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Small Scale Laboratory Studies Of Flow And Transport Phenomena In Pores And Fractures: Phase II

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Abstract

Small scale laboratory experiments, equipped with an ability to actually observe behavior on the pore level using microscopy, provide an economical and easily understood scientific tool to help us validate concepts and assumptions about the transport of contaminants, and offers the propensity to discover heretofore unrecognized phenomena or behavior. The main technique employs etched glass micromodels, composed of two etched glass plates, sintered together, to form a two dimensional network of three dimensional pores. Flow and transport behavior is observed on a pore or pore network level, and recorded on film and video tape. This technique is coupled with related column studies. Specifically we're examining multiphase flow behavior of relevance, for example, to liquid–liquid mass transfer (solubilization of capillary trapped organic liquids); liquid–gas mass transfer (in situ volatilization); colloid movement, attachment and detachment in the presence of fluid–fluid interfaces; bacteria colonization and motility in porous systems; and heterogeneity effects on multi–phase flow, colloid movement and bacteria behavior.

Progress Summary: (9/1/92 - 4/1/92)

This is the first year of a new project. It continues research that was initiated in an earlier project (Phase I) also funded by the Subsurface Science Project. In the reporting period work focused on three themes: 1) wettability effects on multiphase flow behavior, 2) colloid and bacteria transport in the vicinity of multi–fluid phase (mostly air–water) interfaces, and 3) bacteria colonization near a pool of a non–aqueous phase liquid. The work is described below. Over the winter work in area 1 has mainly concentrated on data analysis and preliminary paper drafts, area 1 has mainly focused on writing and submitting papers for journal articles, while area 3 has focused on getting the experiments up and running. A full record of papers and presentations is attached.

Wettability

Recently the wettability studies have examined multiphase fluid behavior in the presence of intermediate wet surfaces. For example, it is often assumed that pore pressure-saturation curves for one fluid pair can be scaled to another fluid pair by the capillary tube equation, through application of the appropriate interfacial tensions. If the surface chemistry is altered by adsorption (or some other process) the contact angle, another parameter in the capillary tube equation, also changes. Scaling is usually assumed to apply here too. Working with glass beads we studied the scaling of pore pressure-saturation curves for intermediate wet surfaces. The surfaces were created by treating the beads with methyltrimethoxysilane. Compared to strongly hydrophilic or hydrophobic treatments, the intermediate bead packs did not scale with contact angle (Burck et. al, 1992). There are several possible explanations for the failure of scaling in the intermediate range, including surface roughness and geometric effects (eg, adhesion of more wetting fluid in pore corners and wedges). Applying classical corrections for these two effects our Subsurface Science Program colleagues at the University of Michigan group found that they were able to scale the pore-pressure saturation curves for water-xylene in the presence of a surface altering surfactant CTAB (cetyltrimethylammonium bromide) (Demond et. al, 1992). We tested these and other geometric scaling corrections on our results. In no case were we able to significantly improve the scaling for intermediate wet conditions. It appears that scaling in the intermediate wet range may not work, or at best may require additional corrections.

This phase of the work will be complete with the submittal of several manuscripts to journals this summer. Additonal wettability work will be focused on supporting the joint wettability study of the Multiphase Fluid Flow Subprogram.

Colloids

The colloid work with multi-fluid interfaces has recently focused on the behavior of latex particles and bacteria as colloids. Previously we've examined iron and titanium oxides, clay minerals, and latex particles (Wan and Wilson, 1992a, 1992b). In this recent work we focused mainly on the hypotheses that (1) particle hydrophobicity plays an important role in the attraction of particles to fluid-fluid interfaces (Wan and Wilson, 1993a, 1993b), and (2) that while in a resting state bacteria behave much like inert particles with a similar surface chemistry (Wan et al., 1993. Experiments in micromodels used hydrophilic and hydrophobic latex particles (measured by both contact angles and surface charge density), and four bacteria strains of varying hydrophobicity (Wan and Wilson, 1993a; Wan et al., 1993). Column experiments used similar latex particles and two bacteria strains (Pseudomonas cepacia 3N3A and Arthrobacter sp. S-139) in a packed quartz bed (Wan and Wilson, 1993b; Wan et al., 1993). The bacteria were in a resting state. The column experiments were run with 0%, 16%, and 46% trapped gas as a second phase. The first of these represents water saturated conditions, and acts as a control. The second represents a non-wetting phase at residual saturation. The last represents a vadose zone situation with continuously connected gas and water phases. For each combination the column experiments were repeated five times. The results and interpretation are given in a series of papers (Wan and Wilson, 1993a, 1993b; Wan et al., 1993) previously submitted to the SSP as project documents. A copy of the last of these papers is attached.

