Chemistry 163B

Electrochemistry

$$BaCl_2\,(s) \rightleftarrows Ba^{2+}(aq) + 2Cl^-(aq)$$
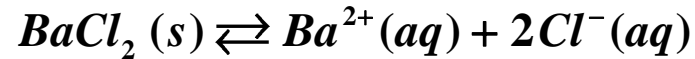
$$K_{sp} = \frac{\left(a_{Ba^{2+}(aq)}\right)\left(a_{Cl^-(aq)}\right)^2}{\left(a_{BaCl_2(s)}\right)}$$

$$a_{BaCl_2(s)} = 1$$

$$a_{Ba^{2+}(aq)} = \gamma_{Ba^{2+}}\left[Ba^{2+}\right]$$

$$a_{Cl^-(aq)} = \gamma_{Cl^-}\left[Cl^-\right]$$

cannot determine $\gamma_{Ba^{2+}}$ *and* γ_{Cl^-} *independently*

but only $\gamma_{Ba^{2+}} = \gamma_{Cl^-} = \gamma_\pm$ $\left(\gamma_+ = \gamma_- \equiv \gamma_\pm\right)$

$$K_{sp} = \frac{(\gamma\pm)^3}{1} \frac{\left(\left[Ba^{2+}\right]/1M\right)\left(\left[Cl^-\right]/1M\right)^2}{(1)}$$

$$K_{sp} = (\gamma\pm)^3 \left[Ba^{2+}\right]\left[Cl^-\right]^2$$

$$H_2 \ (10 \ bar) \longrightarrow H_2(1 \ bar)$$

pfft

1 bar

10
bar

1 bar

10
bar

$$H_2(10\ bar) \longrightarrow 2H^+ + 2e^-$$

$$2H^+ + 2e^- \longrightarrow H_2(1\ bar)$$

$$H_2\ (10\ bar) \longrightarrow H_2(1bar)$$
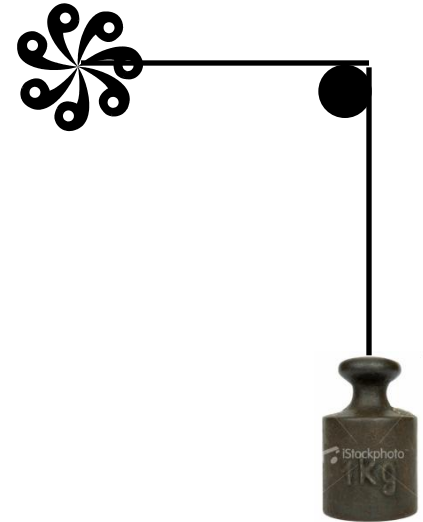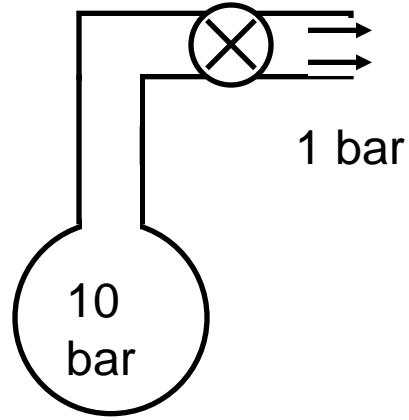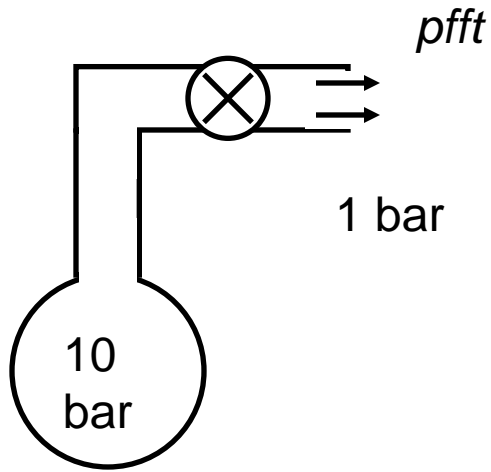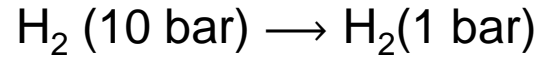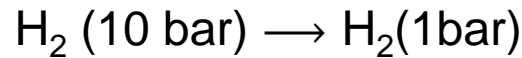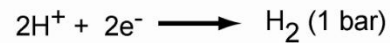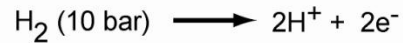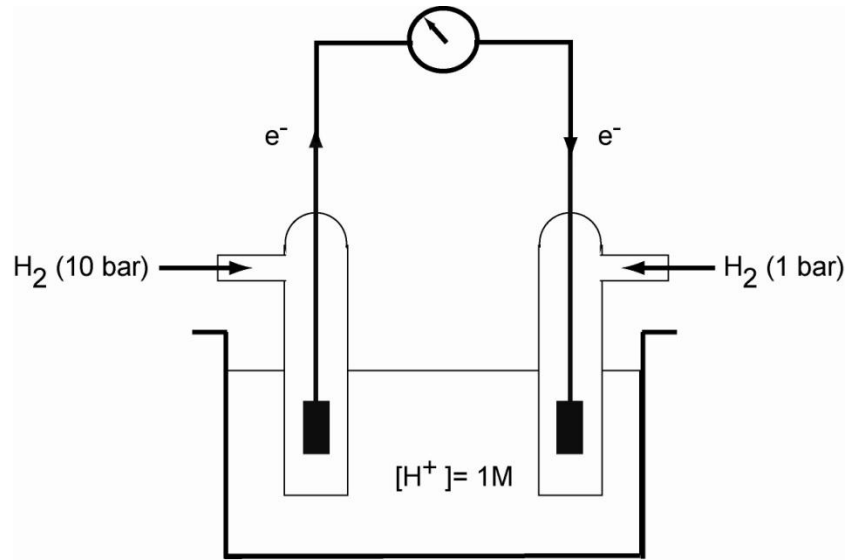
$$\Delta\mu = \Delta\mu^\circ + \underline{R}T\ln Q_{reaction}$$

$$\Delta\mu^\circ = 0 \quad \Delta\mu^\circ \text{ is for reaction } H_2(P=1\ bar) \rightarrow H_2(P=1\ bar)$$

$$\Delta\mu = \Delta\mu^\circ + \underline{R}T\ln\frac{P(1\ bar)}{P(10\ bar)} = -5.706\ kJ\ per\ mole\ H_2$$

