

# **Advanced Polymer Technology for Containing and Immobilizing Strontium-90 in the Subsurface - 8361**

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## **Advanced Polymer Technology for Containing and Immobilizing Strontium-90 in the Subsurface - 8361**

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### **ABSTRACT**

Many Department of Energy (DOE) sites, including Idaho and Hanford, have heavy metals and/or radionuclides (e.g. strontium-90) present that are strongly adsorbed in the vadose zone, but which nevertheless are propagating toward the water table. A key challenge for immobilization of these contaminants is bringing the chosen amendment or remediation technology into contact with the contaminated porous medium, while ensuring that contaminated water and colloids do not escape. This is particularly challenging when the subsurface geology is complex and highly heterogeneous, as is the case at many DOE sites. The Idaho National Laboratory (INL) in collaboration with the University of Texas at Austin (UT) has conducted research sponsored through the DOE Office of Environmental Management (EM) Advanced Remediation Technologies Phase I program that successfully demonstrated application of a novel, pH-triggered advanced polymer for creating a physical barrier that prevents heavy metals and radionuclides in vadose zone soil and soil-pore water from migrating to the groundwater. The focus of this paper is on the column and sandbox experiments conducted by researchers at the Idaho National Laboratory in support of the Phase I program objectives. Proof of these concepts provides a technology basis for confining or isolating a volume of contaminated groundwater, to be implemented in future investigations at the Vadose Zone Research Park (VZRP) at INL.

### **INTRODUCTION**

Hydraulic isolation is useful for many groundwater remediation technologies, but traditional methods for achieving it, such as building freeze walls, driving sheet pilings, or placing grout, are often cumbersome and disruptive. Being able to achieve isolation simply by injecting a relatively small volume of inexpensive polymer solution into wells avoids many of the disadvantages associated with the conventional methods. Several DOE sites are evaluating the implementation of sequestration technologies to help achieve their large scale environmental cleanup objectives. However, many of these sites exhibit complex hydrogeology that limits the use of traditional technologies. The INL is one such site, with alternating layers of sediment and fractured basalt. Observed fluid transport in the subsurface at INL is dominated by extreme contrasts in hydraulic properties of geologic materials [1]. These hydraulic properties vary a great deal spatially and temporally, which results in more rapid and tortuous transport over more extensive volumes than thought at the time operations at INL were established. Given the existence of the perched water zones in localized areas throughout the INL that have not received natural or artificial recharge for several years, it is apparent that highly variable water conditions can exist in the absence of local recharge for extended time periods. The risk of displacing contaminant during remediation operations is, therefore, relatively high. Robust hydraulic control will help reduce this risk. INL sites, like many other DOE sites, have multiple radionuclide contaminants to contend with; however, strontium-90 is common to multiple INL sites and difficult to remediate since there is no currently proven technology. Researchers at the INL have been conducting laboratory and field investigations to evaluate methodologies for *in situ* sequestration of strontium-90 at specific areas on the INL facility. Laboratory studies are investigating bio-chemical urea hydrolysis techniques, which utilize indigenous microbes in the vadose zone perched water at the INL to

precipitate strontium carbonate for long-term stabilization in interbed sediments [2]. *In situ* field and laboratory studies are investigating methodologies for delivering amendments to a contaminated zone some distance away from an injection well, and monitoring techniques for validating sequestration processes [3]. Although the results of these studies will benefit remediation efforts at INL, *in situ* delivery of sequestration amendments is challenging. The presence of isolated perched water zones and co-contaminants in the subsurface beneath INL must be considered when injecting amendments to reduce the risk for contaminant mobilization.

