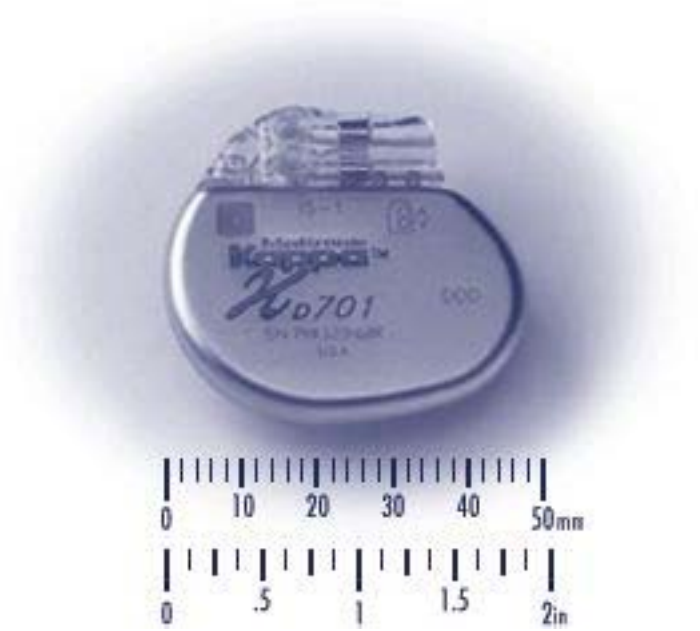
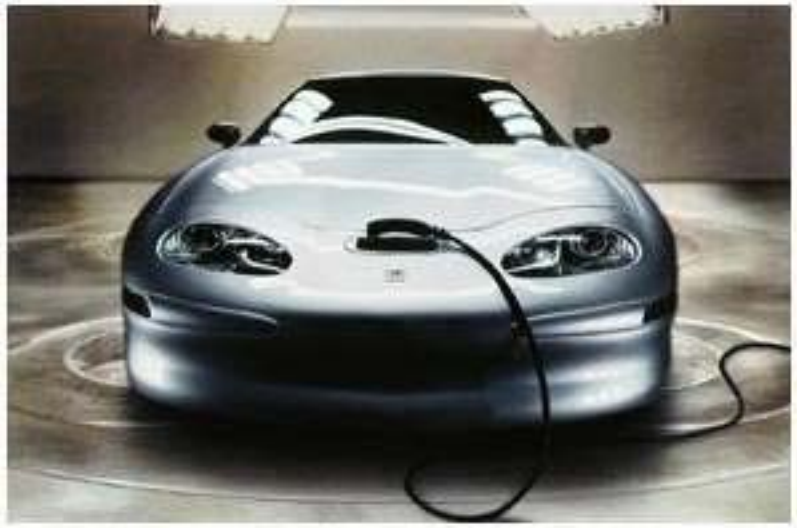
the growing need for portable power in a wireless age

tethered in the wireless age ☞ portable power

enabling radical innovation





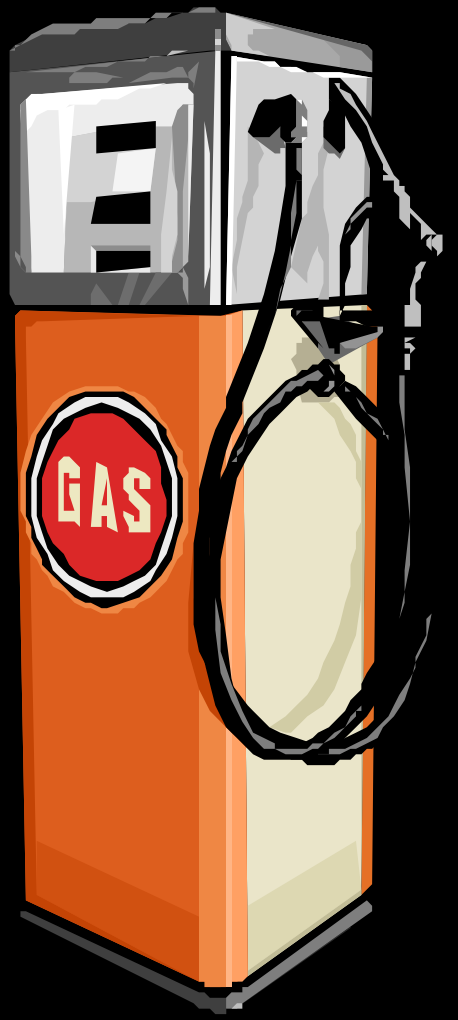
biomedical devices **transportation**

motivation

Imagine driving this:

motivation (continued)

without the need for this:



The message

The road to autonomy is paved with advanced materials.

A bit of automotive history

1888 Frederick Kimball, Boston:

first electric passenger car

why now the renewed interest?

answer: **CARB**

to improve urban air quality

CARB set new standards, including...

CARB Implementation Dates for ZEVs

1998 2% new car sales†

2001 5% new car sales†

2003 10% new car sales†

1991 NESCAUM formed

1992 MA adopts CA standards

✏ in the minds of many policy makers, ZEV implies EV

Problems with EV propulsion

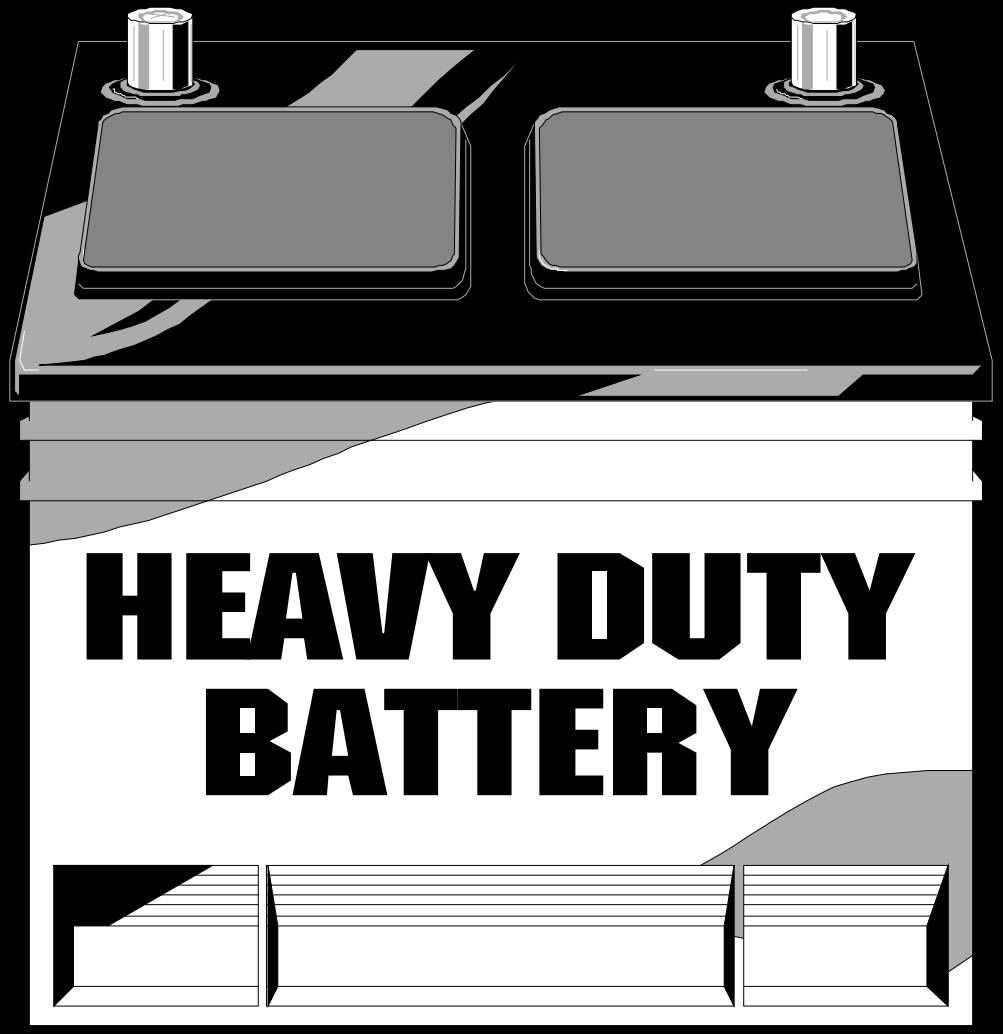
1. **range**: function of energy density of the **battery**.
   Compare gasoline @ 12,000 (theo.) / 2600 Wh/kg
   with the lead-acid **battery** @ 175 (theo.) / 35 Wh/kg

2. **time to refuel**: charge 40 kWh in 5 minutes?
   ⇨ 220 V × 2200 A!!!
   When you pump gasoline @ 20 /min,
   your energy transfer rate is about 10 MW!
   (Hint: energy density of gasoline is 10 kWhth/ .)