For abiotic colloids we've observed results in single phase flow experiments that are consistent with DLVO theory (accounting for electrostatic and van der Waals forces), but also demonstrate the effects of hydrophobic (structural) and capillary forces attracting and holding particles at fluid-fluid interfaces (Wan and Wilson, 1992a,b; 1993a,b). Capillary forces are particularly important in holding particles on the fluid-fluid interface once they become attached (Wan and Wilson, 1993a). If a particle with any finite contact angle touches an interface it will attach because of a capillary force. This same force is strong enough to prevent it from detaching from the fluid-fluid interface. Moving fluid-fluid interfaces, such as during wetting and drying cycle can pick up particles and redistribute them (Wan and Wilson, 1992a,b, 1993a). This phenomenon may play an important role in colloid and bacteria migration in the vadose zone.

We've observed that in a resting state the bacteria behave essentially the same as the latex particles (Wan et al., 1993). Ron Harvey of the USGS has observed differential movement of latex beads and bacteria in laboratory experiments and at Cape Cod. Our experiments clearly show that that his observation depends on experimental conditions. A copy of Wan et al. (1993) is attached.

The attraction of particles and bacteria to fluid-fluid interfaces is substantially greater for the more hydrophobic particles or bacteria, resulting a greater lag and attenuation of movement (Wan and Wilson, 1993b; Wan et al., 1993). The more hydrophobic the particle or bacterium the stronger the force. We've calculated the force for several geometries.

In reviewing our work several people have suggested that the retention of particles by gas bubbles may explain some of the discrepancies in standard single phase flow colloid experiments for sticking efficiency. For example, with hydrophilliv latex particles the 16% residual air saturation columns had only 91% recovery, compared to 99% for the saturated column. If some of the historical single phase flow experiments contained tapped gas they could easily lead to a miscalculated sticking efficiency (Wan and Wilson, 1993b). In reviewing the literature it is not clear that investigators have been aware of this issue, or that they took precautions to insure the absence of trapped gas.

This work is largely complete, but below we propose additional work with colloids and bacteria in the vicinity of non-aqueous liquid - water interfaces.

<u>Bacteria colonization</u>

Bruce Rittman at the University of Illinois (now at Northwestern University) has been studying the bacteria enhance solubilization of a pool of non-aqueous phase liquid in flowing groundwater. We've obtained a pure culture of his toluene degrading bacteria, <u>Pseudomonas putida</u>, and are conducting parallel experiments in etched glass micromodels. The geometry of this experiment is pictured in Figure 1 The pool of toluene phase dissolves into the passing groundwater. The idea is that bacteria, using the dissolved non-aqueous phase as a source of carbon, lower its concentration. With a lower dissolved concentration the rate of mass transfer, and thus the rate of dissolution increases. To study this hypothesis the Rittman group has developed mathematical and sand box models of the geometry shown in the figure. <u>Pseudomonas putida</u> finds high concentrations of toluene toxic. Balancing the toxic effects and the car-

