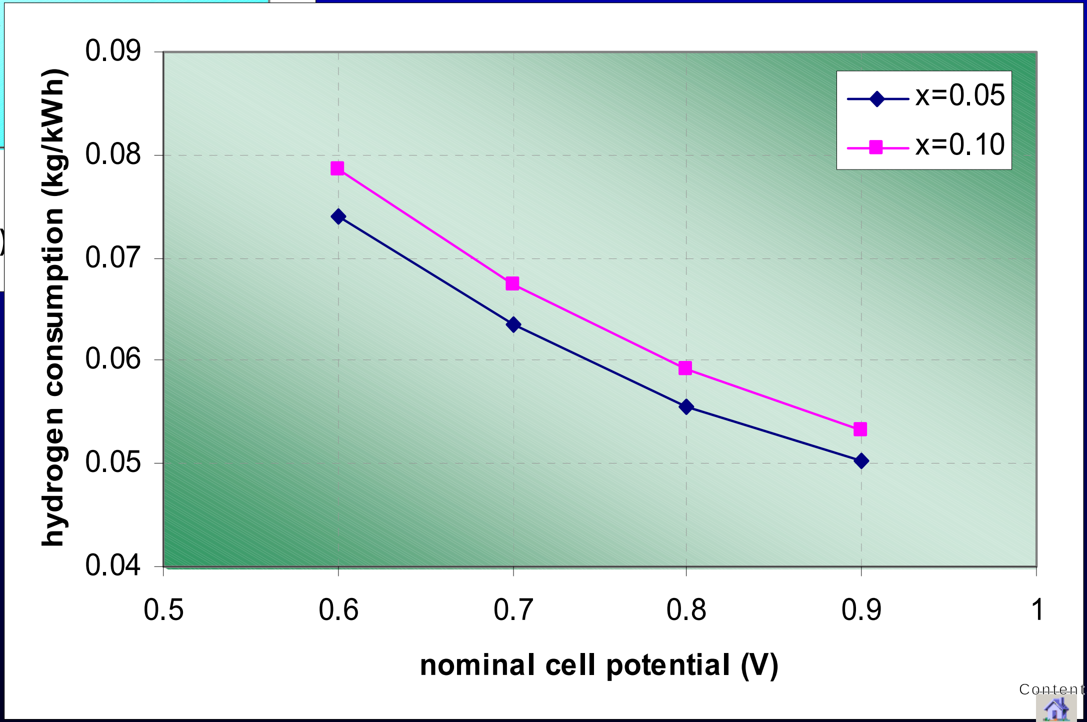
$$\eta_{sys} = \eta_{PCl}\left(1 - \frac{\xi}{\eta_{PCa}}\right)\eta_{FC}$$



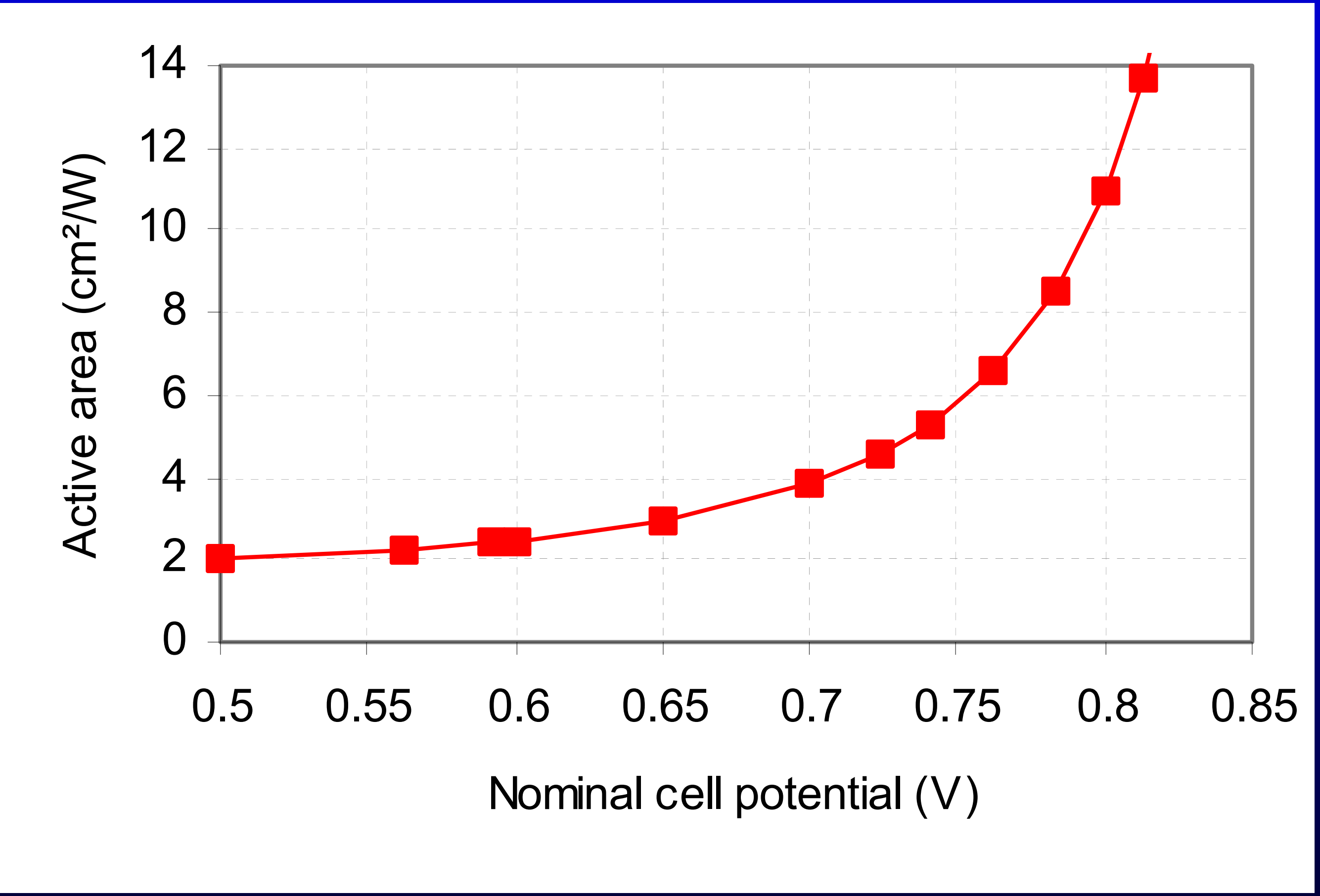
$$\eta_{sys} = \left(\eta_{PCl} - \xi\right)\eta_{FC}$$

Fuel Cell System Efficiency and H_2 Consumption





Higher nominal cell potential – larger fuel cell stack!



