

Implanted Biofuel Cell Anodes



**Gary Binyamin, Ting Chen, Yong-chao
Zhang, Adam Heller**

**Department of Chemical Engineering and
Texas Materials Institute
The University of Texas at Austin**



Power Sources : *Need Driven*

Development

Driver	Year	Power Source	Military Application
Flashlight	1900	Leclanche	WWI Telephony WWII Wireless
Automotive	1930	Lead acid	WW II Vehicles
IC-Mobile Electronics	1970	Primary lithium	Mobile Communication
Laptop	1995	Li ion	CCC electronics

Today's Driver: Medical Electronics



The dominant power source technology drivers are likely to be permanent medical implants with logic functions. They are based on advances in

- Miniaturization of circuits, actuators & fluidics;
 - Biotechnology;
 - Microsurgery;
 - Biomaterials.
- 

Today's Driver: Medical Electronics



- Cells of $\sim 1 \text{ cm}^3$ volume, delivering $\sim 1 \text{ mW}$ continuous power, or pulses of 10-100 mW, are needed for applications exemplified by a system providing urinary control to incontinent elderly people. This translates to a power density of 1 W/L , the volume including the blood flowing through the tubular cell.
- 

Comparison with Primary Lithium Batteries

- The volumetric energy density of the highest energy density lithium batteries is 1000 Whr/L.
- The implanted fuel cell of 1W/L power density produces the equivalent energy in 1000 hrs or 42 days.

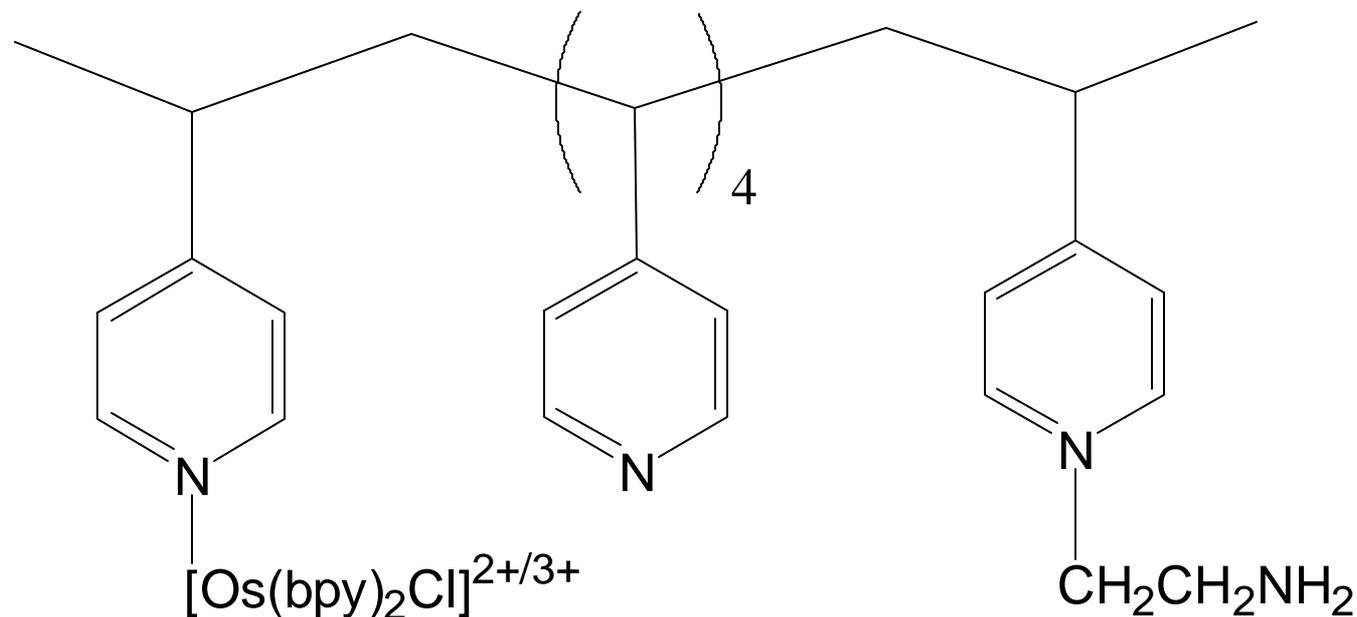
Biofuel Cell Implanted in Blood Vessel

- Tubular glucose electrooxidizing anode
 - Tubular oxygen electroreducing cathode
 - Pump obviated by flow of blood
 - Diameter 2-4mm
 - Length 1 cm
 - Linear flow velocity of blood 1-10 cm sec⁻¹
 - Average current density 1 mA cm⁻²
-

The “Wiring” of Enzymes

- “Wired” enzyme electrodes operate continuously in biological environments, where platinum group metal electrocatalysts are rapidly fouled.
 - Electron transport through the enzyme “wiring” electrocatalysts depends on collisions of redox centers tethered to their crosslinked polymer network.
 - When the chain segments are mobile the conduction is adequate, but the enzyme connecting gels are soft.
-

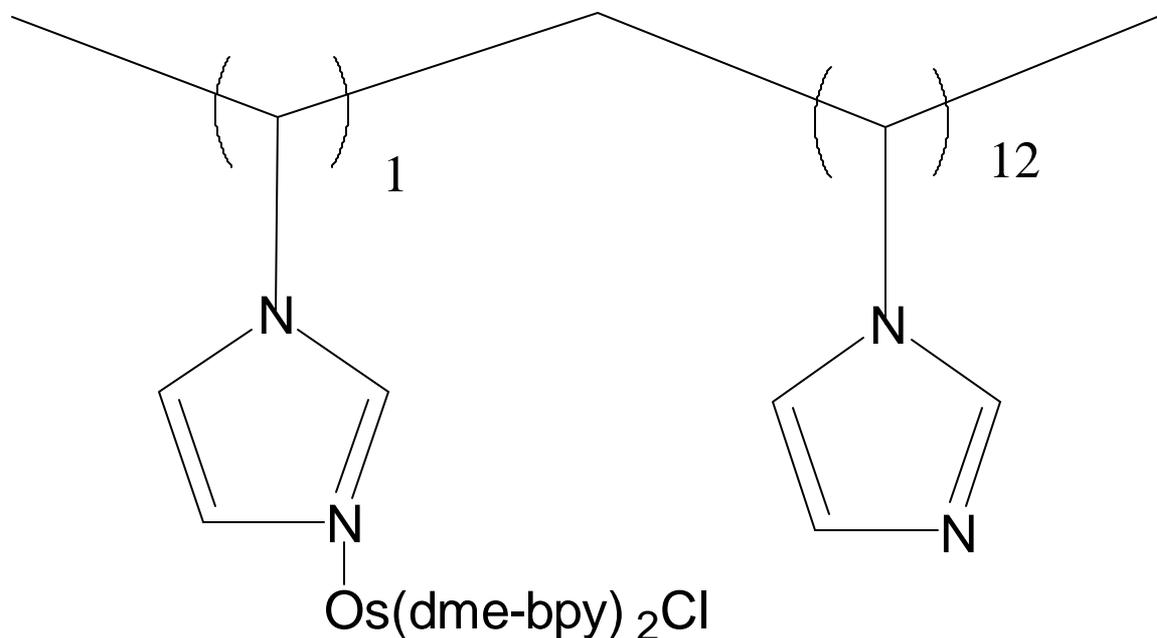
“Wires”: PVP-OsEA



➤ Poly(4-vinylpyridine) partially complexed with osmium bis(2,2'-bipyridine) chloride and quaternized with 2-bromoethylamine