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$$d\mu = d\bar{H} - Td\bar{S} - \bar{S}dT$$

$$d\mu = \underbrace{đq - Td\bar{S}}_{\leq 0 \text{ by 2nd law}} - \bar{S}dT + VdP + đw_{other} \quad \text{(very general)}$$

$$d\mu_{T,P} \leq đw_{other}$$

for a spontaneous process at constant T,P
the MAXIMUM work done ON SURROUNDINGS
is |Δμ| and this occurs when the process approaches

REVERSIBILITY
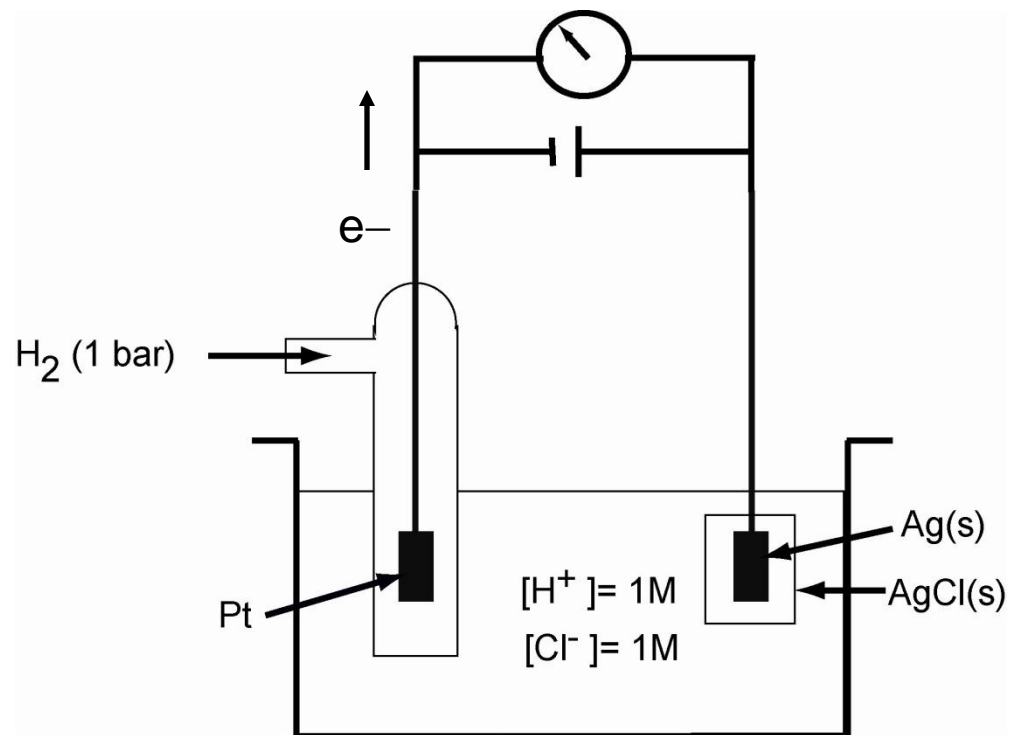
oxidation *anode* H_2 (1 bar) $\longrightarrow$ $2H^+$ [1M] + $2e^-$

reduction *cathode* $2AgCl(s) + 2e^- \longrightarrow 2Ag(s) + 2Cl^-$ [1M]

$2e^- + H_2 (g, 1\ bar) + 2AgCl(s) \longrightarrow 2H^+ [1M] + 2Cl^- [1M] + 2Ag(s) + 2e^-$

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$2e^- + H_2$ (g, 1atm) + 2AgCl(s) $\longrightarrow$ $2H^+$ [1M] + $2Cl^-$ [1M] + 2Ag(s) + $2e^-$
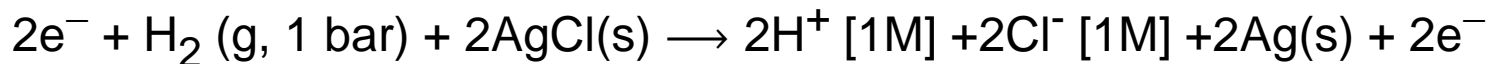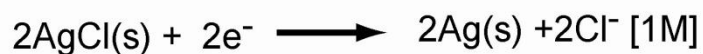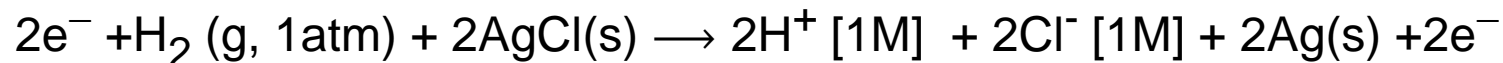
$\Delta\mu_f \approx \Delta G_f$ (kJ)   0   -109.79   0   -131.23   0

$\Delta\mu \approx \Delta G$ = - (0)   -2 (-109.79)   + 2(0)   + 2(-131.23) + 2 (0) = -42.88 kJ

$\boxed{\Delta\mu \text{ =for 2 moles } e^- \text{ transferred}}$

e^- + ½ H_2 (g, 1atm) + AgCl(s) $\longrightarrow$ H^+ [1M] + Cl^- [1M] + Ag(s) + e^-
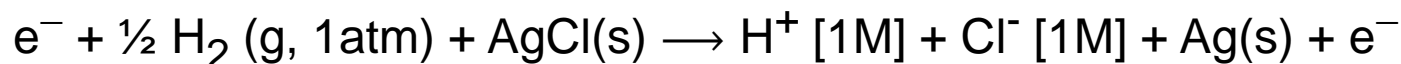
$\Delta\mu \approx \Delta G$ = -21.44 kJ per ½ mole H_2