Types of hydrogen storage

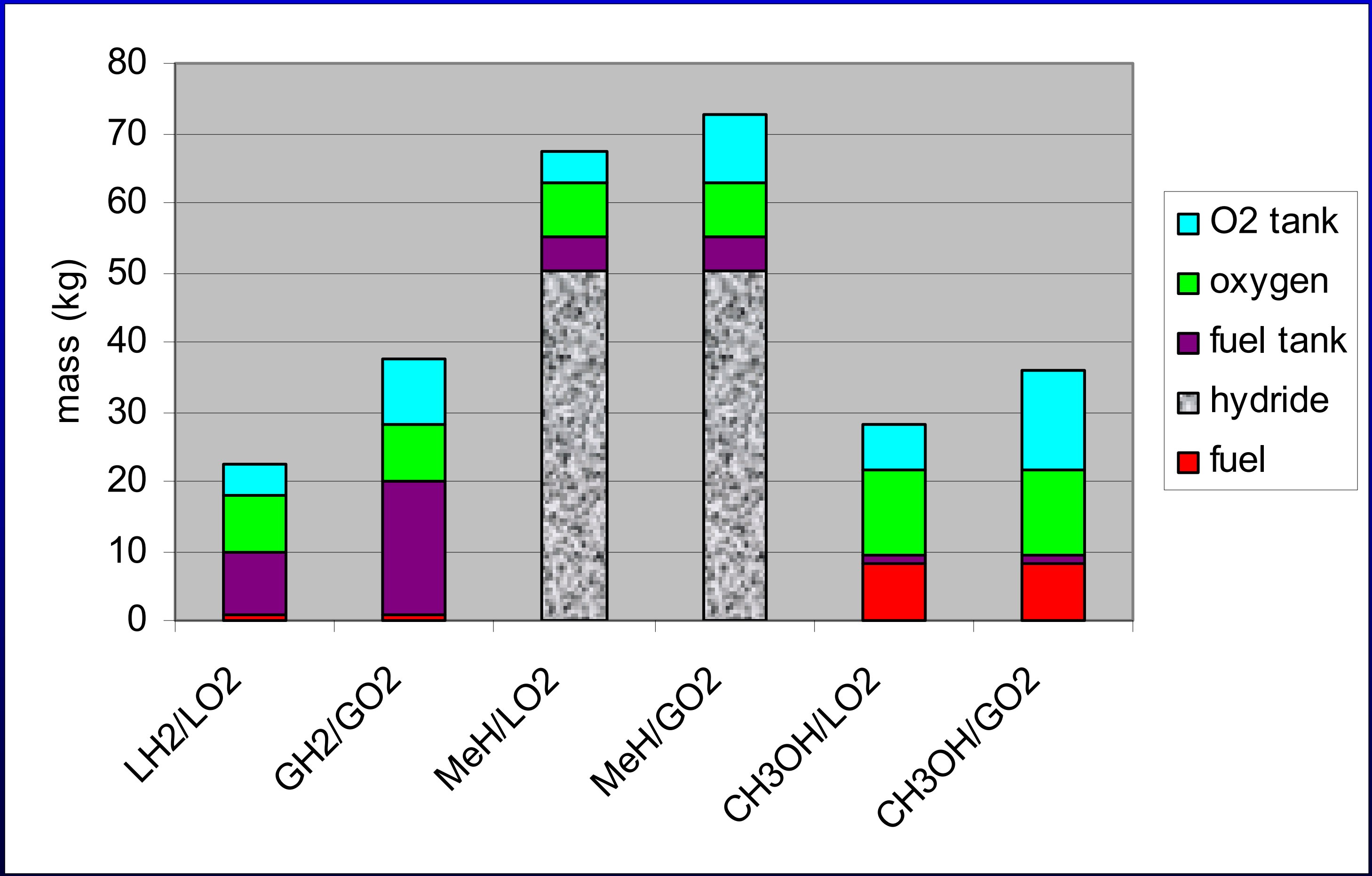
- Liquid
- Compressed Gas
- Metal Hydrides
- “Exotic”
- Hydrocarbons (methanol, diesel)