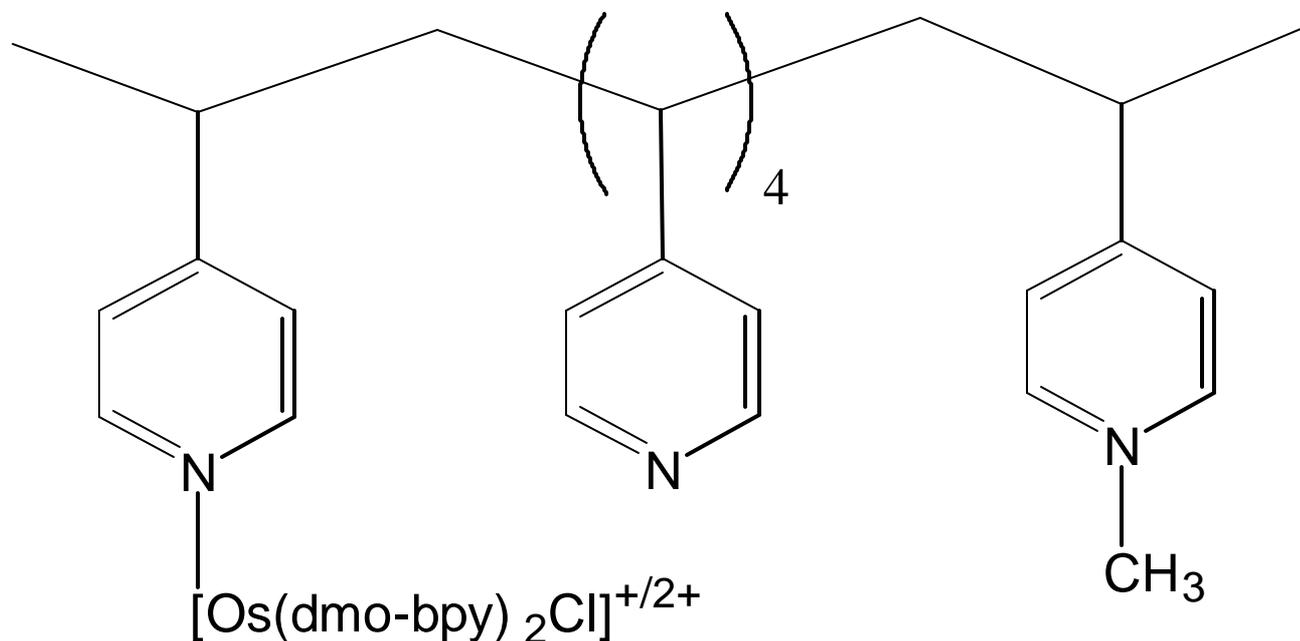
➤ ***Redox potential +270mV vs. SCE***

“Wires”: PVI-Os



- Poly(1-vinylimidazole) partially complexed with osmium bis(4,4'-dimethylbipyridine) chloride
- ***Redox Potential +95mV vs. SCE***

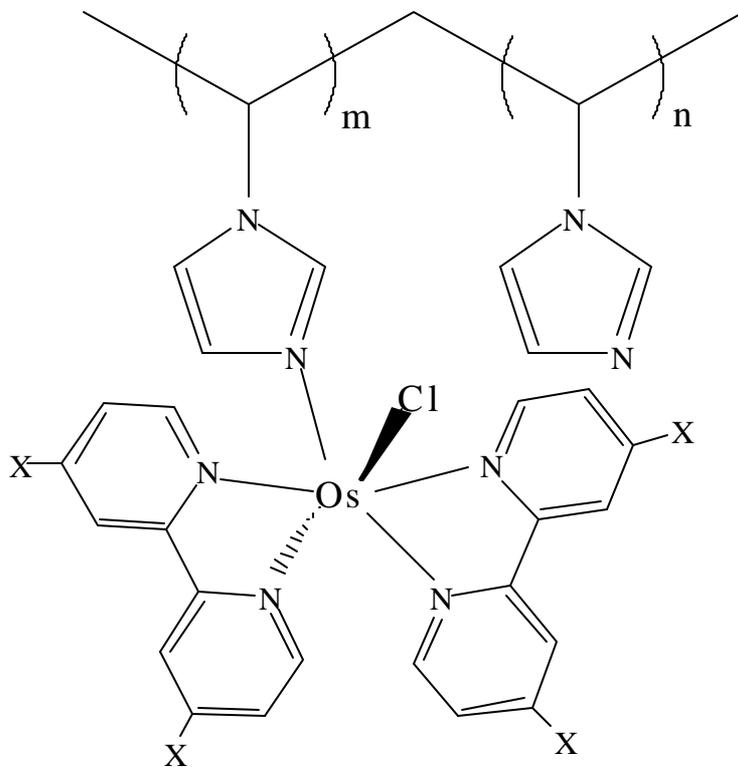
“Wires”: PVP-Osdmo



➤ Poly(4-vinylpyridine) partially complexed with osmium bis(4,4'-dimethoxybipyridine) chloride and methylated with CH_3I

➤ ***Redox potential +44mV vs. SCE***

“Wires” : PVI-DMA-BPY and PVI-DEA-BPY



	Name	Redox Potential (Ag/AgCl)
DMA-BPY	4,4'-bis-(dimethylamino)-2-2'-bipyridine	-260mV
DEA-BPY	4,4'-bis-(diethylamino)-2-2'-bipyridine	-240mV

Increase in Rigidity (Crosslinking) Decreases the Diffusivity of Electrons in the Polymeric “Wires”

Blauch & Saveant’s bounded diffusion

$$D_{\text{app}} = 0.167k_{\text{et}}(\delta^2 + 3\lambda^2)C_{\text{RT}}$$

k_{et} - bimolecular rate constant for e^- transport by self exchange

δ - center to center distance between redox sites

λ - displacement of redox species from equilibrium

C_{RT} - concentration of redox sites

Shearing in Rapidly Flowing Liquids

- Rapidly flowing liquids shear the electrodes.
 - Soft, electron conducting, “wired” enzyme hydrogels disintegrate under the shear stress.
 - Highly crosslinked, tough (leather-like) hydrogels can be made, but are poor electron conductors.
-

Mechanical Erosion of the “Wires”: The Shear Stress Produced by A Flowing Fluid

→ Newtonian fluid

→ No slip at wall

→ $v_{\max} = 10 \text{ cm s}^{-1}$

→ Constant μ (1 cP)

→ Rigid walls $d = 5\text{mm}$

→ Neglect end effects, charges.

Laminar velocity: $v = v_{\max} [1 - (r/R)^2]$

Shear stress: $\boldsymbol{t} = -\boldsymbol{m}(dv/dr)\boldsymbol{i}_R = 2\boldsymbol{m}_{\max} R^{-1} = 0.08 \text{ N m}^{-2}$

Mechanical Erosion of the “Wires”: Shear Stress on a Rotating Disk: The Von Karman and Cochran Equation

Shear Stress

$$\tau = 0.616\rho\nu^{1/2}\Omega^{3/2}r = 6.29 \times 10^{-2} \text{ N/m}^2$$

Average Shear Stress

$$\langle \tau \rangle = 0.205\pi\rho\nu^{1/2}\Omega^{3/2}r = 6.58 \times 10^{-2} \text{ N/m}^2$$

ρ - density of the fluid = 1 g/cm³

μ - viscosity of the fluid = 0.01 poise

r - radius of the disk = 0.15cm

Ω - rotation rate = 1000 minute⁻¹

$\nu = \mu/\rho$ - kinematic viscosity = 0.01 cm²/sec

*Theoretical treatment agrees with experimental data provided that $a^2\Omega/\nu$ is less than 10^5 and greater than unity. ($a^2\Omega/\nu = 37.51$)

Epoxide and Schiff-base Crosslinking Mechanically Stabilize the Anodes

Di-functional epoxide

poly(ethylene glycol) (400) diglycidyl ether (PEGDGE)

or tri-functional crosslinkers

N, N-diglycidyl-4-glycidyl-oxyaniline (DGGA)

