RISK*e*Learning
Nanotechnology –
Applications and Implications for Superfund

February 13, 2007
Session 2:
"Nanotechnology – Metal Remediation"
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Dr. Shas Mattigod, Pacific Northwest National Laboratory

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Contaminant Removal and Water Reuse: Research Opportunities with Nanotechnology

Arsenic Adsorption on Nanoscale Magnetite

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Overview of Arsenic

- Widely distributed in earth’s crust
- In water by dissolution of ores/minerals
- Concentrated in areas by erosion
- Human Activities sources
  - Residue from alloys and treatments
  - Burning of fossil fuels
- Largest threat to humans
  - Inorganic As(III) and As(V)
  - In drinking water

These are the most general and important “first” points to know about Arsenic. **The particularly important point, highlighted in green, is that it is As(III) that is the largest threat to humans.**

Arsenic Mobility Profile

- Arsenates-As(V)
  - Usually occurs as ions: $H_2AsO_4^-$ and $HAsO_4^{2-}$
    - predominates in aerobic soils
- Arsenites – As(III)
  - Occurs as H_3AsO_3 (pH below 9.2)
  - Exists in slightly reduced soils
  - Larger concern than As(V) because of
    - higher toxicity
    - greater mobility
- Arsenic in water
  - rather than solubility equilibrium controlling the mobility of arsenic, it is usually controlled by redox conditions, pH, biological activity, and adsorption/desorption reactions.
- Arsenic immobilization through ionic adsorption can be controlled within normal oxidizing Eh/pH conditions to varying degrees

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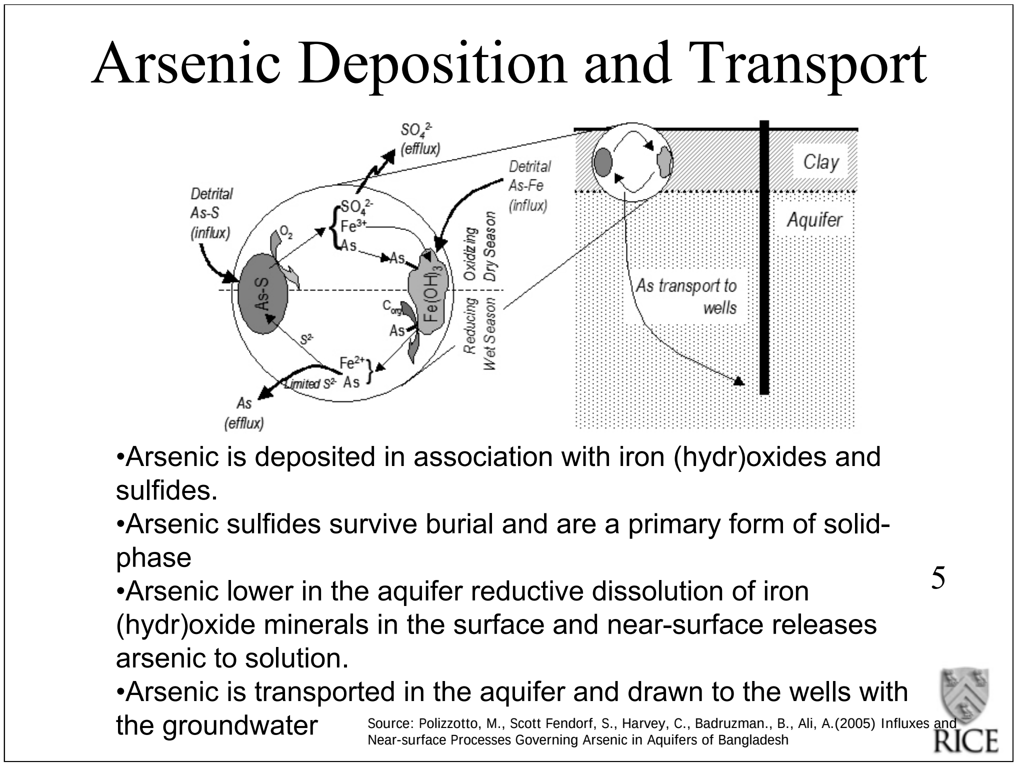
Redox conditions, pH, biological activity and specific chemical reaction are keys to distribution – NOT A GENERAL SOLUBILITY BALANCE!

The last statement is a “soft” way of saying “without normal oxidizing and acid conditions, we have a problem!”

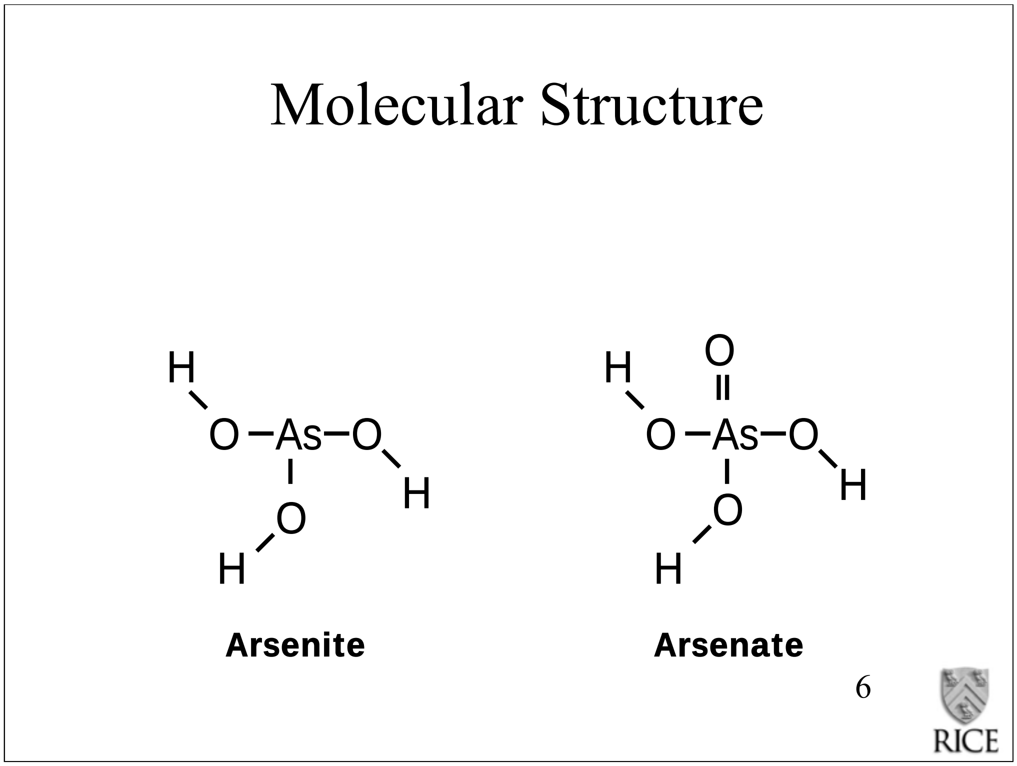


Arsenic Deposition and Transport

- Arsenic is deposited in association with iron (hydr)oxides and sulfides.
- Arsenic sulfides survive burial and are a primary form of solid-phase
- Arsenic lower in the aquifer reductive dissolution of iron (hydr)oxide minerals in the surface and near-surface releases arsenic to solution.
- Arsenic is transported in the aquifer and drawn to the wells with the groundwater

Source: Polizzotto, M., Scott Fendorf, S., Harvey, C., Badruzman., B., Ali, A.(2005) Influxes and Near-surface Processes Governing Arsenic in Aquifers of Bangladesh

This is how arsenic is deposited and gets into a aquifer.

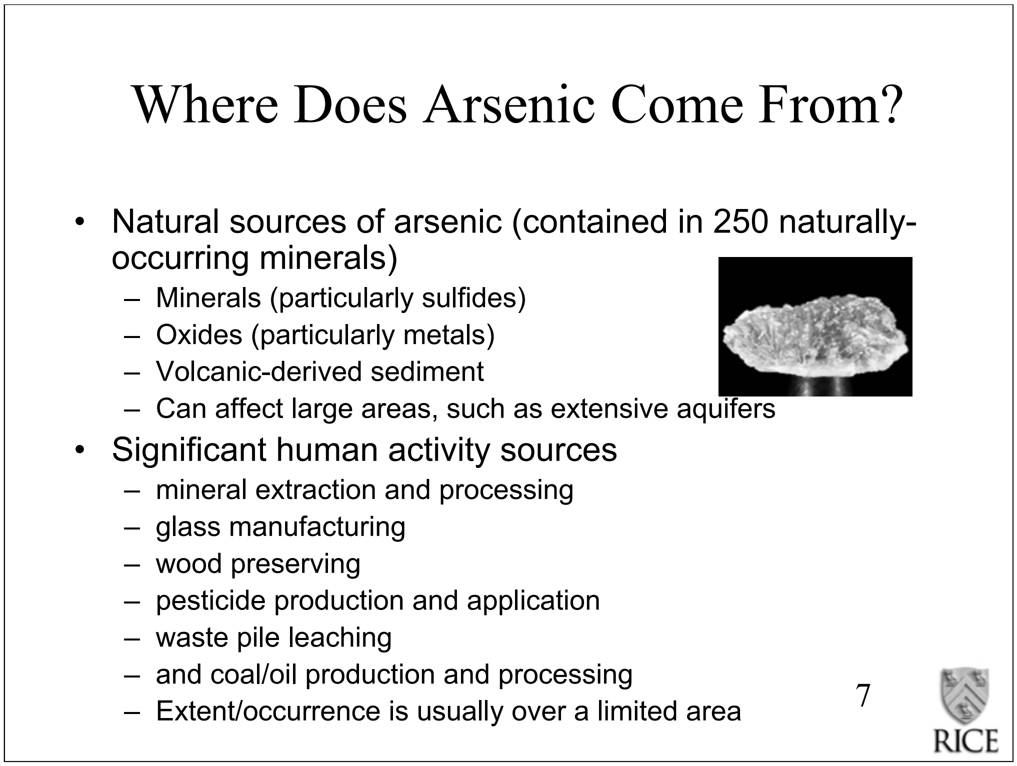


Molecular Structure

Arsenite

Arsenate

For the scientifically and chemically oriented audience members!



Where Does Arsenic Come From?

- Natural sources of arsenic (contained in 250 naturally-occurring minerals)
  - Minerals (particularly sulfides)
  - Oxides (particularly metals)
  - Volcanic-derived sediment
  - Can affect large areas, such as extensive aquifers
- Significant human activity sources
  - mineral extraction and processing
  - glass manufacturing
  - wood preserving
  - pesticide production and application
  - waste pile leaching
  - and coal/oil production and processing
  - Extent/occurrence is usually over a limited area

The picture is a sample of arsenic sulfide.

Important points to emphasize are that:

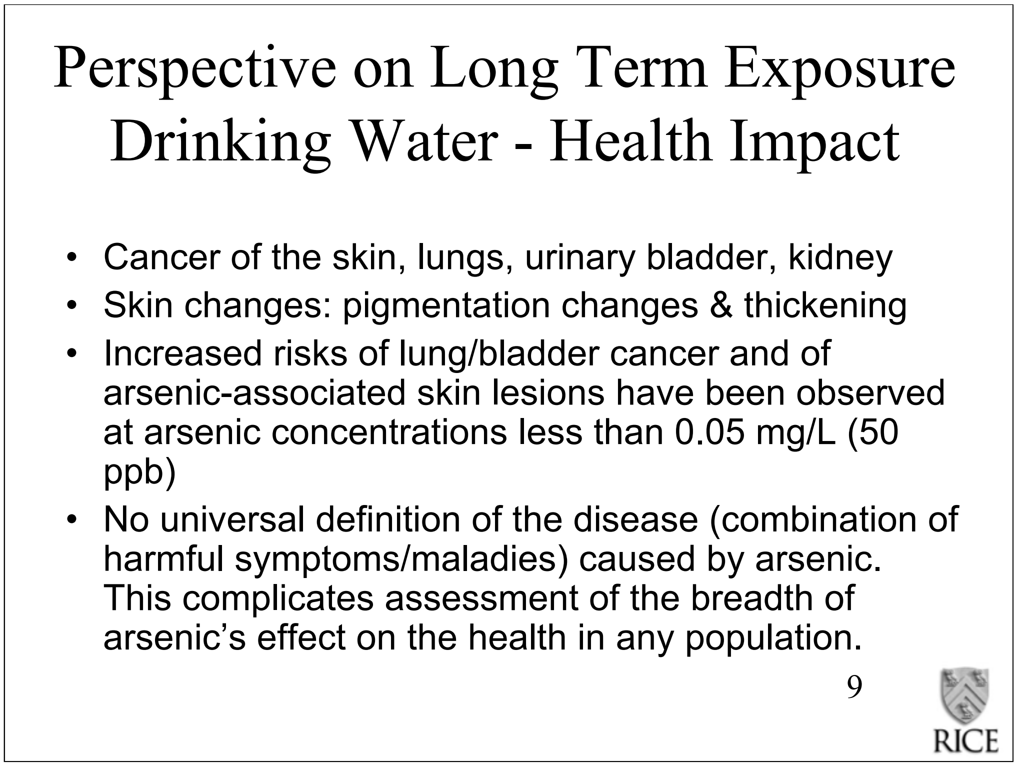
•Aquifers are “vessels” that can, potentially, extend a contamination problem over a wide area.

•Human activity sources of arsenic, though potentially and actually life-threatening, usually create contamination zones that are <u>limited</u>, relative to natural sources.

Arsenic Redox Reaction

- $H_3AsO_4 + 2H^+ + 2e^- \rightarrow H_3AsO_3 + H_2O$
  Arsenate – As(V) Arsenite – As(III)
- The key is that arsenic is “locked away” in iron oxyhydroxides when there is plenty of oxygen present. The oxidized form, arsenate, dominates. When the oxygen level is low, “reducing environment”, arsenate converts to arsenite.
- When arsenite is exposed to oxygen, it oxidizes, but the rate in air is only a few percent in one week.
  (Clifford, D., Ceber, L., Chow, S. (1983)

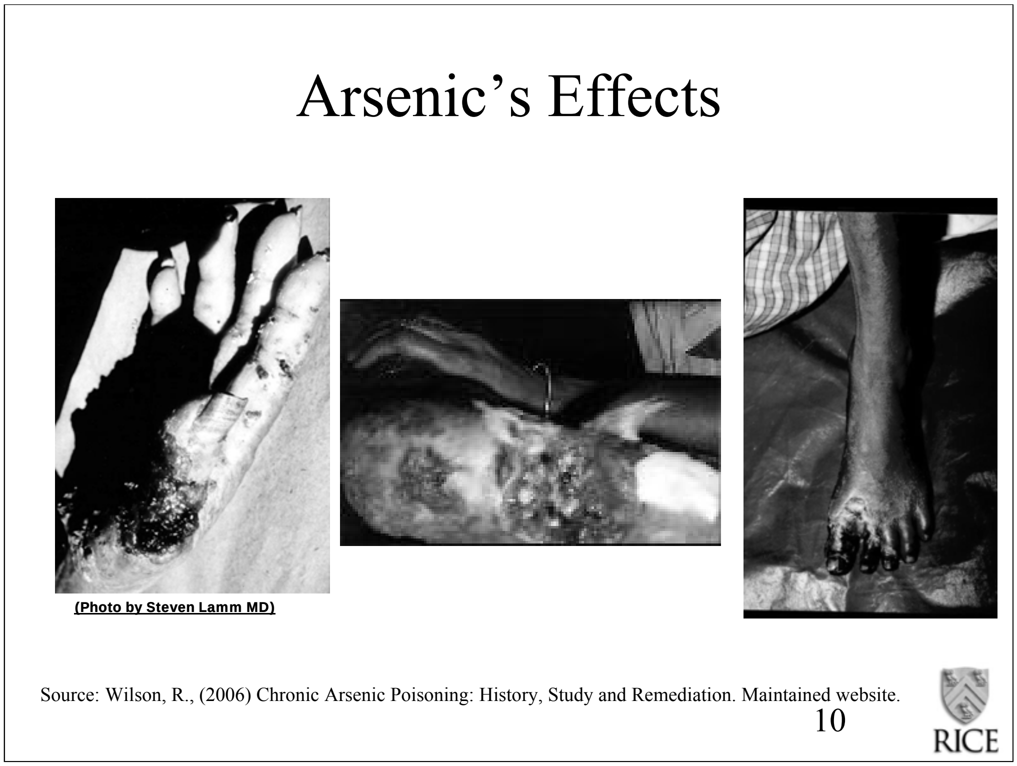
A reducing environment can create and preserve arsenite. When we withdraw it from that environment, as in withdrawing water from a well, it can take a long time for a significant portion of the arsenite to oxidize and become “safer”!



Perspective on Long Term Exposure Drinking Water - Health Impact

- Cancer of the skin, lungs, urinary bladder, kidney
- Skin changes: pigmentation changes & thickening
- Increased risks of lung/bladder cancer and of arsenic-associated skin lesions have been observed at arsenic concentrations less than 0.05 mg/L (50 ppb)
- No universal definition of the disease (combination of harmful symptoms/maladies) caused by arsenic. This complicates assessment of the breadth of arsenic's effect on the health in any population.