$\boxed{\Delta\mu \text{ for 1 mole } e^- \text{ transferred}}$

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TABLE 2.1 Types of Work

Types of Work	Variables	Equation for Work	Conventional Units
Volume expansion	Pressure (P), volume (V)	$w = -\displaystyle\int_{V_i}^{V_f} P_{external}\, dV$	Pa m^3 = J
Stretching	Force (F), length (l)	$w = \displaystyle\int_{x_i}^{x_f} \mathbf{F} \cdot d\mathbf{l}$	N m = J
Surface expansion	Surface tension (γ), area (σ)	$w = \displaystyle\int_{\sigma_i}^{\sigma_f} \boldsymbol{\gamma} \cdot d\boldsymbol{\sigma}$	(N m^{-1})(m^2) = J
Electrical	Electrical potential (ϕ), electrical charge (Q)	$w = \displaystyle\int_{0}^{Q} \phi\, dQ'$	V C = J

BUT

$$đw_{electrical} = \Phi \, dQ$$

electric potential   *charge transfer*

$$dQ = -\mathcal{F}dn$$ ← *moles of e's transferred*

from negative charge on e

$\mathcal{F}$ *is Faraday constant 96,458 coulomb (mole e)$^{-1}$*

$$đw_{electrical} = -\Phi \mathcal{F}dn$$

$$w_{electrical} = -n\mathcal{F}\Phi \quad \text{(n electrons transferred)}$$

$$(w = -n\mathcal{F}\mathcal{E}) \quad \mathcal{E} = electromotive\ force = \Phi_{rev}$$

$$\textbf{E \& R } p260\ z \equiv -n$$

UNITS: [w] = [Q] [Φ]
                joule= coulomb $\times$ volt

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sign of Φ and spontaneity

$$\Delta\mu_{T,P} \leq w_{other}$$

$$\Delta\mu_{T,P} < -n\mathcal{F}\ \Phi_{cell}^{irrev} \qquad \Phi_{cell}^{irrev}\ \text{for\ irreversible}$$

$$\Delta\mu_{T,P} = -n\mathcal{F}\ \Phi_{cell} \qquad \Phi_{cell} = \mathcal{E}mf\ \text{for reversible}$$

$$\boxed{\Delta\mu_{T,P} < 0\ \text{spontaneous} \Rightarrow \Phi > 0\ \text{spontaneous}}$$

$$\Delta\mu = \Delta\mu^{\circ} + \underline{\boldsymbol{R}}\boldsymbol{T}\ln\boldsymbol{Q}_{reaction} = -\boldsymbol{n}\boldsymbol{\mathcal{F}}\Phi$$

$$\Phi = -\frac{\Delta\mu^{\circ}}{n\mathcal{F}} - \frac{\underline{R}T}{n\mathcal{F}}\ln Q_{reaction}$$

$$\Phi^{\circ}$$

$$\Phi = \Phi^{\circ} - \frac{\underline{R}T}{n\mathcal{F}}\ln Q_{reaction}$$

$$T = 298K$$

$$\Phi = \Phi^{\circ} - \frac{0.02569 \text{ V}}{\bar{n}}\ln Q_{reaction}$$

n = moles electrons transferred

$$[\text{n}] = \text{mol}$$

$$\bar{\text{n}} = \text{n} \times \text{mol}^{-1}$$

$$[\bar{\text{n}}] = \textit{unitless}$$

		Φ_0
oxidation *anode*	H_2 (1 bar) $\longrightarrow$ $2H^+$ [1M] + $2e^-$	0
reduction *cathode*	$2AgCl(s) + 2e^- \longrightarrow 2Ag(s) + 2Cl^-$ [1M]	0.22233 V

$2e^- + H_2$ (g, 1bar) $+ 2AgCl(s) \longrightarrow 2H^+$ [1M] $+ 2Cl^-$ [1M] $+ 2Ag(s) + 2e^-$ 0.22233 V

$2e^- + H_2 \text{ (g, 1bar)} + 2AgCl(s) \longrightarrow 2H^+ \text{ [1M]} + 2Cl^- \text{ [1M]} + 2Ag(s) + 2e^-$

$$\Phi = \Phi^\circ - \frac{0.02569 \text{ V}}{\bar{n}} \ln \left[\frac{a_{H^+}^2 \; a_{Cl^-}^2 \; a_{Ag(s)}^2}{a_{H_2} a_{AgCl(s)}^2} \right]$$

$$a_{AgCl} = a_{Ag} = 1$$

$$a_{H^+} = \gamma_{H^+}[H^+] \quad a_{Cl^-} = \gamma_{Cl^-}[Cl^-]$$

can't independently meansure γ_{H^+} and γ_{Cl^-}

$$\gamma_{H^+} = \gamma_{Cl^-} = \gamma_{\pm}$$

$$\Phi = \Phi^\circ - \frac{0.02569 \text{ V}}{\bar{n}} \ln \left[\frac{\gamma_{\pm}^4 [H^+]^2 [Cl^-]^2}{\gamma_{H_2} P_{H_2}} \right]$$

$$\Phi = \Phi^\circ - \frac{0.02569 \text{ V}}{\overline{n}} \ln\left[\frac{\gamma_\pm^4 [H^+]^2 [Cl^-]^2}{\gamma_{H_2} P_{H_2}} \right]$$

0.22233 V   2 e's

$$\Phi = 0.22233 \text{ V} - \frac{0.02569 \text{ V}}{2} \ln\left[\frac{\gamma_\pm^4 [1M]^2 [1M]^2}{\gamma_{H_2} (1 \text{ bar})} \right]$$