Also requires oxygen storage

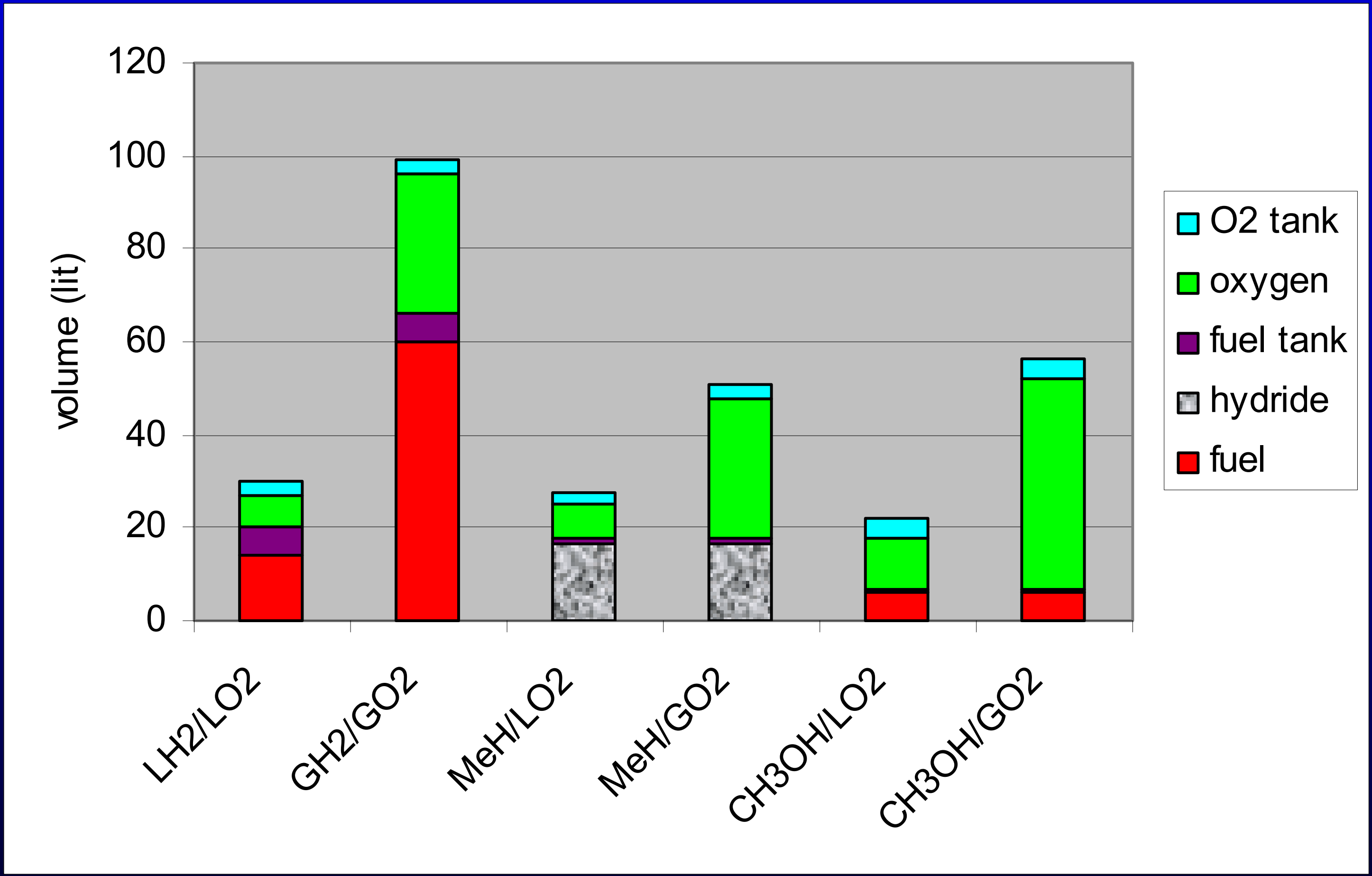
Types of oxygen storage

- Liquid
- Compressed Gas

Mass required to store 1 kg of H_2 and corresponding O_2



Volume required to store 1 kg of H_2 and corresponding O_2



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Optimization of V_{cell}

Higher V_{cell} $\rightarrow$ better efficiency $\rightarrow$ lower H_2 consumption $\rightarrow$ smaller storage

Higher V_{cell} $\rightarrow$ smaller current density $\rightarrow$ larger fuel cell

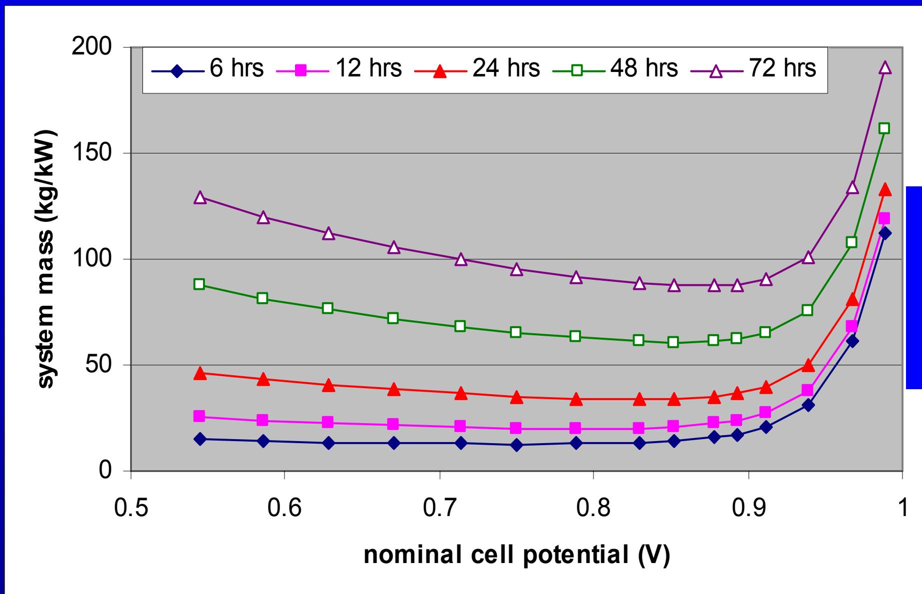
Size (weight or volume) = storage size + fuel cell size