This is the result of arsenic ingestion – including inhalation impact on the lungs. (I don't have a specific reference for the 50 ppb statement, but it is stated in at least one place in USGS or WHO publications. JWC)

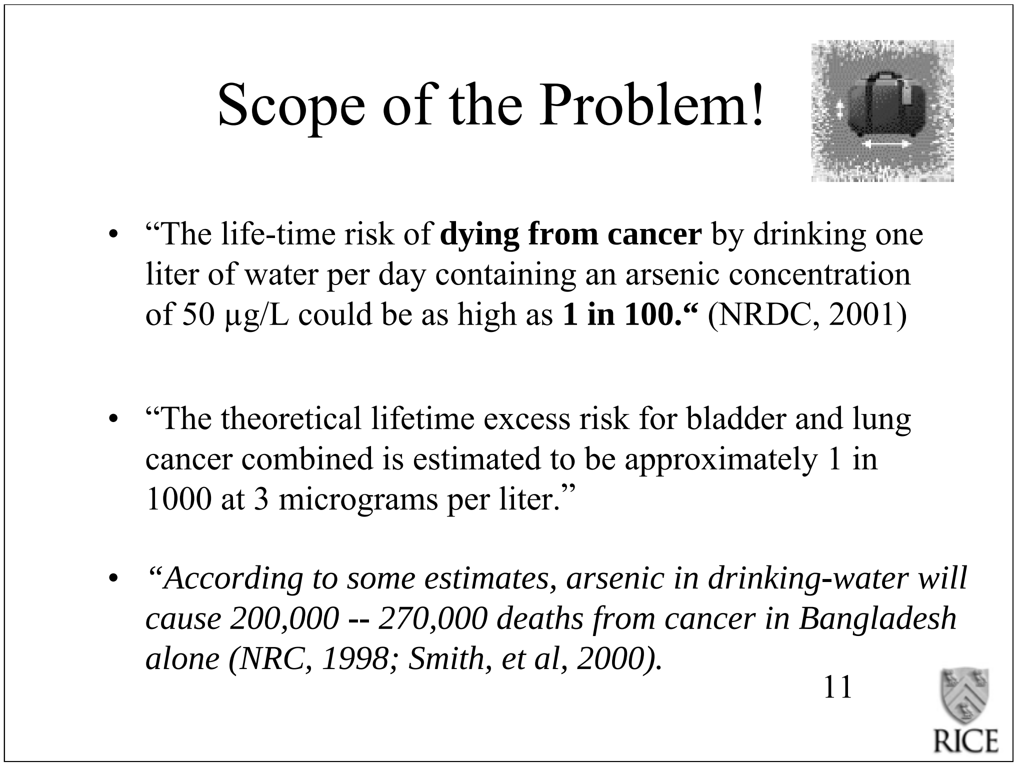


Arsenic's Effects

(Photo by Steven Lamm MD)

Source: Wilson, R., (2006) Chronic Arsenic Poisoning: History, Study and Remediation. Maintained website.

Plenty more on the referenced website!



Scope of the Problem!

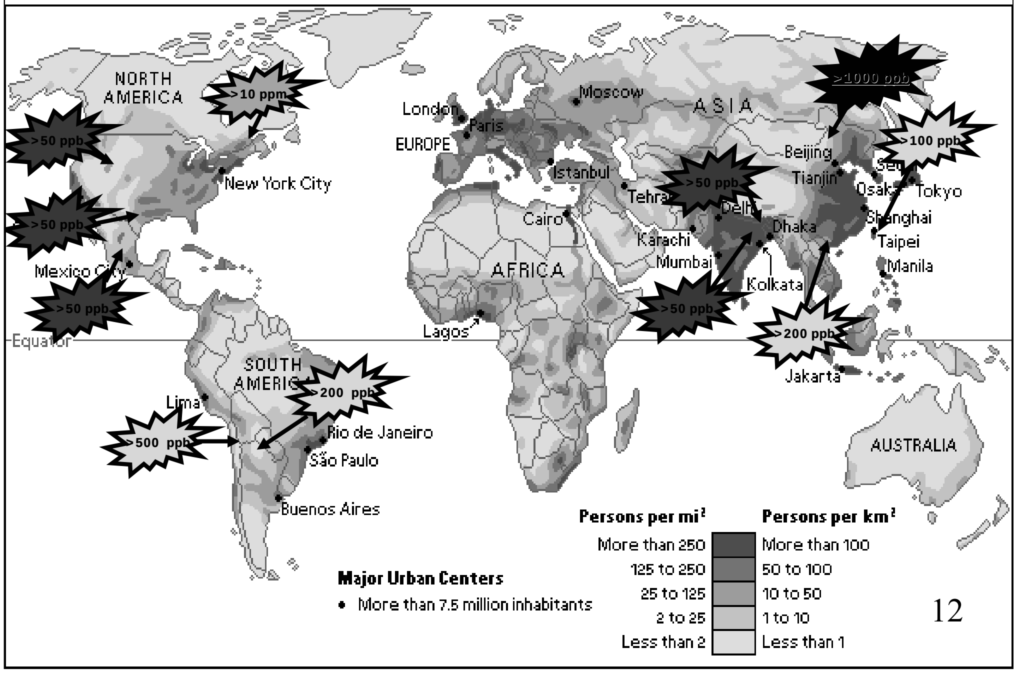
- “The life-time risk of **dying from cancer** by drinking one liter of water per day containing an arsenic concentration of 50 µg/L could be as high as **1 in 100.“** (NRDC, 2001)
- “The theoretical lifetime excess risk for bladder and lung cancer combined is estimated to be approximately 1 in 1000 at 3 micrograms per liter.”
- *“According to some estimates, arsenic in drinking-water will cause 200,000* **--** *270,000 deaths from cancer in Bangladesh alone (NRC, 1998; Smith, et al, 2000).*

This is how the

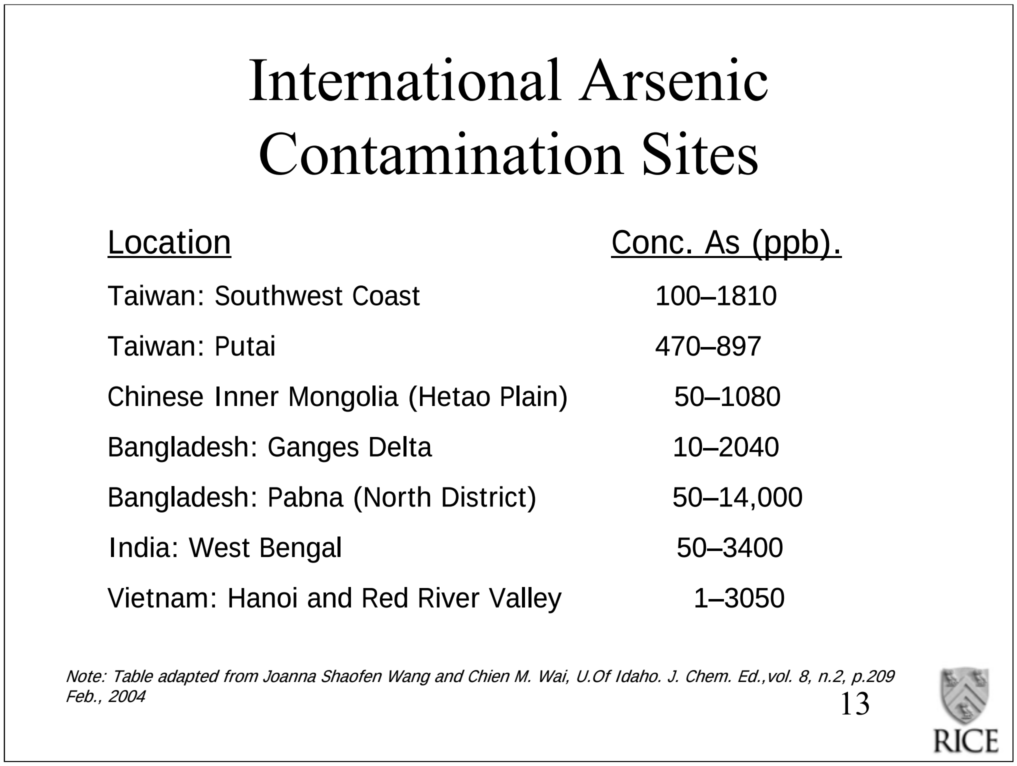
Contamination
Location and Level of contamination
Population
Health
and Life and Death

come together!

Areas of High Arsenic Concentration in Drinking Water



The values shown are far from the highest recordings in these areas, but they are presented to provide a “sampled picture” of how arsenic contamination is spread throughout the world. (The next slide – if used – is a table showing the ranges of concentrations encountered in some of these areas.)

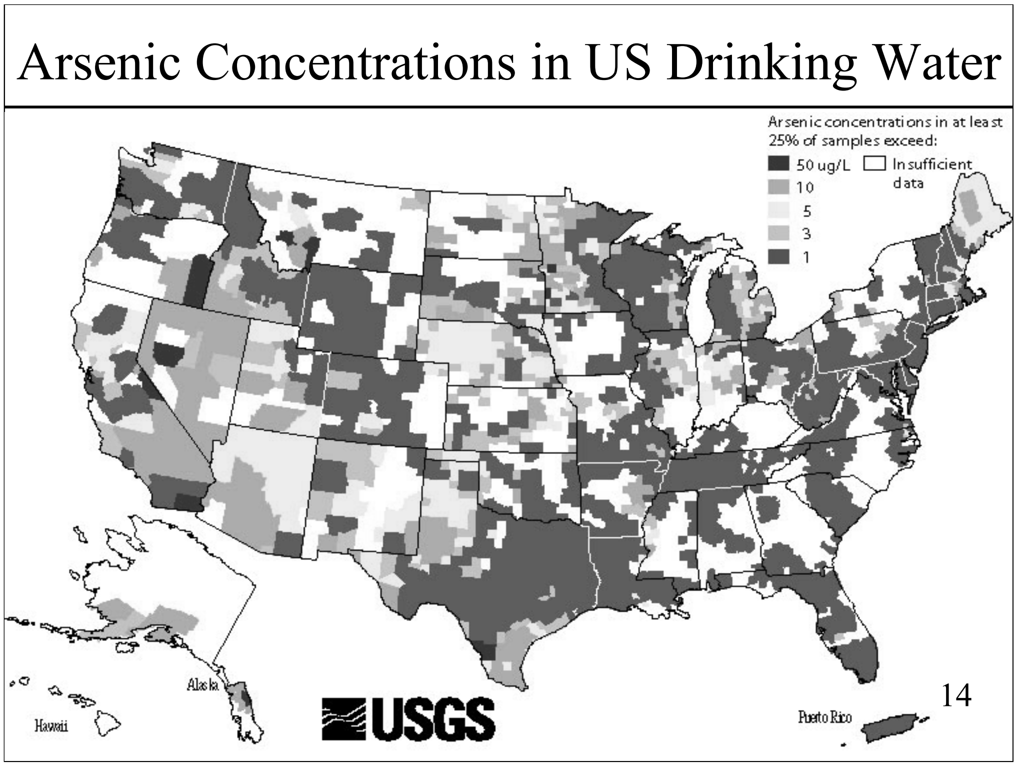


International Arsenic Contamination Sites

Location	Conc. As (ppb).
Taiwan: Southwest Coast	100–1810
Taiwan: Putai	470–897
Chinese Inner Mongolia (Hetao Plain)	50–1080
Bangladesh: Ganges Delta	10–2040
Bangladesh: Pabna (North District)	50–14,000
India: West Bengal	50–3400
Vietnam: Hanoi and Red River Valley	1–3050

Note: Table adapted from Joanna Shaofen Wang and Chien M. Wai, U.Of Idaho. J. Chem. Ed.,vol. 8, n.2, p.209 Feb., 2004

Clearly, the values on the previous slide (which showed 100 ppb in Taiwan, > 200 ppb in Bangladesh and >1,000 in China) were not maximum values! In fact the next slide shows haw bad the problem is in one area in Bangladesh.)



Arsenic Concentrations in US Drinking Water

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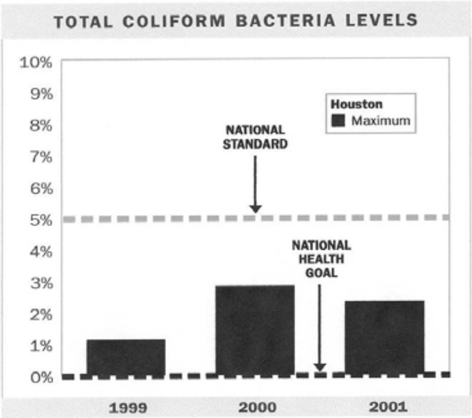
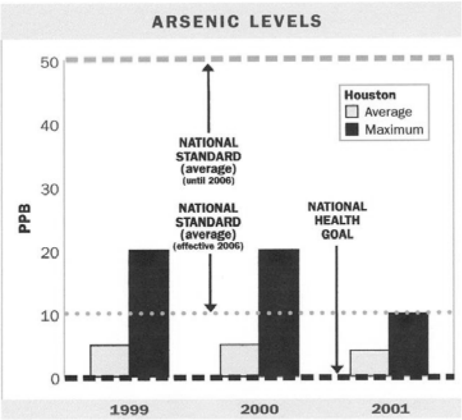
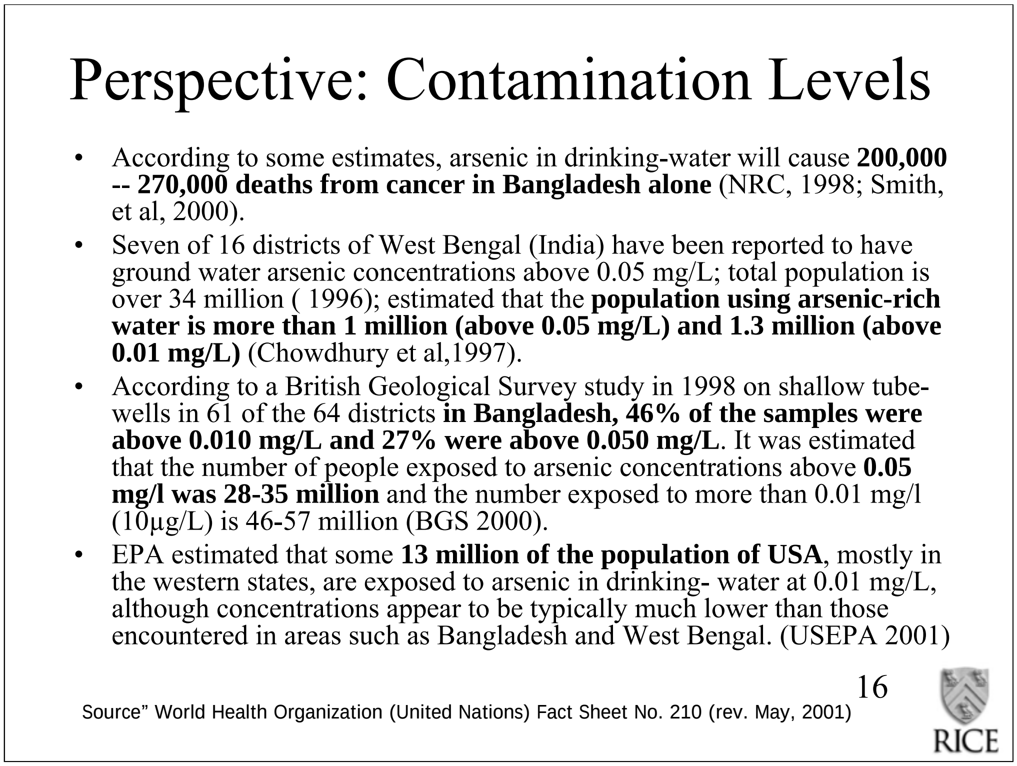
Here is map of the sampled concentrations of arsenic in the water in the United States. Recently (January 2006), the USA has imposed a standard of <10 ppb (<10 mg/L) concentration in drinking water in the Country. This change from the previous 50 ppb has intensified the search for improved processes for reducing the amount of arsenic in drinking water – **on top of** the demands caused by much more hazardous concentrations in other areas of the world.