unitless; have dropped
standard state concs
and pressure from
denominators

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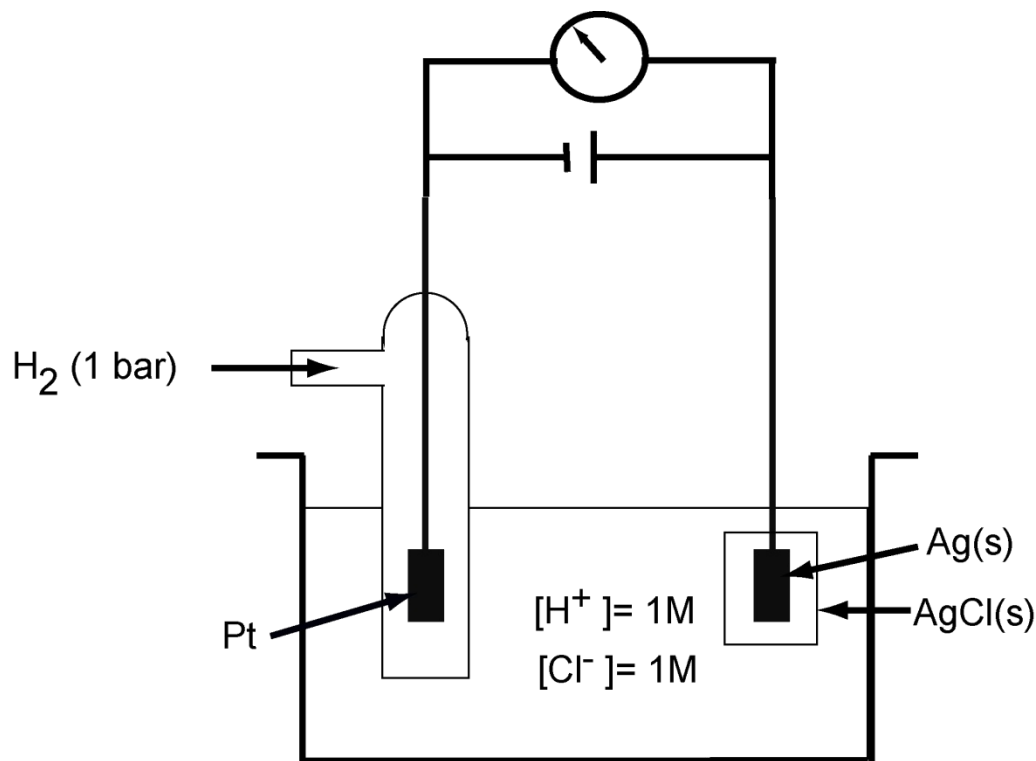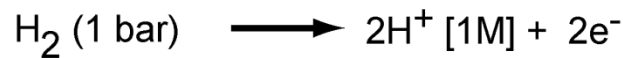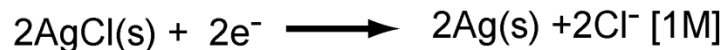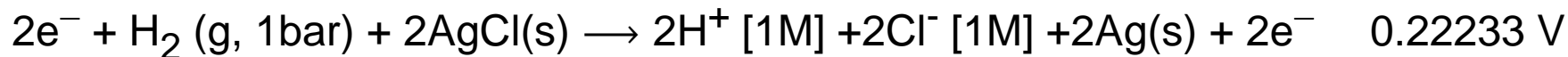
example incorporating activities

$$\Phi = 0.22233 - \frac{0.02569\ \mathrm{V}}{2} \ln \left[\frac{\gamma_\pm^4 [1M]^2 [1M]^2}{\gamma_{H_2}(1\ \mathrm{bar})} \right]$$

- Calculate γ's from observed Φ (HW9, prob 60)
- If γ's =1

$$\Phi = 0.22233\ \mathrm{V} - \frac{0.02569\ \mathrm{V}}{2} \ln[1] = 0.22233\ \mathrm{V} = \Phi^\circ$$

$$\Delta\mu = -n\mathcal{F}\Phi$$

$$\Delta\mu = -2\ mol\left(96{,}485\ C\,mol^{-1}\right)\left(0.22233\,V\right)$$

$$\Delta\mu = -4.290\times10^4\ CV = -42.90\ kJ$$

$\Delta\mu^\circ = -42.88$ kJ for 2 moles e$^-$ transferred [from $\Delta\mu_f^\circ$ earlier]
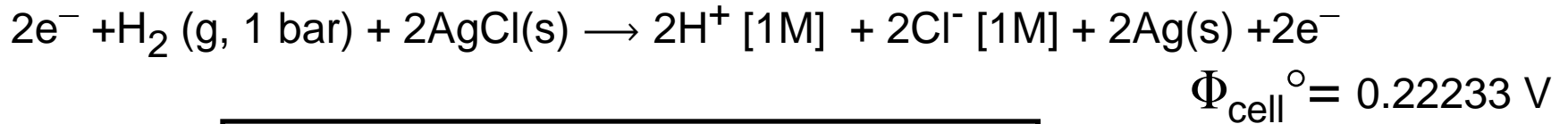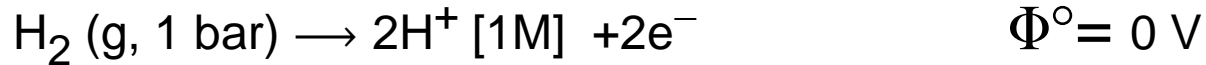
$$H_2 \text{ (g, 1 bar)} \longrightarrow 2H^+ \text{ [1M] } +2e^- \qquad\qquad \Phi^\circ = 0 \text{ V}$$

$$2e^- + 2AgCl(s) \longrightarrow 2Cl^- \text{ [1M] } + 2Ag(s) \qquad\qquad \Phi^\circ = 0.22233 \text{ V}$$

$$2e^- + H_2 \text{ (g, 1 bar)} + 2AgCl(s) \longrightarrow 2H^+ \text{ [1M] } + 2Cl^- \text{ [1M] } + 2Ag(s) +2e^-$$

$$\Phi_{cell}{}^\circ = 0.22233 \text{ V}$$

$$\boxed{\Delta\mu = \text{-42.88 kJ for 2 moles } e^- \text{ transferred}}$$

$$\Phi_{cell\ 2e's} = \Phi^\circ_{cell} - \frac{0.02569 \text{ V}}{2} \ln\left[\frac{a_{H^+}^2\ a_{Cl^-}^2\ a_{Ag(s)}^2}{a_{H_2} a_{AgCl(s)}^2} \right]$$

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intensive Φ vs extensive $\Delta\mu$ $\Phi = -(\Delta\mu/n\mathcal{F})$

