End User Perspective – Industrial
Consumer Electronics Power (< 20-50W)

Department of Energy
Fuel Cell Portable Power Workshop

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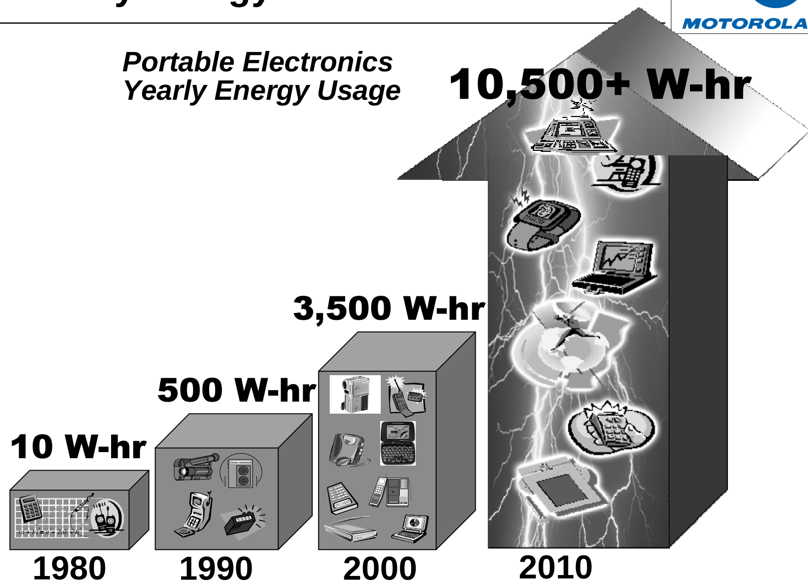
Outline

- Energy & Power of Portable Devices
- Fuel Cell Applications & Cost
- Key Requirements & Challenges
- Fuels for Portable Fuel Cells
- Fuel Transportation Regulations and Standards
- Methanol Fuel Cells
  - Direct Methanol Fuel Cells
  - Reformed Methanol Fuel Cells
- Technical Challenges

On Body Energy

Portable Electronics Yearly Energy Usage



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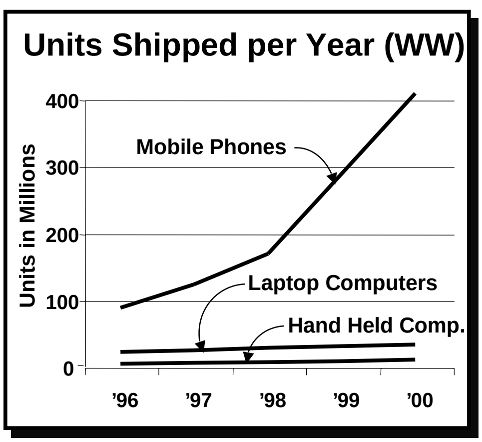
Portable Electronics Growth



Ref: Darnell, IDC, Nomura, Motorola

- Handheld computers becoming more prevalent
- Laptop computer power demands continue to increase
- High unit growth of Mobile phones driving energy demand
- Average Power Consumption by device
  - Hand Held - <0.5W
  - Mobile - ~1.0W
  - Notebook - ~20.0W