Houston Tap Water





NRDC Report 2002



Perspective: Contamination Levels

- According to some estimates, arsenic in drinking-water will cause **200,000 -- 270,000 deaths from cancer in Bangladesh alone** (NRC, 1998; Smith, et al, 2000).
- Seven of 16 districts of West Bengal (India) have been reported to have ground water arsenic concentrations above 0.05 mg/L; total population is over 34 million (1996); estimated that the **population using arsenic-rich water is more than 1 million (above 0.05 mg/L) and 1.3 million (above 0.01 mg/L)** (Chowdhury et al,1997).
- According to a British Geological Survey study in 1998 on shallow tube-wells in 61 of the 64 districts **in Bangladesh, 46% of the samples were above 0.010 mg/L and 27% were above 0.050 mg/L**. It was estimated that the number of people exposed to arsenic concentrations above **0.05 mg/l was 28-35 million** and the number exposed to more than 0.01 mg/l (10µg/L) is 46-57 million (BGS 2000).
- EPA estimated that some **13 million of the population of USA**, mostly in the western states, are exposed to arsenic in drinking- water at 0.01 mg/L, although concentrations appear to be typically much lower than those encountered in areas such as Bangladesh and West Bengal. (USEPA 2001)

Source" World Health Organization (United Nations) Fact Sheet No. 210 (rev. May, 2001)

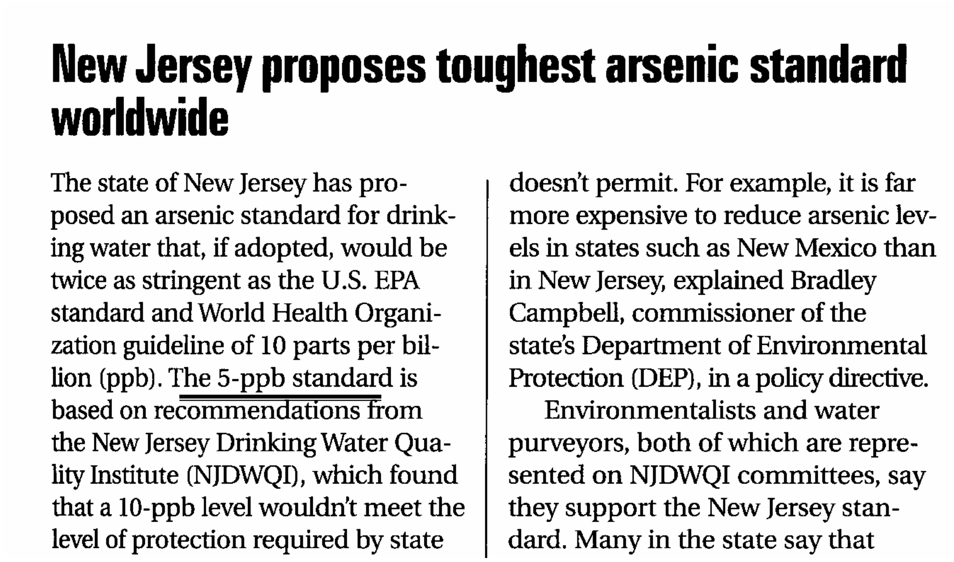
This is an "encapsulation of information" that briefly gives glimpse of the extent of the contamination and potential health impact of arsenic contamination.

Drinking Water
"Recommendations" & "Standards"

- **World Health Organization** Recommendations

Year	Concentration
1958	0.20 mg/L (200 ppb)
1963	0.05 mg/L (50 ppb)
1993	0.01 mg/L (**10 ppb**)

- **United States**
  - 50 ppb was set by Public Health Dept. in 1942
  - EPA adopted this standard in 1975 as "interim" regulation
  - IN 1986 Congress converted this "interim" to a National Regulation and requested EPA review and set new standards.
  - 50 ppb (0.050 mg/L) prior to January, 2006
  - **10 ppb**, currently



New Jersey proposes toughest arsenic standard worldwide

The state of New Jersey has proposed an arsenic standard for drinking water that, if adopted, would be twice as stringent as the U.S. EPA standard and World Health Organization guideline of 10 parts per billion (ppb). The 5-ppb standard is based on recommendations from the New Jersey Drinking Water Quality Institute (NJDWQI), which found that a 10-ppb level wouldn't meet the level of protection required by state doesn't permit. For example, it is far more expensive to reduce arsenic levels in states such as New Mexico than in New Jersey, explained Bradley Campbell, commissioner of the state's Department of Environmental Protection (DEP), in a policy directive.

Environmentalists and water purveyors, both of which are represented on NJDWQI committees, say they support the New Jersey standard. Many in the state say that

ES&T March 15, 2004

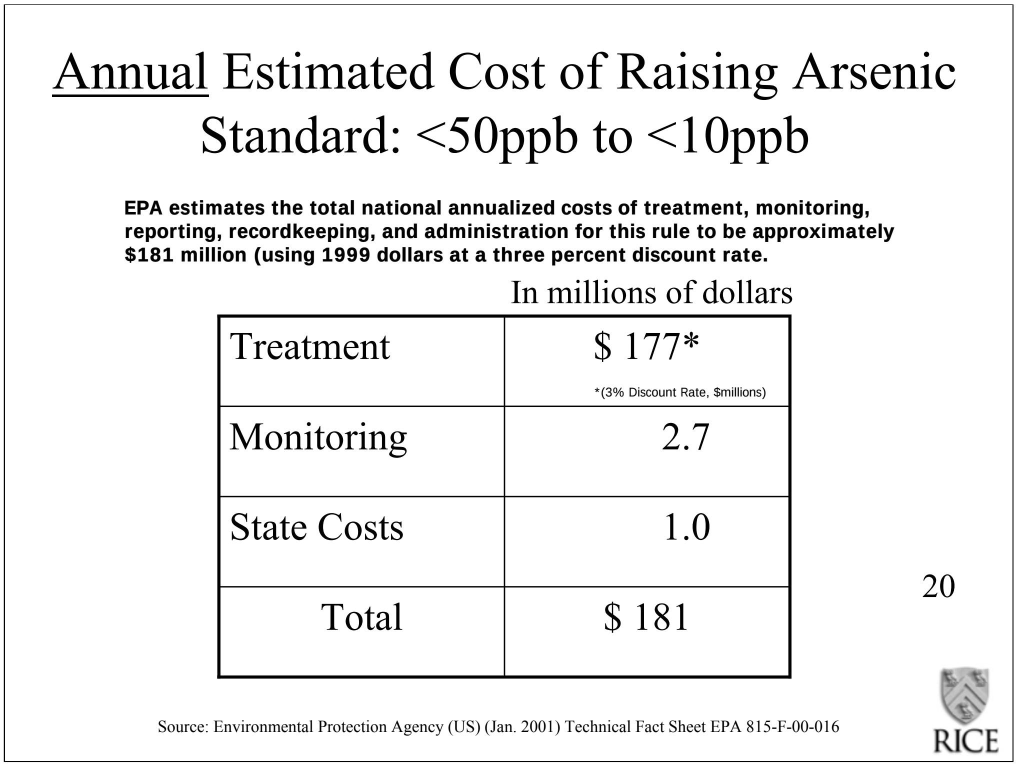
Effects of New Standard

- Max. Levels reduced from 50 μg/L to 10 μg/L
- 13 million people in areas of higher standard (West, Midwest, N. England)
- Annual Estimated Reductions:

	Cases	Deaths
Bladder Cancer	19-31	5-8
Lung Cancer	19-25	16-22
Diabetes	?	?
Heart Disease	?	?

Source: Environmental Protection Agency (US) (Jan. 2001) Technical Fact Sheet EPA 815-F-00-016

Here is the Environmental Protection Agency's assessment of the annual impact of reducing the levels of arsenic in drinking water in the United States



Annual Estimated Cost of Raising Arsenic Standard: <50ppb to <10ppb

EPA estimates the total national annualized costs of treatment, monitoring, reporting, recordkeeping, and administration for this rule to be approximately $181 million (using 1999 dollars at a three percent discount rate.

In millions of dollars

Treatment	$ 177* *(3% Discount Rate, $millions)
Monitoring	2.7
State Costs	1.0
Total	$ 181

Source: Environmental Protection Agency (US) (Jan. 2001) Technical Fact Sheet EPA 815-F-00-016

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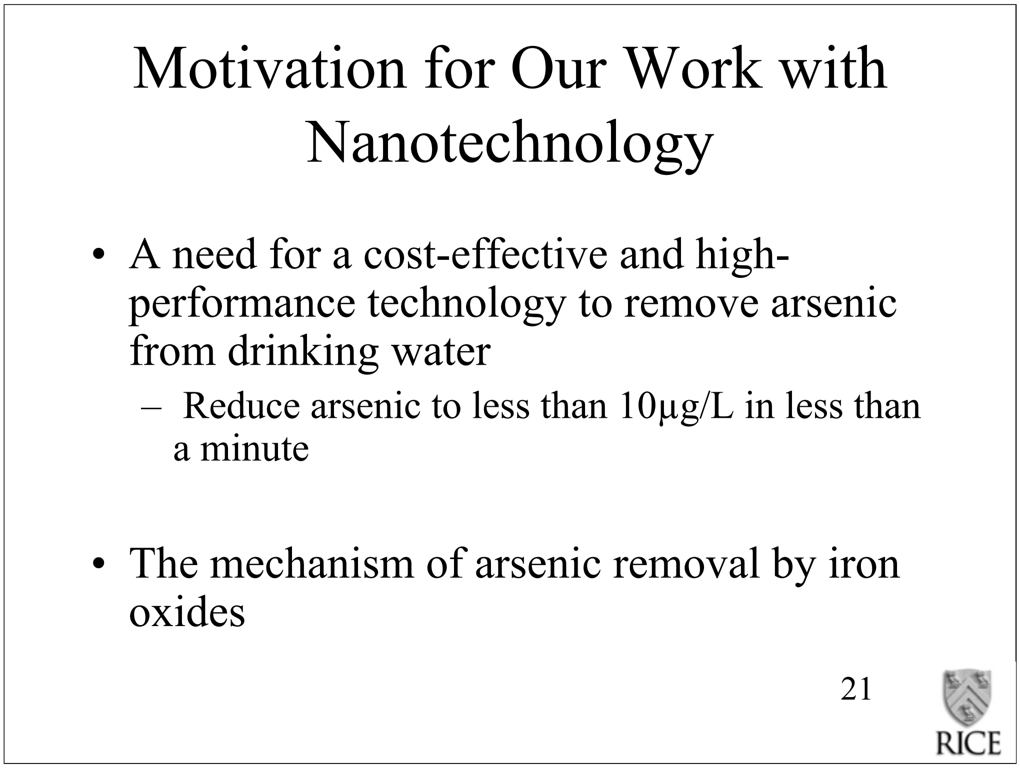
Note that this is the annual cost.



Motivation for Our Work with Nanotechnology

- A need for a cost-effective and high-performance technology to remove arsenic from drinking water
  - Reduce arsenic to less than 10µg/L in less than a minute

- The mechanism of arsenic removal by iron oxides

Current Technologies

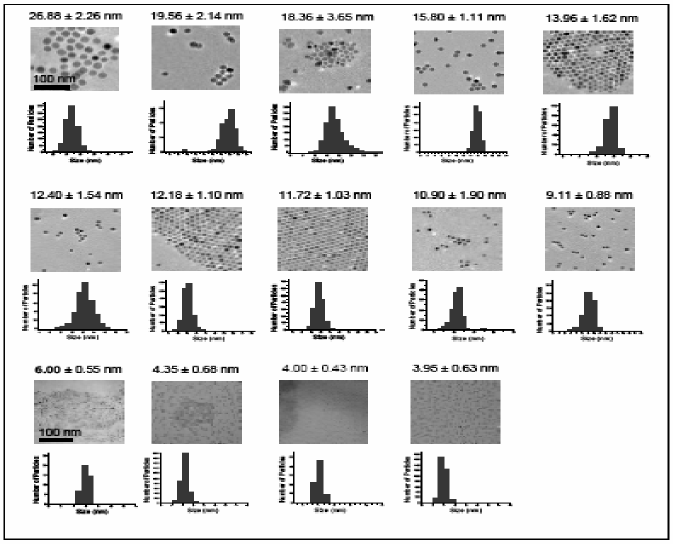
- US EPA As standard level: 10µg/L

Technology	Disadvantages
Ion exchange	No As(III) removal Interference from SO_4^{2-}& TDS
Membrane methods	Expensive
Coagulations with iron salts	Solid-liquid separation

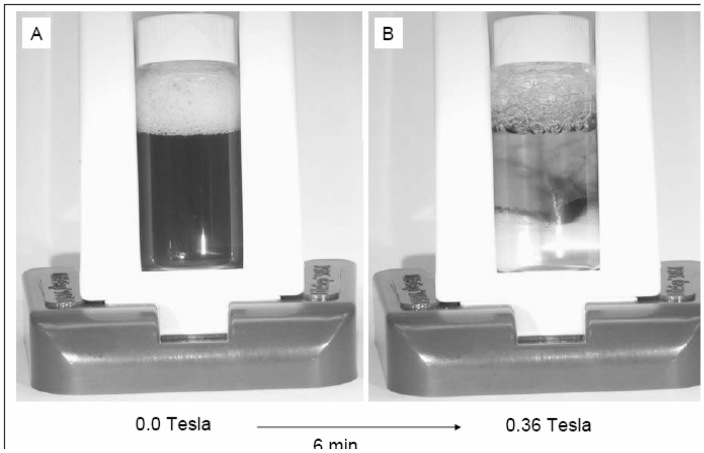
http://www.unu.edu/env/Arsenic/Han.pdf (accessed October 16, 2006)

Nano-Magnetite

Control Synthesis of Engineered Nano-Magnetite
Collaboration with Vicki Colvin: Science 314, 964 2006



Magnetic Properties of Nano-magnetite



Magnetite nanocrystals < 40 nm: Single domain magnet
Size dependent magnetic properties: ferromagnetic (>20 nm)
paramagnetic (6-20 nm)
(Science 2006)

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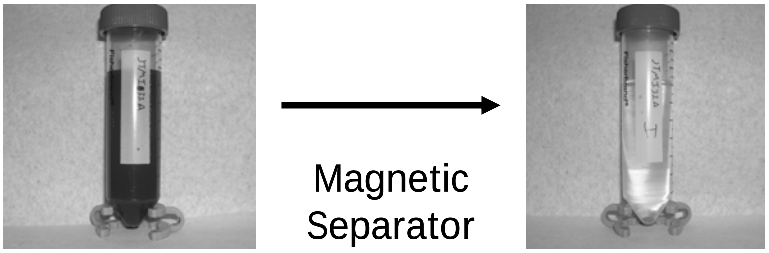
Magnetic Separator



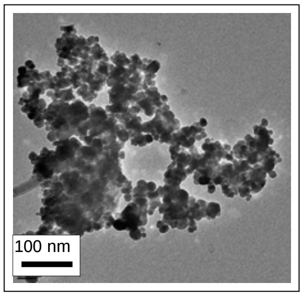
Magnetic Separator

Solution before column

Solution after column

Nano-magnetite can be separated by hand held magnetic device (Science 2006)

Magnetite Nanoparticles



- Mean particle diameter: 20nm
- Surface area: 60m^2/g

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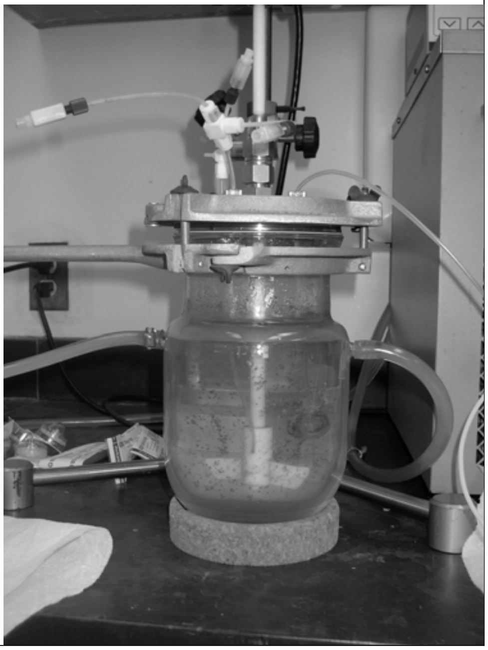
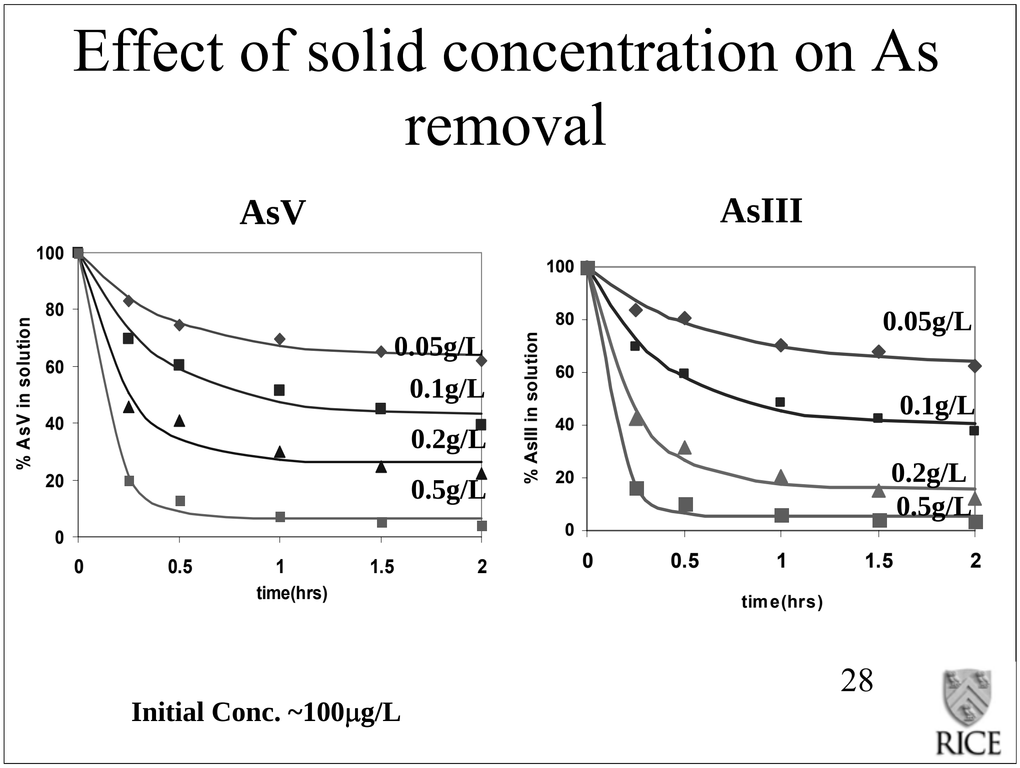
Experimental Set-up: Vessel Apparatus