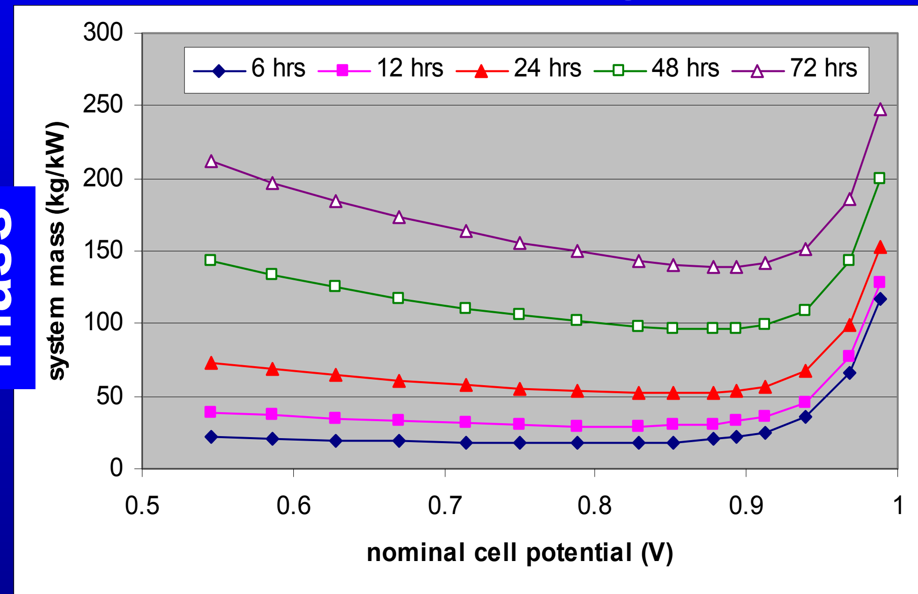
Results of V_{cell} optimization

liquid

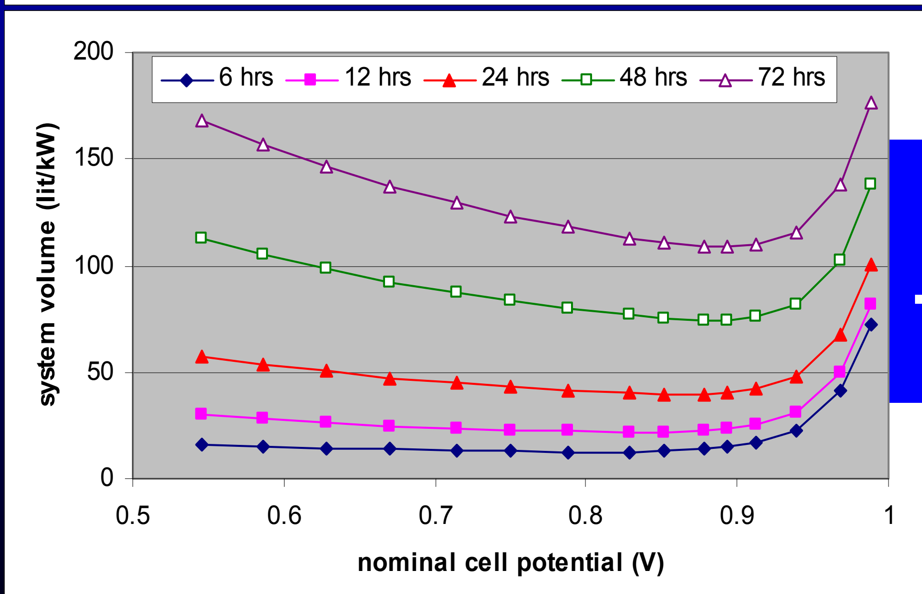
compressed gas

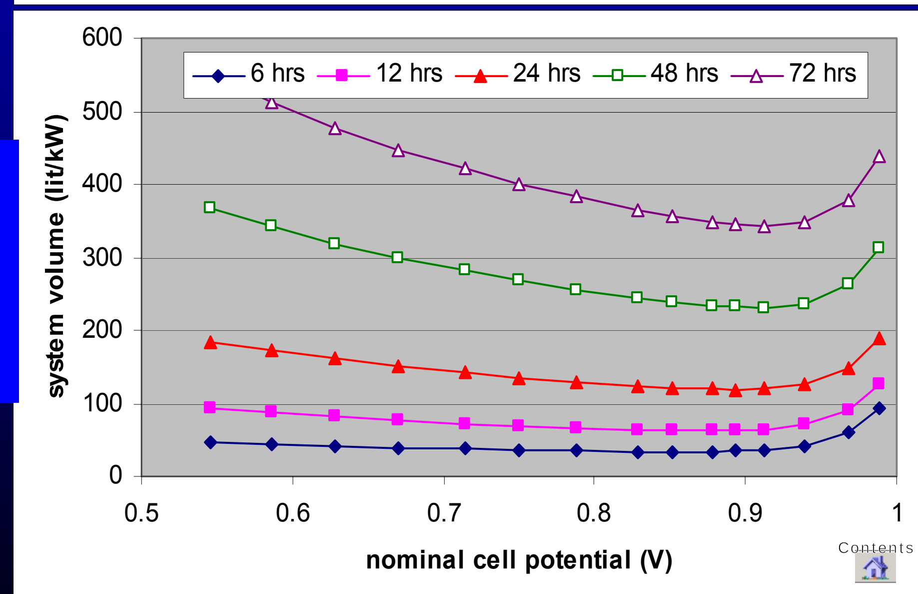
mass





volume





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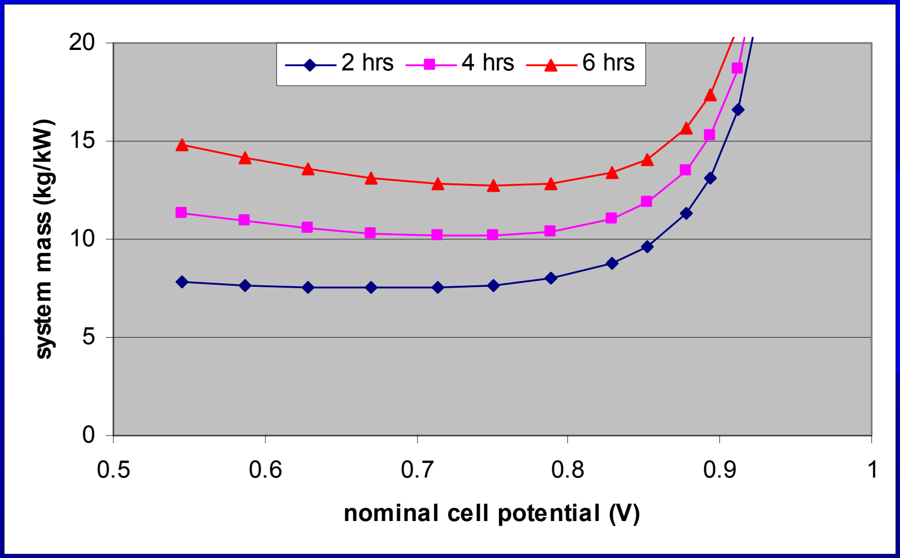
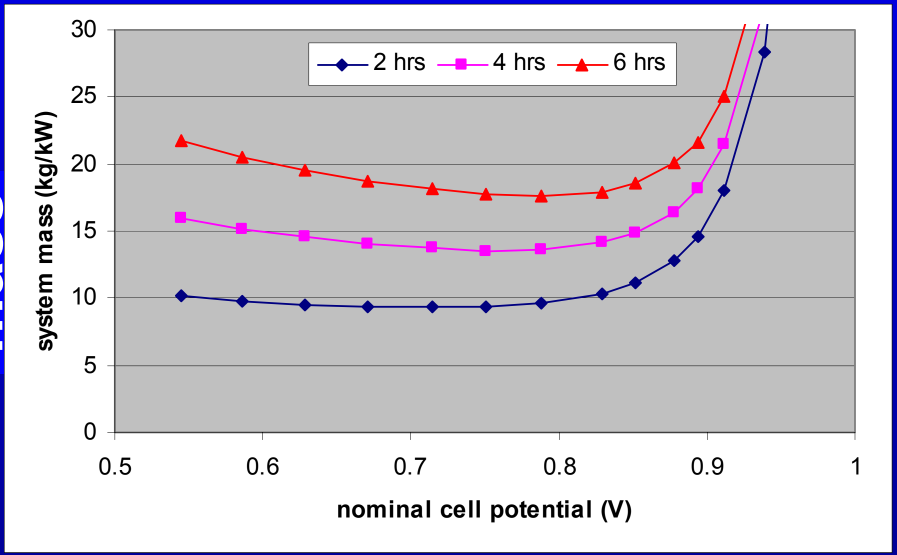
Results of V_{cell} optimization