Problems with EV propulsion

3. **cost**:
   (1) light but safe means higher materials costs,
   e.g., less steel, more aluminum;
   and higher processing costs,
   e.g., fewer castings, more forgings...
   (2) to reduce load on the **battery** requires
   high efficiency appliances ➪ costly
   (3) low cycle life — **batteries** priced @ $4,000 to $8,000
   lasting about 2 years

relevant enabling technology



large format

specific energies of battery chemistries

	(Wh/kg)	(MJ/kg)
lead acid	35	0.13
NiCd	45	0.16
NaS	80	0.28
NiMH	90	0.32
Li ion	150	0.54
gasoline	12,000	43

Sadoway's Rule

1 Wh/kg storage capacity

☞ 1 mile driving range

Battery basics

what is a battery?

a device for exploiting **chemical** energy

to perform **electrical** work

i.e., an **electrochemical** power source

the design paradigm?

choose a chemical reaction with

a **large driving force** (ΔG) and **fast kinetics**

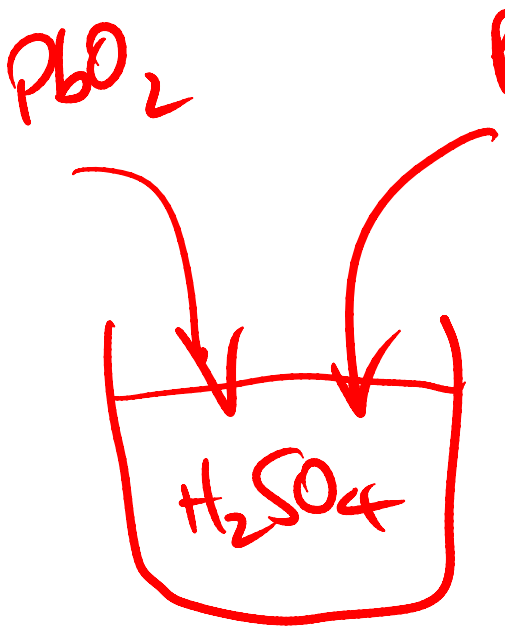
to cause the reaction to occur by steps

involving **electron transfer**


10000 LIRE DIECIMILA
PAGABILI A VISTA AL PORTATORE
IL GOVERNATORE
Antonio Fazio
IL CASSIERE
OFFICINA DELLA BANCA D'ITALIA
MH 195201 V
BANCA D'ITALIA
A VOLTA
MH 195201 V

A simple chemical reaction

$$PbO_2 + Pb + H_2SO_{4(aq)} \Rightarrow 2\,H_2O + PbSO_4$$



intimate mixing of all reactants

Same reaction, but not so simple

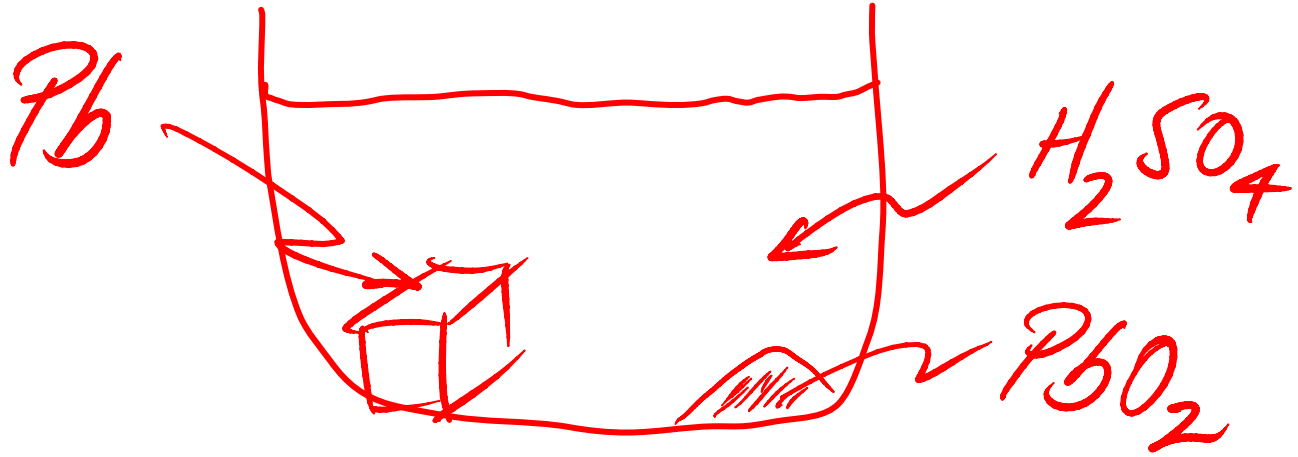
$$Pb + SO_4^{2-}{}_{(aq)} \Rightarrow PbSO_4 + 2\,e^-$$