- Temperature controlled
- Overhead agitator/stirrer
- 3 connectors by 3-way valves
  - Sampling
  - Ar gas
  - Solution injection/gas purging
- Anoxic/ Oxic conditions





Effect of solid concentration on As removal

AsV

AsIII

Initial Conc. ~100μg/L

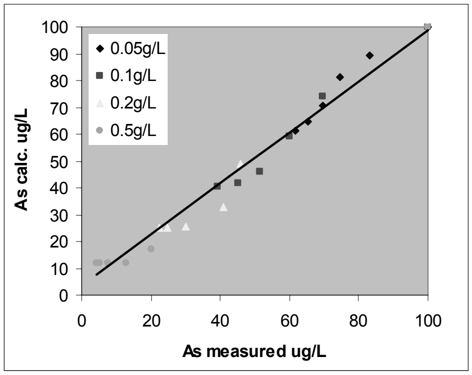
Modified Rate Equation

$$[\mathrm{As}]_t = \frac{[\mathrm{As}]_0}{1 + (q_{max} * b) * r_{sw}} + ([\mathrm{As}]_0 - \frac{[\mathrm{As}]_0}{1 + (q_{max} * b) * r_{sw}}) * e^{k_m * SSA * r_{sw} * t}$$

$[\mathrm{As}]_t$: As concentration at time, t (s)
$[\mathrm{As}]_0$: As concentration at time = 0, (μg/L)
q_{max} *b: Langmuir isotherm (L/g)
r_{sw}: solid to solution ratio (g/L or g/m^3)
SSA: specific surface area (m^2/g)
t: time (s)

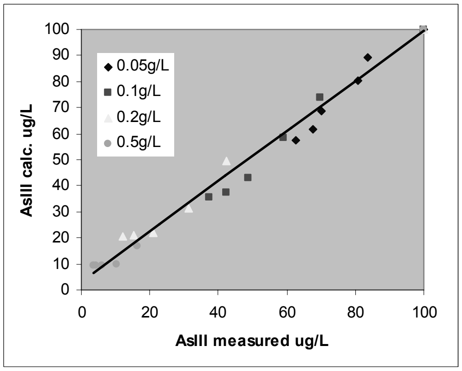
Model Prediction

AsV



q_{max}*b = 15.04 L/g
k_m = 1.057e-7 m/s
r = 0.992

AsIII



q_{max}*b = 19.17 L/g
k_m = 9.360e-8 m/s
r = 0.992

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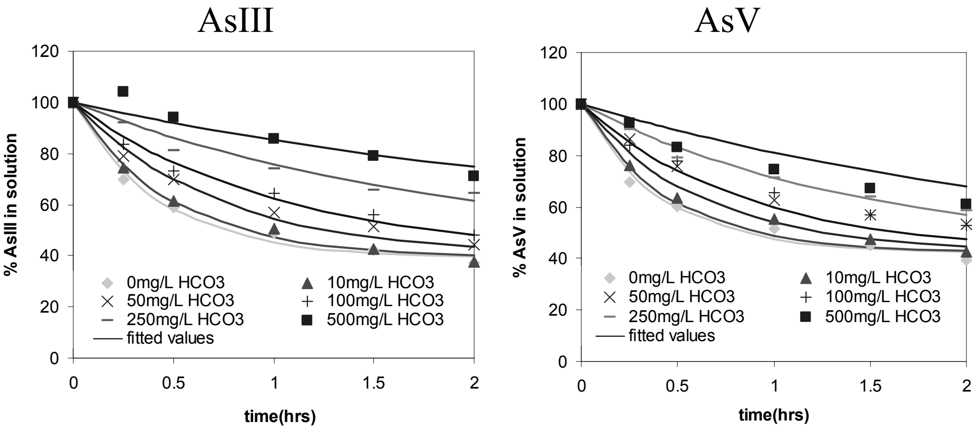
Competitive Adsorption: Bicarbonate



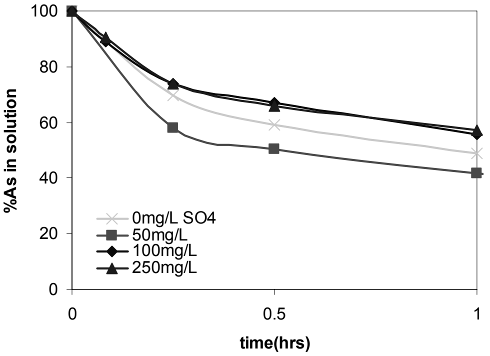
AsIII

AsV

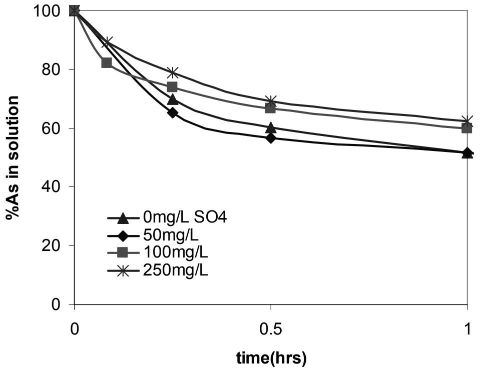
Initial Conc. ~100μg/L

Competitive Adsorption: Sulfate

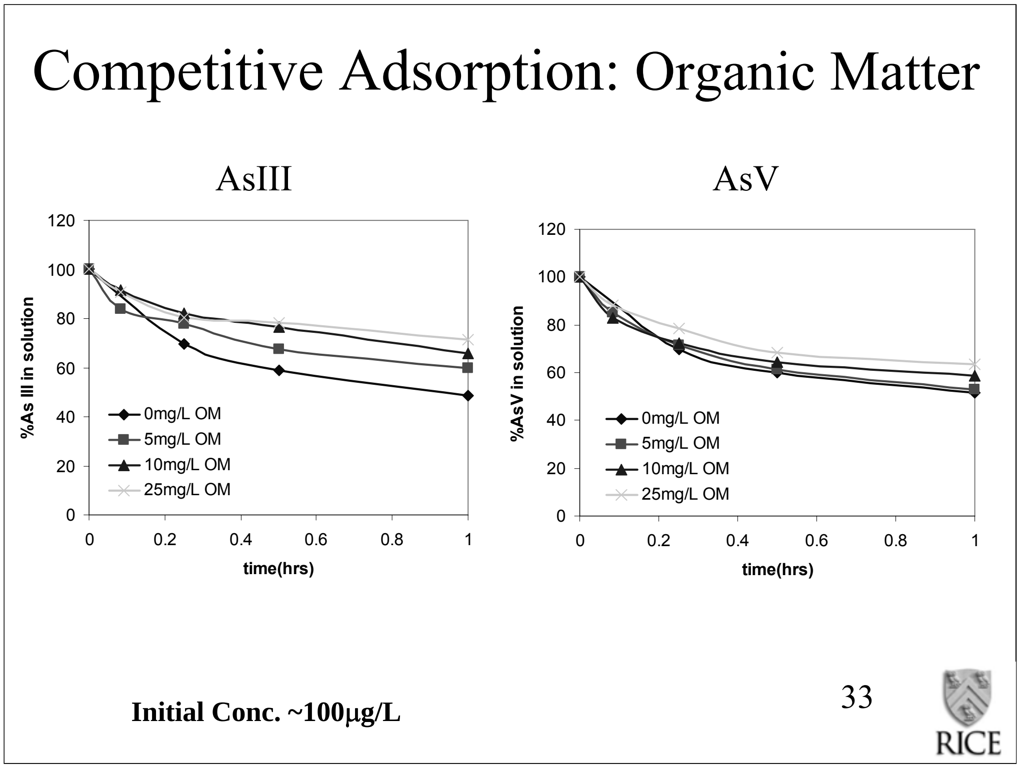
AsIII



AsV



Initial Conc. ~100µg/L

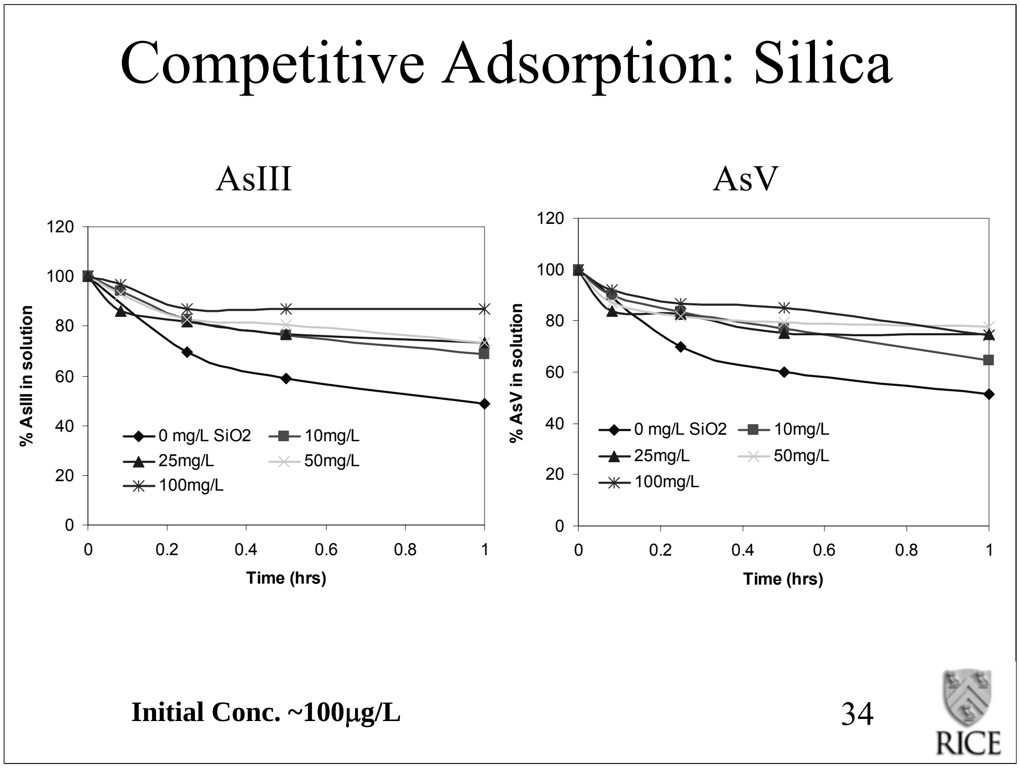


Competitive Adsorption: Organic Matter

AsIII

AsV

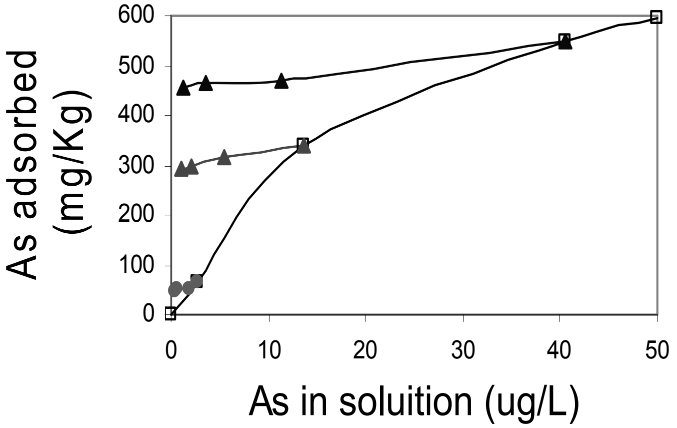
Initial Conc. ~100µg/L



Competitive Adsorption: Silica

Initial Conc. ~100µg/L

As/Nano-Fe3O4
Adsorption/Desorption Hysteresis



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Field Test – Brownsville, TX

- Arsenic-contaminated water from Southmost Regional Authority Desalination Plant Brownsville,TX in August, 2006: Wells #8 and 12 (Brackish water: ~ 5mS/cm)

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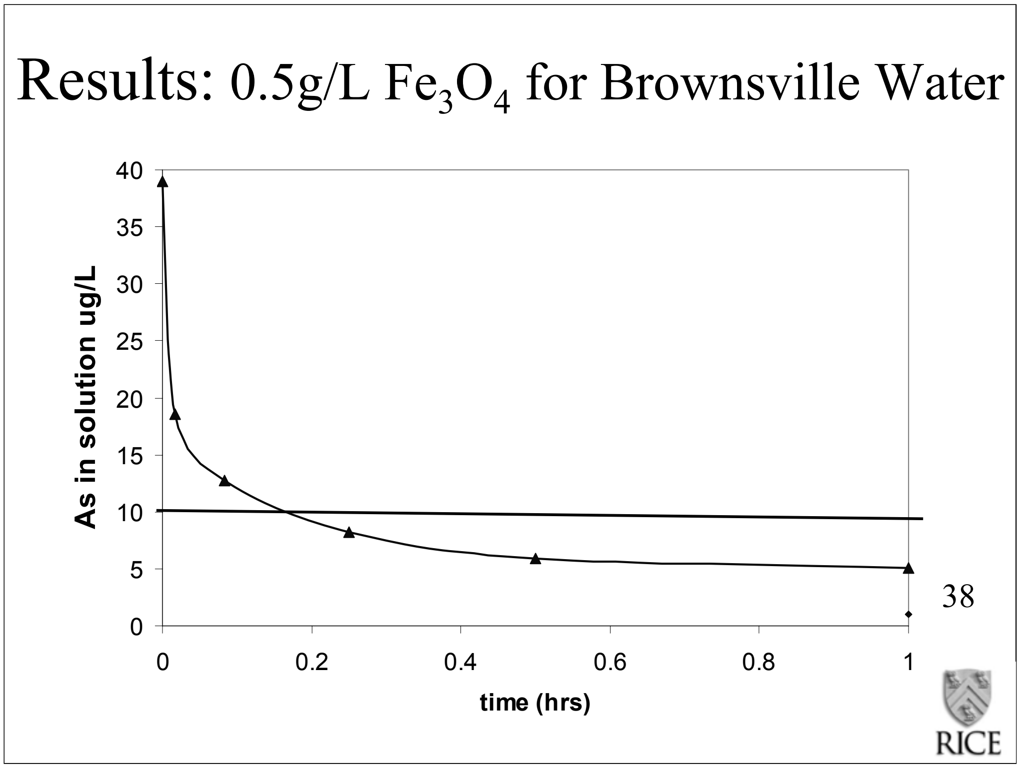
Characterization of Brownsville Wells

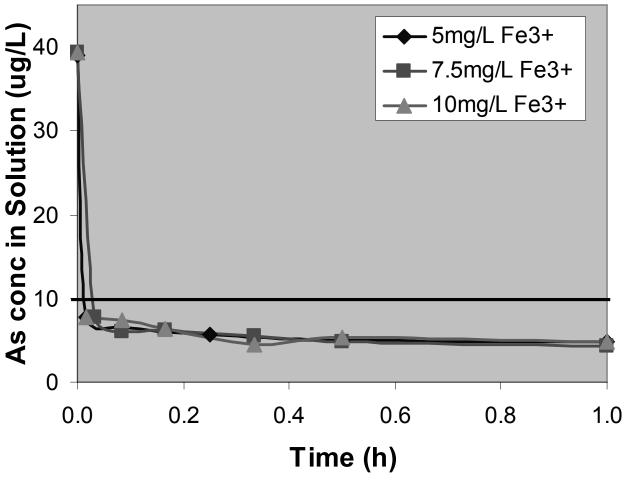
	Well #8	Well #12
Initial As (µg/L)	27.2	39.0
pH	7.32	7.39
Alkalinity (mg/L as HCO_3^-)	335	464.6
SO_4^{2-} (mg/L)	1165	1192.5
Silica (mg/L as SiO_2)	41.4	36.4
PO_4^{3-} (mg/L)	0.23	0.16



