Electrophoretic Mobility Estimated from the Transient Current in a Parallel Plate Cell

Kelly Robinson[1] and Ravi Sharma[2]

[1]Electrostatic Answers LLC
Rochester, NY 14450, USA
e-mail: Kelly.Robinson@ElectrostaticAnswers.com

[2]Bausch and Lomb
Rochester, NY 14517
e-mail: Ravi.Sharma@Bausch.com

This work was funded by the Eastman Kodak Company and was accomplished while both authors were employed there.

Outline

- Introduction
- Surfactants, micelles and charge
- Electrophoresis and mobility
- Current in a parallel plate cell.
- Estimating mobility from current measurements.
- Summary

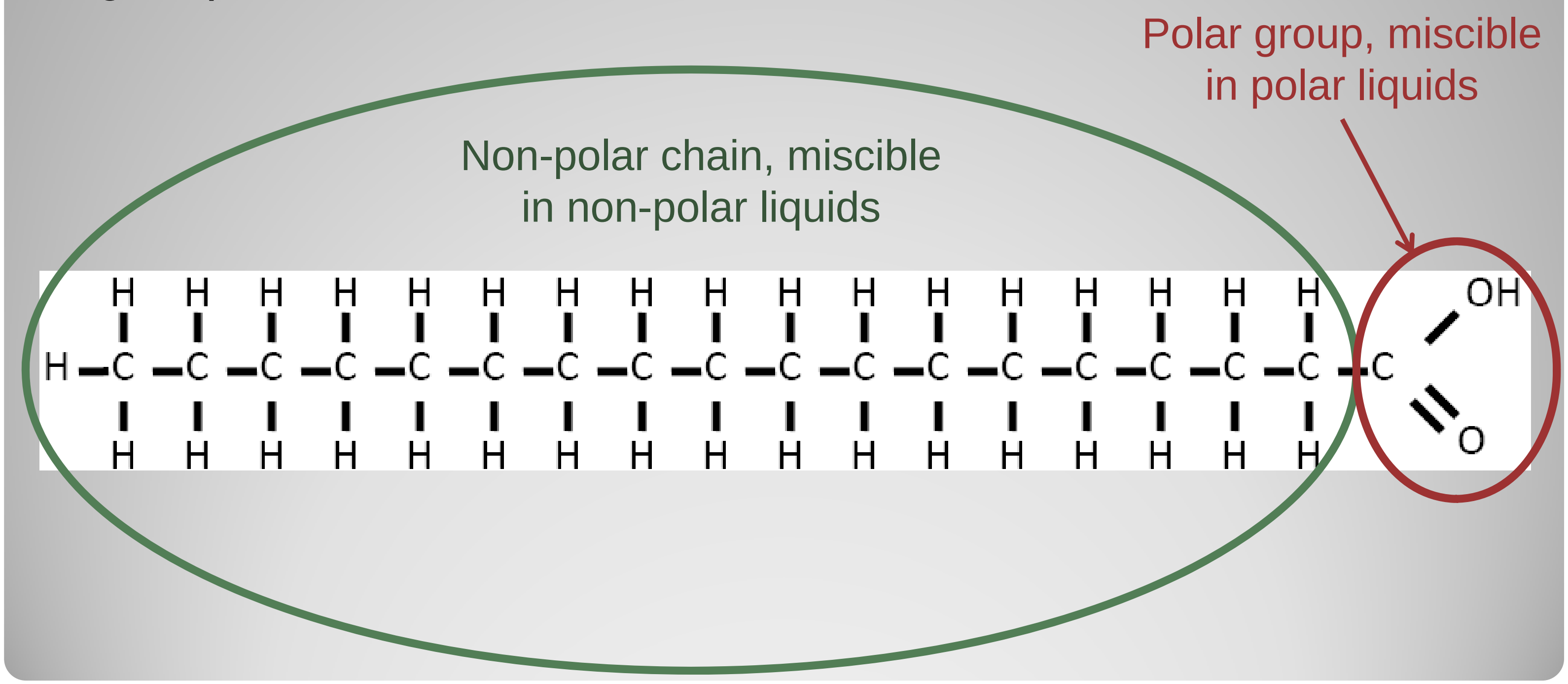
Introduction

- Separation of cells, bacteria, proteins, peptides, (DNA), viruses, membranes, or organelles according to their electrophoretic mobility [1]
- Characterization of nanoparticles, viruses, and liposomes [2]
- Electronic displays [3, 4, 5]
- Imaging using liquid toners [6]
- Electrical conduction in nonpolar liquids (including antistatic additives to prevent fires and explosions [7]