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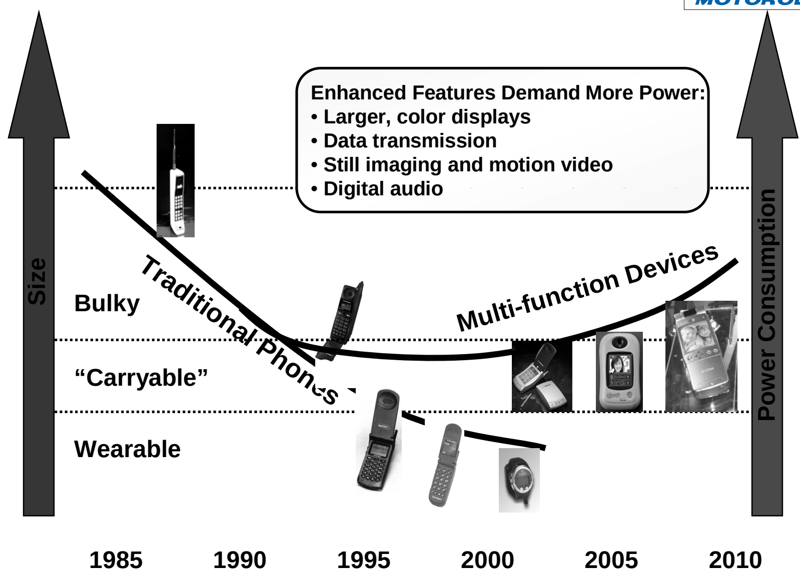
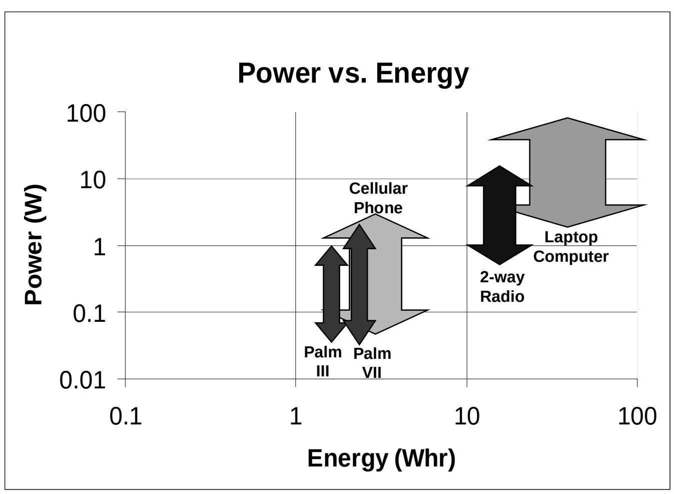
Effect of Convergent Devices



Energy & Power of Portable Devices



Rechargeable Battery Improvement Rate

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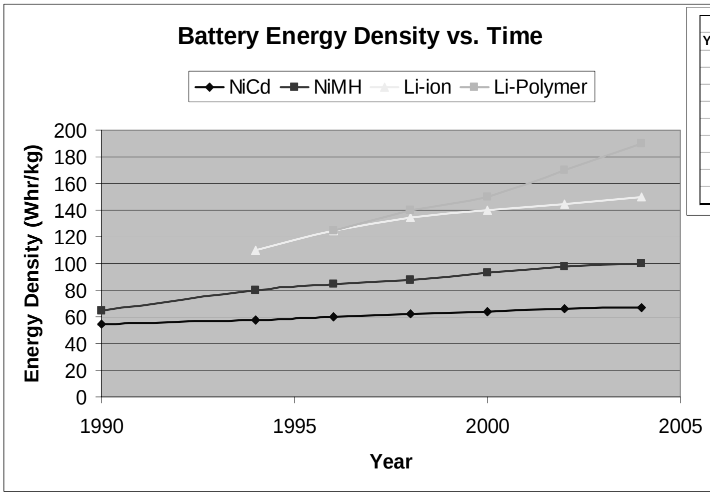

Year	Change per year			
	NiCd	NiMH	Li-ion	Li-P
1970				
1980	3%			
1990	2%			
1994	1%	6%		
1996	2%	3%	7%	
1998	2%	2%	4%	6%
2000	2%	3%	2%	4%
2002	2%	3%	2%	7%
2004	1%	1%	2%	6%

Fuel Cell Applications

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<u>Near-term applications (2002 - 2004):</u>

- **Desktop/travel chargers**
  - **Cell-phones, Laptops, PDAs , etc.**
- **Cordless (no socket, no CLA)**
- **“Instant recharge”**
- **Energy Density less than Li-ion?**
  - **Refill convenience vs. recharge**