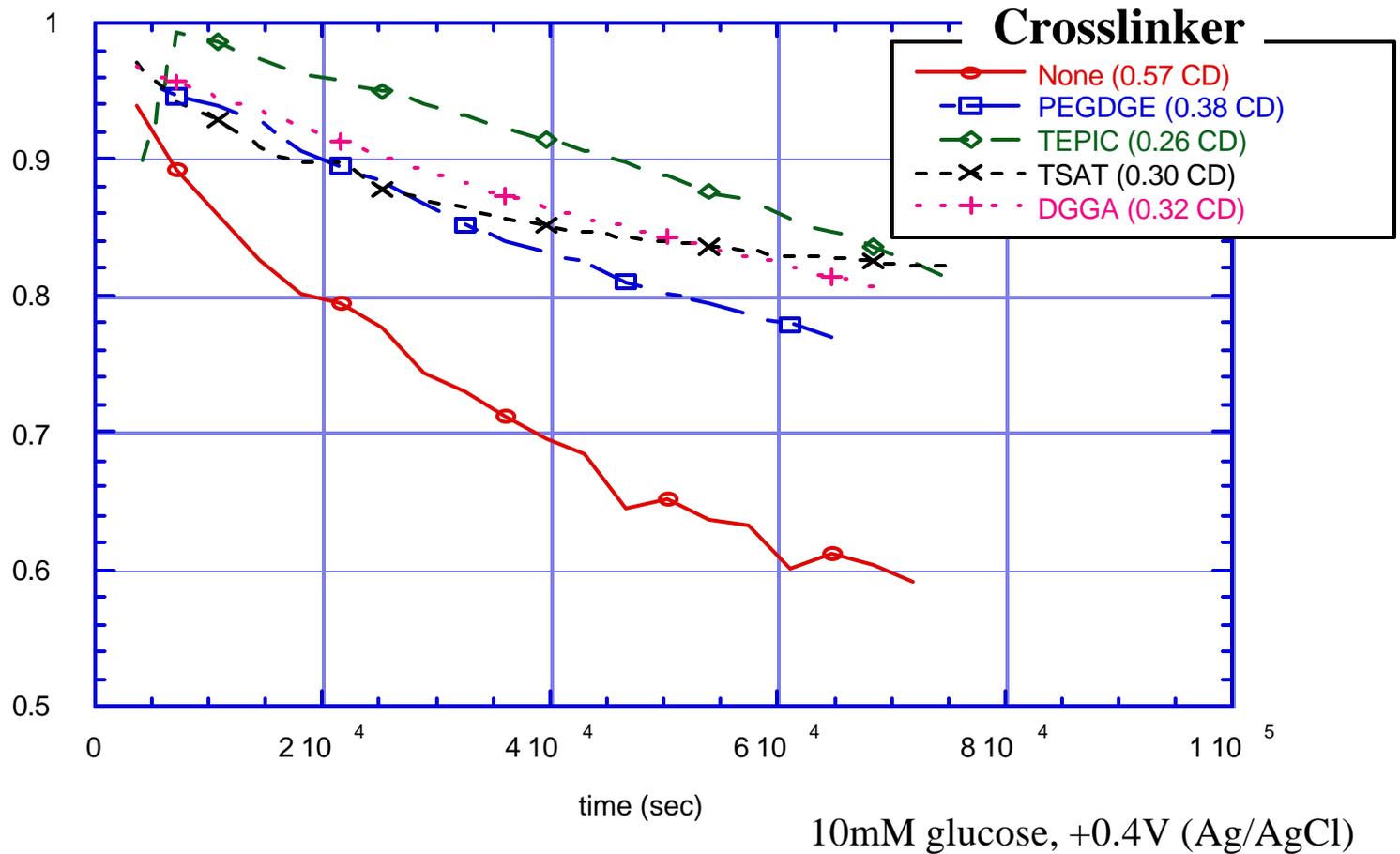
Tris 2,3-epoxypropylisocyanurate (TEPIC)

Tris-sulfosuccinimidyl aminotriacetate (TSAT)

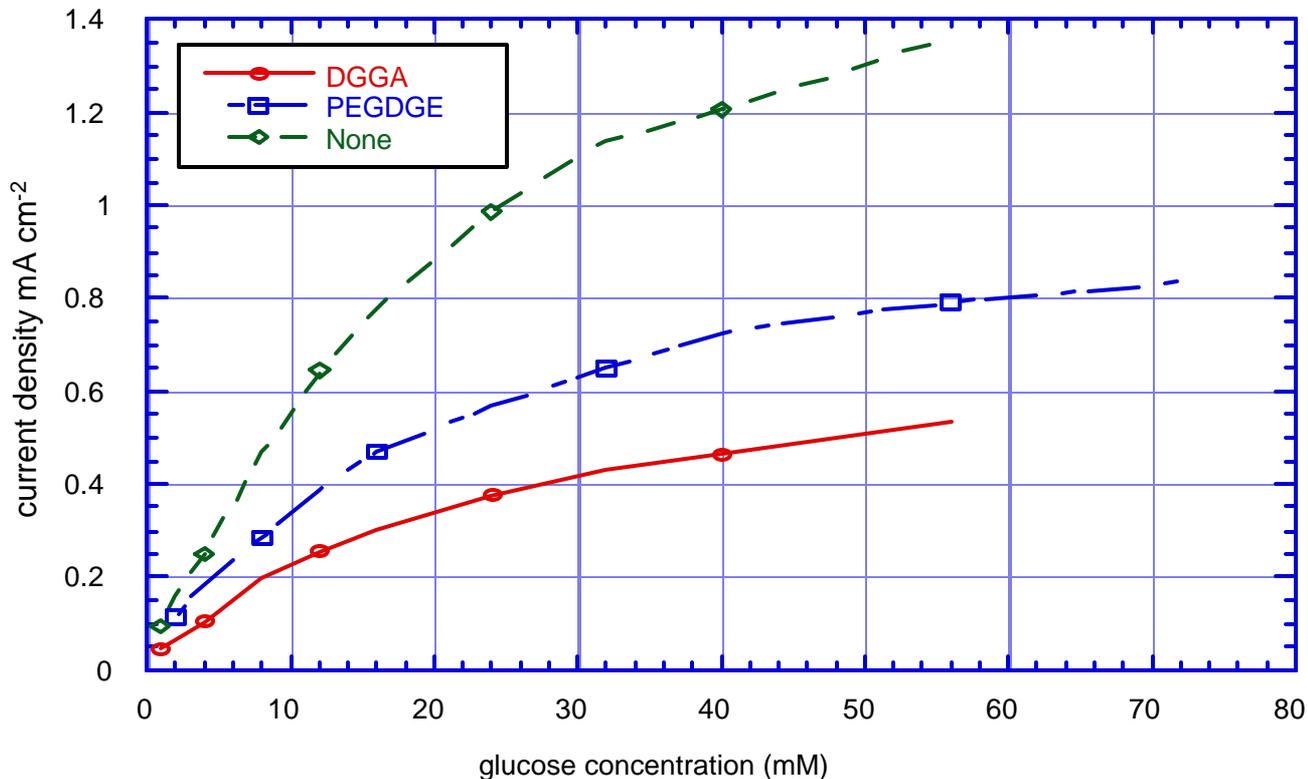
combined with Schiff base formation by periodate
oxidation of enzyme-oligosaccharides

➤ *provide tough leather-like gels, showing little loss
upon shearing.*

Endurance of the PVP-OsEA Anodes under Shear Stress



Loss of Current Density in the Highly Crosslinked Leather-like “Wires” : The PVP-OsEA GOxox Anode



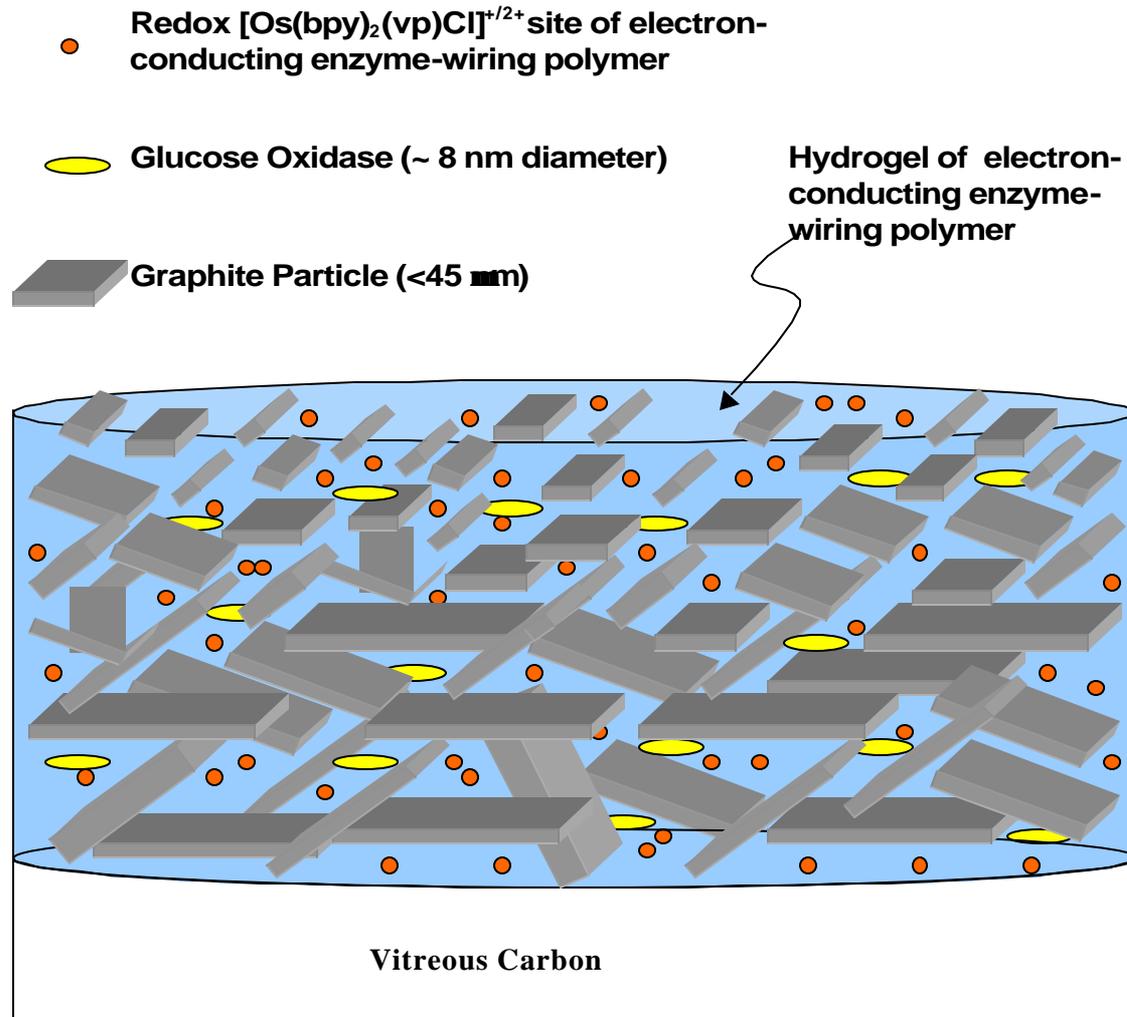
Resolution of the Conflict Between Mechanical Strength and Electron Transport