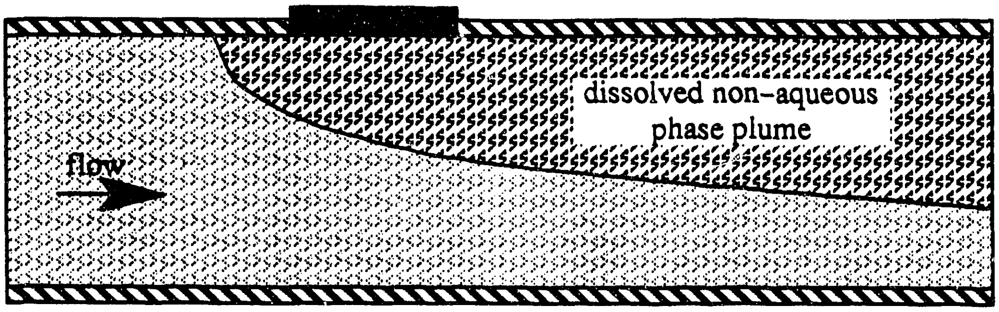

FIGURE 1 Conceptual view of Rittman dissolution experiment

bon source it should establish itself somewhere in a mechanical disperion dominated boundary layer region where toluene concentrations are finite but not too high. We have reproduced their geometry in a micromodel, in order to study this spatial pattern of bacteria colonization near the pool. The toluene pool is contained in the very special pore at the top of the model. The micromodel is currently under testing and refinement. Like the Illinois sandbox, we are running a variety of abiotic experiments to fully understand the flow field and toluene plume before introducing the bacteria. We are also studying alternative methods to enhance visualization of the bacteria, including the use of fluorescent stains and anti-bodies.

This work is schedule to be completed by the end of summer, with a manuscript submitted to a journal by early fall. Additonal work on these lines is proposed below, and will be conducted in closer collaboration with the colloid experiments.

Proposed Research (9/1/93 - 8/31/94)

Background

The second year work will focus on the behavior of colloids and bacteria in the vicinity of interfaces between water and non-aqueous phase liquids. It will be continued into the third year.

Most of our previous work with inorganic colloids (polystyrene latex, iron oxide, clay minerals, silica) and bacteria (Pseudomonas cepacia 3N3A and Arthrobacter sp. S-139) has been with air and water. These air-water experiments demonstrated that (1) particle or bacteria hydrophobicity plays an important role in the attraction of particles to fluid-fluid interfaces due to hydrophobic forces (Wan and Wilson, 1992a, 1993b) (2) their retention on the interface is mainly due to capillary forces (Wan and Wilson, 1993a), and (3) that while in a resting state bacteria behave much like inert particles with a similar surface chemistry (Wan and Wilson, 1992b, 1993; Wan et al, 1993). We earlier performed some colloid experiments with a non-aqueous phase liquids (NAPL) and water, in which clay minerals coated the solid surfaces. The NAPL water interface appeared to collect some of the minerals off of the solids, by capillary forces, and pack them into pore throats. This restructured the pore space and dramatically increased the residual NAPL saturation (Mace and Wilson, 1992). These experiments indicate that the same interfacial forces encountered at the air-water interface are active at the NAPL-water interface. We also conducted some preliminary experiments on the colonization of bacteria (Arth obacter sp., ZAL001, Subsurface Microbiology Culture Collection, Florida State University) in the vicinity of an alkane (isooctane) NAPL blob. The alkane was a secondary substrate. These experiments indicated a preference for these bacteria to colonize in the vicinity of the blob and on its interface with the water (Wan et al, 1993). The bacteria located on the interface itself can be explained by interfacial forces, but the selective colonization of bacteria on the solids located within a pore radius of the blob is more difficult to explain. In our current experiments with Pseudomonas putida in the vicinity of a toluene blob the toluene is a primary substrate, but because the bacteria find high concentrations of toluene toxic we do not expect to find any living bacteria on the toluene-water interface.

The preferential sorption of colloids and bacteria to fluid-fluid interfaces has several practical implications for NAPL-water situations. For example, colloids will be sorbed to the NAPL-water interface. In the case of clay minerals or metal oxides coating the solids, our preliminary experiments suggest that these materials can be mobilized and redistributed within the pore space. If they become packed into pore throats the pore space will be restructured, probably leading to alteration of pore pressure-saturation and hydraulic conductivity, as well as the increased residual non-wetting phase saturation we've already observed. As a second example this attachment suggests a mechanism to deliver colloid-sized packages (capsules, bacteria, endospores, etc) to a NAPL-contaminated zone. One would simply control the chemistry to insure their mobility in the water saturated portions of the aquifer. When they reach the NAPL residual zone they would be easily sorbed onto the NAPL water interface. Then for bacteria or endospores the water chemistry would be adjusted to maximize population growth and degradation of the non-aqueous phase liquid. In a similar way colloid sized capsules could be used to deliver chemical packages to the non-aqueous phase blobs, perhaps to enhance their solubility. We are exploring the patentability of this approach.