insoluble in water

$$PbO_2 + 4\,H^+{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 2\,e^-$$

$$\Rightarrow 2\,H_2O + PbSO_4$$

reactants physically separated

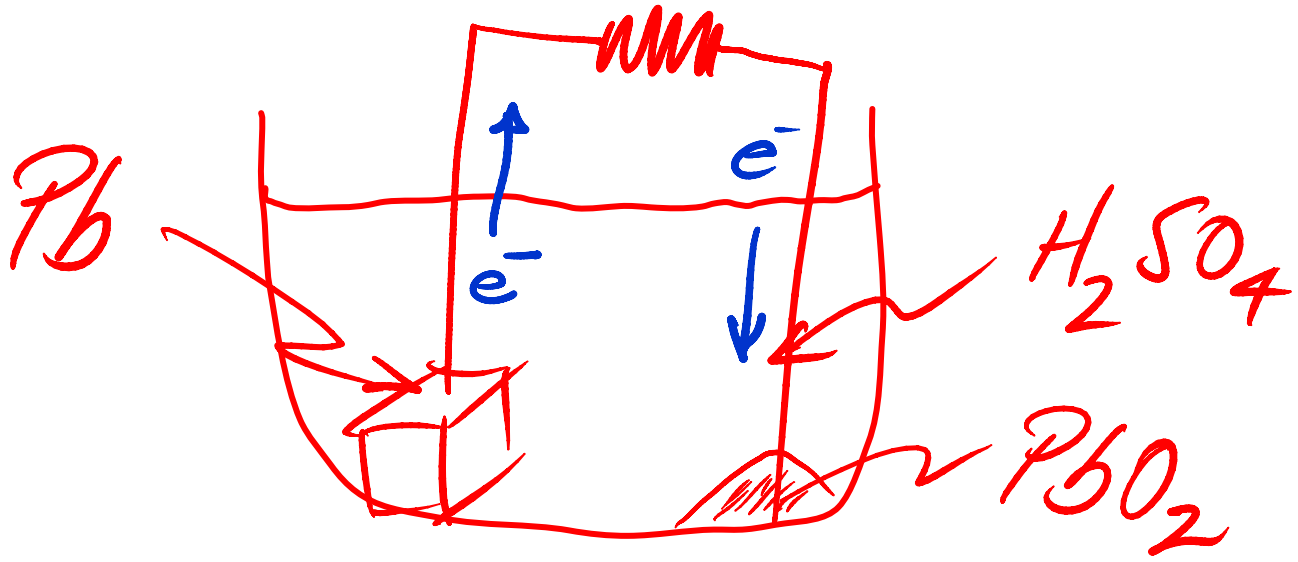


Electrons in motion

$$Pb + SO_4^{2-}{}_{(aq)} \Rightarrow PbSO_4 + 2\,e^-$$

$$PbO_2 + 4\,H^+{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 2\,e^-$$

$$\Rightarrow 2\,H_2O + PbSO_4$$

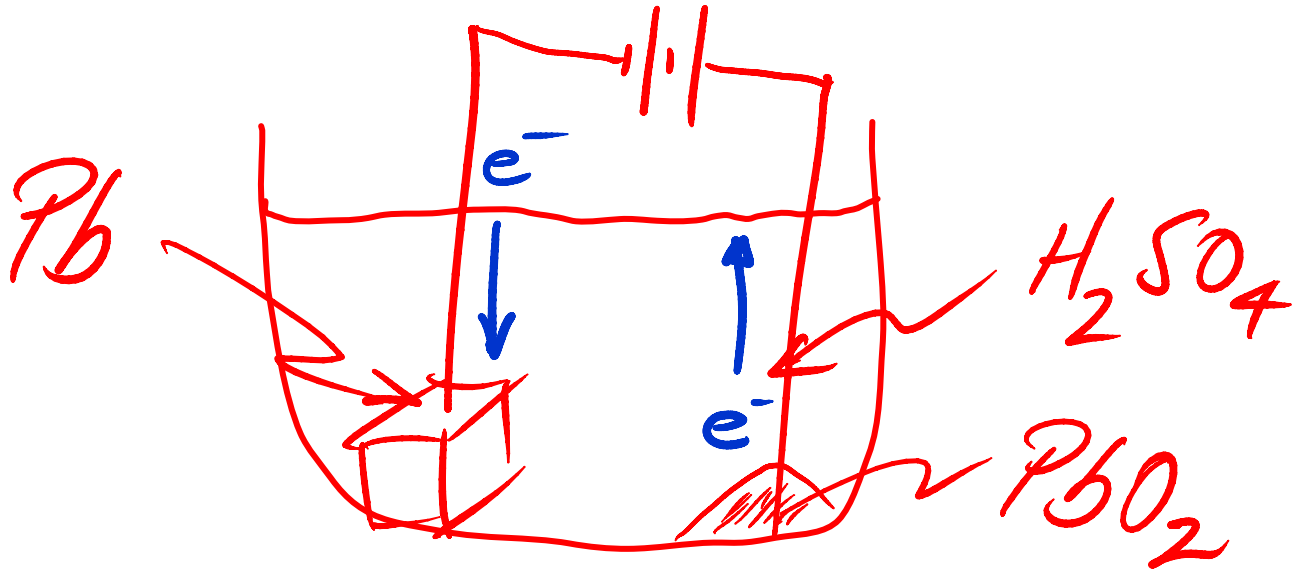


but there's more

$$PbSO_4 + 2\,e^- \Rightarrow Pb + SO_4^{2-}{}_{(aq)}$$

$$2\,H_2O + PbSO_4 \Rightarrow$$

$$PbO_2 + 4\,H^+{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 2\,e^-$$



The lead-acid battery

anode:

$$Pb + SO_4^{2-}{}_{(aq)} \Rightarrow PbSO_4 + 2\,e^-$$

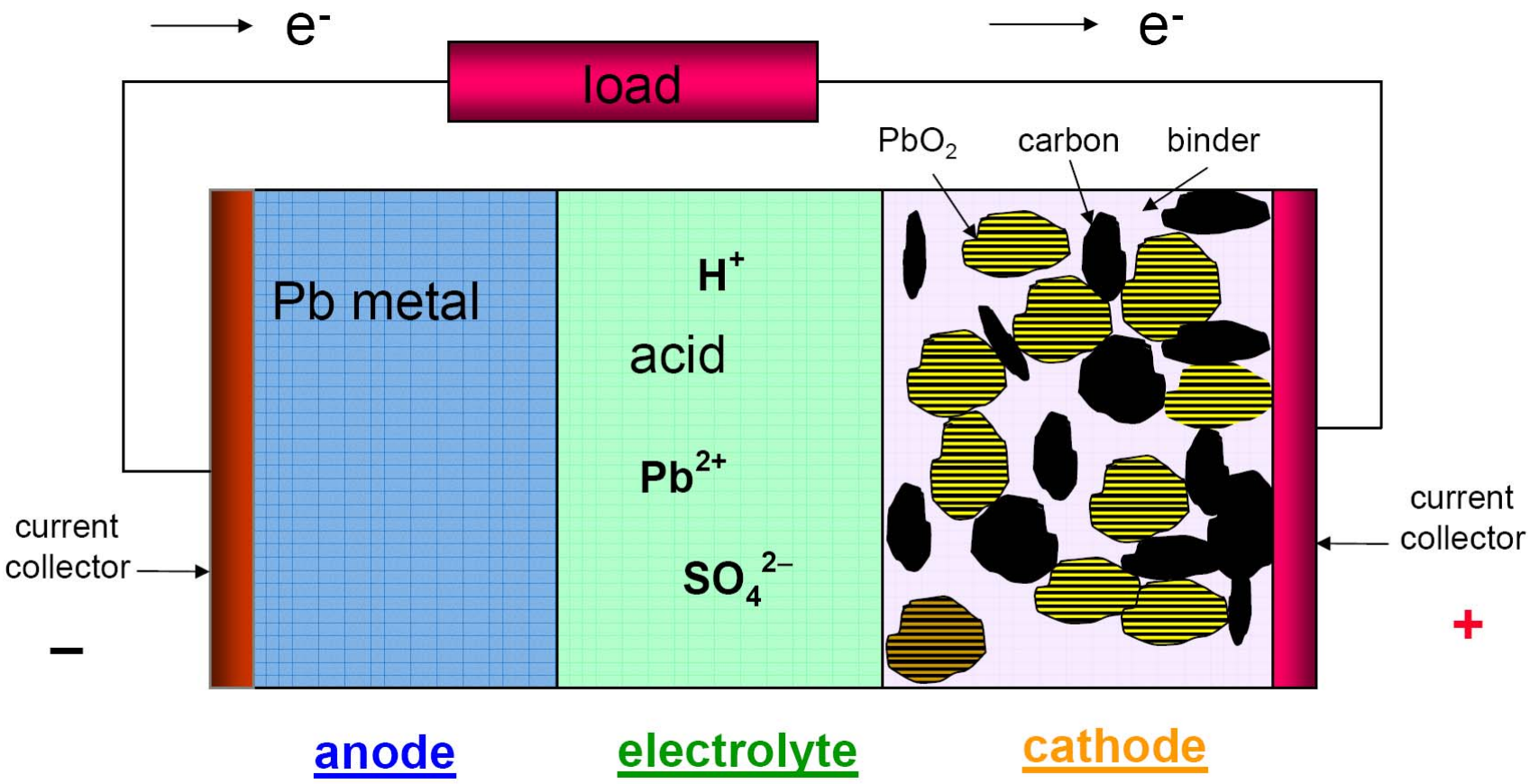
$$\ominus \quad Pb^0 \Rightarrow Pb^{2+} + 2e^- \quad (oxid^n)$$

cathode:

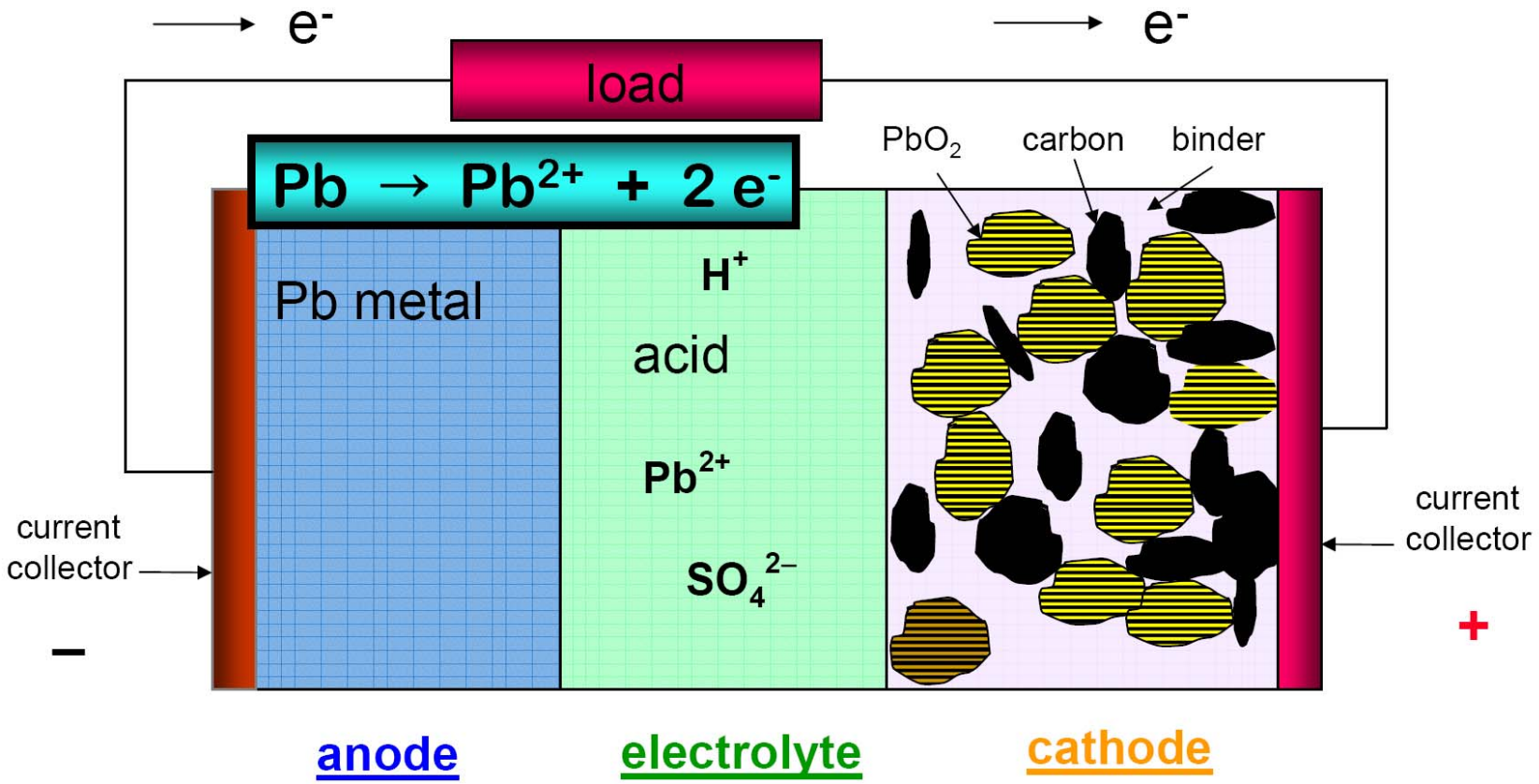
$$PbO_2 + 4\,H^+{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 2\,e^- \Rightarrow 2\,H_2O + PbSO_4$$

$$\oplus \quad Pb^{4+} + 2\,e^- \Rightarrow Pb^{2+} \quad (red^n)$$

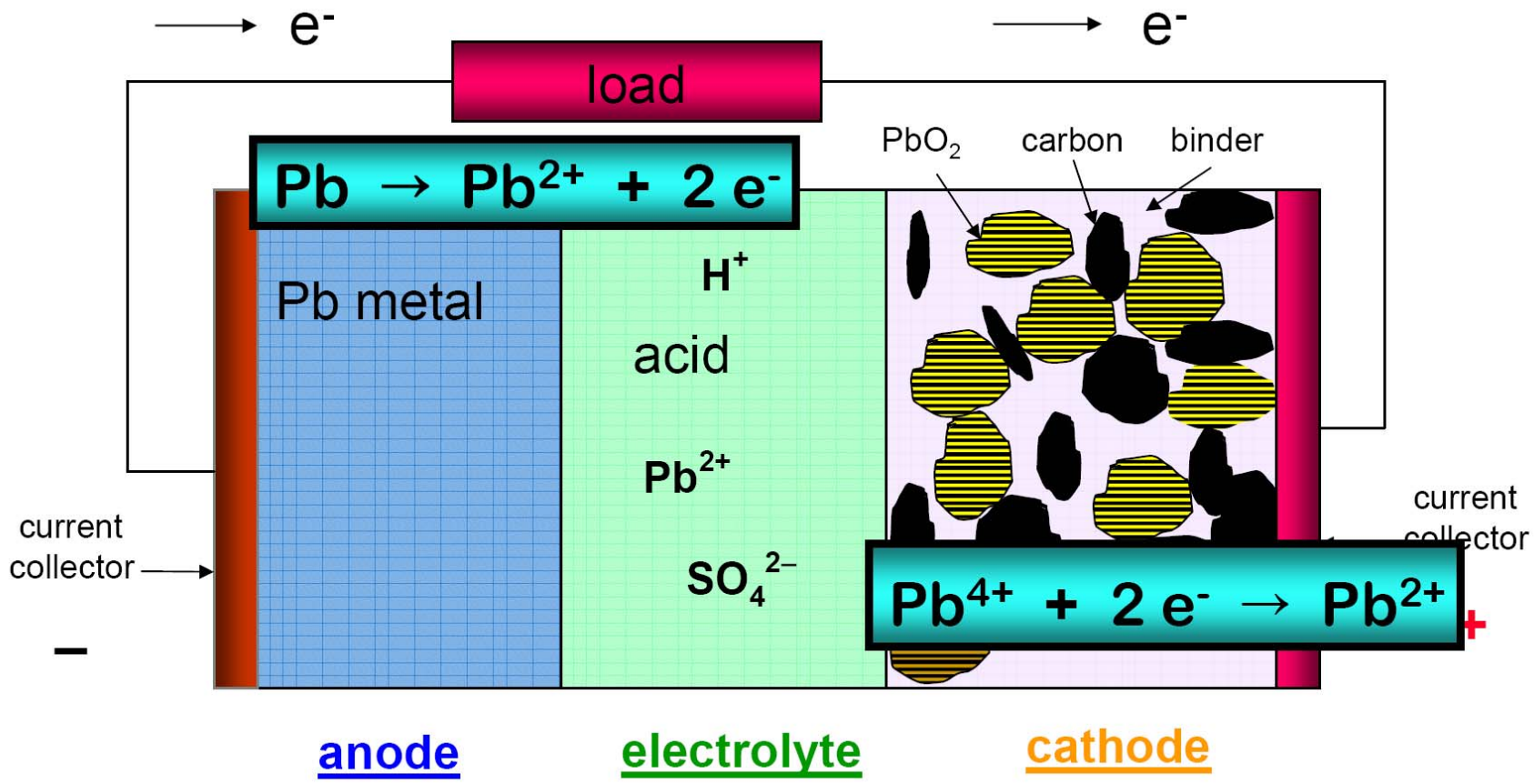
Lead-acid battery on discharge



Lead-acid battery on discharge



Lead-acid battery on discharge



The nickel metal-hydride battery

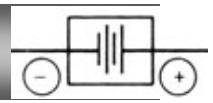
cathode:

$$NiOOH_{(aq)} + 2\,H_2O + e^- \Rightarrow Ni(OH)_{2(aq)} + OH^-_{(aq)}$$

anode:

$$MH + OH^-_{(aq)} \Rightarrow M + H_2O + e^-$$

electrolyte: 30% $KOH_{(aq)}$ (alkaline)