- The classical solution to simultaneous optimization of conflicting materials properties is through design of composites.
 - The weak and the strong components of composites must bond in order for the strong component to control the mechanical properties.
 - If the reinforcer is graphite, its van der Waals surfaces must be modified to make these reactively bonding.
-

Mechanically Strong Composite Glucose Anodes for Use in Fast Flowing Fluids

- The van der Waals planes of graphite are intrinsically hydrophobic.
 - OH radicals make the particles hydrophilic.
 - The “wired” enzyme bonds with the hydrophylized graphite particles forming a tough composite.
 - The composite catalyzes the electrooxidation of glucose.
-

Components of the “Wired” Enzyme Hydrphized Graphite Composite

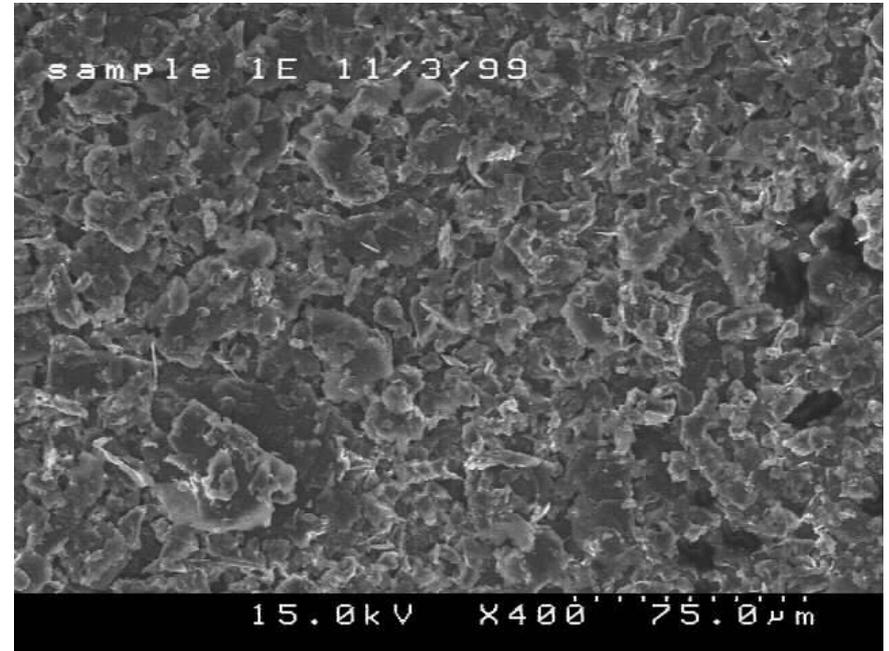


SEM of the Composite Electrolyst

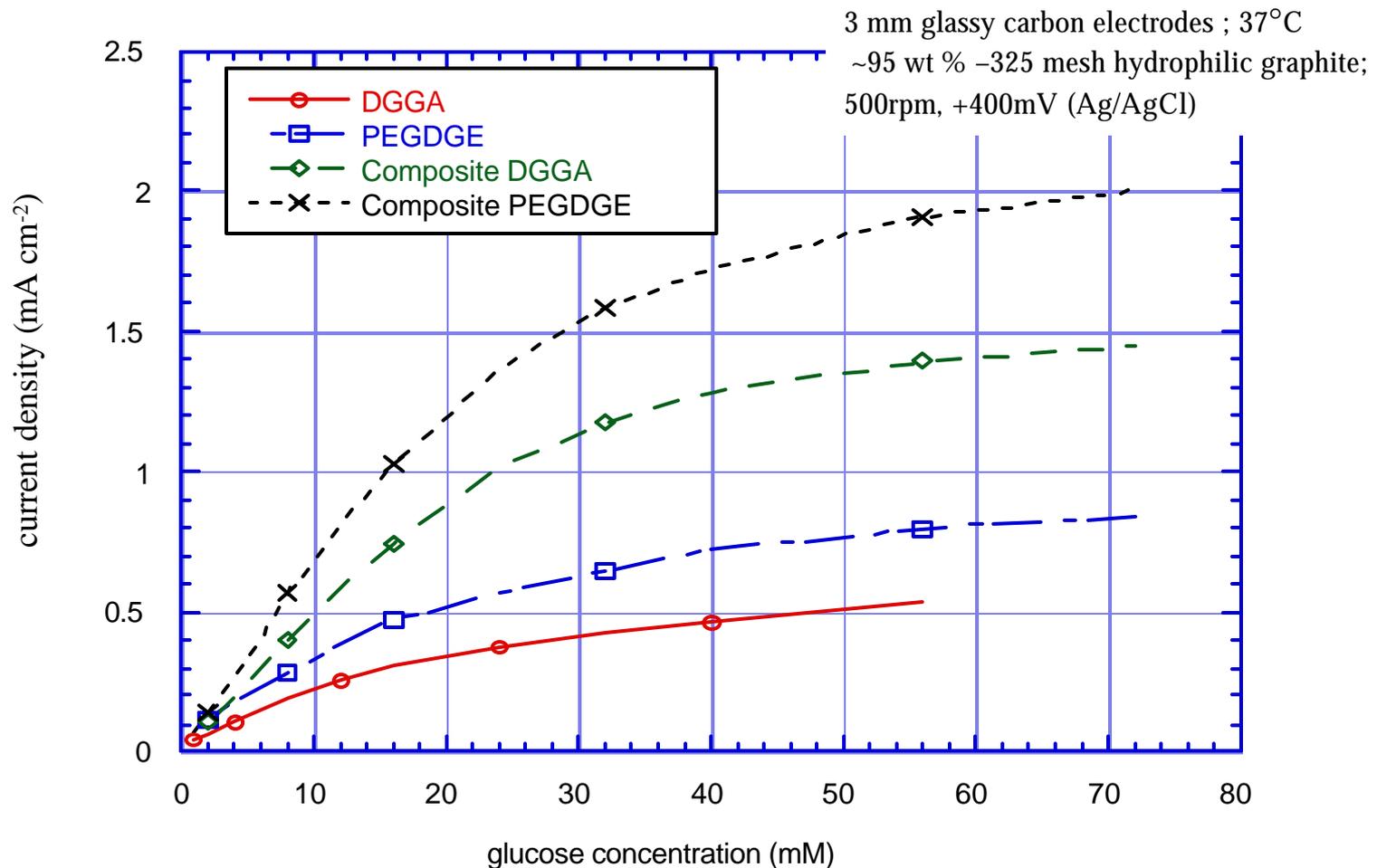
Hydrophilized graphite particles



“Wire” Bound Composite Electrolyst



Current Densities of Composite Glucose Electrooxidizing Anodes:



Composite Anodes: Summary.