Results: 0.5g/L Fe_3O_4 for Brownsville Water

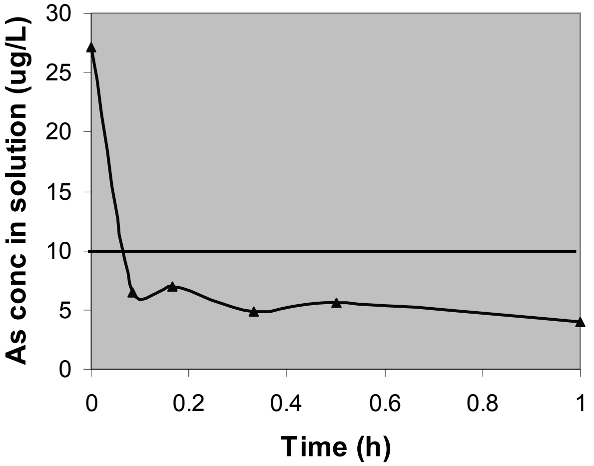
Results – Field Tests: Well #12

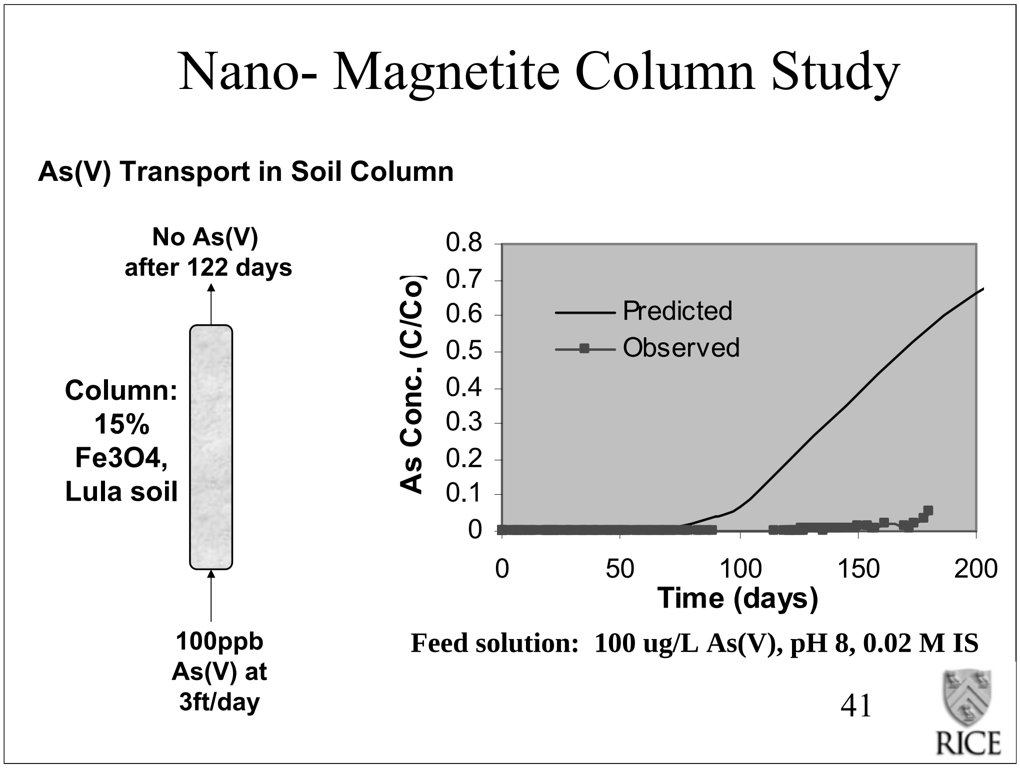
0.1g/L Fe_3O_4 and varying conc. of Fe^{3+}



Results – Field Tests: Well #8

0.1g/L Fe_3O_4 and 5mg/L Fe^{3+}





Nano- Magnetite Column Study

As(V) Transport in Soil Column

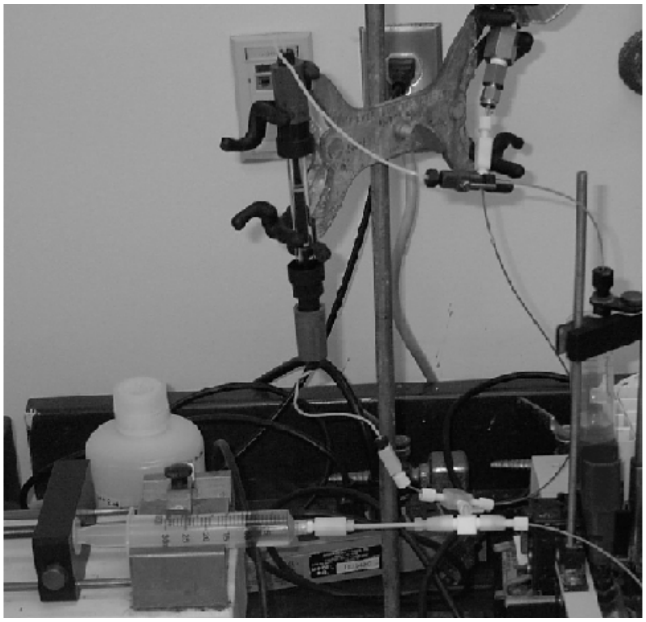
No As(V) after 122 days

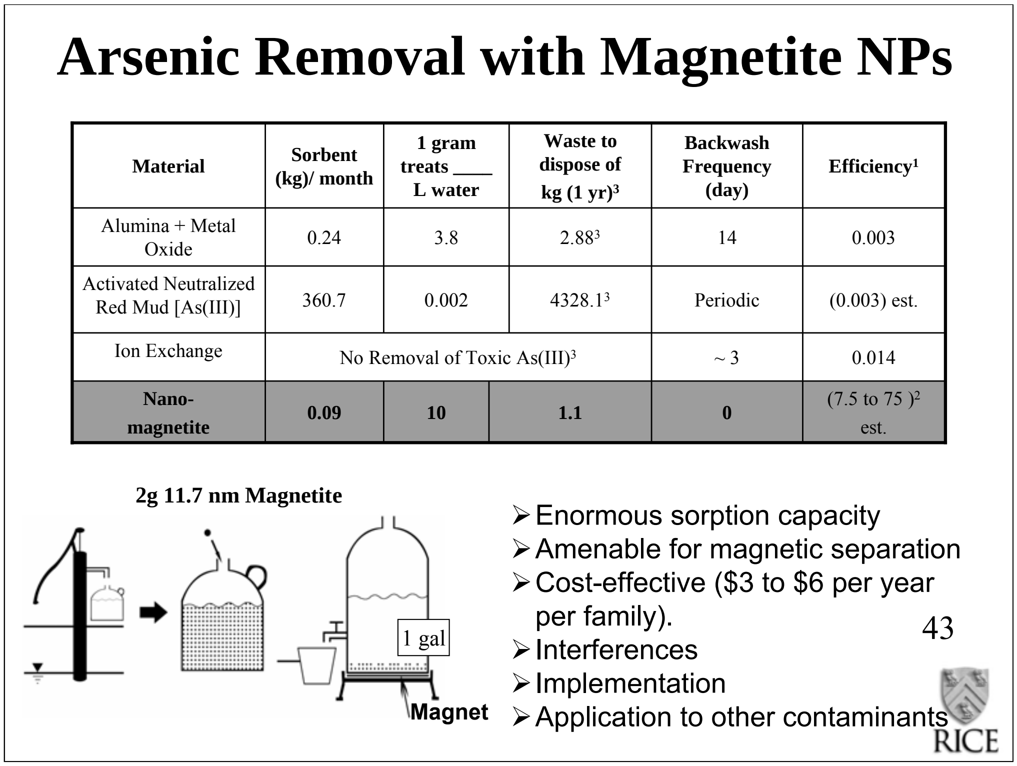
Column: 15% Fe3O4, Lula soil

100ppb As(V) at 3ft/day

Feed solution: 100 ug/L As(V), pH 8, 0.02 M IS

Nano-magnetite Column





Arsenic Removal with Magnetite NPs

Material	Sorbent (kg)/ month	1 gram treats ____ L water	Waste to dispose of kg (1 yr)[3]	Backwash Frequency (day)	Efficiency[1]
Alumina + Metal Oxide	0.24	3.8	2.88[3]	14	0.003
Activated Neutralized Red Mud [As(III)]	360.7	0.002	4328.1[3]	Periodic	(0.003) est.
Ion Exchange	No Removal of Toxic As(III)[3]			~ 3	0.014
Nano-magnetite	**0.09**	**10**	**1.1**	**0**	(7.5 to 75)[2] est.

2g 11.7 nm Magnetite

- ➢ Enormous sorption capacity
- ➢ Amenable for magnetic separation
- ➢ Cost-effective ($3 to $6 per year per family).
- ➢ Interferences
- ➢ Implementation
- ➢ Application to other contaminants

Lets start with some applications.

As you know, Mason and Vicki are working to develop a novel approach to remove arsenic from drinking water using magnetite nanoparticles that are not only superior sorbents with minimal bleed-off potential, but are also amenable for magnetic separation.

This could therefore result in a cost-effective treatment system that could be used at the household-level to alleviate arsenic poisoning in many areas of the world that. Clorox who makes Britta filters has shown a lot of interest.

Conclusions

- Sulfate, organic matter, silica, bicarbonate have intermediate to large effect on adsorption
- Ca, Mg, K, Trace Metals have little to insignificant effect on adsorption
- Arsenic concentration < 10µg/L in a minute by adding iron salts and magnetite nanoparticles
- Successful field test
- Inhibition of arsenic removal and iron oxide formation in the presence of citrate

Acknowledgement

- Funding of this project is from the Center for Biological and Environmental Nanotechnology (CBEN) at Rice University, NSF, and EPA STAR nanotechnology grant

Functionalized Nanoporous Ceramic Sorbents for Removal of Mercury & other Contaminants

Shas Mattigod

Pacific Northwest National Laboratory
Richland, Washington

NIEHS/EPA Nanotechnology & Superfund
February 13, 2007

Functionalized Ceramic Nanoporous Sorbents

1. Introduction

2. Nanoporous Sorbents
    - Substrate Synthesis
    - Monolayer Functionalization process (SAMMS)
    - Host design for molecular recognition

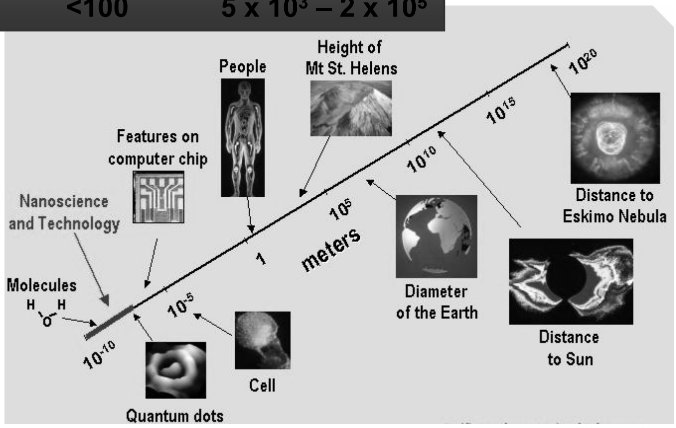
3. Performance – SAMMS (Self Assembled Monolayers on Mesoporous Supports)
    - thiol SAMMS
    - Cu-EDA SAMMS
    - HOPO SAMMS

4. Treatment costs & waste form stability

5. Potential Applications & Commercialization

Nanoscience & Technology

	Nanoparticles	Nanoporous Materials
Surface Area (m^2/g)	10 - 100	600 - 1000
Pore Size (nm)	--	2 - 40
Particle Size (nm)	<100	$5 \times 10^3 – 2 \times 10^5$



Why Nanoporous Sorbents?

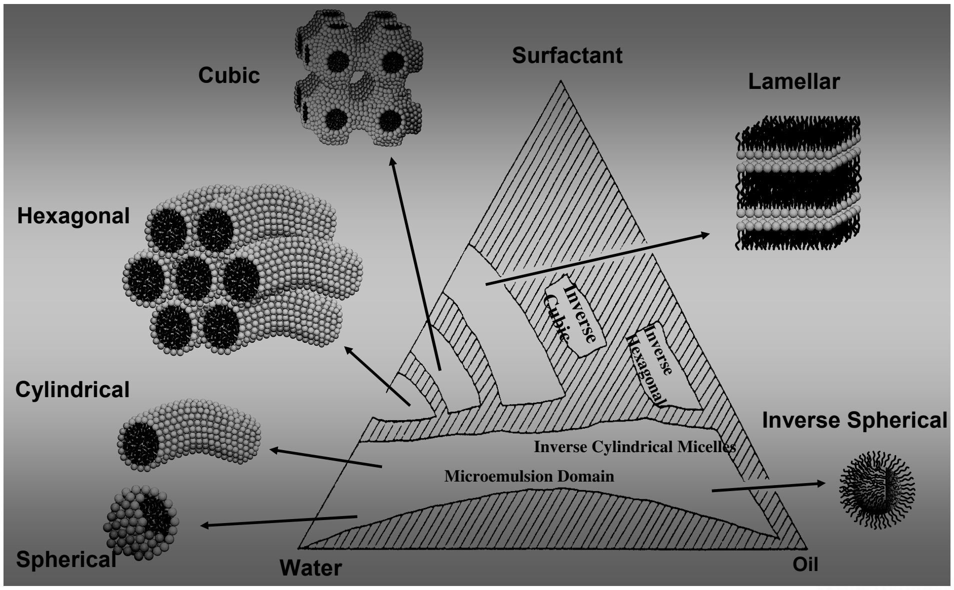
Technology Need
- **ppb – ppt treatment levels**

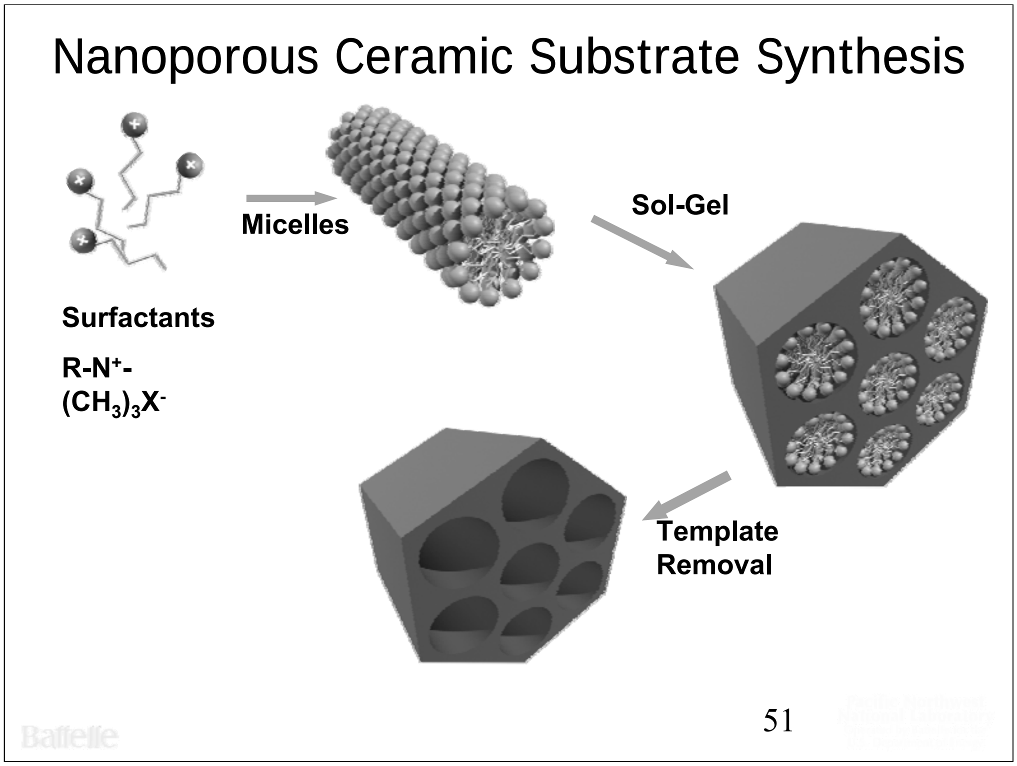
Large surface area - controlled pore size
- **Dense packed functionality**
- **High contaminant loading**
- **Enhanced adsorption kinetics**

Particle size: 5 – 120 µm
- **Silt and sand size material (non toxic)**
- **Easier to fabricate engineered forms (vs nanoparticles)**

Silica based substrate
- **Inexpensive to produce**
- **Environmentally compatible & stable**

Surfactant-Oil-Water Phase Diagram: Template for Nanoporous Silica Substrate Synthesis