The nickel metal-hydride battery

cathode:

$$NiOOH_{(aq)} + 2\,H_2O + e^- \Rightarrow Ni(OH)_{2(aq)} + OH^-_{(aq)}$$

$$Ni^{3+} + e^- \Rightarrow Ni^{2+}$$

anode:

$$MH + OH^-_{(aq)} \Rightarrow M + H_2O + e^-$$

$$H \Rightarrow H^+ + e^-$$

The sodium-sulfur battery

anode: oxidation

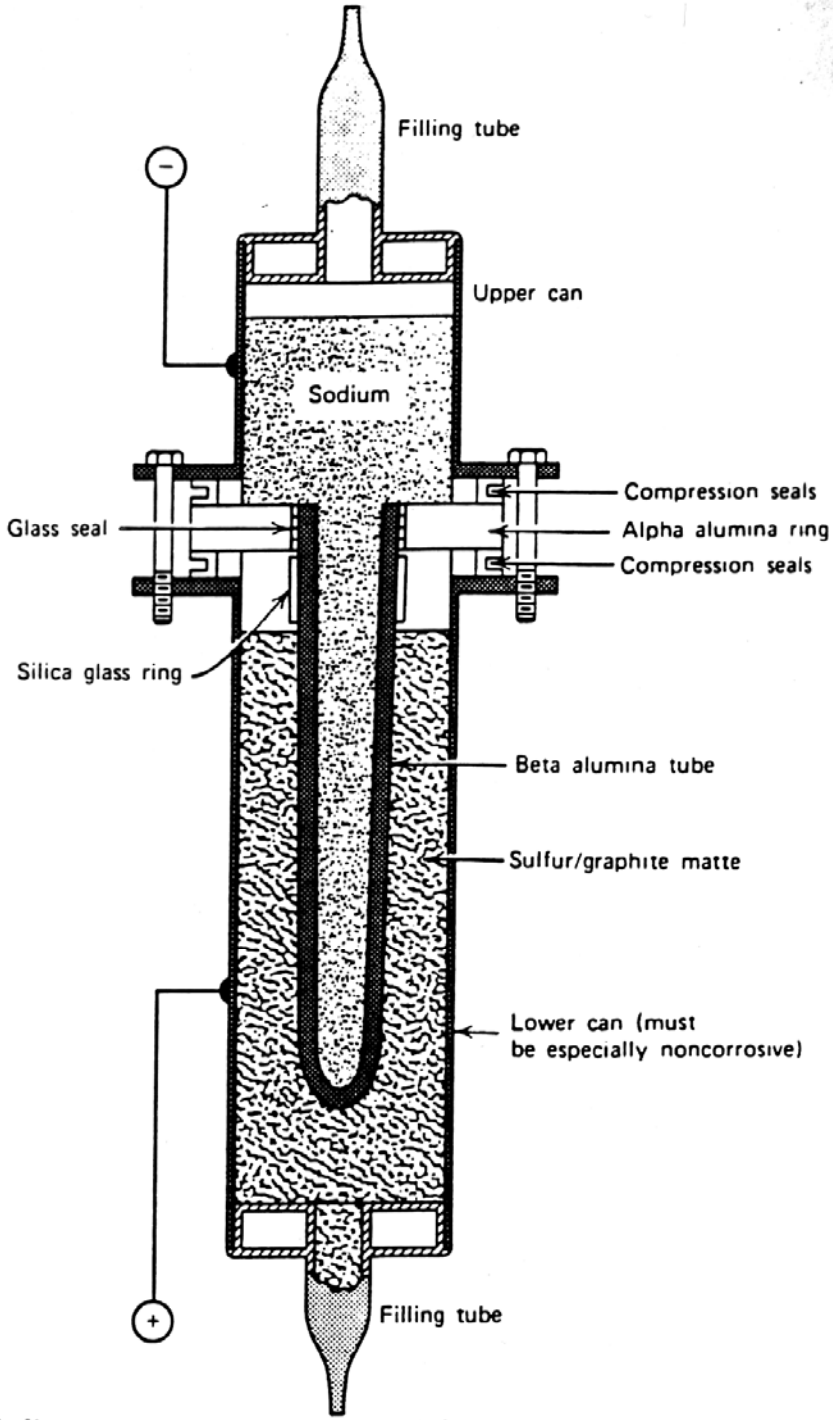
$2\ Na_{(liquid)} \Rightarrow 2\ Na^+ + 2\ e^-$ e⁻ source (−)

cathode: reduction

$2\ Na^+ + 2\ e^- + \underline{S}_{(liquid)} \Rightarrow \underline{Na_2S}_{(liquid)}$ e⁻ sink (+)

electrolyte:

$\beta - Al_2O_{3(solid)}$ Solid electrolyte


Filling tube
Upper can
Sodium
Compression seals
Glass seal
Alpha alumina ring
Compression seals
Silica glass ring
Beta alumina tube
Sulfur/graphite matte
Lower can (must
be especially noncorrosive)
Filling tube

ECOSTAR

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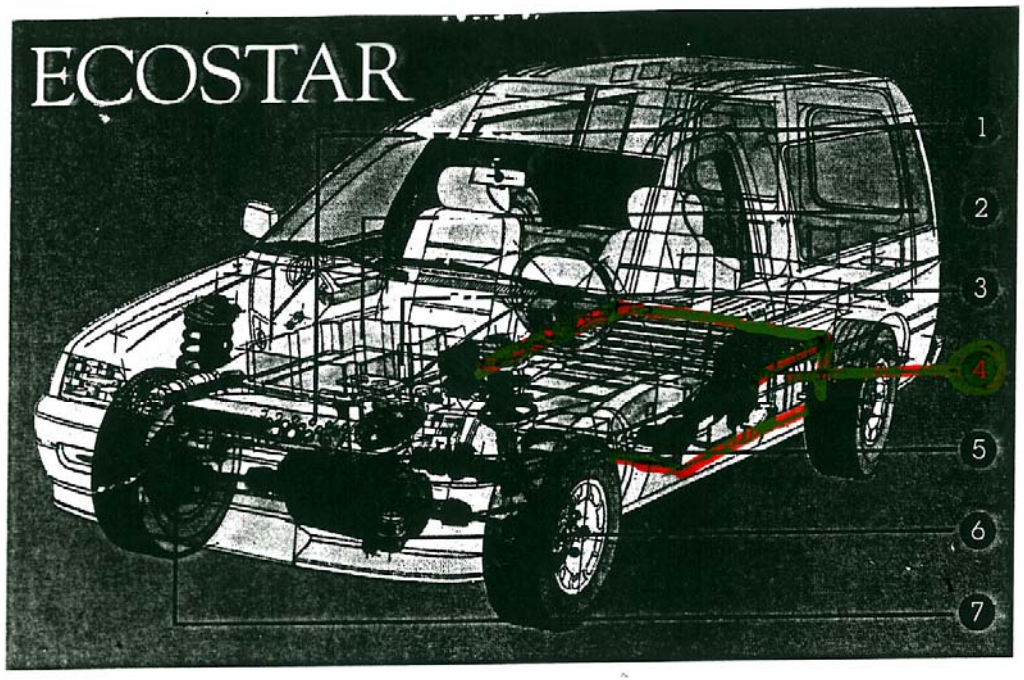


*(1) **Power Ele** charging the l directing pow ditioning com,*
*(2) **Vehicle Sy** monitors all c using multiple*
*(3) **Power Pro** tion functions*
*(4) **Sodium-Su** formance to ei capacity of le*
*(5) **Climate Co** diately withou for more sever conditioning c*
*(6) **Drive Mot** power to a sin*
*(7) **External C** front of the vei retracts into th*

an inverter to change DC current to AC for the driving motor. This module also powers components that were previously run by engine-driven belts, such as the air conditioning compressor and the charging system alternator.

The Ecostar motor has two functions. The first is to power the vehicle. The second is to act as a generator, recharging the battery while it helps slow the vehicle. This is called regenerative braking, and it means that the motor actually helps extend the Ecostar's driving range.

The real-world experiences of working Ecostars will help speed up development of affordable, reliable electric vehicles for an ever expanding range of customers.