- Current densities of 1.9 ma cm^{-2} are realized in composite anodes formed of hydrophilized graphite and “wired” enzymes.
 - The anodes are mechanically stable in rapidly flowing fluids.
-

Potential Causes of Chemical Instability: Production of Reactive Gluconolactone and H_2O_2



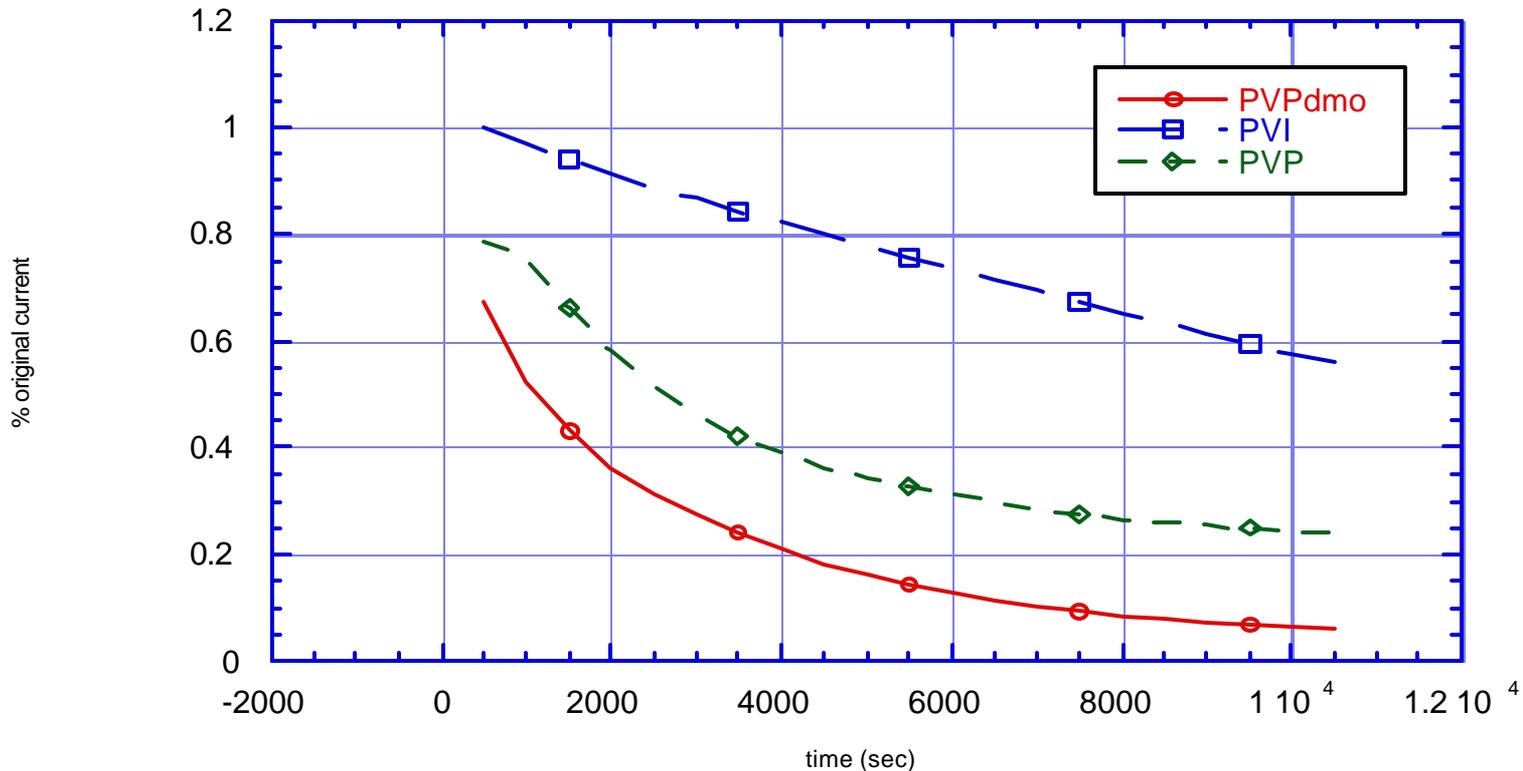
Potential Causes of Chemical Instability: Reaction Products of Glucose Oxidation.

- Gluconolactone attacks the “wire” and
- H_2O_2 attacks glucose oxidase.
- Under stagnant conditions and in absence of an applied potential we find a 36% current loss in 15 hrs at 10 mM H_2O_2 .

But, ➤ We find no loss in 10mM glucose in absence of an applied potential in rotating electrodes.

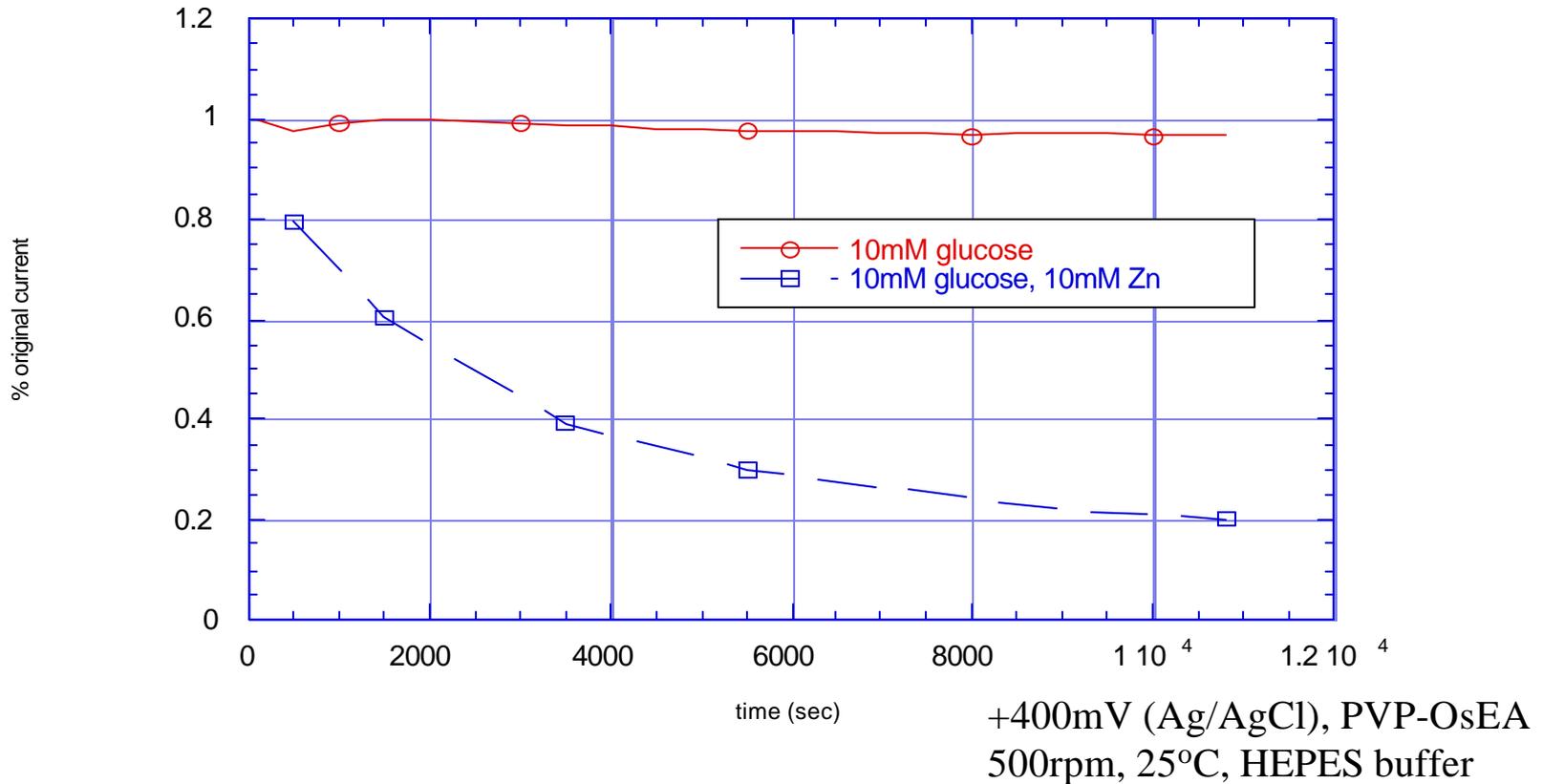
➔ *The reaction products do not destabilize the glucose anode in a flowing fluid because they are rapidly removed.*