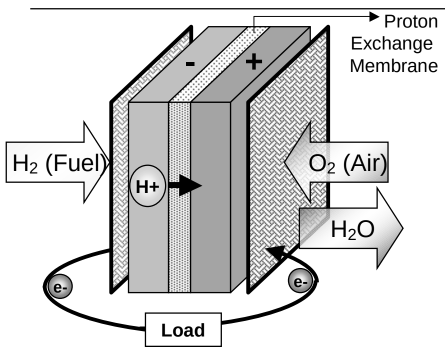
<u>Longer term (2003 - 2005):</u>

- **Hybrid (fuel cell + battery) or battery replacements:**
  - **Cell-phones, Laptops, PDAs, etc.**
- **Energy Density ~ 3 to 5X Li-ion pack**

Fuel Cell Cost

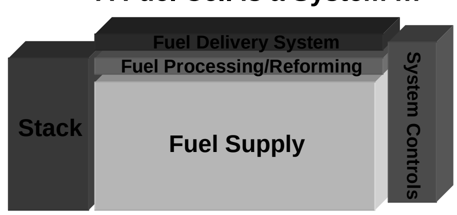
- **Desktop/Travel/Vehicle Charger**
  - **Current battery chargers: $25-50 retail price**
- **Rechargeable Batteries**
  - **NiMH, Li-Ion, Li-polymer**
  - **$20-50 (cell phone)**
  - **$50-150 (laptop)**
- **Fuel Cell System**
  - **Total cost "comparable" to charger/battery**
  - **Includes both fuel cell and battery, supercap, etc.**
  - **Premium for instant recharge/refuel?**

Fuel cell basics



- Anode: Pt/H_2 ($2H_2 = 4H^+ + 4e^-$)
- Cathode: Pt/O_2 ($O_2 + 4H^+ + 4e^- = 2H_2O$)
- Electrolyte: Ion membrane, Phosphoric acid
- Fuel (H2) source: H2 gas, Methanol, Ethanol, Gasoline, Natural gas …

A Fuel Cell is a System !!!



- Dimensions of the stack determines the power output
- Dimensions of the fuel supply tank determines the total energy output
- Fuel delivery, systems controls etc. drive down energy density

Key Requirements and Challenges

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Technical Requirements for Fuel Cells

- **High Energy Density!!!**
  - **Small, lightweight fuel cell system**
  - **High conversion efficiency of chemical to electrical energy**
  - **High energy density fuel/container**
  - ➢ **Majority of volume/weight in system is fuel**

Challenges

- **Fuel cell system comparable to battery**
  - **Size, cost, safety, reliability, recharge/refuel availability**
- **Requires access to air for oxygen**
- **User expectations & perception**
  - **Battery replacement vs. “wireless charger”**

Portable Fuel Cell Energy Source

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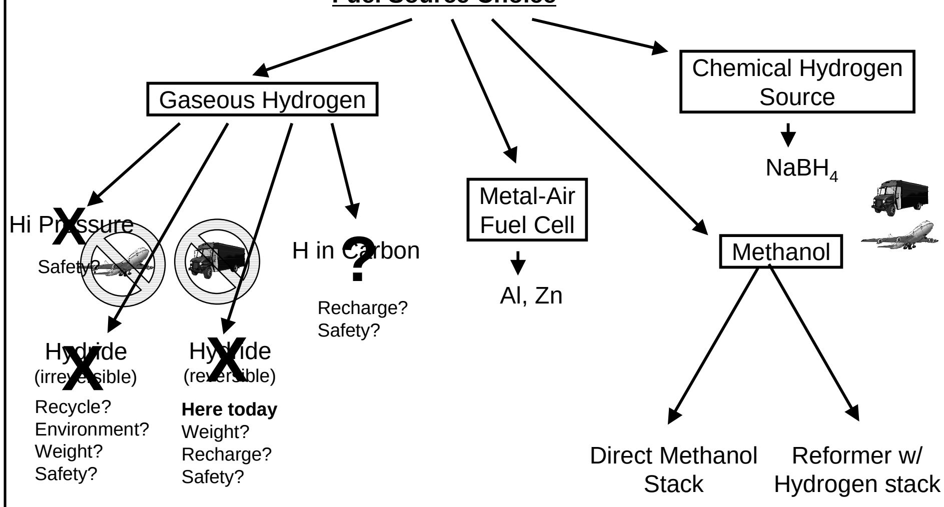
Fuel Source Choice



Anode material energy densities

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Limitation of Li-ion energy density?