We plan to follow up our previous observations and speculations with a series of carefully controlled experiments involving NAPL's and various aboitic and biotic colloids. The individual hypotheses to be tested and their related experiments are outlined below.

In addition we will participate in a Multiphase Fluid Flow (MFF) Subprogram joint study of the effects of wetting on transport. The subprogram has decided to collaborate on a common research question each year. As recalled in Raina Miller's (4/16/93) letter to Frank Wobber (SSP, DOE) this involves a minimum of 10% of each group's effort. The first research topic selected was wettability. We plan to support this effort through micromodel visualization experiments for the aqueous phase composition and NAPL systems developed by Kim Hayes at the University of Michigan. Three systems will be studied: 1) A control without wettability alteration. 2) A system is which only interfacial tensions are altered and 3) a system in which both interfacial tensions and contact angles (wettability) will be altered. These visualization experiments will support the column and other basic property experiments conducted at Michigan and at Pacific Northwest Labs (PNL), as well as related experiments elsewhere within the MFF subprogram. This is a natural continuation of our earlier work on wetting, and allows us to use our unique flow visualization tools in this joint, coordinated effort.

Colloid and bacteria transport in the vicinity of capillary trapped residual NAPL saturation

Over the next two years we propose to investigate the following related hypotheses concerned with the colloid behavior in the vicinity of NAPL blobs:

- Colloids preferentially sorb onto the water-NAPL interface surrounding NAPL blobs.

- Colloid sorption on the blob interface is influenced by hydrophobic and capillary forces, as well as electrostatic and capillary forces. Consequently, sorption depends on aqueous chemistry, colloid chemistry, and NAPL composition.
- NAPL blobs sorb colloids even when aqueous chemistry is unfavorable to their sorption on the solid surfaces.
- The degree of sorption onto the blob interface increases with increasing particle surface hydrophobicity and NAPL hydrophobicity.
- Particles sorbed onto the blob interface are difficult to remove, because of capillary forces.

This work follows up and builds on our previous work with air-water interfaces and gas bubbles.

Colloid redistribution by moving NAPL interfaces

In closely parallel work we'll examine the influence of these processes on the redistribution of colloidal material within the pore space, and its effects on porous media properties. The two major hypotheses are:

- Colloids previously sorbed onto the solid walls of the pore space can be stripped away by invading NAPL interfaces, redistributing the colloids onto the interface and away from the walls. This mechanism enhances particle mobility. Later opposing NAPL-water interfaces can squeeze the water from a pore throat, packing the colloids on the interfaces into the throat and reconfiguring the pore geometry.
- The altered pore space leads to increased capillary trapping, permanently decreased aqueous phase permeability, and altered pore-pressure saturation behavior (it also leads to altered relative permeability, but that is beyond our resources to address).
- Under repetitive drainage-imbibition cycles the pore space continues to be altered resulting in changing pore-pressure saturation behavior that no-long maps onto the same scanning curves. The system hysteresis is changes from cycle to cycle.

This effort also builds on past preliminary experiments (Mase and Wilson, 1992) and our completed air-water colloid work.

Bacteria behavior and colonization in the vicinity of capillary trapped residual NAPL saturation

Extrapolating from our air-water experiments we expect resting state bacteria to behave as if they were colloids, yet in many cases the NAPL blobs are a source of primary or secondary substrate. In an extension of our work with abiotic colloids under the first objective, we'll investigate the same series of hypotheses for bacteria in a resting state, and begin new work with colonization. There are three hypotheses planned for study over the next two years:

- Resting state bacteria preferentially sorb onto the water-NAPL interface, under conditions analogous to abiotic colloids.
- In the absence of toxicity, growing bacteria also preferentially sorb to and colonize the water-NAPL interface.