The use of pH triggered polymer materials to strategically isolate contaminated zones will significantly aid sequestration methodologies being investigated at the INL. In addition, concurrent application of polymers and bio-chemical amendments would retain amendments in contaminated regions long enough to ensure stabilization reactions have reached fruition. The pH triggered polymer technology was originally developed by the UT researchers for improving oil recovery to allow the long-distance transport of micron-size polymer suspended in water through subsurface formations. Upon having sufficient contact with subsurface minerals to increase its pH, the solution then forms a very viscous gel. The gel zone can then serve as a flow barrier, confining the contaminants within the barrier zone, so that no contaminant leakage occurs to the surrounding formation. Moreover, the barrier creates a “bathtub” to control flow during remediation operations, such as placing an amendment intended to immobilize the contaminant or circulating a fluid through the contaminated region.

Being able to introduce polymeric materials to target regions of the subsurface through existing wellbores will provide a substantial operational advantage. Drilling new wells at an INL site requires procedures to handle the contaminants in the shallow soil and, thus, is to be avoided if possible. Relative to conventionally used grout, polymer materials can be propagated at least an order of magnitude farther in the subsurface due to their significantly lower viscosities. Therefore, they provide valuable flexibility for using existing wells in treatment design. Additionally, the polymeric materials being considered for this project are environmentally benign. Indeed, baby diapers are a major user of the pH-triggered microgel (polyacrylic acid). Permitting the use of these materials is, therefore, not expected to require precautions beyond normal due diligence.

The preceding challenges and difficulties are not limited to INL. Qualitatively similar difficulties are being encountered at contaminated sites throughout the DOE complex. It is important to note that while we focus on INL for the purposes of demonstration, the polymer technology discussed in this report is broadly applicable for the purpose of establishing hydraulic control in regions of the subsurface.

### **Technology Application Novelty**

Researchers at the UT and the INL conducted experiments to examine the application of pH-triggered microgels to create a high viscosity barrier in the shallow alluvium zone in support of an Advanced Remediation Technology investigation. In tackling radioactive contaminants, two basic modes of treatment are envisioned. The first leads to containment/immobilization of the contaminant by isolating it hydraulically. The second applies the technology, possibly in combination with injection/extraction well pairs, to guide and contain the placement of an amendment into the contaminated zone. This provides both chemical and hydraulic immobilization. This barrier would block downward movement of contaminant toward the aquifer. In this application, the reaction with minerals in the alluvium soil will raise the pH, activating the viscosification trigger. Even if the mineral reactions are slow, hydraulic control is still assured, because the polymer is self-sealing against intrusion of meteoric water or water from

the perched water body. The neutral pH of these waters will dilute the concentration of protons in the polymer solution, automatically triggering the viscosification.

Two strategies to emplace a gel barrier are being examined. In the first strategy, the polymer in low pH condition is injected at a lower portion of the target alluvium zone, after the pre-flush injection of citric acid, so that the polymer can propagate through the soil without gelation. This will allow the delivery of the polymer solution as a layer beneath the contaminant zone. The second strategy is to create a pancake-shaped horizontal fracture at the alluvium/basalt interface, by injecting a viscous polymer solution above the fracture pressure at the interface. Combined with placement of the pH-triggered microgel vertically around the contaminated zone, this affords complete hydraulic isolation. The longevity of the polymers could be measured in decades at the relatively mild conditions of the shallow subsurface at INL, so this could provide long-term isolation for radionuclides with suitable half-lives (e.g., strontium-90, which has a half-life of 29 yrs).

### **Benefits of the Technology**

The proposed technology has some key advantages over other polymer systems in use in the oil industry today. These advantages will also apply in the environmental applications of interest to DOE Environmental Management. The advantages include: The materials can be pumped into the earth formation with relative ease because it has a low viscosity in the appropriate pH range (i.e. < 3 centipoise [cP] for polyacrylic acid (PAA) microgel, which is the family of polymers we are using). This significantly reduces the near-wellbore pressure drop compared to other materials such as grout and, therefore, the injection pressures required. Other benefits are that the materials are water-soluble and simple to prepare and pump in the field. Additionally, PAA microgels are environmentally friendly and completely non-toxic. They are also anionic such that adsorption on most mineral surfaces is minimal and are consequently not retained to any appreciable degree. Finally, the pH-viscosity trigger is reversible. That is, an increase in pH leads to an increase in viscosity while a reduction in pH reverses the solution into a low viscosity polymer solution. Irreversible chemical reactions, such as cross-linking functional groups on the polymer chains with metal cations, are not needed for inducing viscosity buildup. This is a significant advantage over polymers being used in industry today and conventional grouts that have to be excavated to be removed. Because of these key advantages, it is expected that the polymer could be effectively used to isolate targeted zones at a contaminated site.