Application	Anode material / Fuel	Anode Theoretical Energy density (Wh/kg)
Lithium-ion	Carbon - Graphite	1116
Lithium metal	Lithium	11580
Aluminum-air	Aluminum	4000
Zinc-air	Zinc	1000
Hydrogen Fuel Cell (FC)	Hydrogen	42,000
Methanol FC	Methanol	5960

(Lithium-ion, Lithium metal:) Cathode adds to weight. Reduces energy density.

(Aluminum-air, Zinc-air, Hydrogen Fuel Cell (FC), Methanol FC:) Air (O2) electrode. Requires additional components, controls, etc.

Which will leap-frog overall Lithium-ion performance? When?

How Do Fuel Cells Compare?

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Energy Source	Volumetric Energy Density (Watt*Hours per Liter)	Specific Energy Density (Watt*Hours per Kg)
Rechargeable Batteries		
Ni/Cd (cell only)	**130**	**40**
Ni/MH (cell only)	**200**	**60**
Li-Ion Polymer (cell only)	**300**	**160**
Li-Ion (cell only)	**310**	**125**
Li-Ion Polymer (pack)	**170**	**105**
Li-Ion (pack)	**190**	**100**
Fuel Cells		
Methanol (theoretical)	**4,780**	**5,960**
Methanol (35% eff)	**1,673**	**2,086**
Methanol (35% + FC)	**<< 1,673**	**<< 2,086**

Energy Density of Fuel + Container

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Energy Source	Volumetric Energy Density (Watt*Hours per Liter)	Specific Energy Density (Watt*Hours per Kg)
Hydrogen		
Compr H2 (2000psi)	520	248
Compr H2 (50% eff)	260	124
Compr H2 (50% eff + FC)	<260	<124
Metal Hydride	600	236
Metal Hydride (50% eff)	300	118
Metal Hydride (50% + FC)	<300	<118
Fuel Cells		
Methanol (theoretical)	4,780	5,960
Methanol (35% eff)	1,673	2,086
Methanol (35% + FC)	<< 1,673	<< 2,086

Fuel Packaging and Distribution

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Methanol "cartridge"

- 20-100cc Methanol (pure vs. diluted)
- Leak-proof interface to fuel cell (& resealing)
- Additives for color, taste, smell?
  - Effect on fuel cell
- Refillable/recyclable vs. disposable

Distribution

- Cost of raw methanol in cartridge very low
  - Few ¢ (@$1/gallon)
- Cost of cartridge should be < $1
  - Battery recharging is "free"
- Introduction to large geographic markets

Fuel Transportation Issues

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Initial Findings from USFCC Study

- Hydrogen, metal hydrides, and methanol are:
  - Hazardous materials (DOT)
  - Dangerous goods (UN).
- Current regulations do not allow carry-on in passenger airlines.
- Limited quantity of metal hydride or methanol may be allowed (exemption):
  - Checked baggage only, not carry-on.
  - Exemption for methanol assumes dilution in water (<24%).
  - Hydrogen storage in metal hydrogen may invalidate exemption classification.
- Compressed hydrogen, water reactive metal hydride not currently exempted.
- Limited quantity of $NaBH_4$ mixture may be allowed.

Fuel Transportation Issues

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Initial Findings from USFCC Study

- Potential exemptions and/or rulemakings precedents were identified (butane lighters):
  - Limitation on quantity & pressure
- Other uses of fuels & fuel cells must be evaluated:
  - Sealed vs. opened fuel container
  - Fuels (cartridge) inside Fuel Cell
  - Operation of Fuel Cell
- Fuel Cells (without fuel) not classified as hazardous.