Stability in Serum



- *The decay is similar in buffer when 0.5 mM Zn²⁺ and 0.5 mM urate are added.*

Causes of Losses in Serum: Zn^{2+}

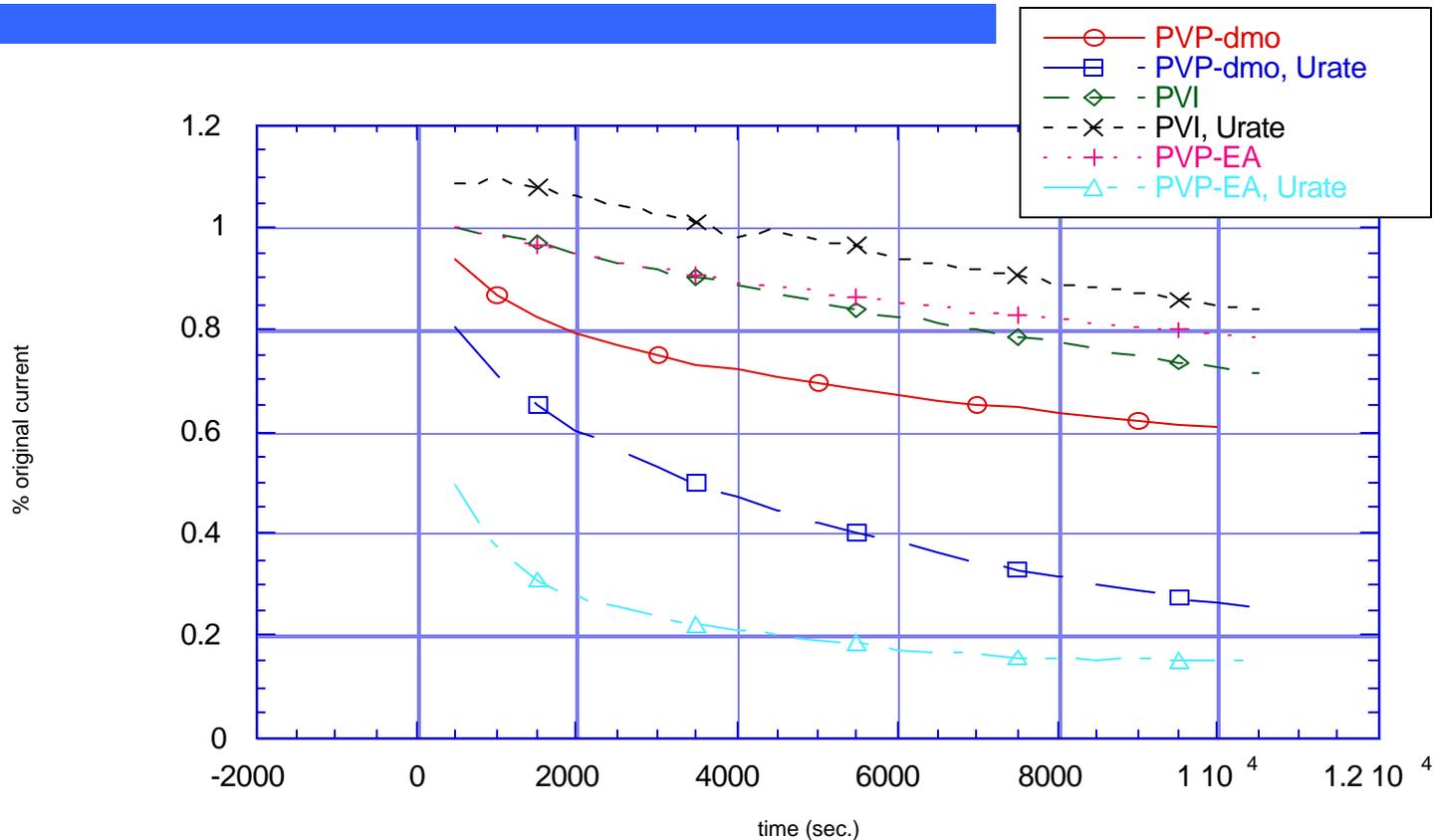


- *Electron transport is slowed: The losses in the voltammetric peak heights parallel the losses of current showing damage to the “wire”.*
- *The transition metal ions also inhibit glucose oxidase.*

Causes of Loss in Serum: Coordinative Crosslinking of the Heterocyclic Nitrogens of the “Wires” by Transition Metal Ions

- The equilibrium constants (β_2) are 100-1000 $L^2 \text{ mol}^{-2}$.
 - The high (2M) concentration of ligands in the redox polymers leads to coordinative crosslinking, even at low transition metal ion concentrations.
 - In the resulting rigid polymers the segments are less mobile, the electron diffusivity is reduced and the electroactive zone is thinner.
-

Causes of Instability in Serum: Urate-Caused Loss.

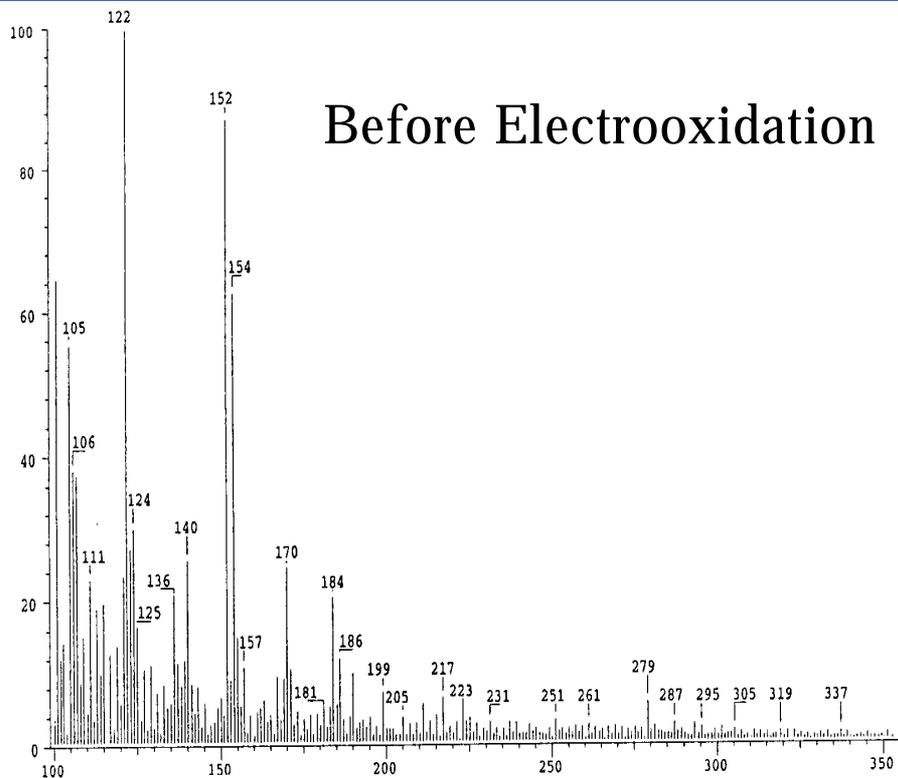


- *The decrease in the voltammetric peak heights parallels the loss of current showing damage to the “wire”.*
- *Above 400 mV (Ag/AgCl) the loss does not depend on the applied potential.*

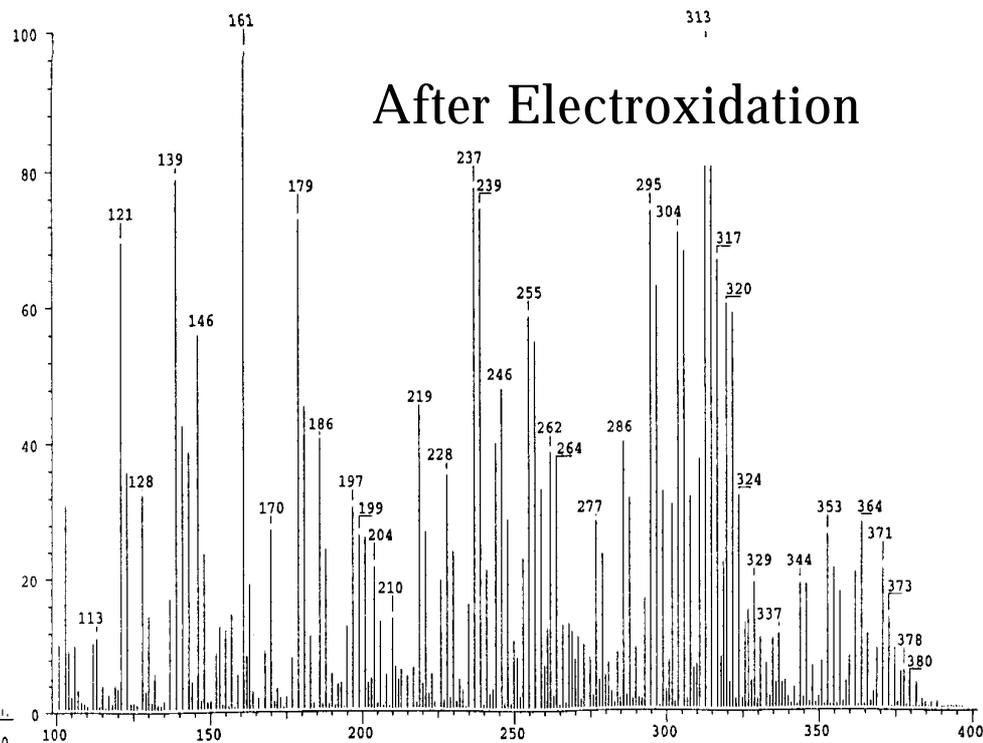
Causes of Instability in Serum: Urate Caused Loss