½H$_2$ (g, 1 bar) $\longrightarrow$ H$^+$ [1M] +e$^-$ $\Phi° = 0$ V

e$^-$ + AgCl(s) $\longrightarrow$ Cl$^-$ [1M] + Ag(s) $\Phi° = 0.22233$ V

e$^-$ +½H$_2$ (g, 1 bar) + AgCl(s) $\longrightarrow$ H$^+$ [1M] + Cl$^-$ [1M] + Ag(s) +e$^-$
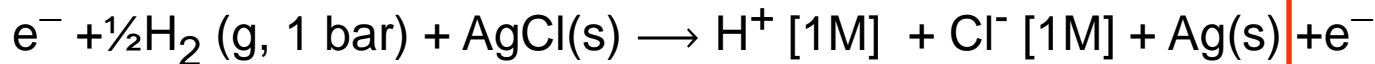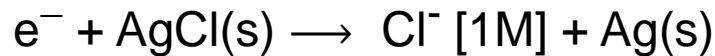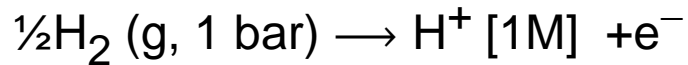
$\Phi_{cell}° = 0.22233$ V

$\Delta\mu = -21.44$ kJ for 1 moles e$^-$ transferred

$\Phi°$ intensive
same as for 2 mole e's
Φ is oomph per electron

$$\Phi_{cell\ 1e} = \Phi_{cell}° - \frac{0.02569\text{ V}}{1}\ln\left[\frac{a_{H^+}^1\ a_{Cl^-}^1\ a_{Al(s)}^1}{a_{H_2}^{½}\,a_{AgCl(s)}^1}\right]$$

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intensive Φ vs extensive Δμ   Φ = - (Δμ /nℱ)

$\Delta\mu$ = -42.88 kJ for 2 moles e⁻ transferred

$$\Phi_{cell\ 2e's} = \Phi^{\circ}_{cell} - \frac{0.02569\ \text{V}}{2} \ln\left[\frac{a_{H^+}^2\ a_{Cl^-}^2\ a_{Ag(s)}^2}{a_{H_2}\ a_{AgCl(s)}^2}\right]$$

$$\Delta\mu_{2e} = 2\Delta\mu_{1e}$$
two times greater

$$\Phi_{cell\ 2e} = \Phi_{cell\ 1e}$$
same

$\Delta\mu$ = -21.44 kJ for 1 moles e⁻ transferred

$$\Phi_{cell\ 1e} = \Phi^{\circ}_{cell} - \frac{0.02569\ \text{V}}{1} \ln\left[\frac{a_{H^+}^1\ a_{Cl^-}^1\ a_{Ag(s)}^1}{a_{H_2}^{\frac{1}{2}}\ a_{AgCl(s)}^1}\right]$$

Δμ extensive: depends on stoichiometry

$$\Delta\mu = -n\mathcal{F}\Phi$$

Φ intensive: independent of 'how reaction is written' ooomph PER electron

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CytC=cytochrome C
standard state pH=7, [H+]=10^{-7}

	$\Phi^{\circ\prime}_{red}$(V) pH7

standard REDUCTION potentials

$2e^- + \quad 2CytC(Fe^{3+}) \longrightarrow 2CytC(Fe^{2+})$ 0.25

$2e^- + \frac{1}{2}O_2(g) + 2H^+(aq) \longrightarrow H_2O\ (\ell)$ 0.816
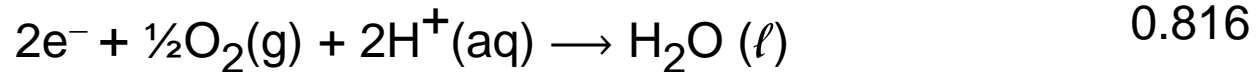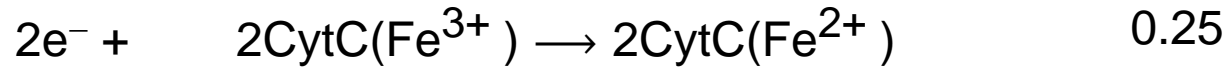
reaction: the oxidation of CytC(Fe^{2+}) $\Phi^{\circ\prime}$(V)

oxidation $2CytC(Fe^{2+}) \longrightarrow 2CytC(Fe^{3+}) + 2e^-$ - 0.25

reduction $2e^- + \frac{1}{2}O_2(g) + 2H^+(aq) \longrightarrow H_2O\ (\ell)$ 0.816

$\frac{1}{2}O_2(g) + 2H^+(aq) + 2CytC(Fe^{2+}) \longrightarrow 2CytC(Fe^{3+}) + H_2O\ (\ell)$ **?=** $\Phi^{\circ\prime}_{cell}$
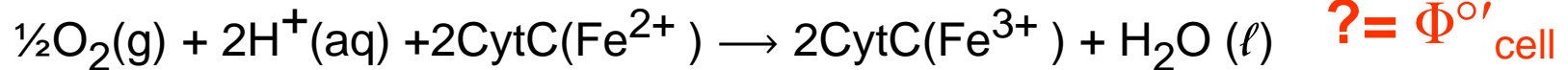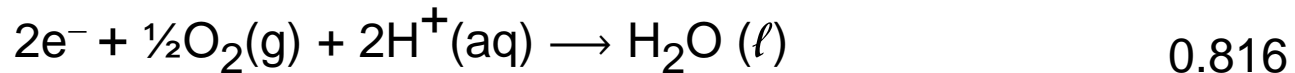
standard state [H$^+$]=10^{-7}

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$$\tfrac{1}{2}O_2(g) + 2H^+(aq) + 2CytC(Fe^{2+}) \longrightarrow 2CytC(Fe^{3+}) + H_2O\ (\ell)$$
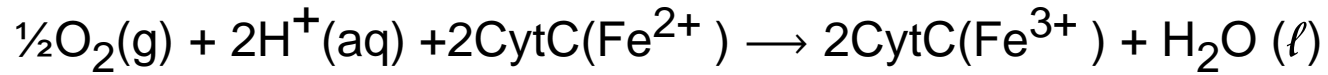
$$\Phi_{cell} = \Phi_{cell}^{\circ\,'} - \frac{RT}{n\mathcal{F}}\ln[Q] = \Phi_{cell}^{\circ\,'} - \frac{RT}{n\mathcal{F}}\ln\left[\frac{\ldots\ldots}{\ldots\ldots\left(\dfrac{\gamma_\pm[H^+]}{10^{-7}M}\right)^2\left(\dfrac{\gamma_{O_2}P_{O_2}}{1bar}\right)^{\frac{1}{2}}\ldots}\right]$$

standard state '

what's $\Phi^{\circ\prime}$?
what's Q   ?
what's n   ?