- DOT suggestions:
  - Begin work on standards immediately
  - In short term next 1-2 years, individual companies apply for exemption – based on (draft) standards
  - Rulemaking possible after more experience with devices

Methanol Fuel Cells

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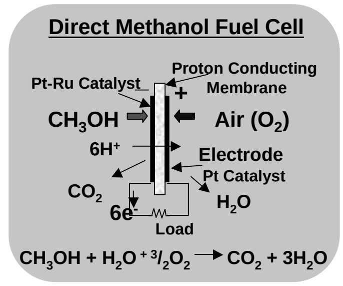
Two Approaches

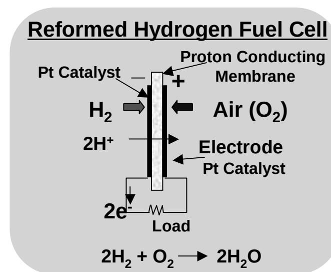
Direct Methanol Fuel Cells

- Lower Power Density (10-50mW/cm^2)
- RT - 80^{o}C Operation
- Liquid & Gas Handling

Reformed Methanol-Hydrogen Fuel Cells

- Higher Power Density (25-200mW/cm^2)
- Reformer Operating Temp >200^{o}C
- Liquid & Gas Handling





Direct Methanol Fuel Cell System

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Objective:

- Direct Methanol Fuel Cells system for portable electronics.

System features:

- Fuel: Liquid Methanol
- Air Supply: Air breathing --> forced air
- Operating Temp: Ambient --> elevated temp (60^{o}C)

Integrated DMFC Prototype

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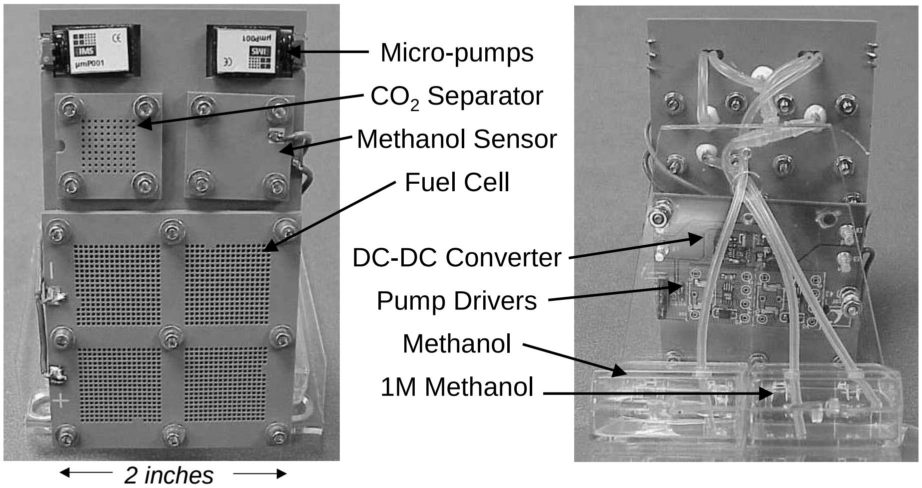
Prototype Integrated 100mW DMFC System



Power Budget For Integrated DMFC Prototype

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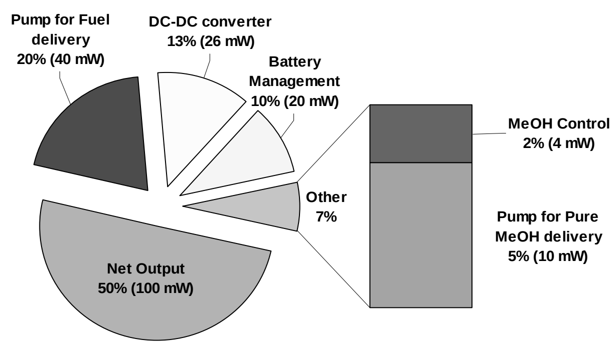
200 mW gross power output from Fuel Cell