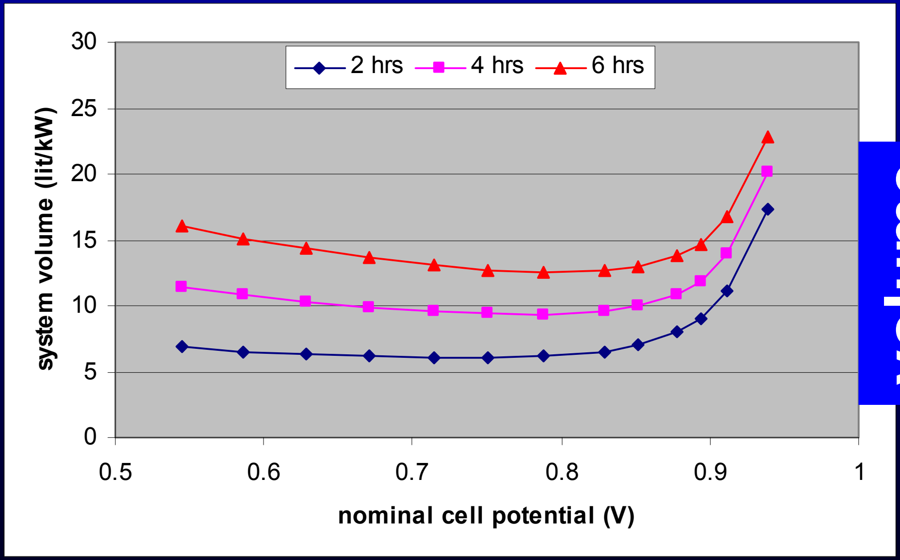
liquid



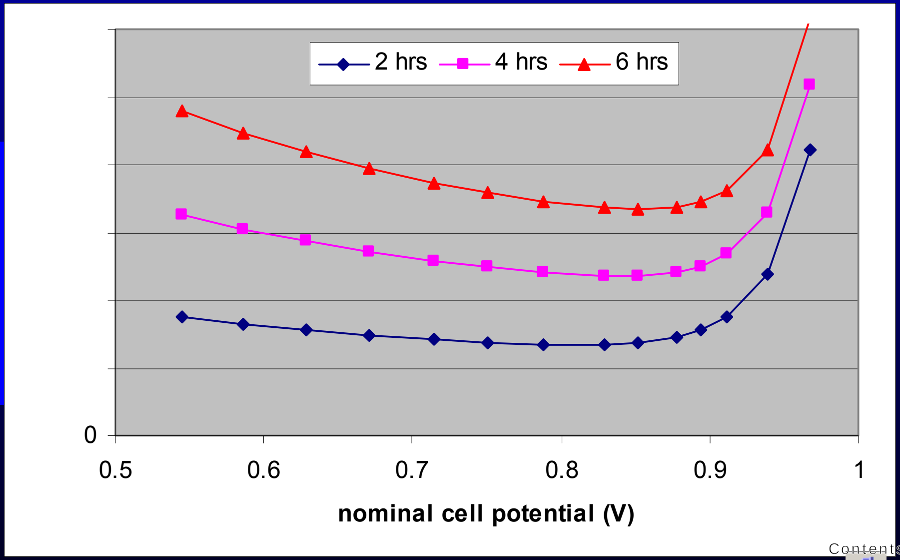
compressed gas



mass



volume



Other FC Design Considerations

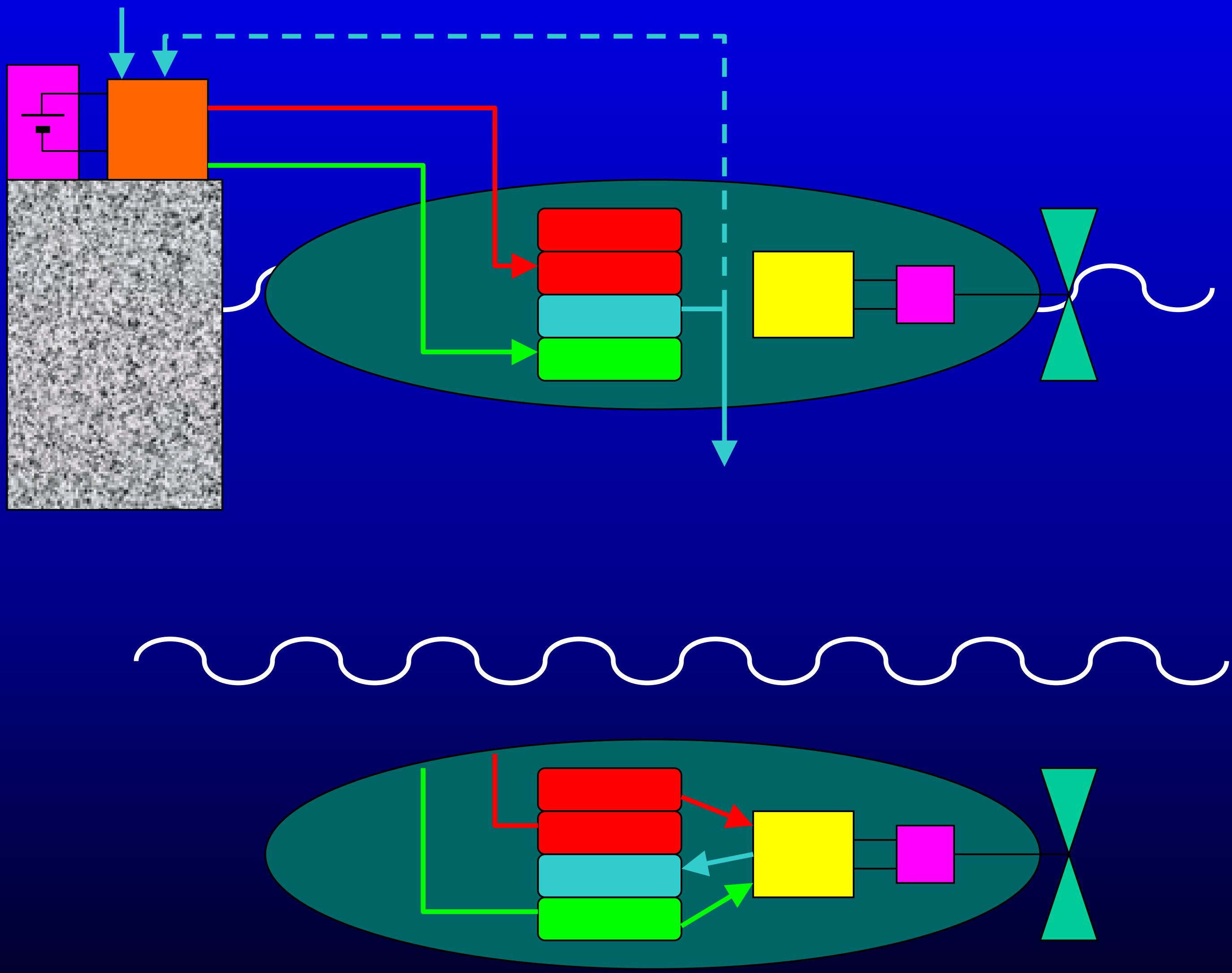
- Operating pressure
- Membrane thickness