$$\Delta\mu = -n\mathcal{F}\Phi$$

$$\Phi = -\frac{\Delta\mu}{n\mathcal{F}}$$

$$\Delta\mu^{\circ} = -\underline{R}T\ln K_{eq} \quad \Rightarrow \quad \Phi^{\circ} = \frac{RT}{n\mathcal{F}}\ln K_{eq}$$

$$\left(\frac{\partial\Delta\mu}{\partial T}\right)_{P} = -\Delta\bar{S} \quad \Rightarrow \quad \left(\frac{\partial\Phi}{\partial T}\right)_{P} = \frac{\Delta\bar{S}}{n\mathcal{F}}$$

$$\left(\frac{\partial\dfrac{\Delta\mu}{T}}{\partial T}\right)_{P} = -\frac{\Delta\bar{H}}{T^{2}} \quad \Rightarrow \quad \left(\frac{\partial\dfrac{\Phi}{T}}{\partial T}\right)_{P} = \frac{\Delta\bar{H}}{n\mathcal{F}T^{2}}$$

$$\left(\frac{\partial \Delta\mu}{\partial T}\right)_P = -\Delta\bar{S} \quad \Rightarrow \quad \left(\frac{\partial \Phi}{\partial T}\right)_P = \frac{\Delta\bar{S}}{n\mathcal{F}}$$

$$\Delta\mu = \Delta\bar{H} - T\Delta\bar{S}$$

$$\Delta\bar{H} = \Delta\mu + T\Delta\bar{S} = -n\mathcal{F}\Phi + T\,n\mathcal{F}\left(\frac{\partial \Phi}{\partial T}\right)_P$$

$$\left(\frac{\partial \Delta\bar{H}}{\partial T}\right)_P = \Delta C_p = -n\mathcal{F}\left(\frac{\partial \Phi}{\partial T}\right)_P + n\mathcal{F}\left(\frac{\partial \Phi}{\partial T}\right)_P + n\mathcal{F}T\left(\frac{\partial^2 \Phi}{\partial T^2}\right)_P$$

$$\Delta C_p = n\mathcal{F}T\left(\frac{\partial^2 \Phi}{\partial T^2}\right)_P$$

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Electrochemistry:

$\bullet \Delta\mu_{reaction} = -n\mathcal{F}\Phi_{cell}$

$$\Phi = \Phi^{\circ} - \frac{RT}{n\mathcal{F}}\ln Q$$

$$\Phi = \Phi^{\circ} - \frac{0.02569\ \mathbf{V}}{\bar{n}}\ln Q \quad at\ T = 298K$$

battery -
- nicely package electrochemical cell
- closed system
- runs irreversibly ($\Phi < \mathcal{E}$)
- may be recharged (storage battery)

fuel cell-
- electrochemical cell
- open system (reactants continuously flow in)

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compare:

    w$_{electrical}$ (on surr) from lead storage battery

        ΔG=-377 kJ mol^{-1}, ΔH =-228 kJ mol^{-1}

with

    w$_{P-V}$ (on surr) of heat engine using q$_{upper}$= -$\Delta H_{storage\ battery}$

heat engine: T$_u$=600K, T$_L$=300K

ϵ=(600-300)/600= 0.5

w$_{P-V}$=(0.5)*228 kJ mol^{-1} = 114 kJ mol^{-1}

battery: ΔG=-377 kJ mol^{-1}, T=300K
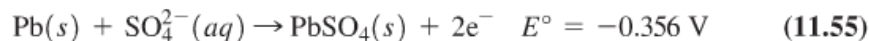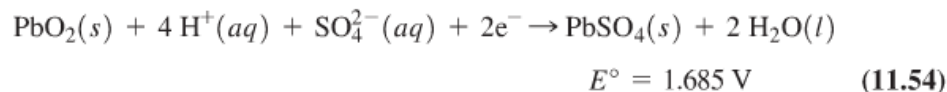
w$_{electrical}$=- ΔG = 377 kJ mol^{-1}

the winner:

$$\frac{w_{electrical}}{w_{P-V}} = \frac{377}{114} = 3.31$$

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types of batteries

Lead storage
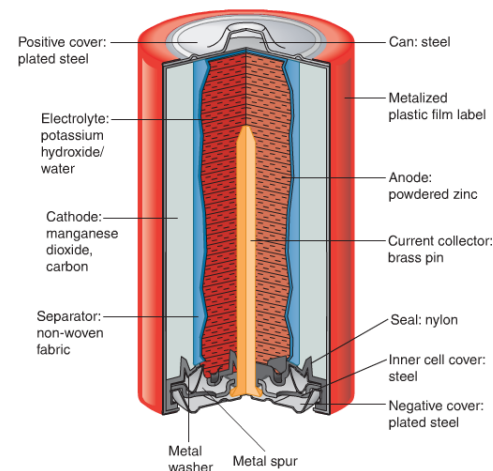Pb(s) oxidized to Pb^{2+} PbO_2 reduced to Pb^{2+}

$$PbO_2(s) + 4\,H^+(aq) + SO_4^{2-}(aq) + 2e^- \rightarrow PbSO_4(s) + 2\,H_2O(l)$$
$$E° = 1.685\ \text{V} \qquad (11.54)$$

$$Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4(s) + 2e^- \quad E° = -0.356\ \text{V} \qquad (11.55)$$

respectively, and the overall reaction is

$$PbO_2(s) + Pb(s) + 2\,H_2SO_4(aq) \rightleftharpoons 2\,PbSO_4(s) + 2\,H_2O(l)\ \ E° = 2.04\ \text{V}\ \ (11.56)$$
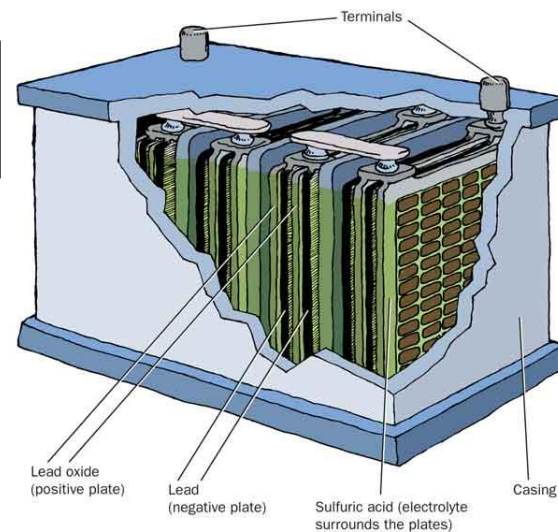
Alkaline storage (no liquids)
Zn(s) oxidized to Zn^{2+} MnO_2 reduced to Mn_2O_3