"Active" DMFC Technology

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Features

- Nafion-based MEA
  - With reduced crossover & water drag
- Good catalyst activity (>30 mW/cm^2 @RT)
- Active water recovery/MeOH dilution, CO_2 separation
- Pure MeOH fuel
- Power down/off – no self discharge

Possible Issues

- Water recovery/elimination
- Miniature, low-power pumps
- "Balance of Plant" efficiency
- Overall system energy density

"Passive" DMFC Technology

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Features

- Polymer membrane with reduced crossover
  or
  Liquid electrolyte
- High catalyst activity
- No moving parts?

Possible Issues

- Water recovery/elimination
- Energy density of fuel (30-50% MeOH) - system
- Fuel replacement/delivery
- Power down/off (self-discharge?)
- Liquid electrolyte: caustic, corrosion

Reformed Hydrogen Fuel Cell System

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Objective:

- **Miniature in-situ H_2 generator & fuel cell system.**

System features:

– Fuel/Air: Liquid Methanol – Forced Air
– Reformer: Methanol Steam Reformer (~225°C)
– Heater: Methanol combustion
– Fuel Cell Type: High Temperature PEM (~150°C)
– CO clean up: None (<2% CO in reformate stream)

Fuel Reformer with Integrated Chemical Combustor

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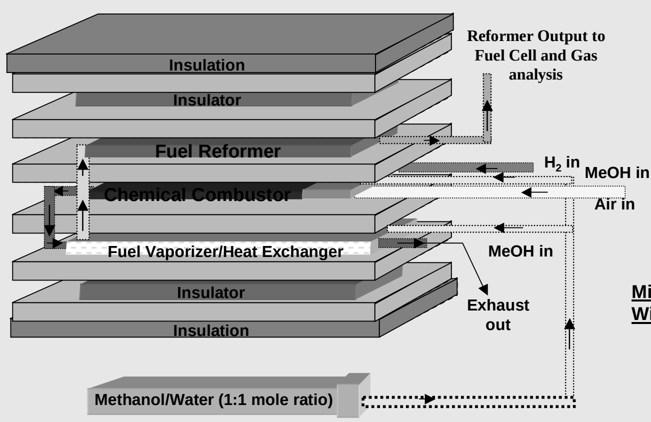
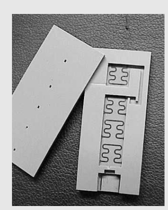
Prototype Device Under Development



Liquid Feed Pump: 10- 25 uL/min



Miniature Reformer With Electrical Heaters

Ceramic RHFC Technology

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Features

- Reformed Methanol-to-Hydrogen Fuel Cell
- MeOH + H2O fuel
- CMEMS thermally integrated construction
- High-temp PBI-based MEA (>100 mW/cm^2)

Possible Issues

- Miniature, low-power pumps
- BOP efficiency
- Overall system energy density

Other RHFC Technologies

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Features

- Gasoline or methanol steam reformer
  - Metallic reactors (discrete components)
- "Standard" PEMFC stack

Possible Issues

- Integration of components
- Thermal integration
- CO cleanup (size of WGS + PROX)

Chemical Hydrogen Source

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Features

- Sodium Borohydride – chemical hydrogen source
- "Standard" PEMFC stack

Possible Issues

- $NaBH_4$ delivery – gravity independent?
- Control of reaction – limited release of hydrogen
- Micropumps

Fuel Cells for Portable Electronics

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Technical challenges to overcome

- DMFC
  - Performance degradation (catalyst vs. flooding)
  - Temperature range (operating, storage)
  - Catalyst activity vs. loading
  - Water recovery
  - Methanol crossover & water drag (simplifies system)
- RHFC
  - Methanol reformer catalyst (stability, durability)
- Common
  - Miniature, low power pumps (liquid, gas)
  - Fuel additives/packaging (flammability, toxicity), distribution
- H2 PEMFC
  - Hydrogen storage, safety