[1] Bauer, Johann, Max-Planck Institute, Martinsried, Germany, "Free Flow Electrophoresis (FFE)," Copyright © 2000 - 2007, The American Electrophoresis Society, http://www.aesociety.org/areas/ffe1.php, 6/5/2007.
[2] Gale, Bruce K., University of Utah, "A Decade of Progress in Microscale Electrical Field-Flow Fractionation," Copyright © 2000 - 2007, The American Electrophoresis Society, http://www.aesociety.org/areas/GaleArticle.pdf, 6/5/2007.
[3] "E Ink Corporation | Technology | Electronic Paper Displays," © 1997-2005 E Ink Corporation, http://www.eink.com/technology/, 6/5/2007.
[4] Liang, R-C., S. C-J Tseng, Z-A. G. Wu, H-M. Zang, H-K. Chuang, "Electrophoretic display and novel process for its manufacture," US Patent 6,788,449, SiPix Imaging, Inc., 9/7/2004.
[5] Kim, Junhyung, John L. Anderson, Stephen Garoff, and Luc J. M. Schlangen, "Ionic conduction and Electrode polarization in a Doped Nonpolar Liquid," Langmuir, Vol. 21 (2005), pg. 8620-8629.
[6] Ertel; John P. , "Encapsulated liquid toner printing apparatus," US Patent 5,923,412, Hewlett-Packard Company, July 13, 1999.
[7] Morrison, Ian D. and Sydney Ross, Colloidal Dispersions, Suspensions, Emulsions, and Foams, Wiley-Interscience, 2002, pp. 282.

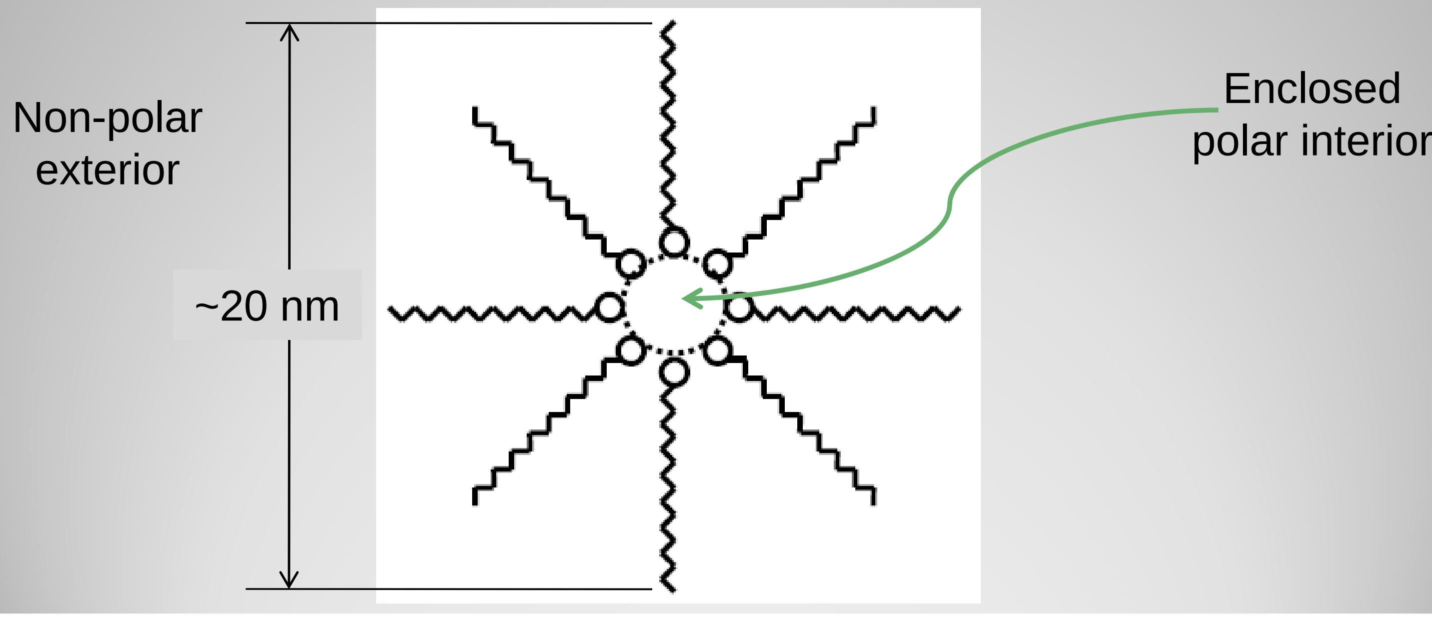
Surfactants

- Surfactants (Surface Active Agents) are molecules composed of a non-polar chain terminated with a polar group such as stearic acid.