Zn (s) + 2OH⁻(aq) → ZnO (s) + H_2O (l) + 2e−   +1.26V
2MnO_2 (s) + H_2O (l) + 2e− →Mn_2O_3 (s) + 2OH− (aq)   0.275
Zn (s) + 2MnO$_2$ (s)   → ZnO (s) + **Mn$_2$O$_3$ (s)**   **+1.5 V**

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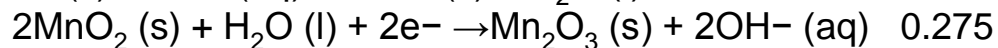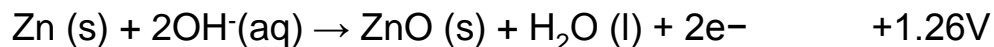
NiMH- Nickel Metal Hydride
M='intermetallic compound', e.g. M=AB_5,
A is a rare earth mixture of lanthanum, cerium, neodymium, praseodymium
B is nickel, cobalt, manganese, and/or aluminum

Ni^{2+} oxidized to Ni^{3+} H^+ reduced to H^-, "M" oxidized
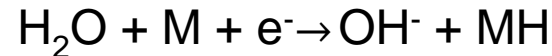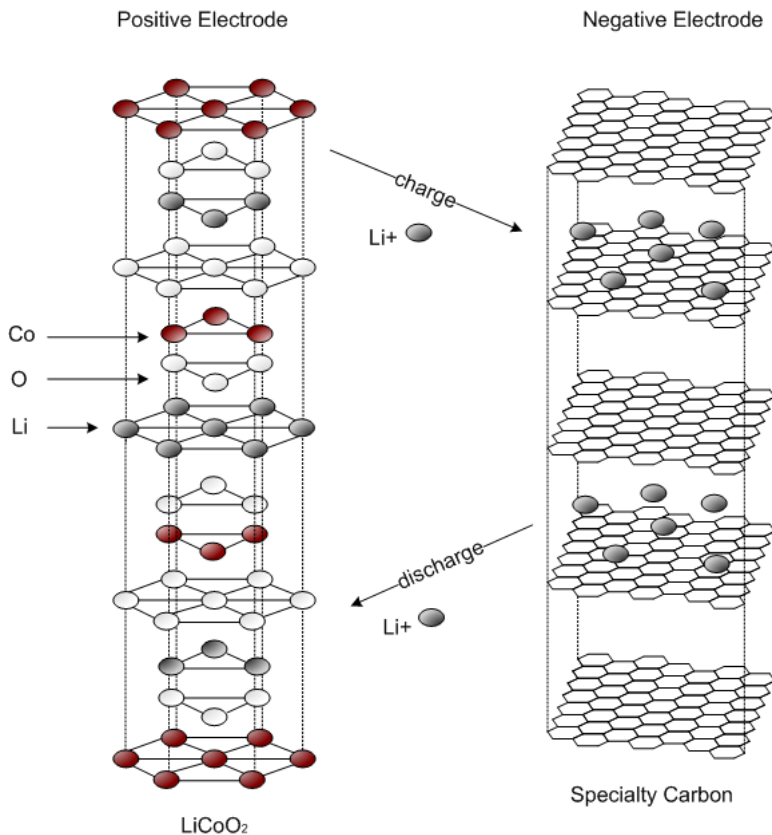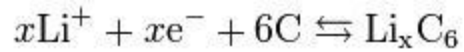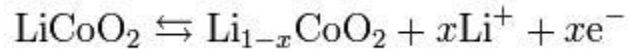
$$H_2O + M + e^- \rightarrow OH^- + MH$$
$$Ni(OH)_2 + OH^- \rightarrow NiO(OH) + H_2O + e^-$$

High power Ni-MH battery of Toyota NHW20 Prius

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Li-ion batteries can pack more energy into smaller and lighter weight units than other types of batteries. Those attributes have spurred enormous growth in their use for cell phones, laptop computers, and other portable electronic devices.