- In the presence of toxicity growing bacteria will colonize at a distance from the NAPL blob.

In all cases we expect behavior to be influenced by aqueous chemistry, bacteria strain hydrophobicity, and NAPL hydrophobicity. The third hypothesis is also an extension of our current work on a single toluene blob, but in the presence of an entire population of similar blobs. In principle, with a dense enough population of blobs, no living bacteria should be observed.

Visualization of wettability alteration and its effects on NAPL behavior- MFF joint project

The specific hypotheses to be investigated through these visualization experiments will evolve over the next six months in collaboration with other MFF investigators. Our preliminary assessment is that we will study the following wettability related hypotheses for the MFF water-NAPL system over the next year:

- Altered interfacial tensions do not significantly change capillary trapping or pore-pressure saturation behavior, as long as critical Bond and Capillary numbers are not exceeded.

- Altered wetting in the strongly hydrophobic range leads to a symmetric switch in fluid behavior on a pore scale. The NAPL becomes the wetting fluid and the water the non-wetting fluid. As it is displaced from the model by water, the NAPL behaves as if it were on the secondary drainage curve, being drained by water. At residual the water becomes disconnected drops, isolated in pore bodies. The NAPL residual remains continuous and interconnected through wedges and films. The results should be easily compared to the NAPL-water experiments with a water wet surface, by reversing the roles. This is the micromodel equivalent of scaling.

- Altered wetting in the intermediate wet range leads to both phases remaining continuous and interconnected over all ranges of saturation.

- In the intermediate wet range contact angle hysteresis leads to a variable wettability with the pore system, due to spatial differences in saturation history.

- In the intermediate wet range the spatial distribution of fluids has no resemblance to or symmetry with either the strongly water wet or hydrophobic experiments. This significant difference in saturation geometry suggests that simple scaling, accounting for interfacial tensions, contact angles and even pore geometry fails to work.

The first of these hypotheses is fairly well established (see original proposal) and is really more of a control experiment. The second hypothesis has also been previously validated, albeit with a different fluid system. The remaining hypotheses have not been well studied, especially in the context of the fluid systems of the joint MFF project.

Experimental Approach and Methods

To investigate these hypotheses we employ three basic experimental tools: micromodel visualization experiments (Conrad et al., 1992; Wan and Wilson, 1993a; and Wan et al., 1993), column experiments (Wilson et al., 1990; Mace and Wilson, 1992; Wan and Wilson, 1992a, 1992b, 1993b; Wan et al., 1993), and surface behavior experiments. The visualization and column experimental tools have previously been described in the original proposal and in the papers cited above, most of which are submitted project documents (see attached list, and the attached paper by Wan et al. (1993), which contain some detailed descriptions and examples). Both micromodels and columns will be used in the colloid and bacteria experiments. The wettability experiments will be confined to micromodels, supporteing related column and sandbox experiments being conducted elsewhere (U. Michigan, PNL, Oregon St.U). The surface behavior experiments concern contact angle measurements on surfaces (Burck et al., 1992; Wei et al, 1993), colloids (Wan and Wilson, 1992b,1993a, 1993b), and bacteria (Wan et al., 1993), as well as new experiments on the ability to strip away attached particles, descibed below.

Etched glass micromodels are composed of a network of pore bodies connected to pore throats. The networks are only two–dimensional although the pores are three dimensional. Fluid flow, colloid transport and bacteria behavior can be visually observed in these models using microscopy (Carl Zeiss Axiophot equipped with transmitted and reflected light; epifluoresent light; and dark field). Our conventional micromodels have pores ranging from 100 microns to a few millimeters in size, but Wan and Wilson (1993a) describe new models with pores as small as 20 microns. The smaller pore sizes are needed in our colloid and bacteria work.