POWERTRAIN

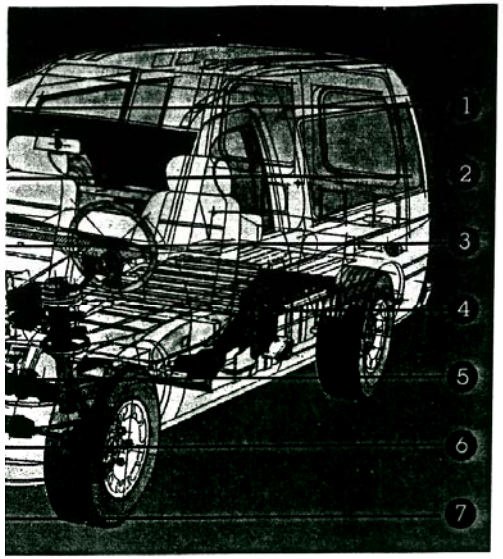
Motor ..... 143 ft-lb., 13,500 rpm, 75hp (56kW) 3-phase, AC induction
Transmission ..... Single-speed integrated front-wheel drive

STANDARD FEATURES

Steering ..... Manual rack-and-pinion
Brakes ..... Power-assisted hydraulic braking and regenerative braking
Heater ..... Electronically controlled electric resistive heating element (4-5 kW)
Wheels/Tires ..... Lightweight 14" aluminum alloy wheels with specifically developed P195/70R14 low rolling resistance tires
Other ..... Solar power assisted ventilation; High thermal efficiency glass; AM/FM stereo cassette radio

OPTIONS

A/C ..... Electrically driven high-efficiency scroll compressor. Non-flouro-carbon refrigerant.
Heater .....Fuel-fired heater for operation in severe climates



(1) ***Power Electronics Center.*** *The PEC manages the flow of electricity, charging the battery from the power grid or regenerative braking, and directing power from the battery to the 3-phase AC drive motor, air conditioning compressor and vehicle lighting and power system.*

(2) ***Vehicle System Controller.*** *The microprocessor based controller monitors all critical functions and optimizes complete vehicle operation using multiplex technology.*

(3) ***Power Protection Center.*** *The PPC combines protection and isolation functions for safety while driving, charging or during service.*

(4) ***Sodium-Sulfur Battery.*** *The NaS traction battery brings new performance to electric vehicles with three to four times the energy storage capacity of lead-acid batteries.*

(5) ***Climate Control System.*** *A PTC electric heater provides heat immediately without a warm-up. An optional fuel-fired heater provides heat for more severe climates. And the optional high-speed scroll-type air conditioning compressor means quiet, efficient operation.*

(6) ***Drive Motor/Transaxle.*** *The high-speed, 3-phase AC motor delivers power to a single-speed, direct-coupled transaxle.*

(7) ***External Charger Door.*** *The door is conveniently located at the front of the vehicle for quick and easy access to the charger cable which retracts into the vehicle when not in use.*

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charging system

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OPTIONS

A/C ..... Electrically driven high-efficiency scroll compressor. Non-flouro-carbon refrigerant.

Heater ..... Fuel-fired heater for operation in severe climates

BATTERY

Type ..... sodium sulfur

Energy capacity rating @ 80% DOD 30kWh

Power ratings ..... peak intermittent 52 kW-70 hp maximum continuous 30kW-40 hp

Charger ..... On board (120/240V) with 12' charging cord on reel. Requires 240V @ 30 amp. AC single phase for maximum charging rate.

PERFORMANCE

Maximum vehicle weight ..... 4080 lb (1851kg)

Vehicle curb weight ..... 3060 – 3200 lb (1388 – 1452 kg)

Payload ..... 880 – 1020 lb (400 – 463 kg)

Rated top speed (governed) ..... 70 mph (113 km/hr)

Rated 0-50 mph (0-80 km/hr) acceleration time ..... 12 seconds

Range (FUDS) ..... 100 miles (161 km)

For more information, call Ford

1-800-ALT-FUEL

Ford

The lithium ion battery

anode (-)

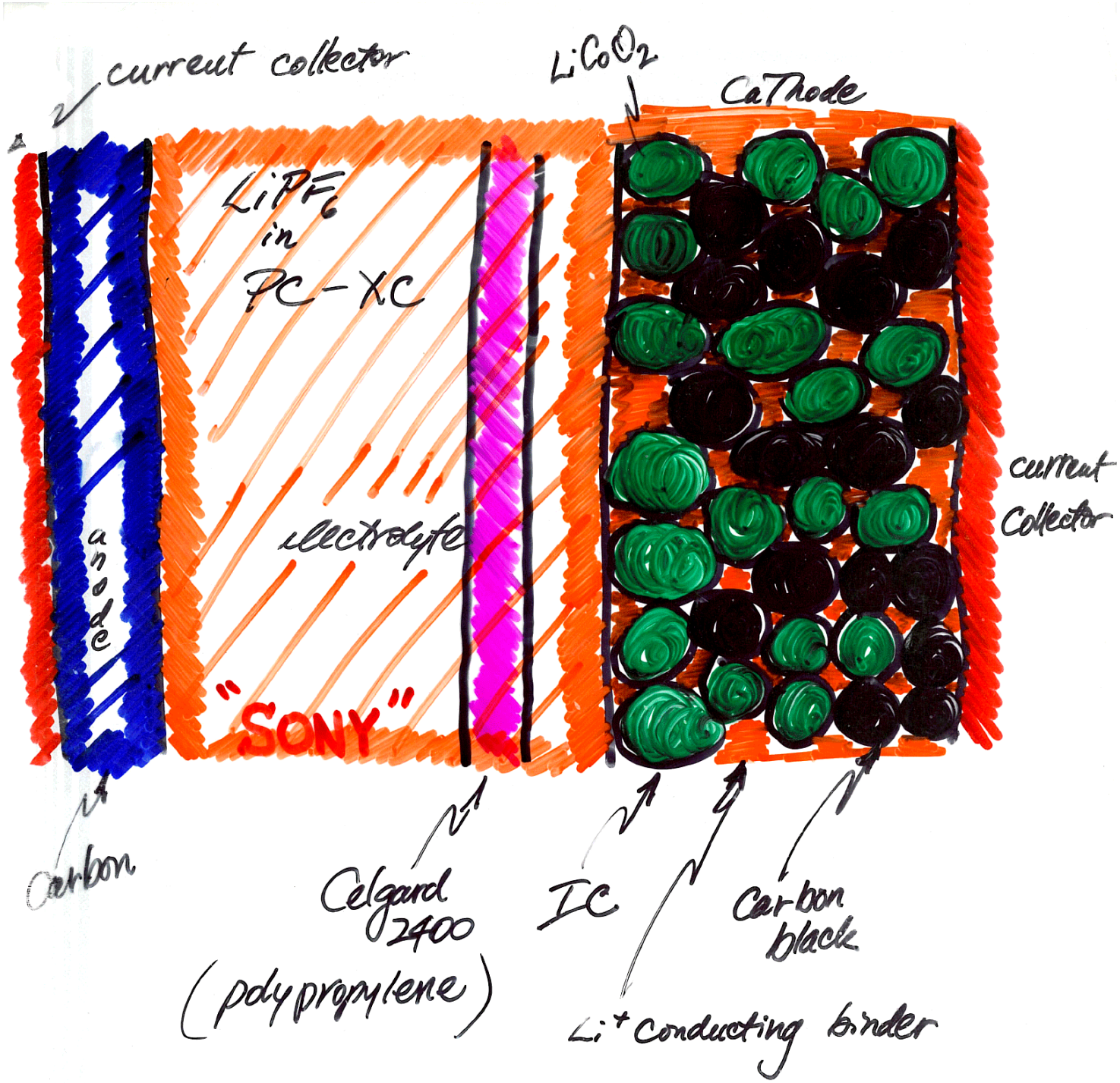
$$Li_{\text{in carbon}} \rightarrow Li^+ + e^-$$

cathode (+)