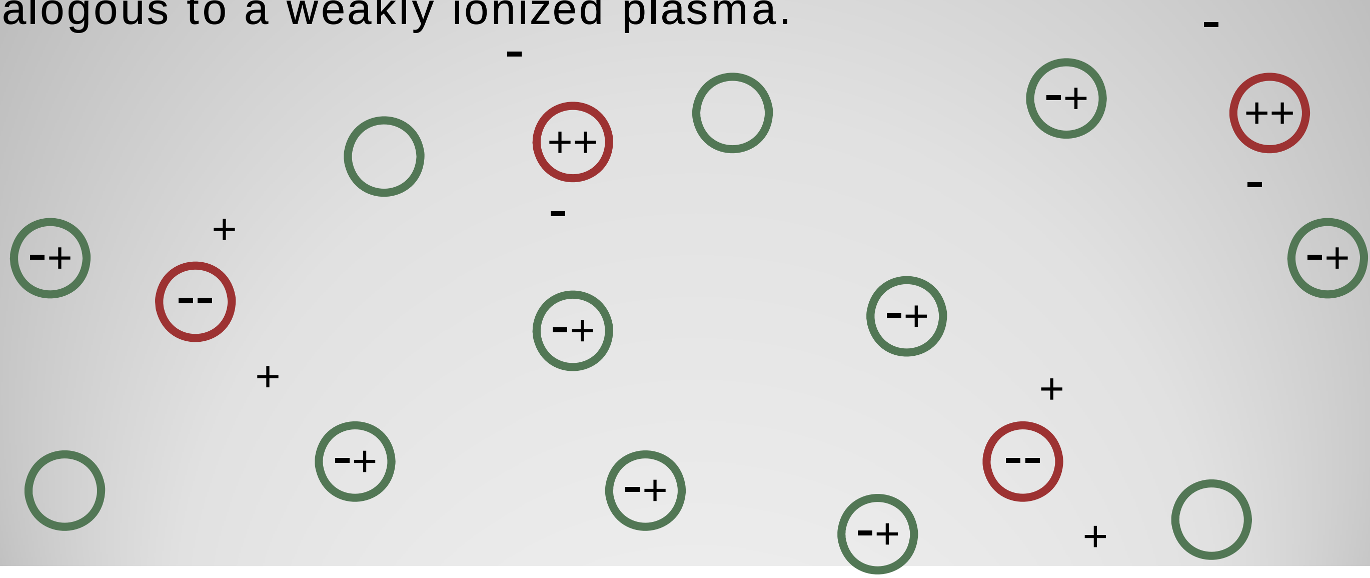
(Inverse) Micelles

Above the critical micelle concentration (CMC), surfactant molecules "find each other" and form clusters or "micelles." In a non-polar liquid such a dodecane, the non-polar chains of the surfactant molecules are oriented outward forming "inverse micelles."