Nanoporous Ceramic Substrate Synthesis

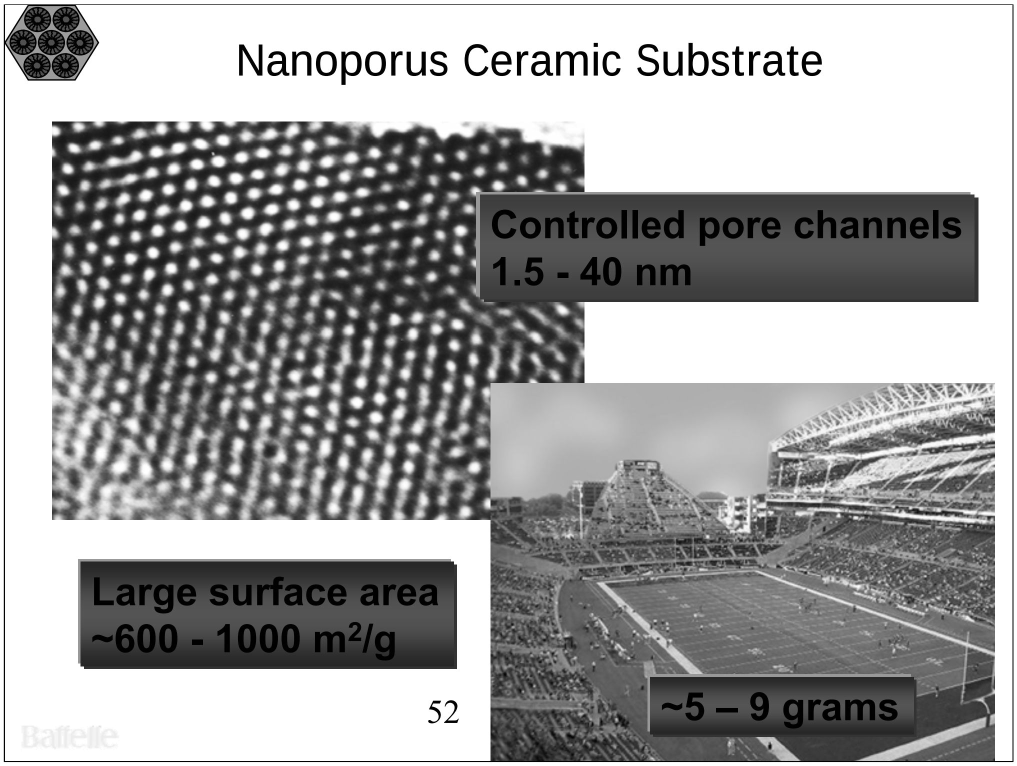
Surfactants

R-N^+-
$(CH_3)_3X^-$

Micelles

Sol-Gel

Template Removal

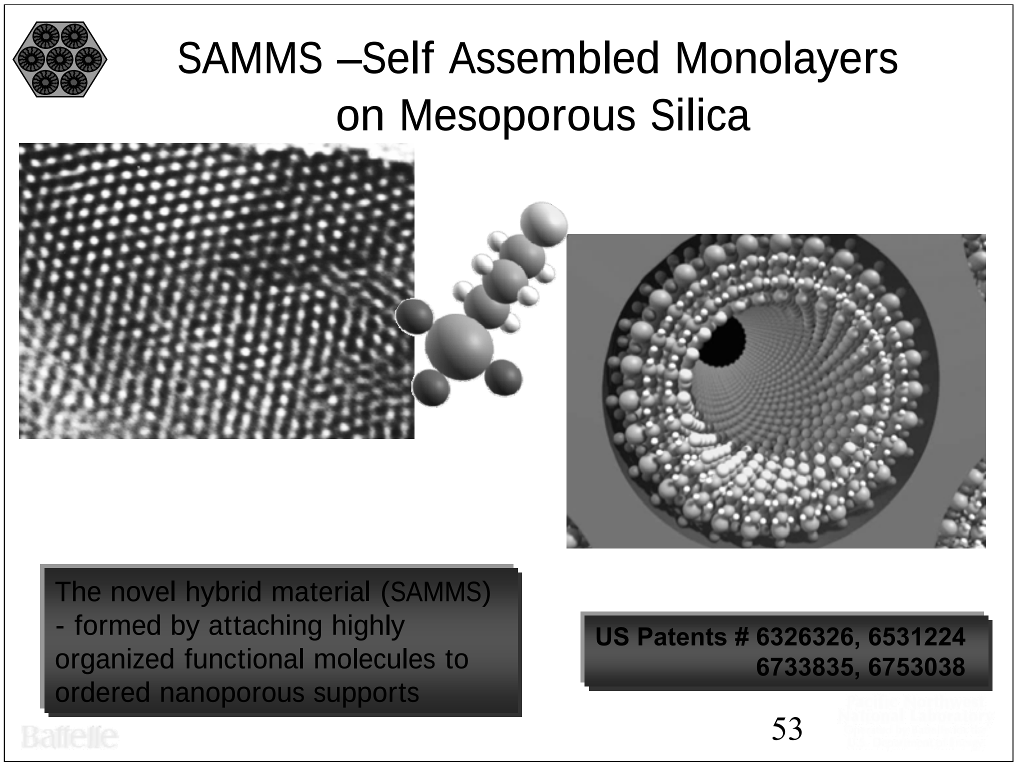


Nanoporus Ceramic Substrate

Controlled pore channels
1.5 - 40 nm

Large surface area
~600 - 1000 m^2/g

~5 – 9 grams



SAMMS –Self Assembled Monolayers on Mesoporous Silica

The novel hybrid material (SAMMS) - formed by attaching highly organized functional molecules to ordered nanoporous supports

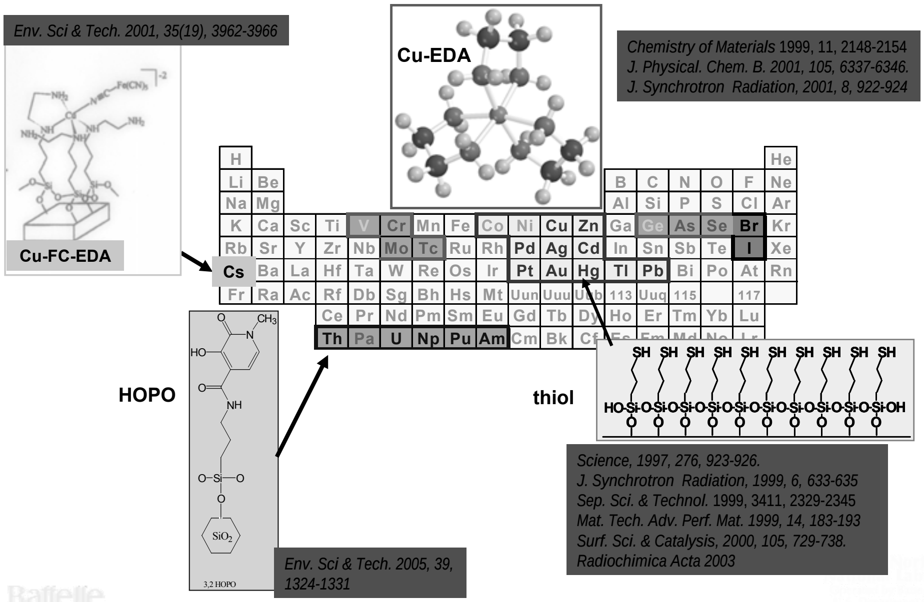
US Patents # 6326326, 6531224 6733835, 6753038

SAMMS -Tailored Surface Chemistry

Host Design for Molecular Recognition

Env. Sci & Tech. 2001, 35(19), 3962-3966

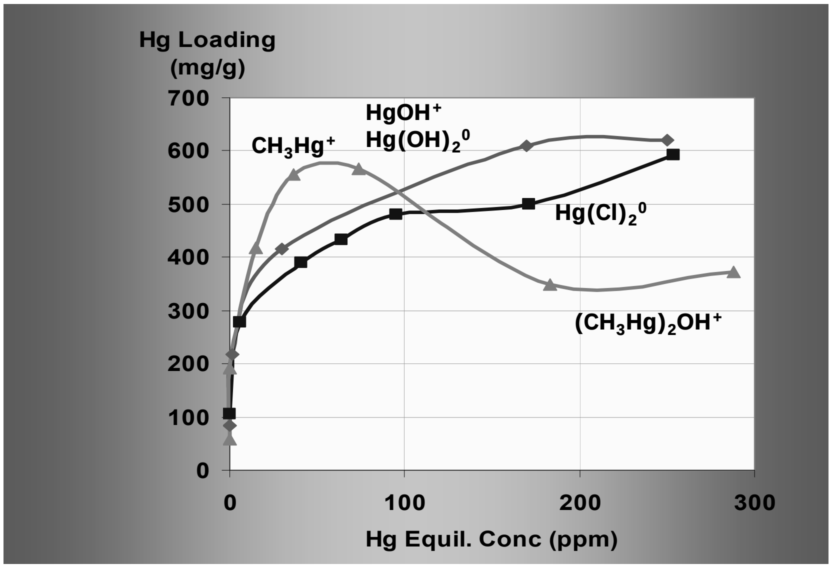
Chemistry of Materials 1999, 11, 2148-2154
J. Physical. Chem. B. 2001, 105, 6337-6346.
J. Synchrotron Radiation, 2001, 8, 922-924



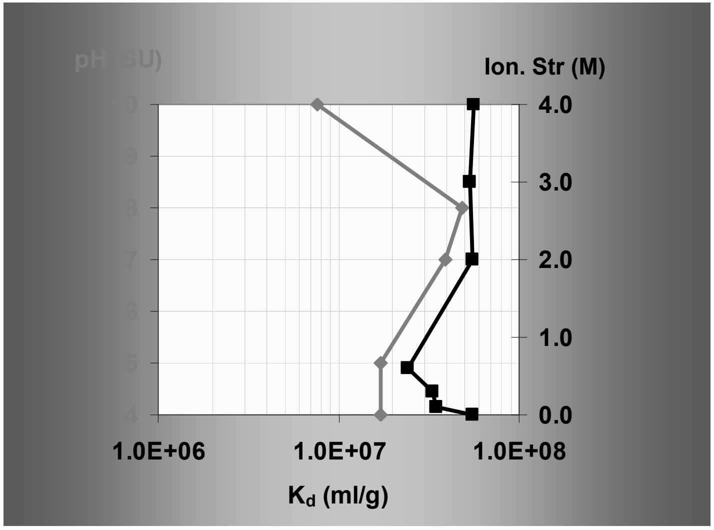
Science, 1997, 276, 923-926.
J. Synchrotron Radiation, 1999, 6, 633-635
Sep. Sci. & Technol. 1999, 3411, 2329-2345
Mat. Tech. Adv. Perf. Mat. 1999, 14, 183-193
Surf. Sci. & Catalysis, 2000, 105, 729-738.
Radiochimica Acta 2003

Env. Sci & Tech. 2005, 39, 1324-1331

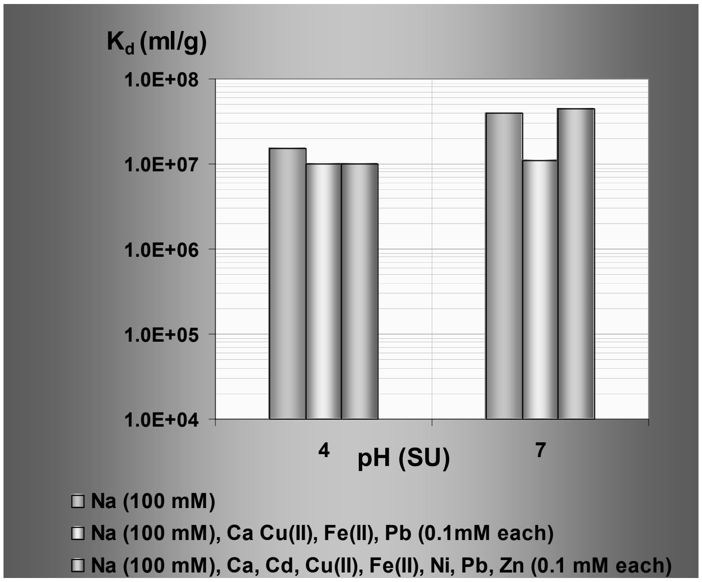
Thiol-SAMMS^{TM} Adsorption of Hg Species

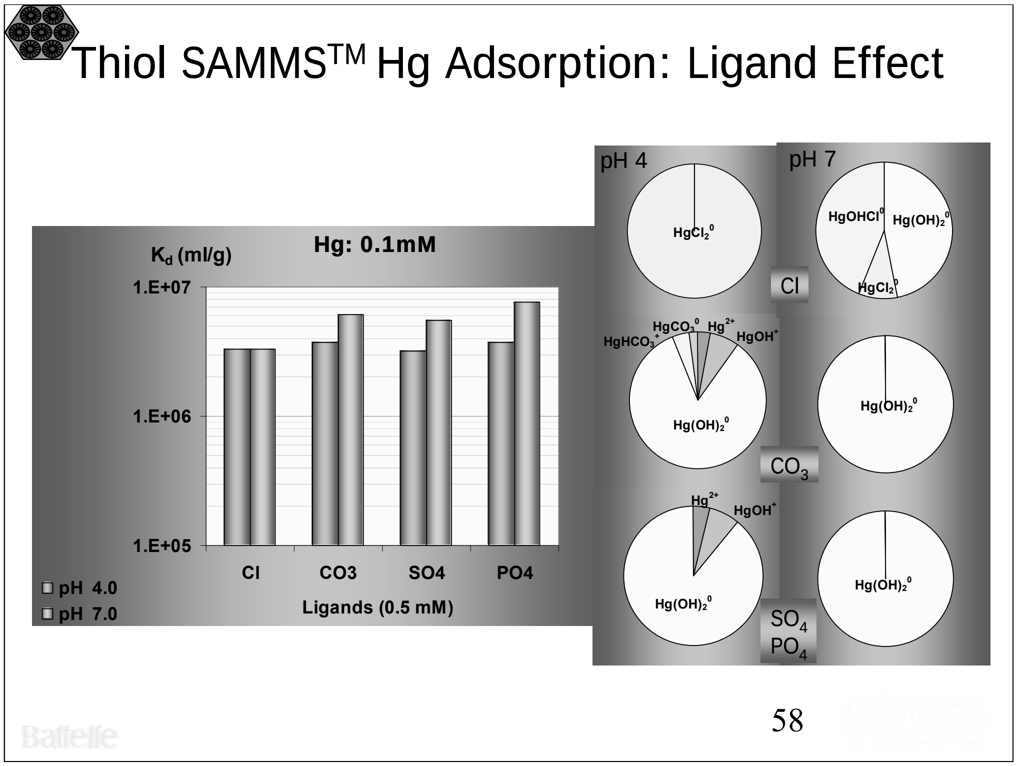


SAMMS^{TM} – Hg Adsorption
Ionic Strength & pH Effects



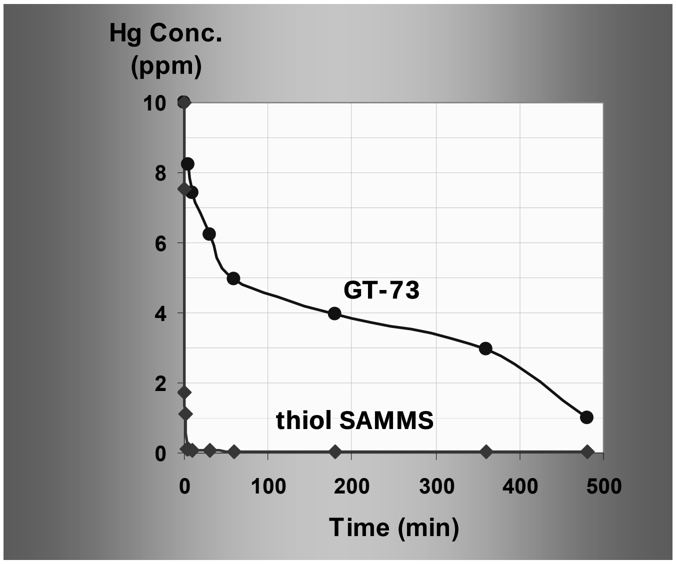
Thiol SAMMS^{TM} Hg Adsorption: Cation Effects



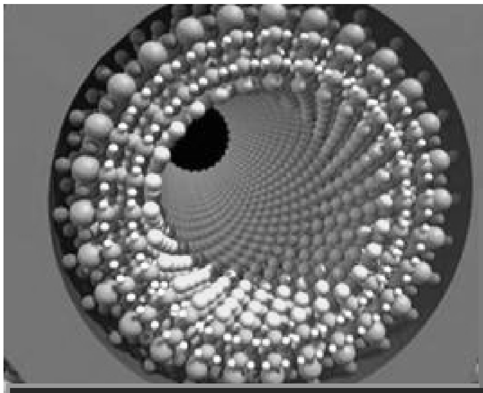


Thiol SAMMS^{TM} Hg Adsorption: Ligand Effect

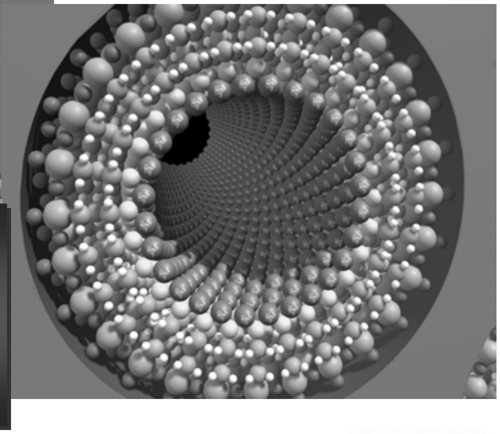
Thiol SAMMS^{TM} - Hg Adsorption Kinetics