### **Project Goals**

The overall objective of the proposed technology application is to evaluate commercially available, pH-triggered polymers/microgels for use in the hydraulic isolation of contaminants in vadose zone perched water and unsaturated alluvium that represent a complex hydrogeological setting. If successful in complex hydrogeological settings, this technology would be readily applicable to simpler subsurface conditions. Analogous applications of these polymers have been carried out successfully in the oilfield, but to our knowledge this technology has not been applied for environmental cleanup. For the purpose of demonstrating the technology, we have focused on a particular example, namely the challenges arising from the commitment to ultimately remediate subsurface contamination at the INL site. At the INL, radionuclide contaminants are present in vadose zone alluvium and perched water zones located in alluvium sediment interbeds between layers of fractured basalt. The polymer technology was not tailored to the INL situation, nor does it rely on any conditions particular to that site, but can be applied successfully to most subsurface soils. The specific objectives of Phase I of the project are 1) to investigate changes in rheological properties of solutions of a commercial PAA microgel as a function of design variables (i.e. polymer properties, pH, salt/brine composition, polymer concentration, operating conditions and lithology of the subsurface formations); and 2) to assess the effectiveness of the microgel solution

as a hydraulic isolation agent for contaminants in fractured basalt and alluvium sediments by conducting laboratory flow tests.

To accomplish these objectives, laboratory column floods (one-dimensional [1D] and three dimensional [3D] packings of INL sediments and basalts) were conducted at the INL and the UT to demonstrate the activation of the viscosity trigger by the materials comprising the subsurface formations at INL. Additionally, the researchers also demonstrated the subsequent resistance to fluid flow afforded by the high viscosity fluid within the void space in these materials.

The focus of this paper is on the column and sandbox experiments conducted by researchers at the INL in support of these objectives. Proof of these concepts provides a technology basis for confining or isolating a volume of contaminated groundwater, to be implemented in future investigations at the VZRP at INL.

## RESULTS

### Description of pH Triggered Polymers

Cross-linked PAA polymers, Carbopol series from Noveon Inc., were used to prepare the microgel dispersion in synthetic INL groundwater. The polymers (available in powder form) have carboxyl functional groups that control rheological properties of the dispersion. The Noveon™ polymers are synthetic, high molecular weight, nonlinear carbomer polymers of acrylic acid cross-linked with a polyalkenyl polyether. Carbopol® 934, 980, and 981 were used for the various tasks of this study. They are chemically similar to each other, differing only in molecular weights. Preliminary laboratory tests conducted by Noveon™ have determined that the polymers are non-toxic, nonbiodegradable, and compatible (non-reactive) with electrolytes in solution, except for multivalent cations (eg, calcium  $[Ca^{+2}]$ , strontium  $[Sr^{+2}]$ , and aluminum  $[Al^{+3}]$ ) that form non-soluble precipitates when mixed with carbomer polymer reagents. This reaction byproduct is beneficial for contaminant stabilization because mobile metal contaminants (e.g., metals present in pore-water as colloids or dissolved cations) should precipitate out of mobile perched water zones and be bound in the high viscosity, low permeability barriers that form as the polymer solution thickens.