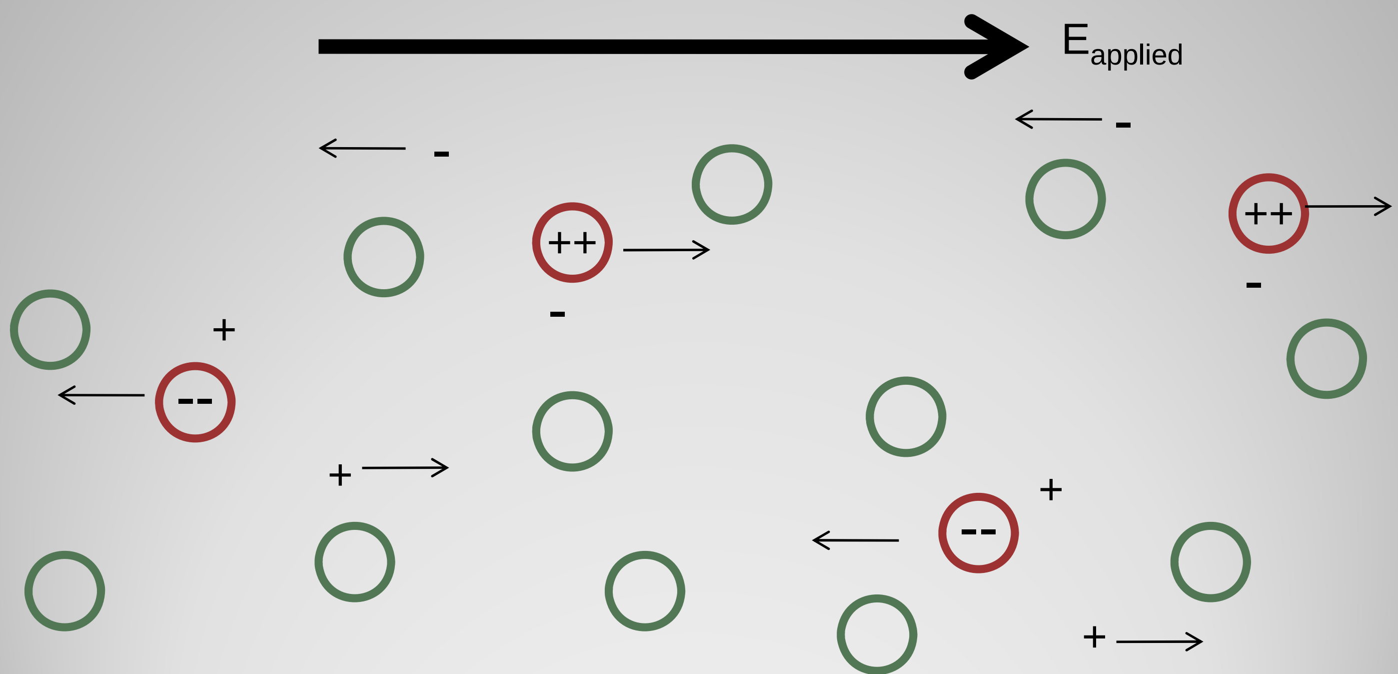
Inverse Micelles can be charged

The polar interior of inverse micelles capture water, salt, and other impurities. Some inverse micelles carry charge resulting from collisions between neutral, inverse micelles, charge separation within the polar interior of the aggregate, and the formation of oppositely charged inverse micelles [5]. Also, nearby counter ions in the fluid are bound to the charged, inverse micelles by coulombic attraction. A dispersion of a surfactant in a non-polar liquid is analogous to a weakly ionized plasma.