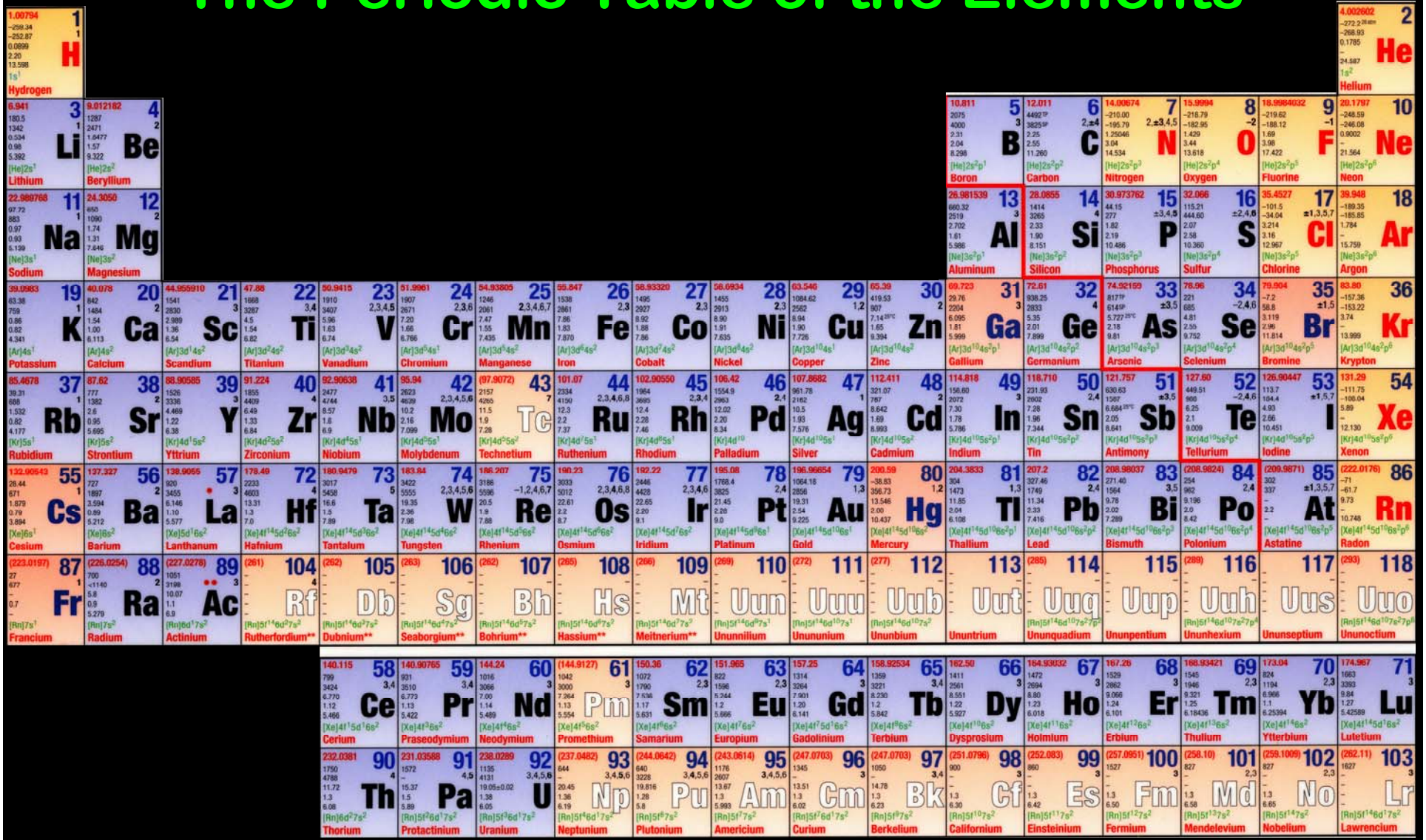
$$Li^+ + e^- + Li_xCoO_2 \rightarrow Li_{1+x}CoO_2$$

$$Li^+ + e^- + Co^{4+} \rightarrow Li^+ + Co^{3+}$$

electrolyte: 1 M $LiPF_6$ in
1:1 ethylene carbonate – propylene carbonate


current collector
$LiCoO_2$
CaThode
$LiPF_6$
in
PC-XC
anode
electrolyte
"SONY"
current
Collector
carbon
Celgard
2400
(polypropylene)
IC
carbon
black
Li^+ conducting binder

The Periodic Table of the Elements



It’s a Dell!

It’s a Dell!

safety first

ask the unthinkable

Can we eliminate the flammable liquid that serves as the electrolyte in the Li-ion battery?

Without loss of performance?

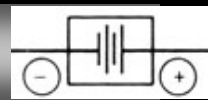
ask the unthinkable

Can we eliminate the liquid that serves as the electrolyte in the Li-ion battery?

Without loss of performance?

How about a solid electrolyte?

☞ 100% solid-state battery!



anode	electrolyte	Cathode
Solid	liquid	Solid
liquid	Solid	liquid
Solid	Solid	Solid

Journal of The Electrochemical Society, **146** (1) 32-37 (1999)
S0013-4651(98)05-005-8 CCC: $7.00

Rubbery Block Copolymer Electrolytes for Solid-State Rechargeable Lithium Batteries

Philip P. Soo, Biying Huang, Young-Il Jang,* Yet-Ming Chiang,**
Donald R. Sadoway, and Anne M. Mayes[z]**

Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA

Journal of The Electrochemical Society, **152** (1) A1-A5 (2005)
0013-4651/2004/152(1)/A1/5/$7.00 © The Electrochemical Society, Inc.

Rubbery Graft Copolymer Electrolytes for Solid-State, Thin-Film Lithium Batteries

Patrick E. Trapa,[a,*] You-Yeon Won,[a] Simon C. Mui,[a,*] Elsa A. Olivetti,[a] Biying Huang,[a] Donald R. Sadoway,[a,*] Anne M. Mayes,[a,*,z] and Steven Dallek[b]

[a]*Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139-4307, USA*
[b]*Naval Surface Warfare Center, Carderock Division, West Bethesda, Maryland, 20817, USA*

Journal of The Electrochemical Society, **153** (6) A1098-A1101 (2006)
0013-4651/2006/153(6)/A1098/4/$20.00 © The Electrochemical Society

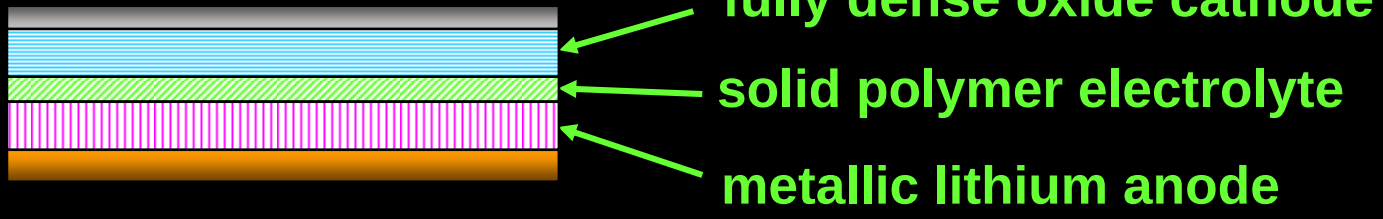
Polarization in Cells Containing Single-Ion Graft Copolymer Electrolytes

Patrick E. Trapa,[a] Allan B. Reyes, Raj Shekar Das Gupta,[b,*] Anne M. Mayes,[*] and Donald R. Sadoway[*,z]

Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA

what's the best we can expect today?

thin-film battery

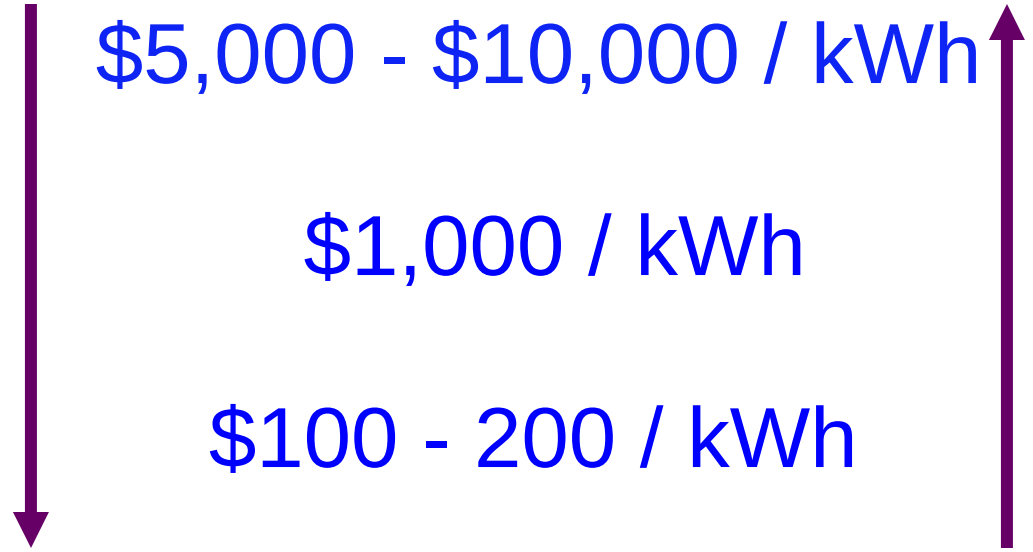


- multilayer, flexible laminate
- fully dense oxide cathode (0.5 μm)
- solid polymer electrolyte (1.0 μm)
- metallic lithium anode (0.37 μm)