The columns employ a high purity quartz sand (Uninin Co., Ne Canaan, CT., the same material and supplier agreed upon by the MFF subprogram) in cylindrical glass columns (ACE Glass, Inc.). We have developed careful cleaning procedures (Wan and Wilson, 1993b) which we shall coordinate with Kim Hayes of the University of Michigan. Experimental procedures for NAPL water experiments are well documented (Wilson et al., 1990; Mase and Wilson, 1992), but relatively fragile. We expect to modify and improve the procedures in collaboration with Avery Demond at Michigan and Bob Lenhard at PNL.

The column and micromodels colloid and bacteria experiments will consist of saturating the experiments with water, then displacing the water with a NAPL. Afterwards the NAPL will be displaced to residual non–wetting phase saturation by water. A slug of 1 or more pore volumes of dilute colloid or bacteria suspension will be injected. The slug will be followed by suspension free solution. The micromodels only have pore volumes of 100–500 microliters, so their slug may be as large as 30 pore volumes. In the columns the effluent will be collected by a fraction collector at a rate of 6 or more samples per pore volume, while in the micromodels the colloids or bacteria will be observed and recorded. The column effluent concentrations will be plotted as breakthrough curves.

The hypotheses regarding colloid behavior will be investigated in a series of controlled experiments by altering aqueous chemistry (most likely, ionic strength while keeping pH constant), particle surface hydrophobicity and charge, and NAPL hydrophobicity. Most of these experiments will be conducted with polystyrene latex particles (Interfacial Dynamics Corp.) because of convenience, and their availability with a wide range of surface chemistries, well characterized surfaces and visibility under the epifluoresent microscope. The visualization experiments will also be conducted with clay minerals (montmorillonite), hematite (α–Fe_2O_3), and possibly silica. The clay minerals and hematite represent classes of naturally available colloids in aquifer materials. Some or all or these natural colloid types may also be used in some of the column experiments, provided we can find a way to economically measure their concentration in the effluent. All particles will be characterized by size analysis, electrophoretic mobility, and contact angle. We have not yet picked out our candidate NAPL's, but plan on conducting at least some of the experiments with MFF subprogram common chemicals.

The hypotheses concerning redistribution of colloids by moving NAPL interfaces will be studied by sorbing candidate colloids (montmorillonite, hematite, or possibly silica) onto the micromodel surface and quartz minerals in the columns. Several different sorption mechanisms will be studied. Our first approach will be to pass a suspension of many pore volumes through the column under aqueous chemistry conditions favorable for sorption (eg, high ionic strength). Then we'll flood the experiment with NAPL and chase it with the same type water. In the micromodel experiments we'll observe and record the movement and redistribution of colloids. In the column experiments we'll record pore-pressure saturation behavior and, at various stages (but not all) we'll measure aqueous phase permeability In order to test the hypothesis that the hysteretic scanning curves change from cycle to cycle we'll have to conduct these experiments through at least three drainage-imbibition cycles.

We intend to develop new surface behavior experiments to more closely study the stripping of adsorbed colloids from solid surfaces. We'll coat a the surface of a glass (no. 2947, Corning Glass Works) or quartz (Heraeus Amersil) slide with colloidal material (montmorillonite, hematite, or possibly silica) then submerge it under an appropriate aqueous solution. A 2-ml microburet will be used to expand and contract a drop of NAPL, advancing and receding the NAPL-water-solid contact over the slide. The behavior of the coated colloids and interfaces will be observed and recorded through a microscope (Carl Zeiss Steroscope) fitted with a goniometer and video camera/recorder.

The hypotheses concerning bacteria behavior present several experimental problems. We first want to study bacteria in a resting state. We can do this by finding several pure bacterial strains with different surface hydrophobicity that cannot degrade a class of NAPL's. We suspect that one possibility are aliphatic compounds. To test the hypothesis that NAPL hydrophobicity plays a role then we can use aliphatics with different carbon numbers. To contrast the same bacterial strain under both resting and growing stages we must find bacteria minus the plasmid that allows them to degrade the subject NAPL. In the case of toluene this is the TOL plasmid and we could use Pseudomonas putida. However this organism finds high concentrations of toluene toxic, so we would not expect to find living cells sorbed on toluene blobs under either growing or resting conditions. Obviously, we then seek a bacteria that can live on the interface of the appropriate NAPL which has an identified plasmid for the degradation of that NAPL. We don't know of such a bacteria/NAPL combination, but are presently conducting a search.