- Quartz crystal microbalance measurements show an increase in film mass when the anodes electrooxidize urate.
-

Causes of Instability in Serum: Mass Spectra Showing Electropolymerization of Urate



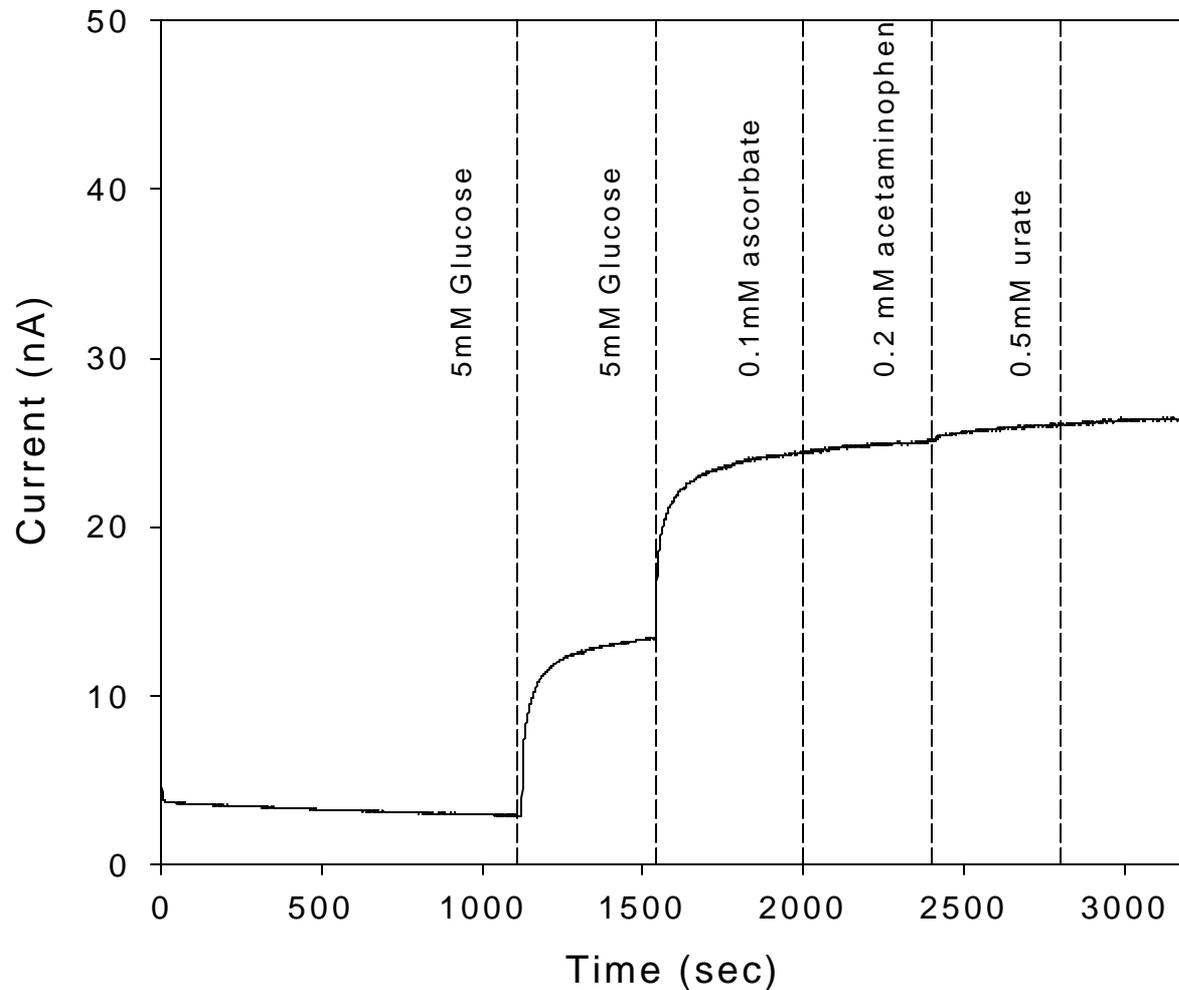
Before Electrooxidation



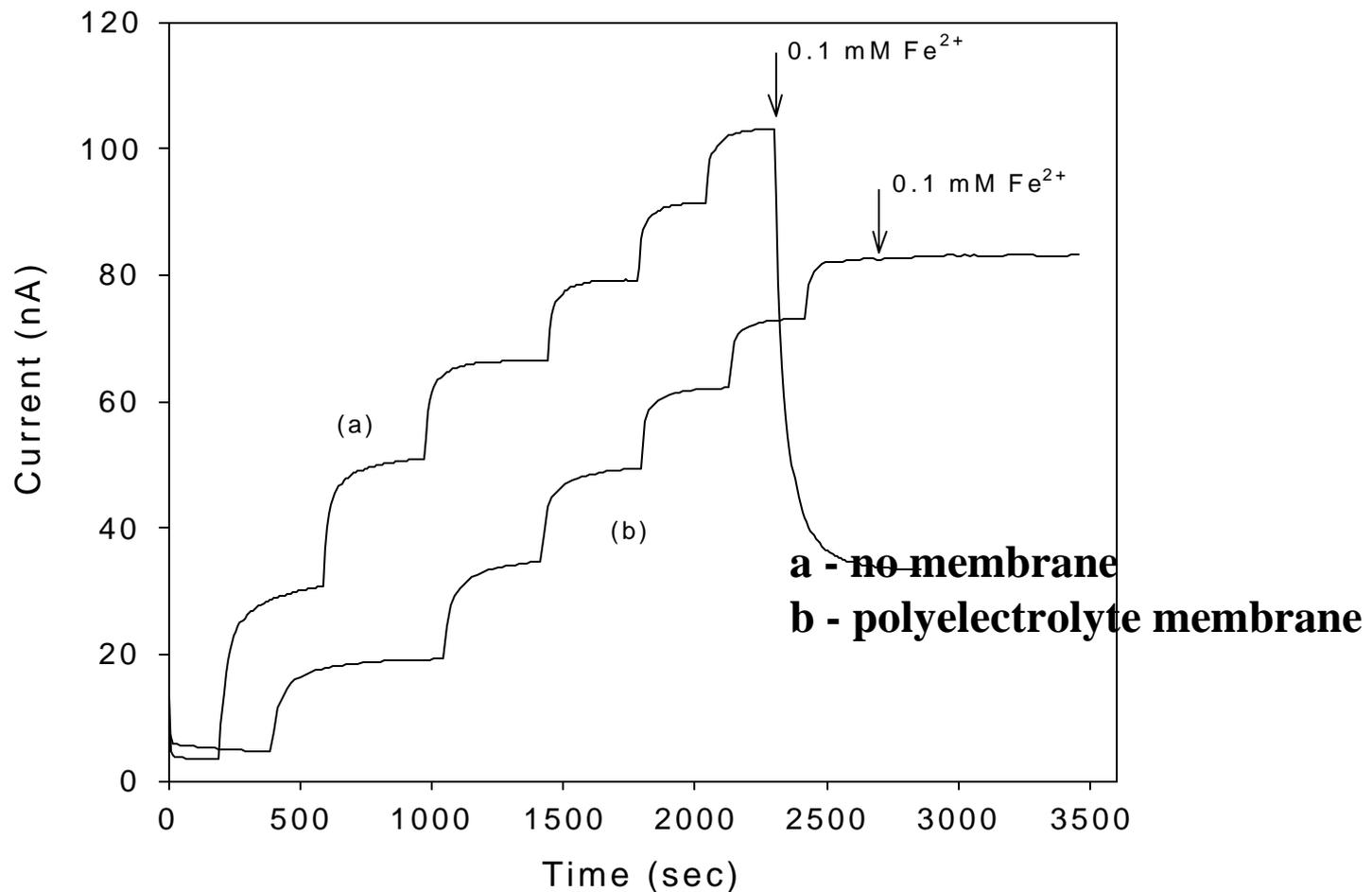
After Electrooxidation

**0.5mM Urate; pH 12 phosphate buffer.*

Causes of Instability: Alleviation of the Urate Caused Loss by a Layer-by-Layer Assembled Polyelectrolyte Membrane



Causes of Instability: Alleviation of the Fe^{2+} Caused Loss by A Transition Metal Ion Capturing Polyelectrolyte Membrane