☞ **400 Wh/kg** (700 Wh/L) & **650 W/kg** (1.1 kW/L)

Enormous market potential of rechargeables

APPLICATION	PRICE POINT
laptop computer	$5,000 - $10,000 / kWh
communications	$1,000 / kWh
automobile traction	$100 - 200 / kWh



The storage battery is, in my opinion, a catch-penny, a sensation, a mechanism for swindling the public by stock companies. The storage battery is one of those peculiar things which appeals to the imagination, and no more perfect thing could be desired by stock swindlers than that very self-same thing... Just as soon as a man gets working on the secondary battery it brings out his latent capability for lying... Scientifically, storage is all right but, commercially, as absolute a failure as one can imagine.

- Thomas A. Edison, 1883

fuel cells:
electrochemical combustion of hydrogen

compare direct chemical reaction

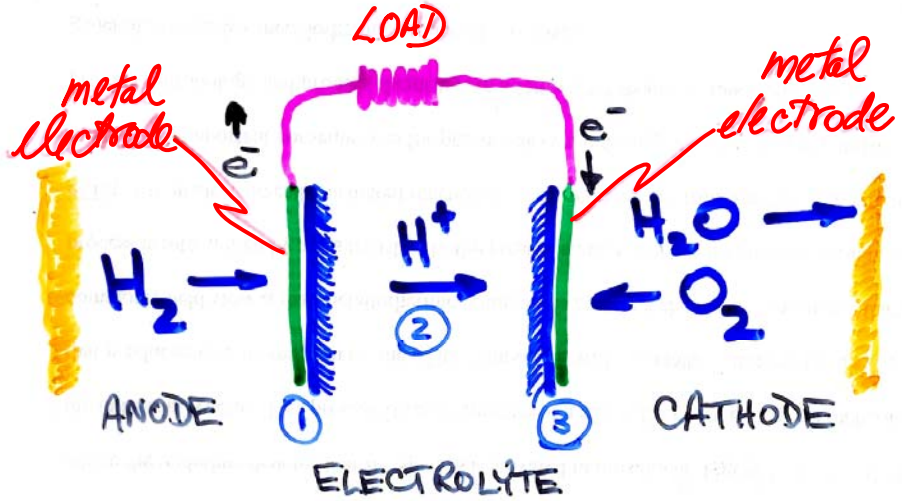
$H_2\,(g) + \frac{1}{2}\,O_2\,(g) \rightleftharpoons H_2O\,(g)$

with electrochemical reaction

❶ $H_2\ (g) \Rightarrow 2\ H^+\ (electrolyte) + 2\ e^-\ (anode)$

❷ $2\ H^+\ (electrolyte,\ anode) \Rightarrow 2\ H^+\ (electrolyte,\ cathode)$

❸ $2\ H^+\ (electrolyte) + 2\ e^-\ (cathode) + O_2\ (g) \Rightarrow H_2O\ (g)$



— aqueous solution

— Solid polymer electrolyte (SPE)

req'd: * proton conductor

* H_2 blocker

The hydrogen fuel cell

cathode:

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \xrightarrow{Pt} H_2O$$

anode:

$$H_2 \xrightarrow{Pt} 2\,H^+ + 2\,e^-$$

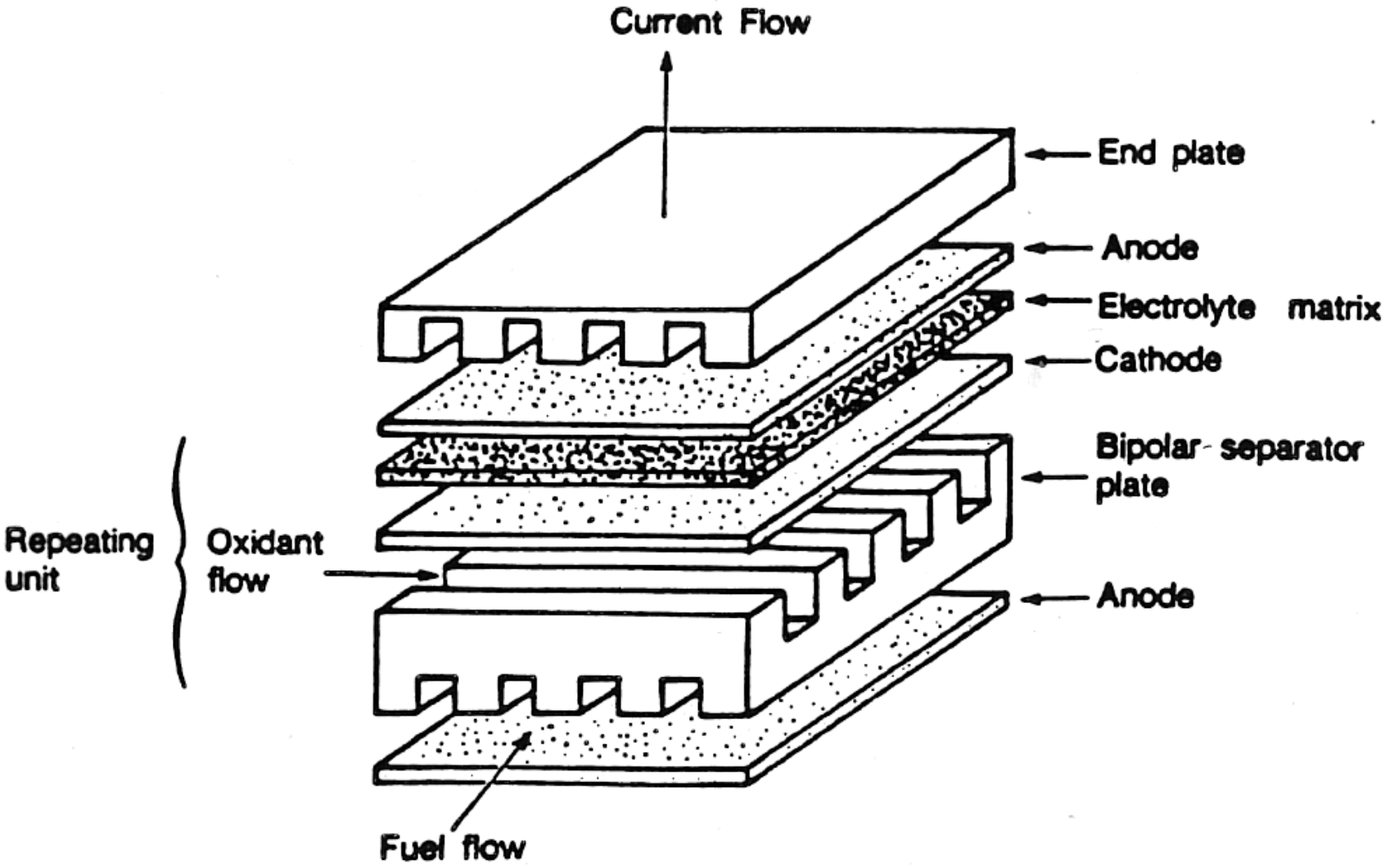
electrolyte:

protonic (H^+) conductor,

i.e., proton exchange membrane (PEM)

➪ both electrode reactions occur on substrates made of platinum-group metals

Basic Fuel Cell Structure



The hydrogen fuel cell

technical issues:

- hydrogen on board? pure H_2? $LaNi_5$?
- generation of hydrogen?
  - water electrolysis?
  - cracking of natural gas or even gasoline?
- electrode stability:
  - corrosion, contamination, mechanical disturbance, conversion efficiency
- electrolyte stability: breakdown, impurities