Bonding Mechanism: thiol – Hg^{2+} Ion

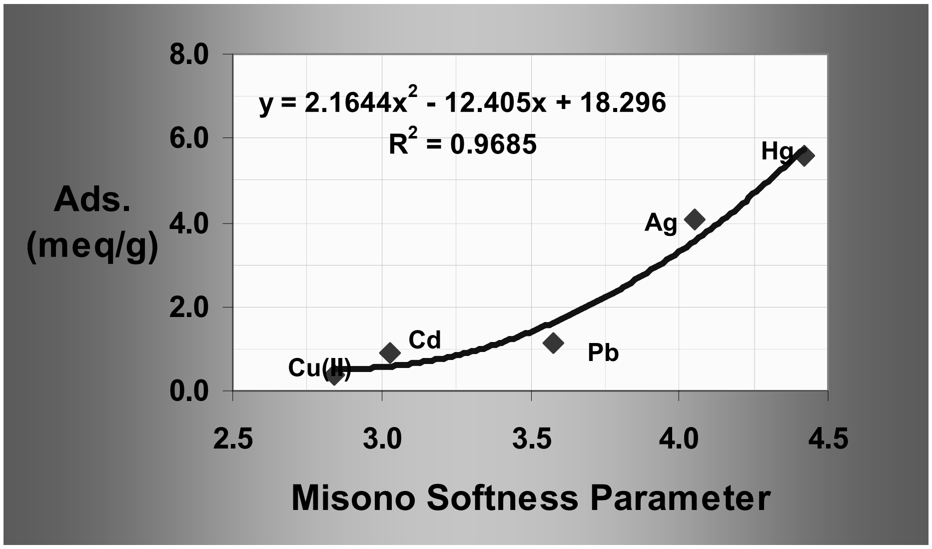


A graphic of self-assembled monolayer within the nanopores of the silica substrate The monolayer consists of tris-methoxy mercaptopropylsilane molecules crosslinked and anchored into the pore surface. The yellow spheres represent the thiol functionality



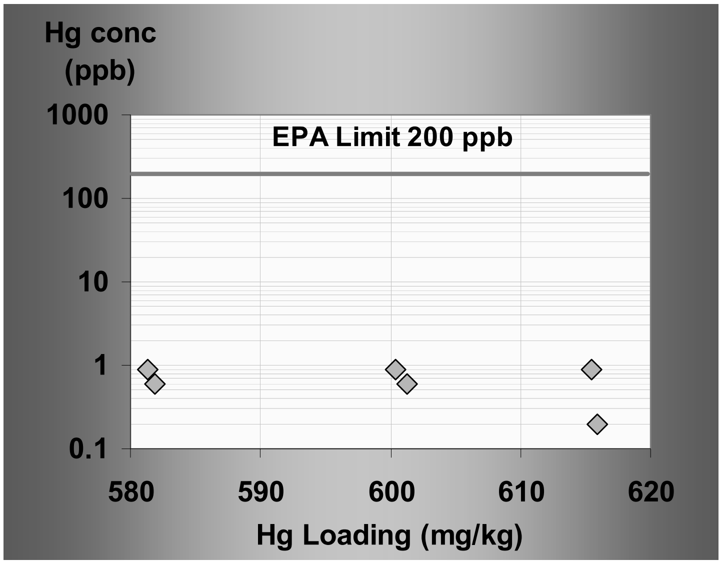
Bidentate bonding of Hg to thiol functionalities
Bond Length: 2.39 – 2.41 Å
J. Sync. Radiation 1999, 6, 633 - 635

Adsorption vs MSP - thiol SAMMS

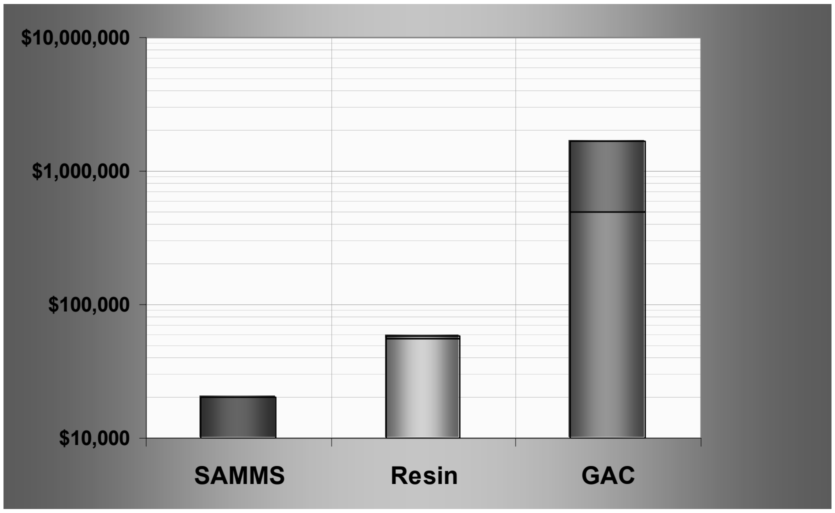


INORG. CHEM. COMM (1): 96-98 2006

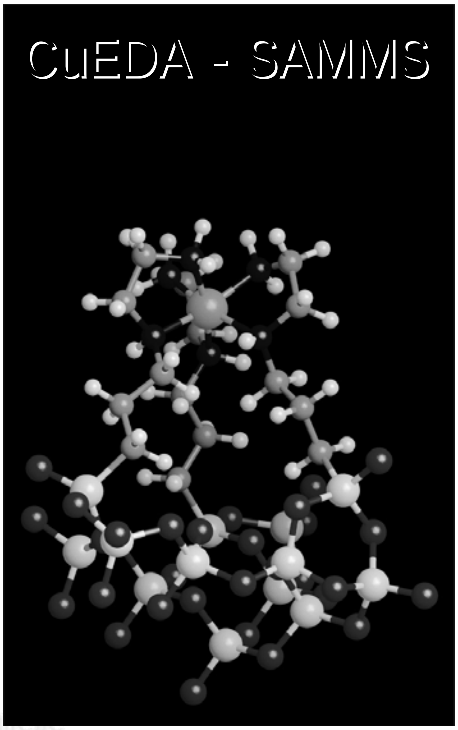
Thiol-SAMMS – Waste Form Stability
TCLP Test

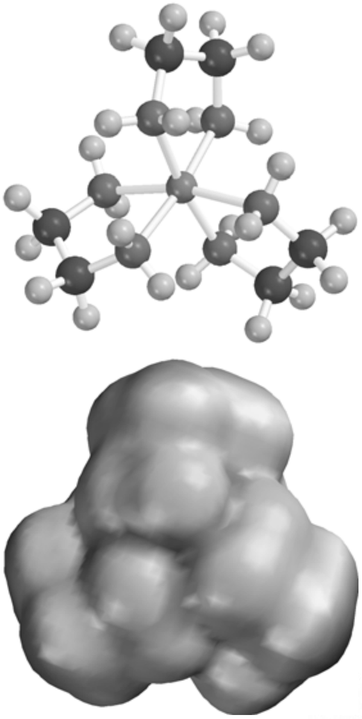


Mercury Removal
Preliminary Cost Comparison

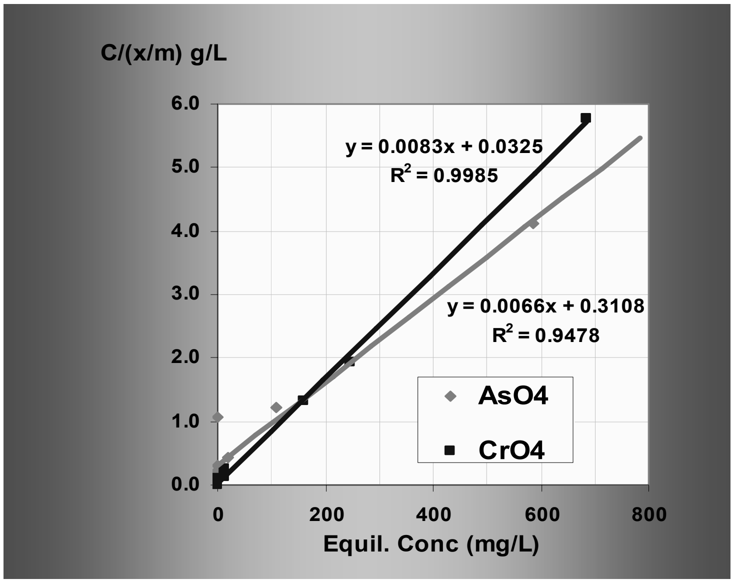


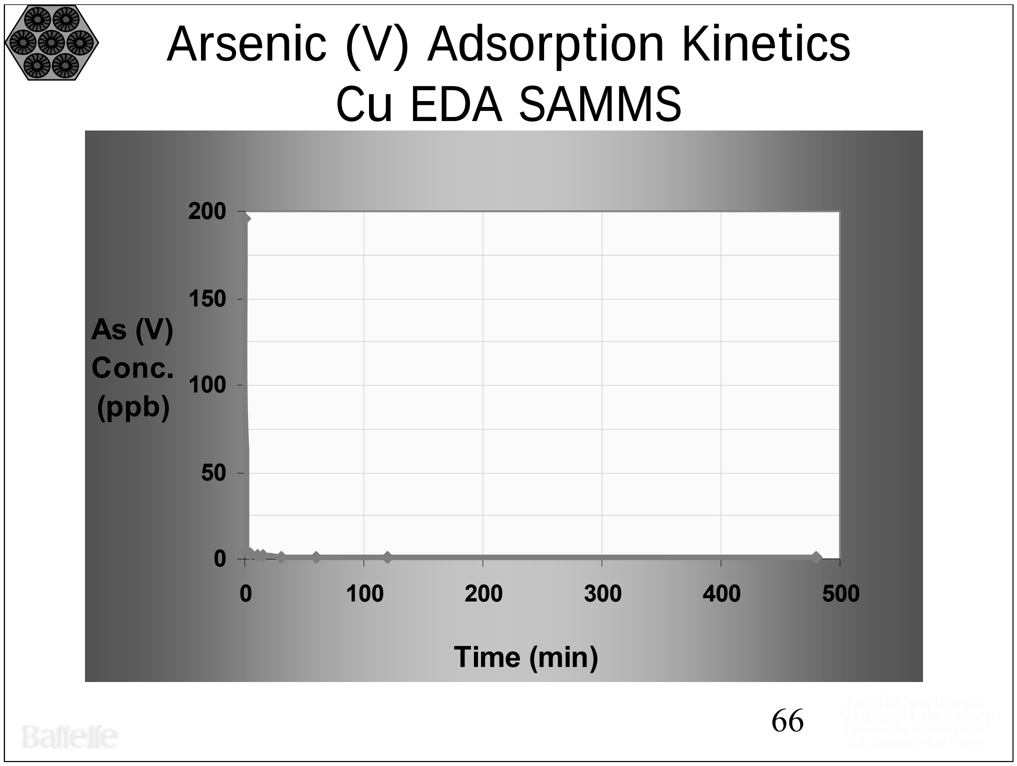
CuEDA - SAMMS



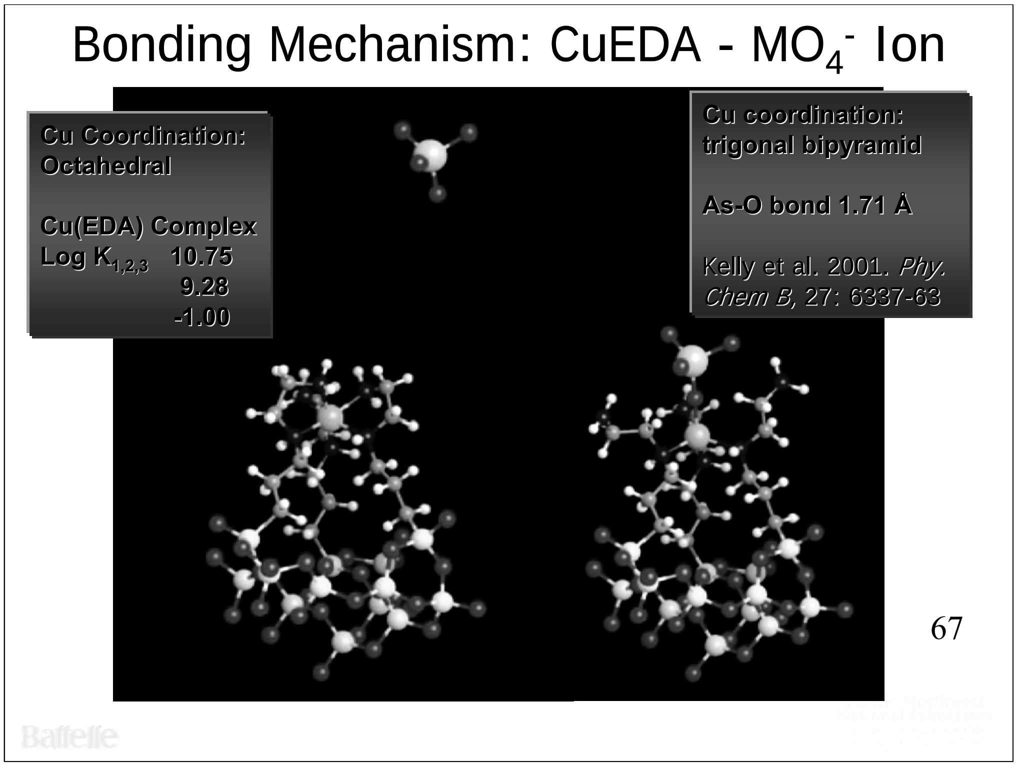


Adsorption - CrO_4 & AsO_4 CuEDA-SAMMS





Arsenic (V) Adsorption Kinetics
Cu EDA SAMMS



Bonding Mechanism: CuEDA - MO_4^- Ion

Cu Coordination:
Octahedral

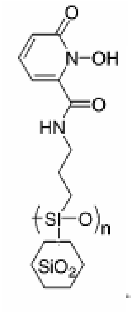
Cu(EDA) Complex
Log $K_{1,2,3}$ 10.75
9.28
-1.00

Cu coordination:
trigonal bipyramid

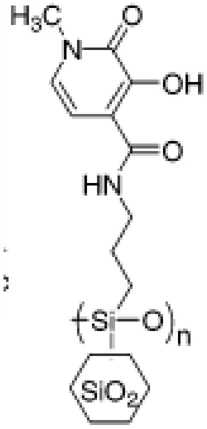
As-O bond 1.71 Å

Kelly et al. 2001. *Phy. Chem B*, 27: 6337-63

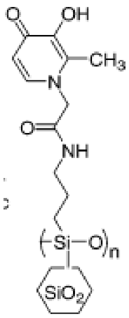
Actinide Binding SAMMS



1,2-HOPO SAMMS



3,2-HOPO SAMMS



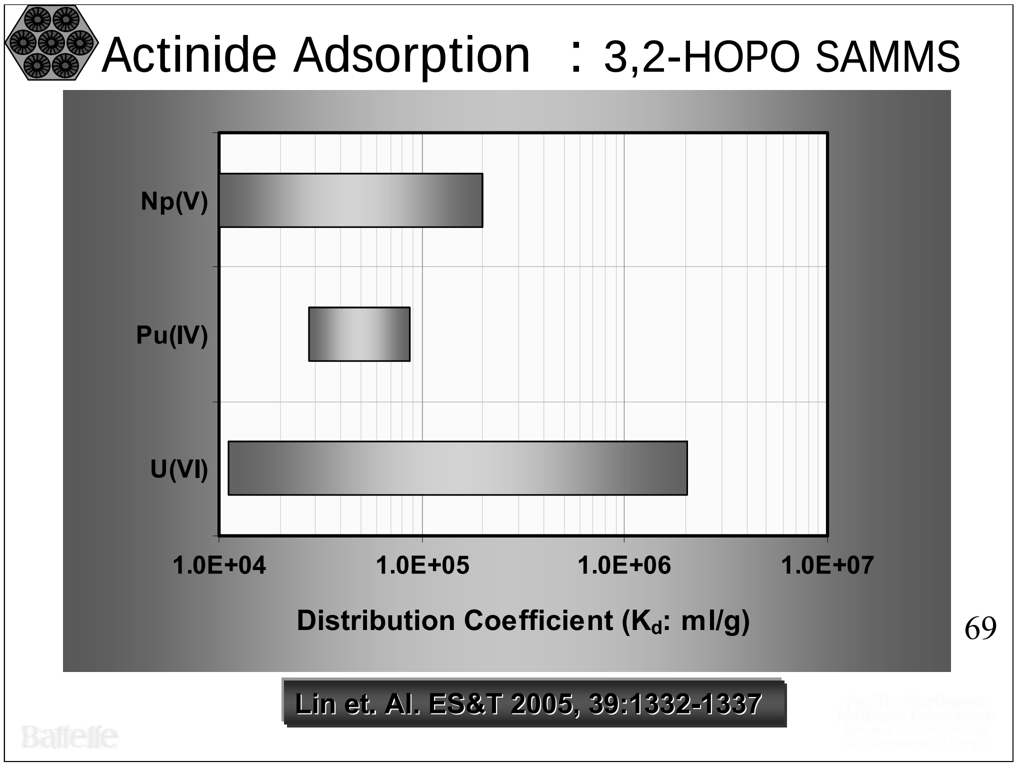
3,4-HOPO SAMMS

Need for actinide separation from nuclear wastes

Hydroxypyridonates (HOPO) - selectively bind actinides

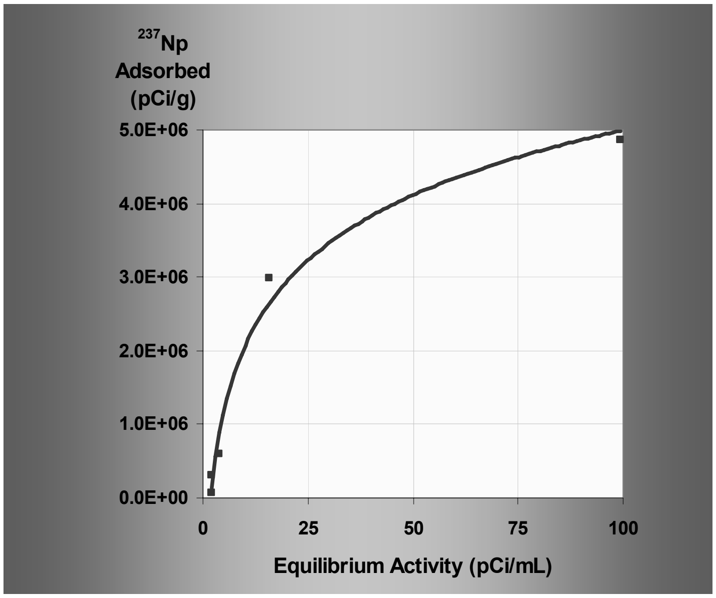
HOPO SAMMS – superior class of actinide sorbents