### Geochemical Characterization

Preliminary work conducted by researchers at the UT [4] established that for many subsurface formations with a sufficient contact time, the low pH of the injection fluid could be increased to a value higher than the critical pH for the drastic viscosity increase. The extent and timing of the pH increase depends on the formation's mineral composition, as the injected hydrogen ion is consumed by the geochemical reactions. A primary target for in situ application of this technology is a pilot test at INL's VZRP. The subsurface geology at the site consists of several hundred feet of alternating layers of alluvial sediment and basalt. A comprehensive set of subsurface geochemical data for the INL spill site and for the VZRP area were obtained by INL researchers and employed for a contaminant migration modeling work at the INL [5]. Evaluation of the mineralogy and geochemistry site characterization data provided by INL shows that the mineralogy of the alluvium is comprised mainly of aluminosilicate minerals, as shown in Table 1. The mineralogy of the basalt is predominantly aluminosilicates (i.e. 50% by weight as silica  $[SiO_2]$  and 15% as alumina  $[Al_2O_3]$ ), which is typical of weathered lava flows. Aluminosilicate minerals have significant capacity to react with  $H^+$  cations and thus increase pH (see Bryant and Buller, 1990 and references therein). Therefore, both the alluvium and basalt subsurface soils should have the capacity to increase the low pH of the injection fluid (i.e. <3 cP) to a value beyond the critical viscosification pH. Batch experiments with alluvium material confirmed that

INL ALLUVIUM MINERALOGY	
Mineral	Weight% [Range (avg)]
<i>Quartz</i>	30 – 53 (38)
<i>Plagioclase</i>	15 – 33 (23)
<i>K-feldspar</i>	0 – 13 (5)
<i>Clay minerals</i>	0 – 25 (15)
<i>other phases</i>	0 – 22 (13)

Table 1. INL alluvium mineralogy presented as weight % range (average value in parentheses).

pH increased with time, triggering the viscosification. (See Figure 1 and Table 2). Because of the prevalence of aluminosilicate and carbonate minerals in the subsurface, acidic solutions will be buffered (neutralized) as they migrate through any subsurface material. Thus the pH trigger technology is widely applicable.

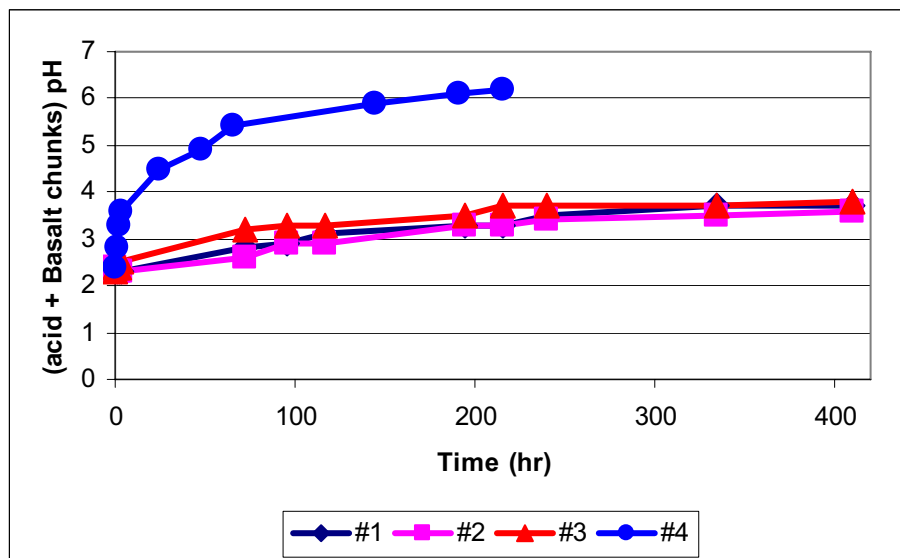


Figure 1. pH response with time for test cases

Case #	Rock Volume , cm <sup>3</sup>	Acid Volume, cm <sup>3</sup>	acid/rock ratio
1	20	80	4
2	17	85	5
3	25	75	3
4	60	90	1.5