The resting state experiments will follow the same procedure used for the abiotic colloids, with the addition that we must first culture the bacteria. In our past air-water experiments with Pseudomonas cepacia 3N3A and Arthrobacter sp. S-139 we grew the bacteria in a 10% PTYG broth at 27° on a shaker. When the culture reached a late logarithmic stage of growth (48hr.) the cells were harvested by centrifugation (5000g for 10 minutes) and washed three times in 1.0 mM $NaNO_3$ (pH6.6). Cells were then suspended in the same solution to the final concentration used in the experiments of about $5x10^7$ cell/ml. We use a modification of the method of van Oss and Gillman (1972) to measure contact angles, employing a filter layer-captive drop technique (Wan and Wilson, 1993a)

The growth vs. resting state experiments will involve a bacteria with and without the necessary plasmid for degradation of the NAPL compound. The resting state experiment will proceed as above. The growth experiment will involve the innoculation of the experiment with a suspension of the bacterial strain. There are several options for this stage of the experiment but the most obvious is the displacement of 1 or more pore volumes of bacterial suspension through the column, followed by a suspension free solution containing appropriate nutrients. The observed behavior and breakthrough during this stage of the experiment should be analogous to the colloid or resting state experiments. Afterwards bacteria colonization of the pore space will be observed in the micromodel, and NAPL concentrations in the effluent of aqueous phase will be observed in the column experiment. The inoculum could also simply consist of a small part of a pore volume. We'll repeat the experiments for the toxic and non-toxic NAPL's (respectively, Pseudomonas putida and toluene for the toxic case, and a yet to be determined bacterial strain and NAPL for the non-toxic case).

Staffing

For the proposed work we will be starting with new staff. We've proposed one Ph.D. student to work on the NAPL-colloid issues. To get this effort kick started we've also proposed one month of a Post-Doc, Dr. Jiamin Wan. Dr. Wan has accepted a position with Lawrence Berkeley Laboratory. She will continue her colloid work there, and return to New Mexico Tech to work in the laboratory from time to time. When she is working at Tech on the proposed project she will take a leave-of-absence from LBL and work as a Post-Doc. We've also budgeted a half-time technician. We've previously dropped proposed technician time, in negotiating budgets, in order to support two graduate students on the project. This year we propose to keep the technician and eliminate the graduate student. We feel that the technician can better support the joint effort on wettability, while still assisting with the experiments on NAPL-colloid issues. Thus the technician will be running the wettability visualization experiments and most of the experiments on porous media property changes caused by colloid redistribution via moving NAPL interfaces. Finally we expect to get consulting from our collaborators in the MFF subprogram and from SSP investigator and microbiologist Tom Kieft. Additional advice from other SSP microbiologists will be sought.

Equipment

We are proposing a modest equipment budget reflecting, on one hand the maturity of our project and the level of overall funding, and on the other hand the migration of our experiments into microbiology. We are proposing:

1. a constant temperature bath to maintain constant temperature conditions during the microbial growth experiments (VWR Model 1166);
2. two addtional pumps to support addional simultaneous column experiments, improving productivity (ISCCO WIZ pump or equivalent);
3. two fraction collectors for the same purpose (ISCO Retriever II or equivalent)
4. a low light video CCD or CID camera to improve observation of bacteria via immunofluorescence; capable of extended exposures of several hours (for example: CID-Tech, PULNiX NV-5086FG, or SpectraSource MCD 220).

The budget for the low light camera is sufficient to purchase any number of low resolution (eg, 192 x 165 pixel format) cameras. Higher resolution (512 x 512) cameras cost two to three times the budgeted figure. We will also explore adding phase contrast capability to our Zeiss Axiophot microscope, with funds from other sources, in order to improve visibility of bacteria in the micromodel. With DOE's permission some of this projects propsed equipment money may be diverted to assist with this purchase.

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