The Ballard® Mark 900 Series Fuel Cell Power Module

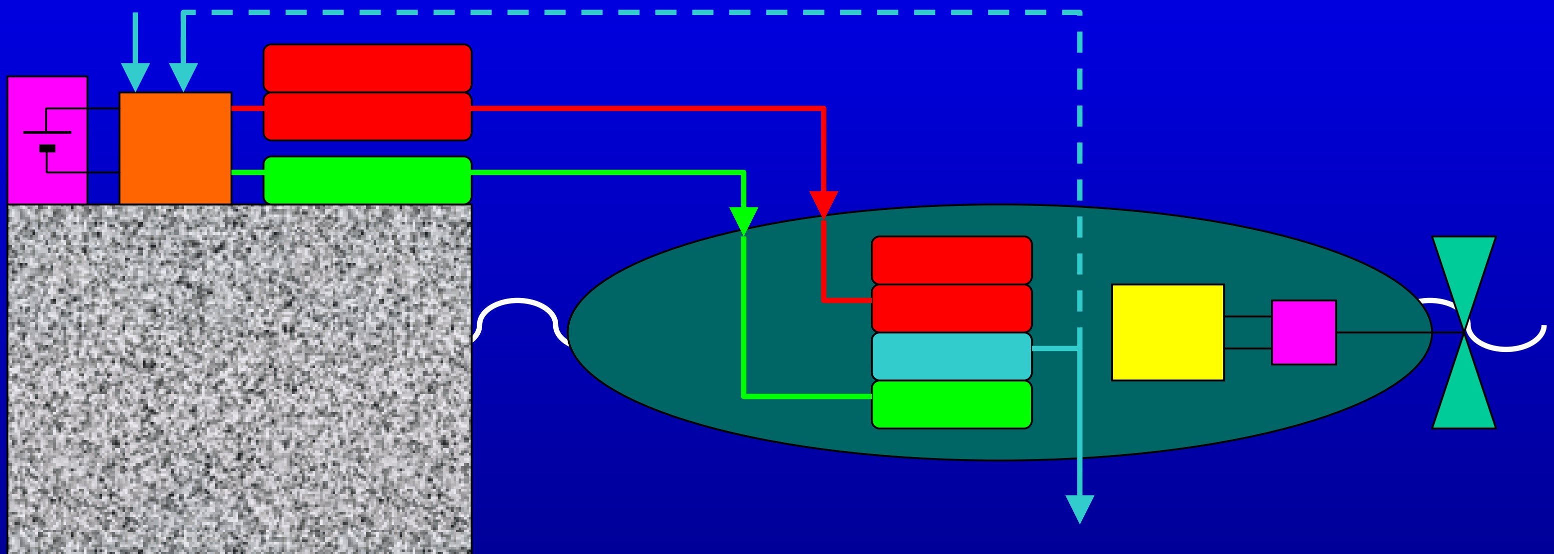
Hydrogen/Oxygen Fueling Options

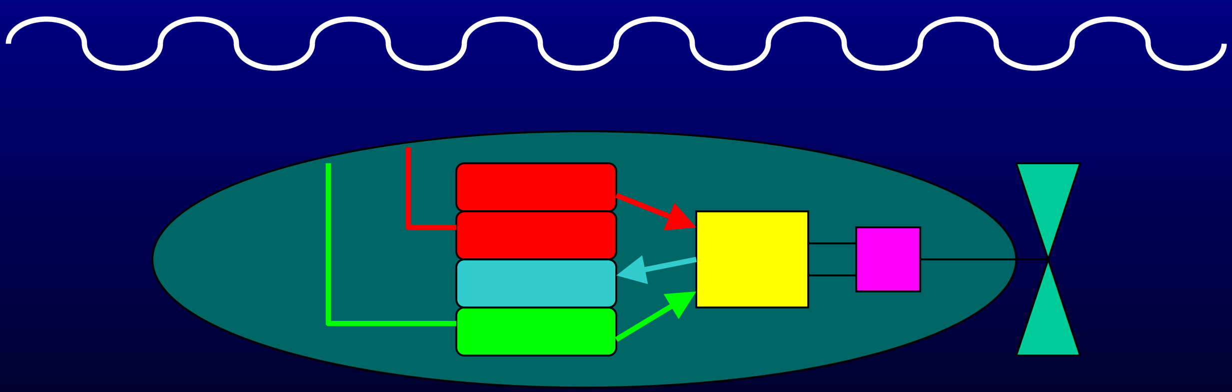
- Liquid hydrogen/oxygen
  - supply
- Gaseous hydrogen/oxygen
  - supply
  - on-site generation
  - on-board generation – regenerative fuel cell