$$LiCoO_2 \leftrightarrows Li_{1-x}CoO_2 + xLi^+ + xe^-$$

$$xLi^+ + xe^- + 6C \leftrightarrows Li_xC_6$$

Positive Electrode

Negative Electrode

charge

Li+

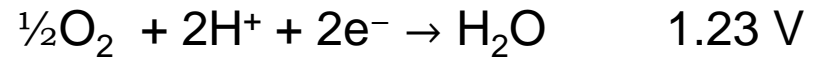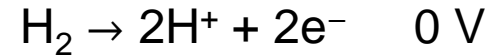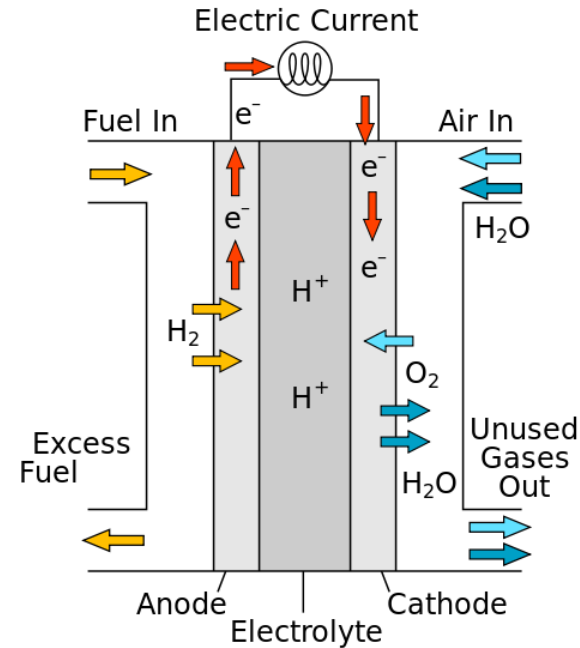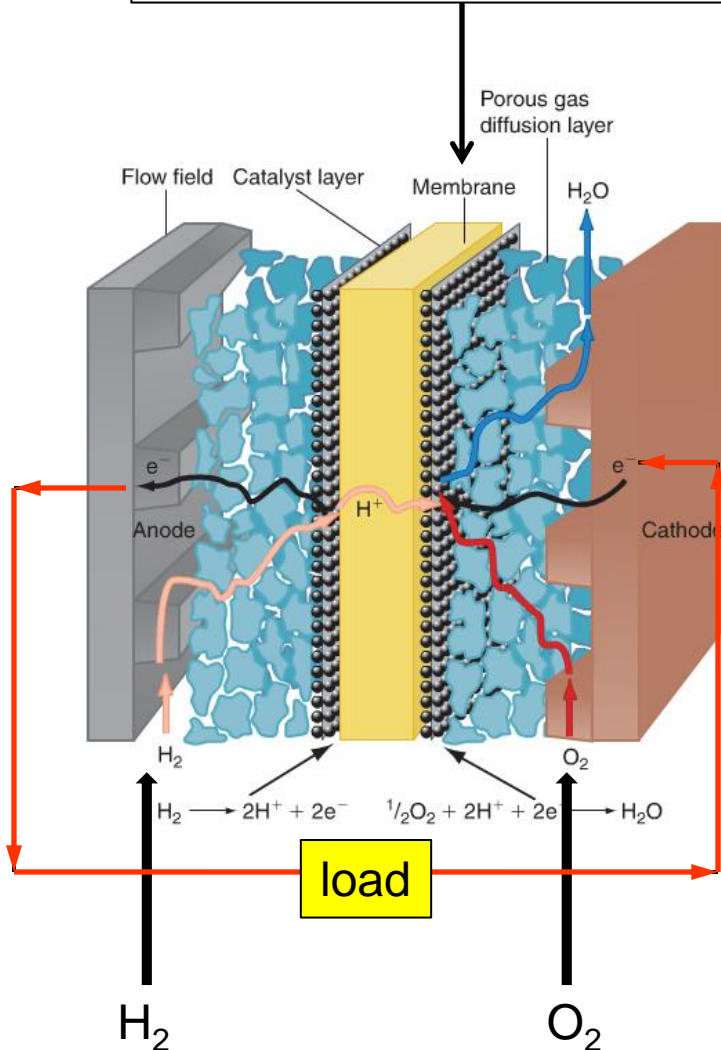Co

O

Li

discharge

Li+

LiCoO₂

Specialty Carbon

A downside of Li-ion cells, however, is that they contain a flammable electrolyte solution consisting of lithium salts in organic solvents such as ethylene carbonate and ethyl methyl carbonate. This is not the case for other commercial battery types.

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battery property comparison

Zinc	1.5V	**Non-rechargeable**–first the forerunner and later an inexpensive alternative to Alkaline batteries. However, reductions in the price of Alkalines have made both Zinc-Carbon and Zinc-Chloride batteries all but obsolete.
Alkaline	1.5V	**Rechargeable–** Alkaline rechargeable batteries are lower capacity (don't hold a charge as long) than the more popular NiMH rechargeables. The advantage of the rechargeable Alkaline over the NiMH or the NiCAD is that it loses its charge gradually,
Nickel-Metal Hydride (NiMH)	1.25V	**Rechargeable-** Lightweight and rechargeable, the NiMH has a higher capacity than the NiCAD plus you can throw it away since it doesn't contain toxic metals and it isn't classed as a hazardous waste item.
Lithium ion	3.6V	**Rechargeable–** For a given voltage, a lithium ion battery is smaller in size and lighter in weight than a nickel cadmium (NiCd) or nickel metal hydride (NiMH) battery. In addition, lithium ion has virtually no self-discharge. This allows a lithium ion battery to be stored for months without losing charge. The battery chemistries can be compared as follows:

fuel cells

PEM- *proton exchange membrane*

Porous gas diffusion layer

Flow field   Catalyst layer   Membrane H_2O

Anode

H^+

Cathode

H_2 O_2

$H_2 \longrightarrow 2H^+ + 2e^-$ $^1/_2 O_2 + 2H^+ + 2e^- \longrightarrow H_2O$

load

H_2 O_2

Electric Current

Fuel In e^- Air In

e^-

e^- H_2O

e^-

H^+

H_2

O_2

H^+

Excess Fuel

Unused Gases Out

H_2O

Anode   Cathode
Electrolyte

$$H_2 \rightarrow 2H^+ + 2e^- \qquad 0 \text{ V}$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad 1.23 \text{ V}$$

Fuel cells come in a variety of sizes. Individual fuel cells produce relatively small electrical potentials, about 0.7 volts, The energy efficiency of a fuel cell is generally between 40–60%.

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End of Lecture

$\tilde{\mu}_i$ the electrochemical potential

$$dG - \bar{d}w_{elec} = -SdT + VdP + \sum_{i,\gamma} \mu_i^{(\gamma)} dn_i^{(\gamma)}$$

$$\left(\Delta G_{reaction}\right)_{T,P} - w_{elec} = \sum_{i,\gamma} \nu_i^{(\gamma)} \mu_i^{(\gamma)} = \left(\Delta \mu_{reaction}\right) \leq 0$$

VS

$$dG = -SdT + VdP + \sum_{i,\gamma} \tilde{\mu}_i^{(\gamma)} dn_i^{(\gamma)}$$

$$\left(\Delta G_{reaction}\right)_{T,P} = \sum_{i,\gamma} \nu_i^{(\gamma)} \tilde{\mu}_i^{(\gamma)} \leq 0$$

$$\mu_i^{(\gamma)} = \mu_i^{(\gamma)} + \left(\bar{d}w_i^{(\gamma)}\right)_{elec}$$

$\tilde{\mu}_i$ assigns electrical work to each species including electrons transferred

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