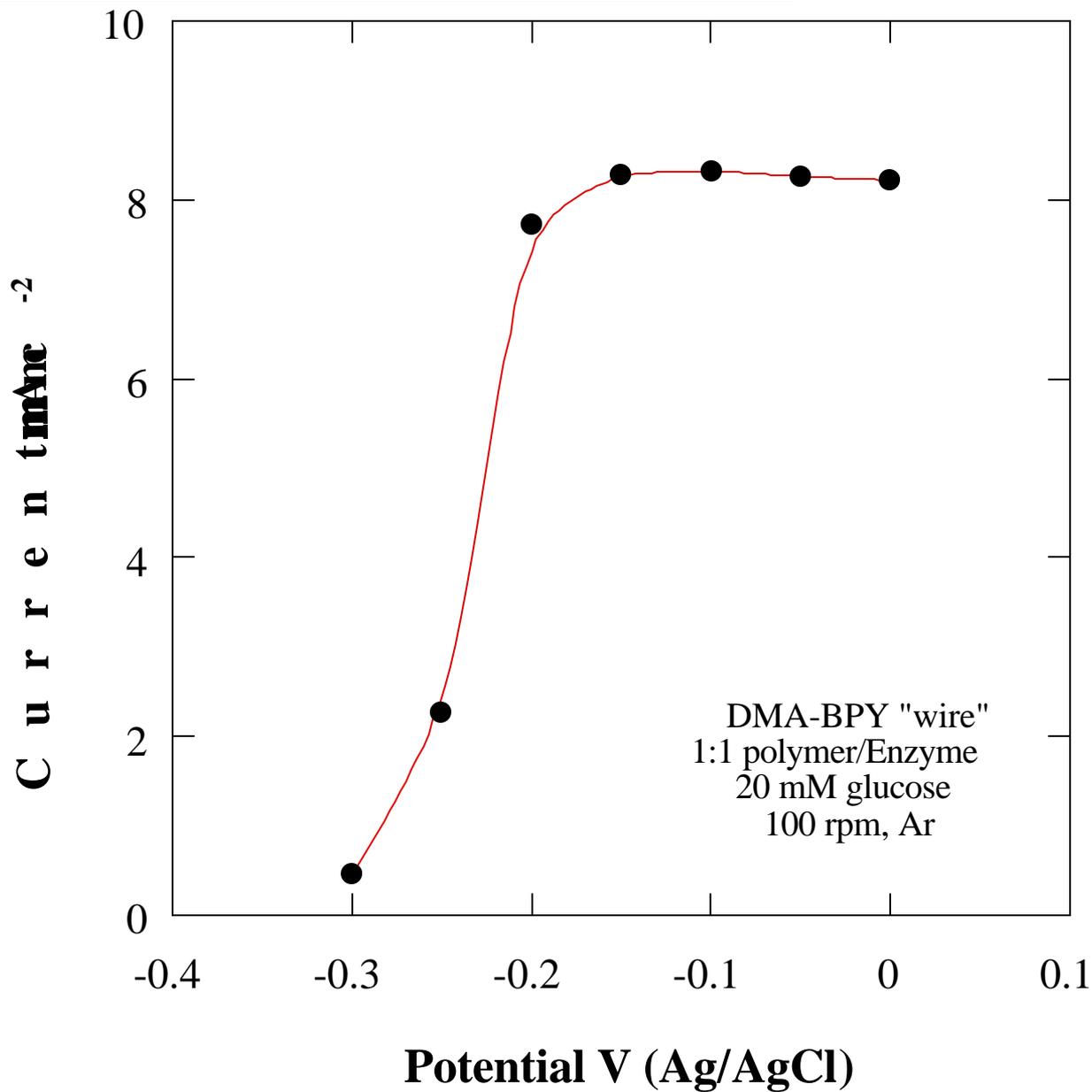


Chemical Instability in Serum: Summary

- The glucose anodes are stable in buffer but are unstable in serum.
- The dominant causes of instability are (a) electro-oxidation of urate, (b) crosslinking by transition metal ions; and (c) enzyme-inhibition by transition metal ions.
- Both the transition metal ions and the urate can be excluded by ultra-thin, layer-by-layer -assembled membranes which reduce the mass transport only minimally.

Potential of the Glucose Anode:
Operation at
–220 mV vs. Ag/AgCl.

-220mV (Ag/AgCl) Glucose Anode



Anode Potential: Summary.

- Glucose electrooxidizing anodes operating at -220mV (Ag/AgCl) are now in hand.
 - High current densities are expected in composites made with hydrophylized graphite.
-

Estimated Cell Potential

Glucose Oxidase ($E^{\circ} = -350\text{mV}$ vs Ag/AgCl)

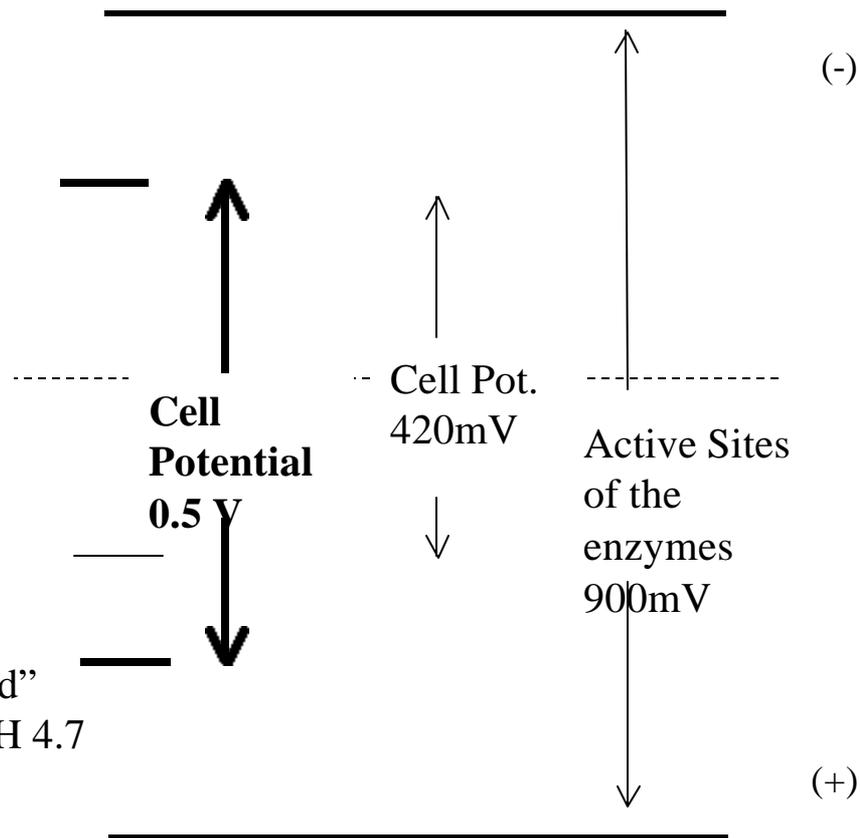
Potential of the glucose oxidase "wired" anode (-220mV vs Ag/AgCl)

Ag/AgCl

Potential of the Pt/ H_2O_2 cathode ($E^{\circ} = 200\text{mV}$ vs Ag/AgCl)

Potential of the reported "wired" Laccase cathode (400 mV at pH 4.7 vs Ag/AgCl) (Donal Leech)

Laccase, O_2 reduction ($E^{\circ} = 550\text{mV}$ vs Ag/AgCl)



)

Summary: Glucose Anode Operating in Serum

- Following the understanding of the cause of the mechanical instability, a mechanically stable composite anode was designed and successfully tested under the shear stress produced by the rapidly flowing fluid.
- The composite anode, made of hydrophilized graphite particles bound by the “wired” enzyme, operates at a current density of 1.9 mA cm^{-2} , exceeding the original estimate.

Summary: Miniature Glucose Anode Operating in Serum

- Following understanding of the dominant underlying causes of the chemical instability in serum the glucose anode was stabilized by a thin molecule-by-molecule assembled membrane, which did not substantially impede the mass transport.

Summary: Miniature Glucose Anode Operating in Serum

- An anode now operates at -220 mV vs. Ag/AgCl; Its current density is expected to increase when made of a hydrophylized graphite composite.
- An operating potential of 0.5 V is projected for a cell with a “wired” laccase cathode and the glucose anode. The potential is close to the original 0.56 V estimate.

Implanted Biofuel Cell: Continuation and 24 month Target

- Develop composite glucose anode operating at 200mV vs Ag/AgCl at a current density of $> 1 \text{ mA cm}^{-2}$.
- Determine feasibility of oxygen cathode based on operating at $> 300 \text{ mV}$ vs. Ag/AgCl based on “wiring” of superoxide dismutase.
- Demonstrate 24 hour operation of integrated miniature cell with a buffered aerated 5 mM glucose solution flowing at a linear flow rate of 5 cm^{-1} .
- Demonstrate 24 hour operation of integrated miniature cell with serum flowing at a linear flow rate of 5 cm^{-1} .