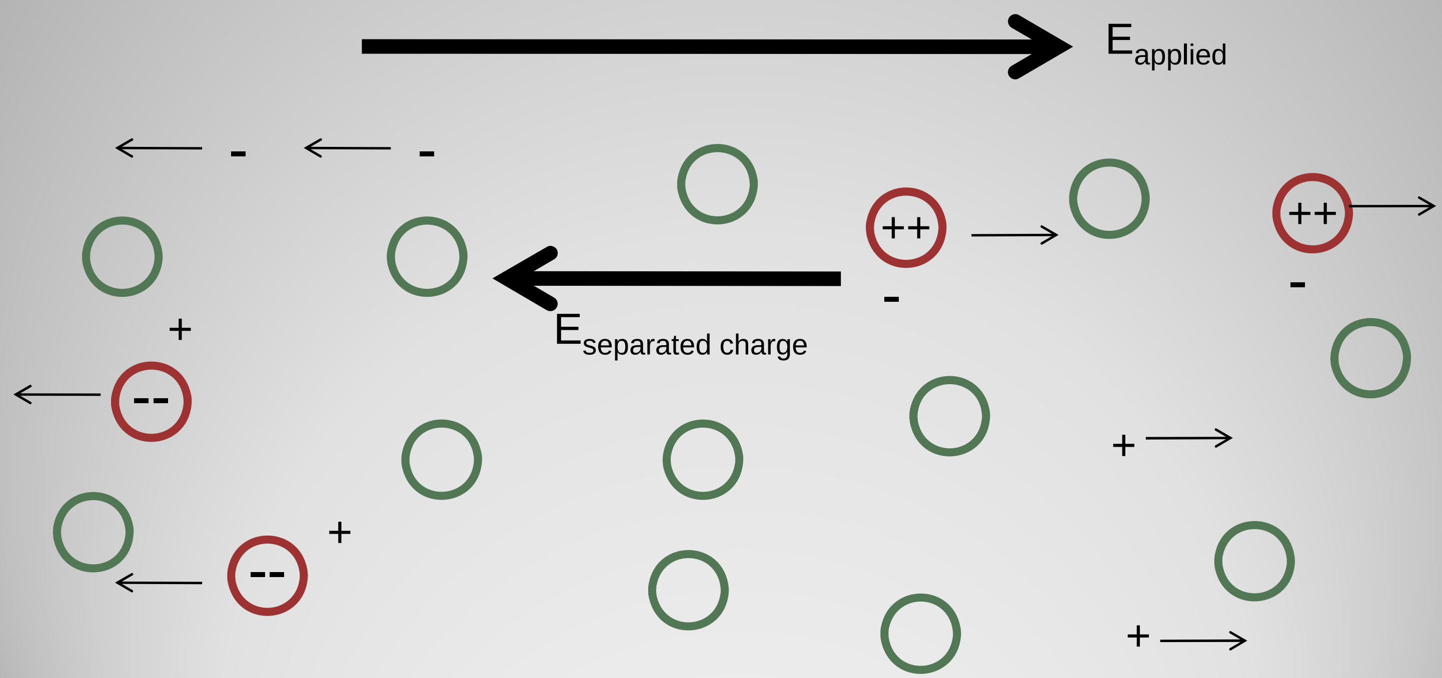
Electrophoresis

When an electric field is applied, loosely bound counter ions are stripped from the charged, inverse micelle. The micelle carries a net charge and becomes a mobile charge carrier.



Polarization

The electric field from the separated charge opposes the applied electric field. The total field is reduced, and the motion of charge carriers decreases.



|| Cell Current –Governing Eq.

$\vec{J} = (nqb)\vec{E}$	Ohmic Current
$\vec{E}$	Electric field
$\vec{j}$	Current density
b	Mobility
n	Charge carrier number density
q	Charge per carrier

$$J_x = (nqb)E_x$$

$\frac{\partial n}{\partial t} + \nabla \bullet (n\vec{U}) = 0$	Charge conservation
$\vec{U} = b\vec{E}$	Velocity

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nbE_x) = 0$$

|| Cell – Separation of Variables

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}\left(nbE_x\right) = 0$$

Conservation of charge

Let $n(x,t) \equiv \mathbf{N}(x)\mathbf{T}(t)$
$E(x,t) \equiv \mathbf{E}(x)\mathbf{T}(t)$

$\mathbf{N}(x)$ #/m^3

$\mathbf{E}(x)$ V/m

$\mathbf{T}(t)$ 1 (dimensionless)

$$\mathbf{N}\frac{d\mathbf{T}}{dt} + b\mathbf{T}^2 \frac{d}{dx}(\mathbf{NE}) = 0$$

$$\frac{\mathbf{N}\frac{d\mathbf{T}}{dt} + b\mathbf{T}^2 \frac{d}{dx}(\mathbf{NE})}{\mathbf{NT}^2} = 0$$

$$\frac{1}{\mathbf{T}^2}\frac{d\mathbf{T}}{dt} + b\frac{1}{\mathbf{N}}\frac{d}{dx}(\mathbf{NE}) = 0$$

Separation is achieved.

|| Cell – Time dependence

$$\frac{1}{\mathbf{T}^2}\frac{d\mathbf{T}}{dt} = -b\frac{1}{\mathbf{N}}\frac{d}{dx}(\mathbf{NE}) = -\frac{1}{\tau}$$

Constant with units of s^{-1}

$$\frac{d\mathbf{T}}{dt} + \frac{1}{\tau}\mathbf{T}^2 = 0$$

$$\mathbf{T}(t) = \frac{1}{1+\left(\frac{t}{\tau}\right)}$$

|| Cell – Transient Current

$$E(x,t) = \mathbf{E}(x)\mathbf{T}(t); \quad n(x,t) = \mathbf{N}(x)\mathbf{T}(t)$$

$$J(x,t) = nqbE = qb\mathbf{NET}^2 = \frac{qb\mathbf{N}(x)\mathbf{E}(x)}{\left[1+\left(\frac{t}{\tau}\right)\right]^2} = \frac{J_{EP}(x)}{\left[1+\left(\frac{t}{\tau}\right)\right]^2}$$