Fueling with an electrolyzer

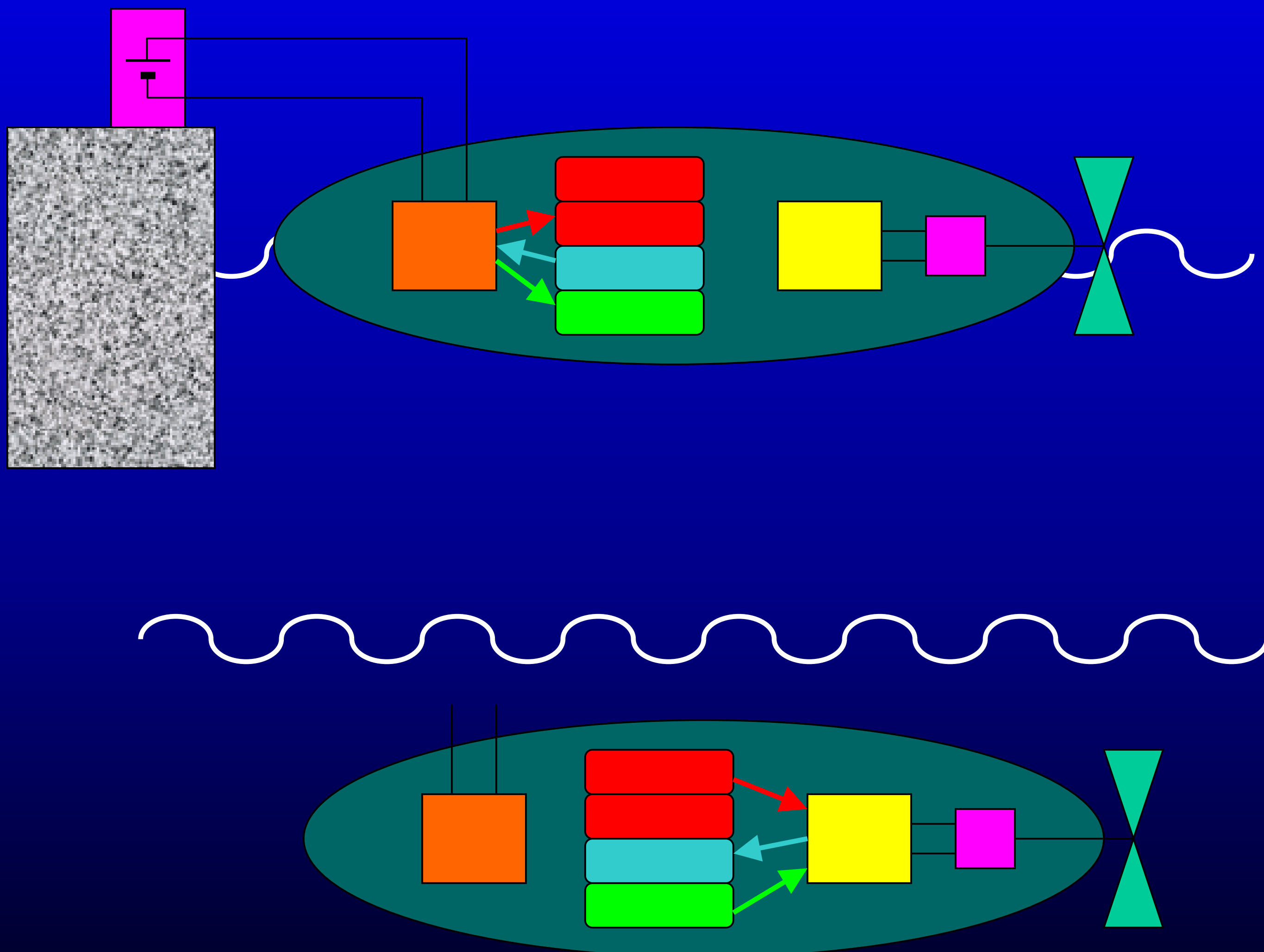


Quick fueling with an electrolyzer w/ storage

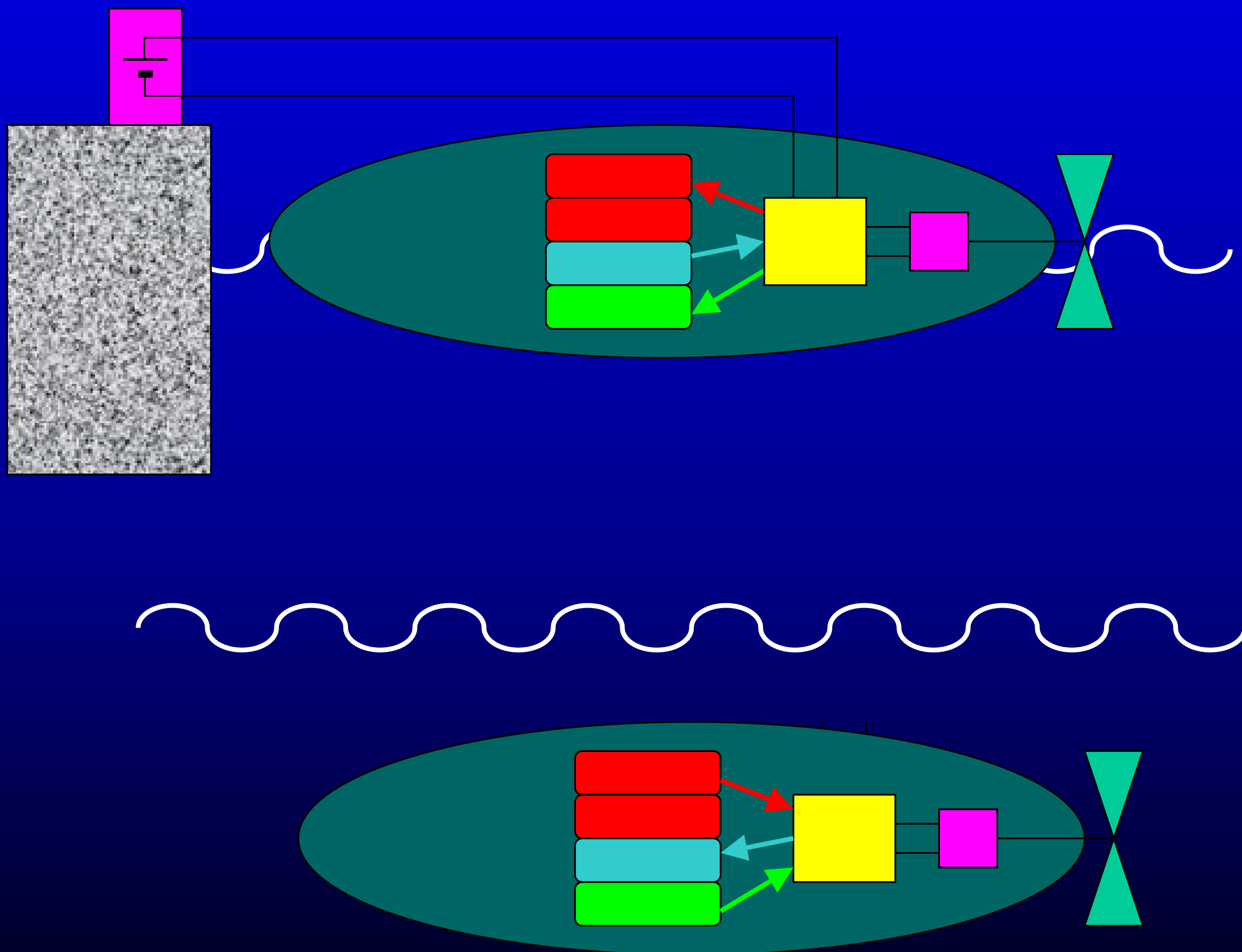




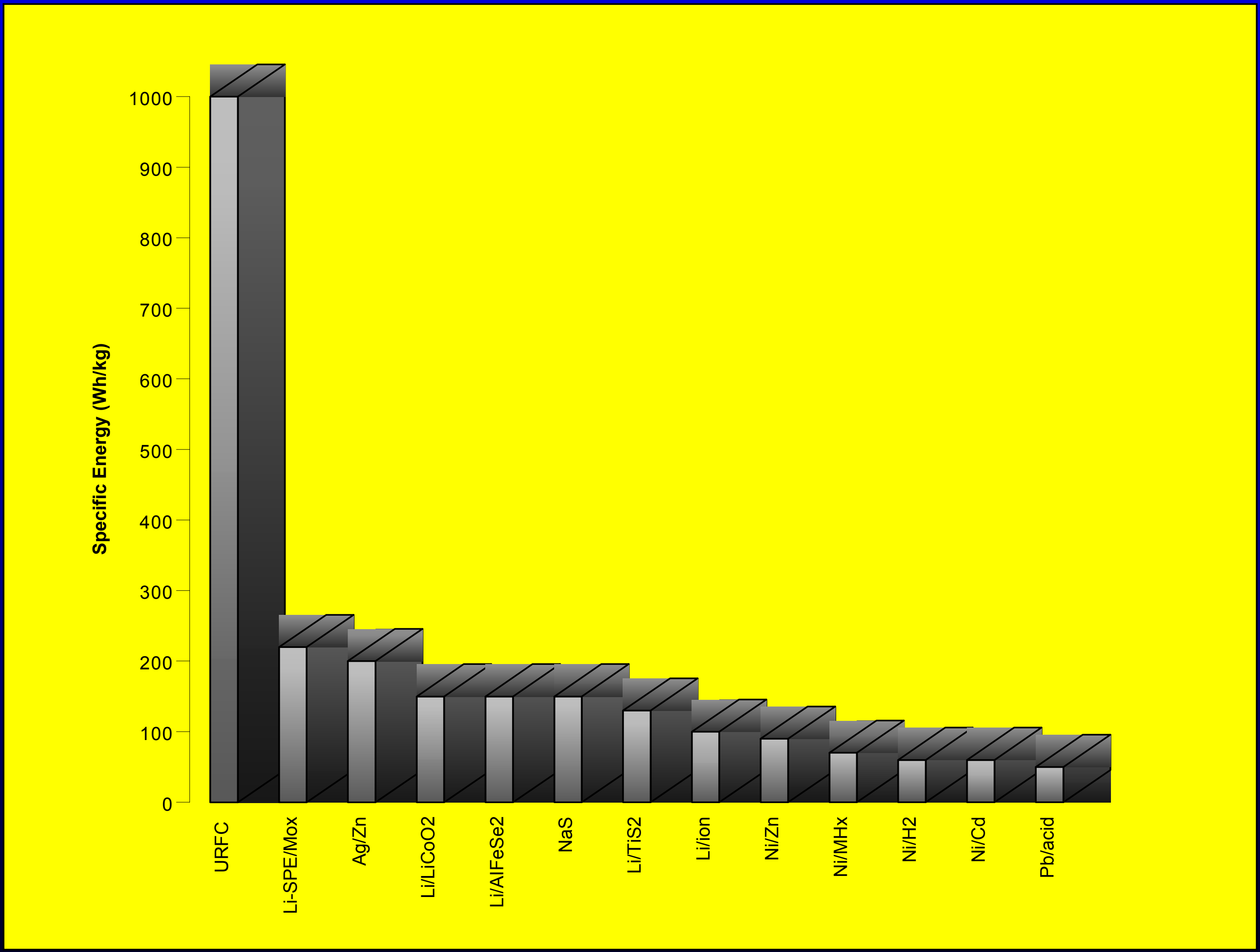
Fueling with an on-board (discrete) regenerative fuel cell



Fueling with an on-board (unitized) regenerative fuel cell



Regenerative fuel cell vs. batteries



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Regenerative fuel cell system energy density

Function of:

Fuel cell efficiency

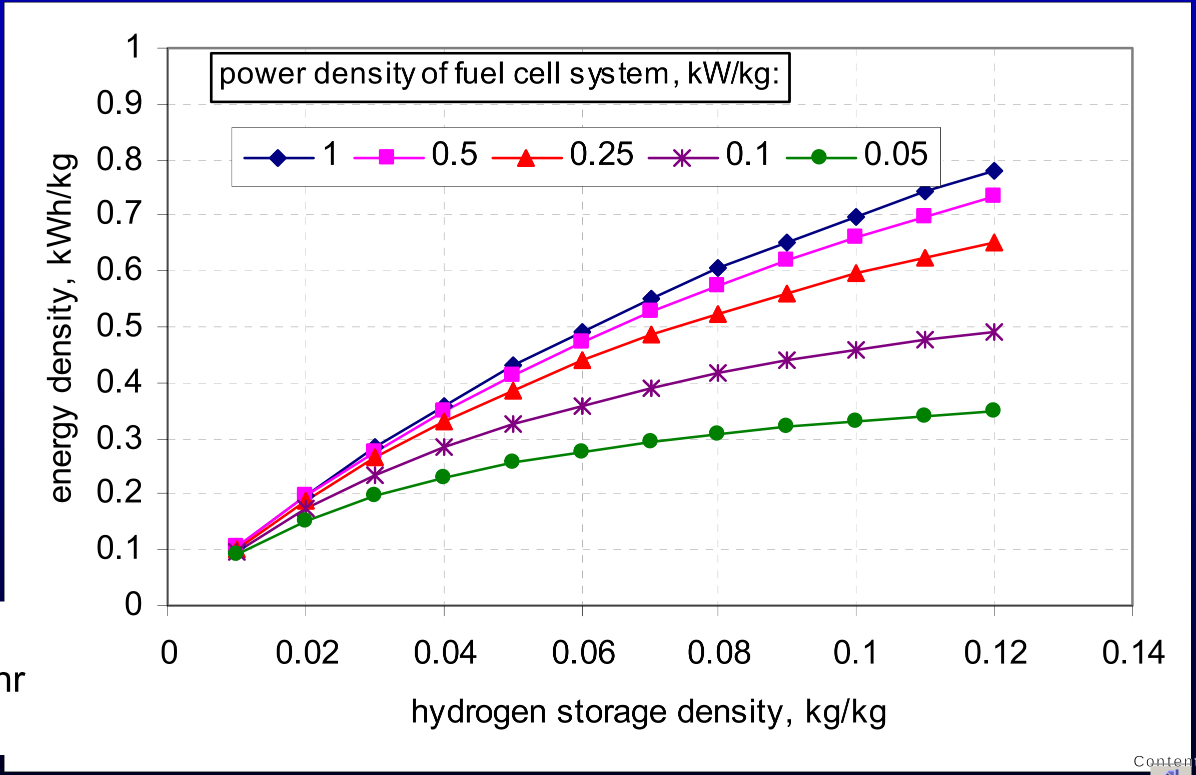
H_2 storage density

Duration of operation

Capacity factor

Fuel cell power density

$$\varepsilon = \frac{\eta \cdot \xi \cdot \tau \cdot C_f \cdot \sigma}{\tau \cdot C_f \cdot \sigma \cdot (0.2233\xi + 0.045) + \eta \cdot \xi}$$



Fuel cell efficiency (LHV):	0.5
Duration of operation:	12 hr
Capacity factor:	1.0

Contents

Conclusions

Advantages of fuel cells for AUVs

- High efficiency
- Low noise level
- Depth independence of the process
- Good operational and control features
- Neutral buoyancy
- Low heat transfer to the sea water
- Quick refueling

Disadvantages of fuel cells for AUVs

- Storage of reactants
  - size and weight
  - safety aspects