Actinide Adsorption : 3,2-HOPO SAMMS

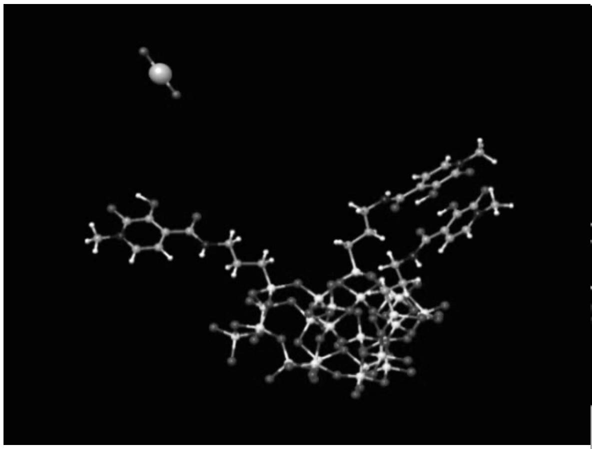


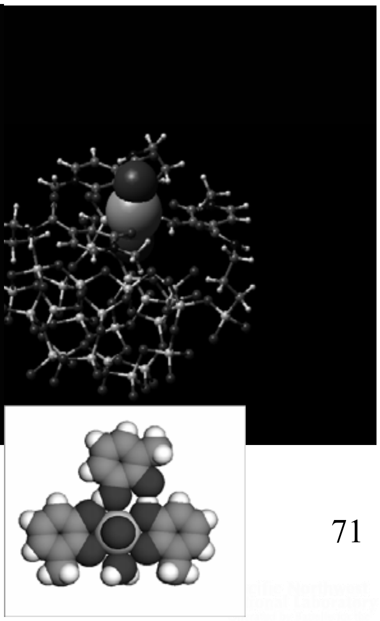
Lin et. Al. ES&T 2005, 39:1332-1337

^{237}Np Adsorption – HOPO SAMMS

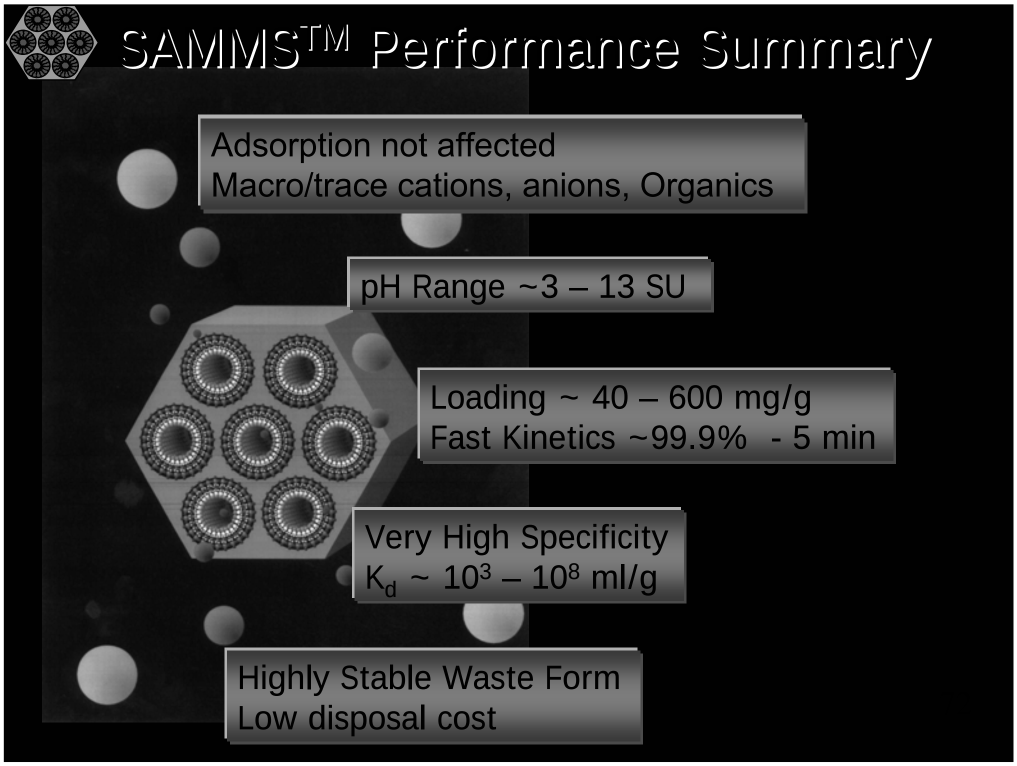


Molecular Model - HOPO SAMMS binding NpO_2^+





Vorpagel 2004
LANL2ZP ECP Basis Set Modeling



SAMMS$^{\mathrm{TM}}$ Performance Summary

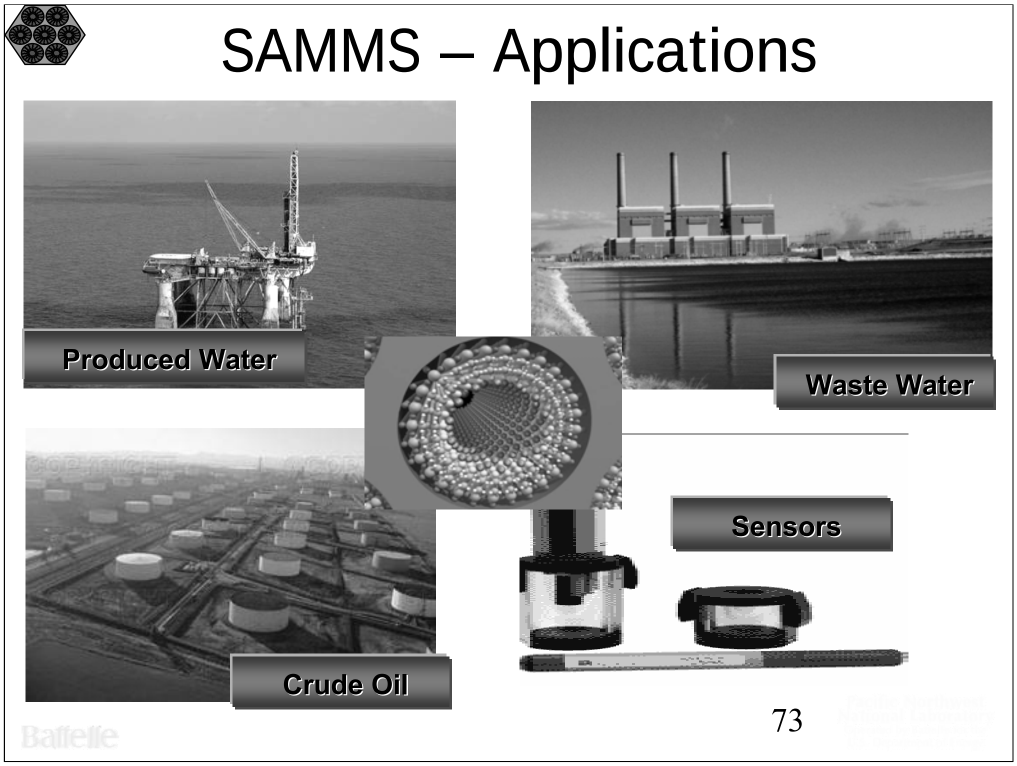
Adsorption not affected
Macro/trace cations, anions, Organics

pH Range ~3 – 13 SU

Loading ~ 40 – 600 mg/g
Fast Kinetics ~99.9% - 5 min

Very High Specificity
$K_d \sim 10^3 – 10^8$ ml/g

Highly Stable Waste Form
Low disposal cost



SAMMS – Applications

Produced Water

Waste Water

Sensors

Crude Oil

SAMMS^{TM} Commercialization

SES Steward Environmental Solutions

SAMMS patents Licencee
Chattanooga, TN

50 L Batch Production – Green Chemistry
Thiol functionalization using supercritical CO_2

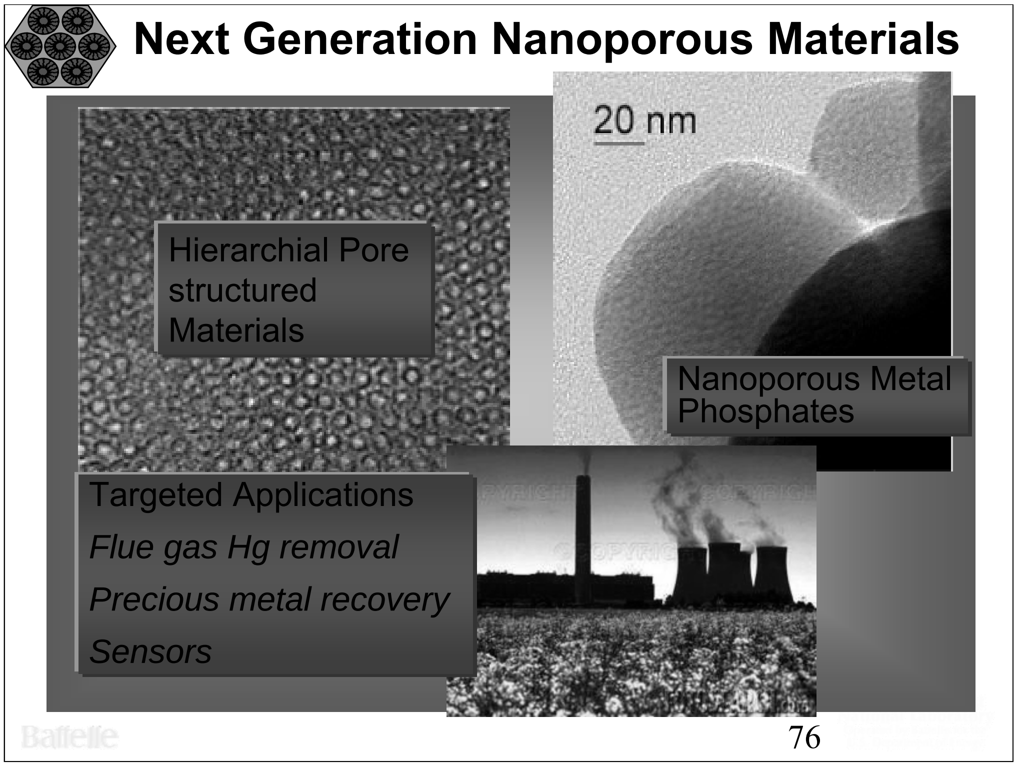
Federal Laboratory Consortium FLC for Technology Transfer

Battelle

SAMMS^{TM} Commercialization

Engineered Forms
Perry Equipment Corporation
Mineral Wells, TX

Produced water
Natural Gas
Gas Condensates
Crude Oil



Next Generation Nanoporous Materials

Hierarchial Pore structured Materials

Nanoporous Metal Phosphates

Targeted Applications

- *Flue gas Hg removal*
- *Precious metal recovery*
- *Sensors*

Research Support

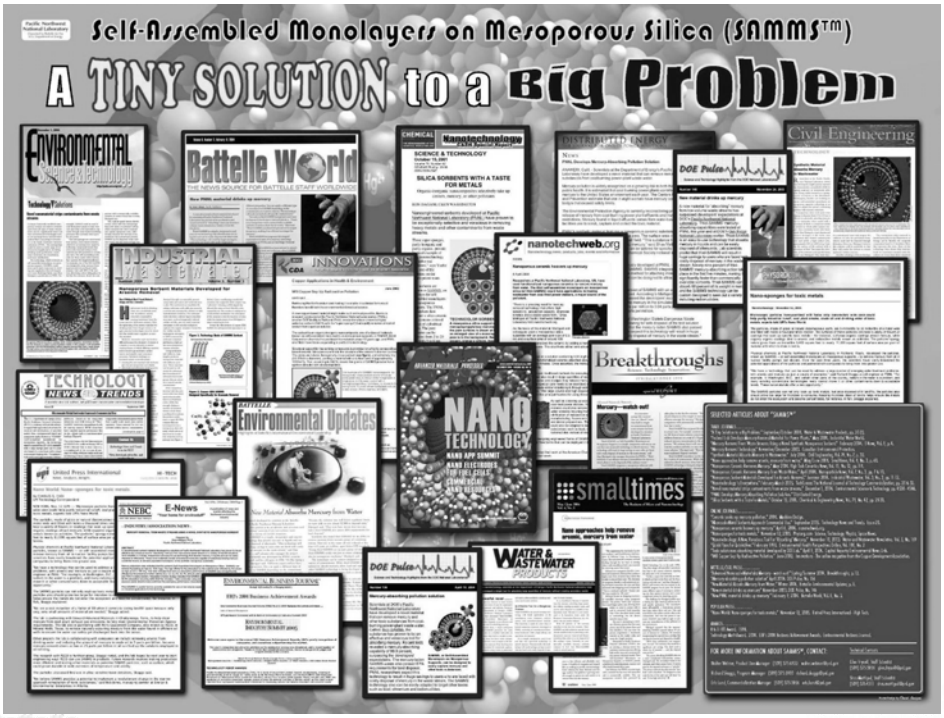
United States Department of Energy

Battelle

Pacific Northwest National Laboratory

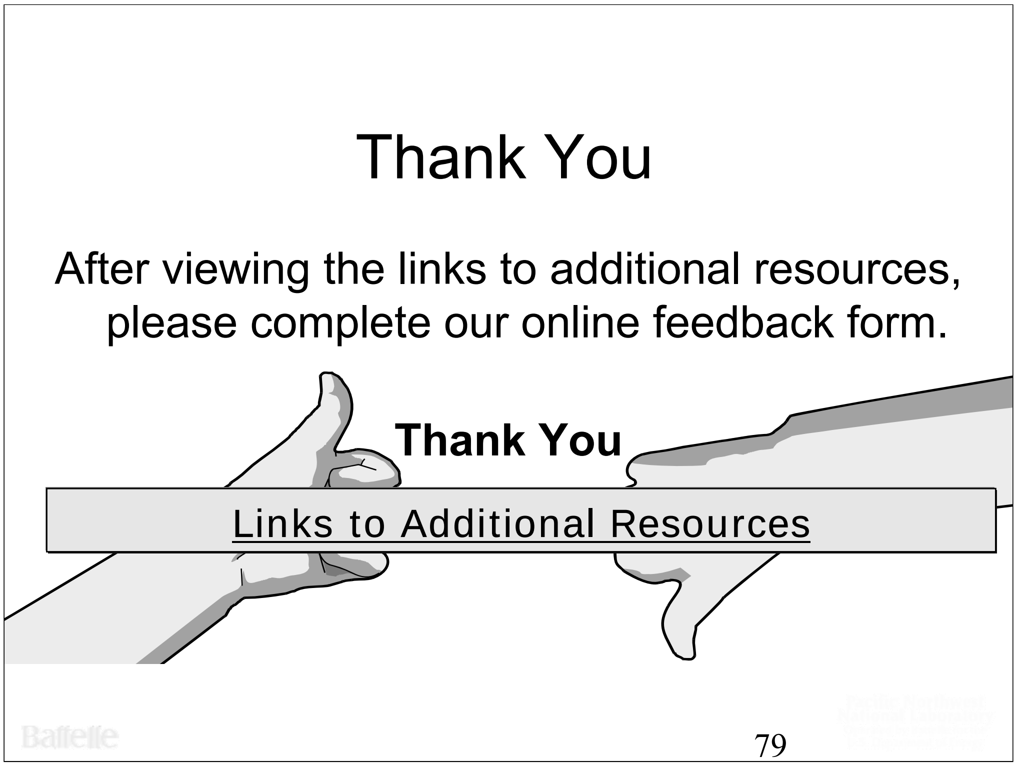
Perry Equipment Corporation

Steward Environmental Solutions



Self-Assembled Monolayers on Mesoporous Silica (SAMMS™)

A TINY SOLUTION to a Big Problem



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