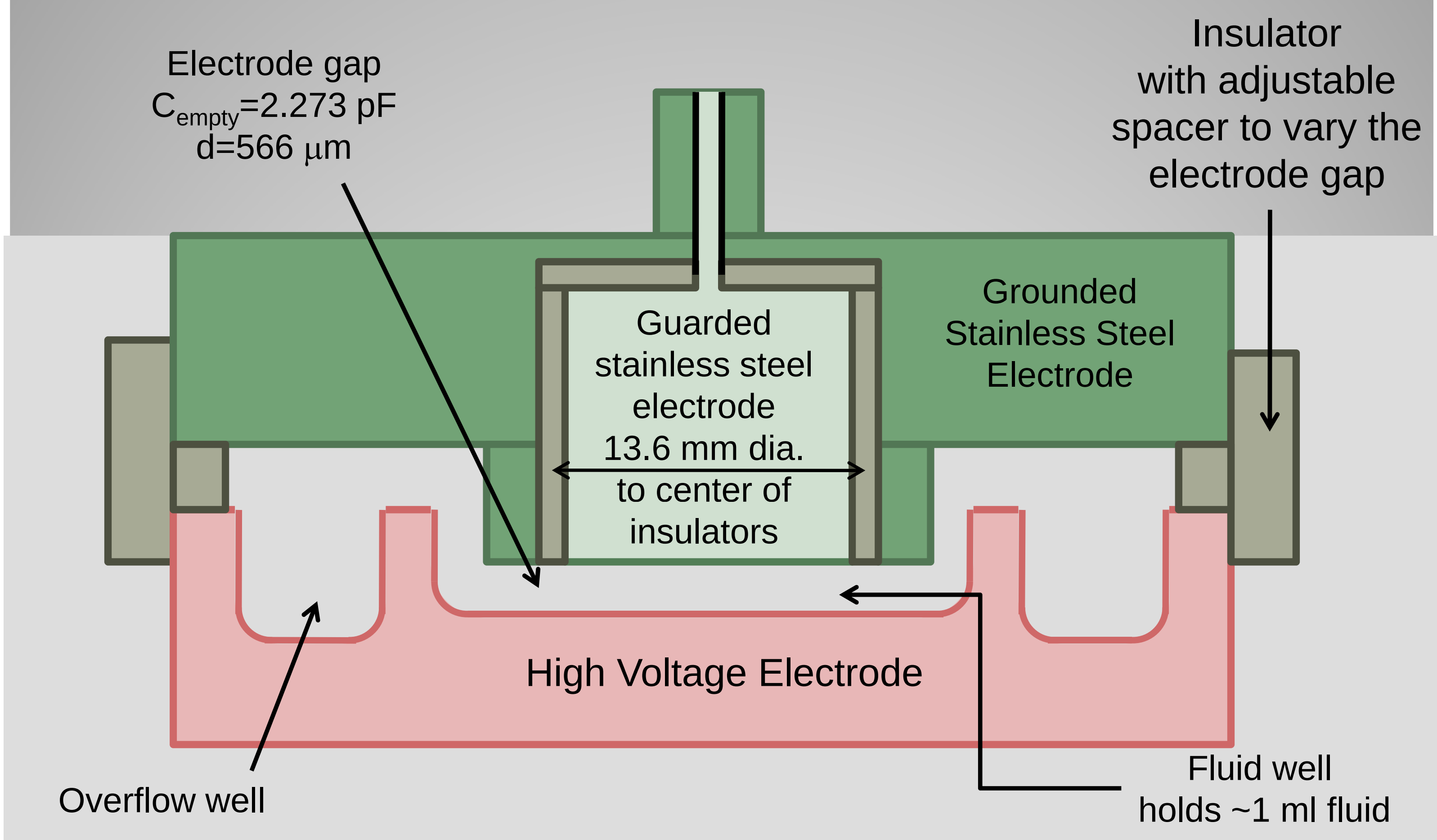
$$I(t) = AJ(x=0,t) = \frac{I_{EP}}{\left[1+\left(\frac{t}{\tau}\right)\right]^2}$$

Ideal current, 1 EP species

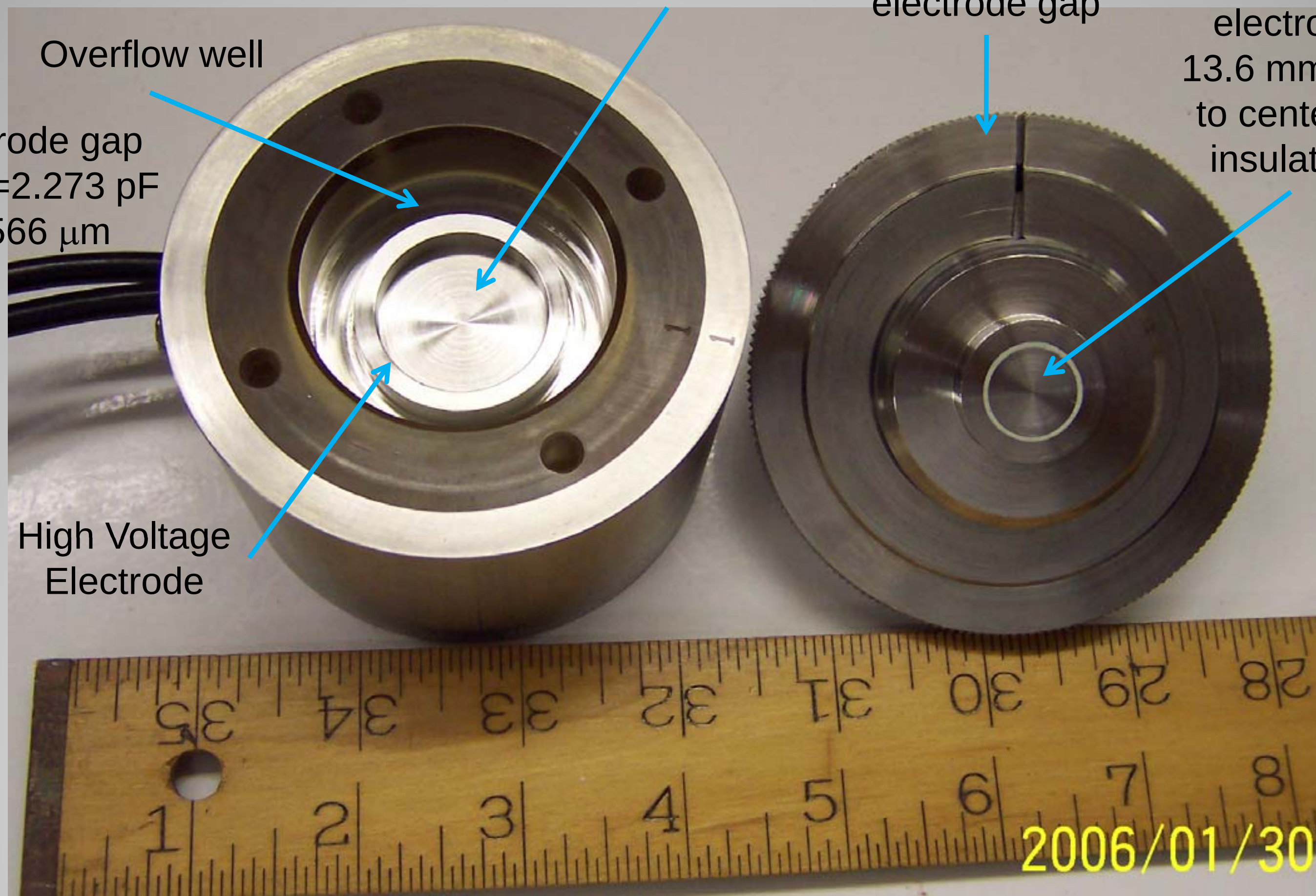
$$I_x(t) = I_{ss} + \frac{I_{EP,1}}{\left[1+\left(\frac{t}{\tau_1}\right)\right]^2} + \frac{I_{EP,2}}{\left[1+\left(\frac{t}{\tau_2}\right)\right]^2}$$

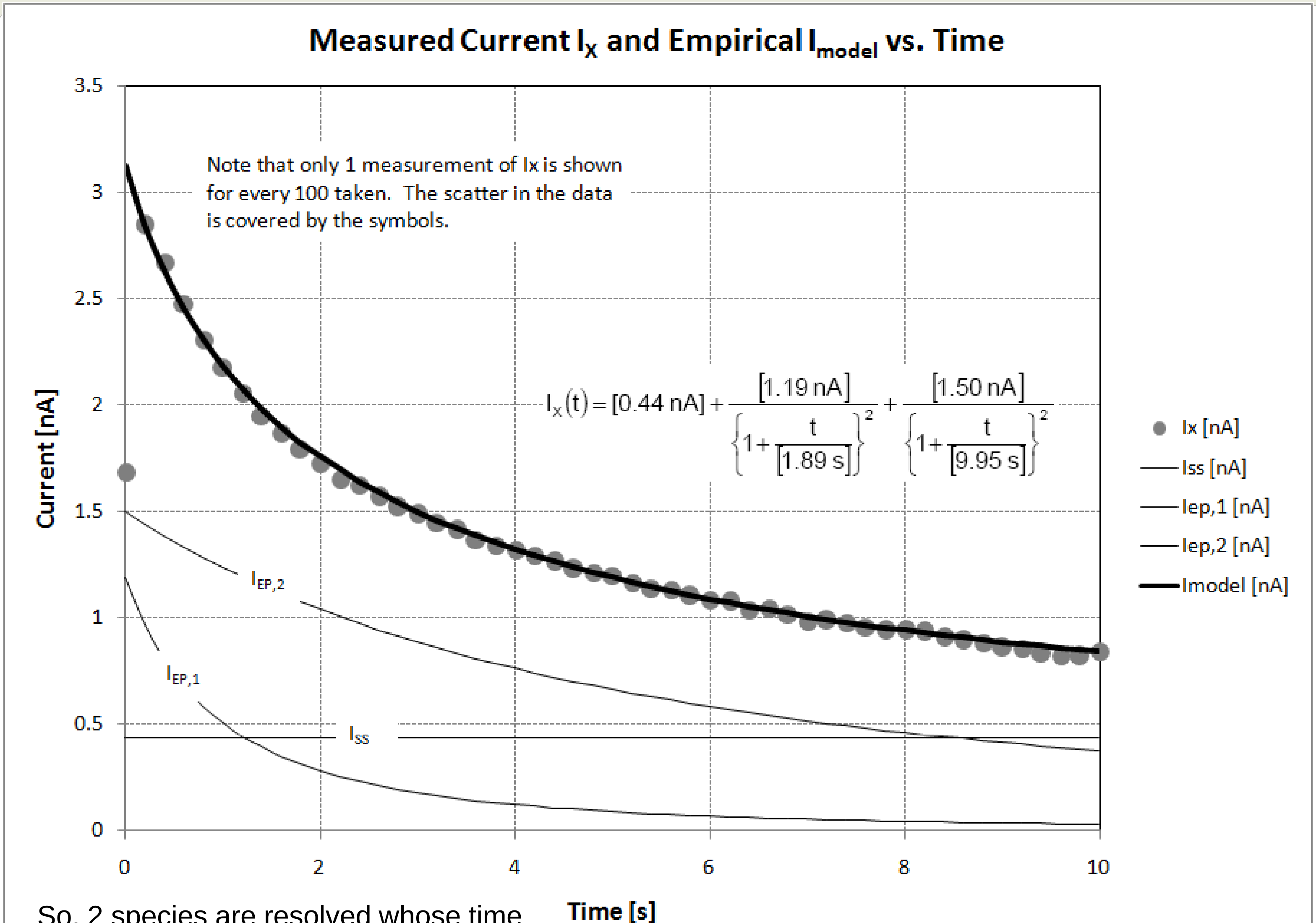
Expected current, with 2 EP species

Experimental Apparatus



Cell Photo


Fluid well
holds ~1 ml fluid
Clamping
collar adjusts
electrode gap
Guarded
stainless steel
electrode
13.6 mm dia.
to center of
insulators
Overflow well
Electrode gap
C_{empty}=2.273 pF
d=566 μm
High Voltage
Electrode
2006/01/30



So, 2 species are resolved whose time constants differ by about 5X.

Estimating Mobility

$$\frac{\partial n}{\partial t} + \nabla \bullet \left(nb\vec{E} \right) = 0$$

Conservation of charge

$$\frac{n}{\tau} - \frac{1}{d}\left(nb\frac{V}{d} \right) \approx 0$$

Estimate using “characteristic time” and “characteristic distance.”

$$b \approx \frac{d^2}{V\tau}$$

Estimated mobility.

Estimating Number Density

$$\vec{J} = nqb\vec{E}$$

Current density

$$\frac{I_{EP}}{A} \approx nq\left(\frac{d^2}{V\tau}\right)\frac{V}{d}$$

Estimates using "characteristic time" and "characteristic distance."

$$n \approx \frac{\tau I_{EP}}{qAd}$$

Estimated number density of charge carriers

Parameter	Species 1	Species 2
I_{EP} [nA]	1.20	1.50
τ [s]	1.89 s	9.95 s
b [m^2/Vs]	$3.4\text{x}10^{-7}$	$0.64\text{x}10^{-7}$
n [$\#/m^3$]	$1.4\text{x}10^{+17}$	$9.5\text{x}10^{+17}$
σ [nS/m]	29.4	36.8

A_{elec} = 46.2 mm^2
d_{gap} = 566 mm

17

Summary (1/2)

- To conserve charge, the time dependence of the current must be:

$$I_{EP}(t) = \frac{I_{init}}{\left(1 + \frac{t}{\tau}\right)^2}$$

- The mobility and number density of charge carriers are estimated by:

$$b \approx \frac{d^2}{V\tau} \qquad n \approx \frac{I\tau}{qAd}$$

Summary (2/2)

- In a 1% solution of OLOA in dodecane, 2 charged species are present. The properties of the species at 0.5 V (E=880 V/m) are summarized below.

Parameter	Species 1	Species 2
I_{EP} [nA]	1.20	1.50
τ [s]	1.89 s	9.95 s
b [$^{m^2}/_{V\,s}$]	3.4×10^{-7}	0.64×10^{-7}
n [$^{\#}/_{m^3}$]	$1.4 \times 10^{+17}$	$9.5 \times 10^{+17}$
σ [$^{nS}/_{m}$]	29.4	36.8

A_{elec} = 46.2 mm^2
d_{gap} = 566 mm