Table 2. Rock/acid composition of test cases

### Laboratory Studies Conducted at the INL

A series of laboratory tests were conducted at the Idaho National Laboratory to evaluate the feasibility of using pH triggered polymers for reducing permeability in INL sediments. The experimental hypothesis proposed that a pH triggered polymer solution could be injected into

INL sediments at low viscosity, slowly increasing viscosity as the solution reacted with geologic mineralogy, ultimately reducing the hydraulic conductivity of the porous media. The reduction in hydraulic conductivity would create a barrier for fluid infiltration, thus stabilizing and/or isolating contaminants in the subsurface at the INL. The objectives of the laboratory tests were to: 1) select a polymer reagent best suited for reaction with INL sediments, 2) evaluate sensitivity of polymer kinetics to solution chemistry, 3) determine the optimum delivery flux rate, 4) determine the optimum polymer/sediment residence time, 5) measure reduction in sediment hydraulic conductivity, and 6) evaluate the use of Electrical Resistivity Tomography (ERT) to monitor polymer placement and subsequent alterations in fluid pathways within a heterogeneous sandbox.

Batch experiments were conducted to determine the optimum polymer reagent, polymer concentration, mixing technique, solvent chemistry, and polymer kinetics. 1D soil column experiments were conducted to determine the optimum polymer injection rate, polymer residence times, and reduction in hydraulic conductivity. A layered sandbox experiment was conducted to examine polymer placement within a heterogeneous system, alterations in flow paths after a polymer injection, and the effectiveness of ERT technology for monitoring the process.

Carbopol polyacrylic acid polymers were selected based on preliminary laboratory tests conducted at the University of Texas at Austin (UT) [4]. A variety of polymer and salt concentrations were examined using both Carbopol 981 and Carbopol EZ4 polymer reagents. The objective of the batch experiments was to determine the optimum polymer reagent, mixing technique, and concentration for delayed polymer reactions. Delayed polymer swelling (due to changes in solution pH) will enable the solutions to propagate longer distances through a sediment matrix before clogging transport pathways. Both 1 wt% and 3 wt% polymer mixtures dissolved in sodium chloride (NaCl) solutions were tested by mixing the polymer solutions with INL alluvium at various solid/solution ratios.

The polymer/sediment solutions were mixed for 24 hours on a rotating wheel, measuring pH, electrical conductivity, and solution density periodically. Observations of fluid consistency were noted with time to evaluate reaction kinetics. Initial pH of all the polymer solutions was adjusted to 3.0 prior to adding geologic materials. The EZ4 polymer reacted instantaneously regardless of polymer and salt concentration; therefore, it was eliminated from subsequent column and sandbox tests. Immediately after adding alluvium to each vial, the pH increased to between 4.0 and 5.6 depending on mass of sediment. After approximately 7 hours, the pH stabilized between 7.0 and 8.0 depending on sediment mass. The majority of the samples thickened within the first hour to the same consistency observed after 24 hours, with exception of 3 samples that took longer to thicken and had slightly slower reaction times (based on changes in pH). These samples contained a solution of 2 wt% 981 polymer diluted 50% with deionized (DI) water (i.e. 1 part solution to 2 parts DI water).

1D soil column experiments were designed based on the batch experiment results, selecting 1 wt%, 1.2 wt %, and 1.5 wt % (i.e. 10,000 parts per million [ppm] 12,000 ppm and 15,000 ppm) Carbopol 981 polymer and 400 ppm NaCl solutions. The properties of the solutions are listed in Table 3. The objective of the 1D soil column tests was to determine injection flux rates that would allow polymer propagation without premature clogging and significantly reduce soil permeability. The results of the batch and column studies were used to design 3D layered sandbox experiments.

PPM	Electrical Conductivity (uS/cm)	Density (g/cm <sup>3</sup> )	Adjusted pH
15000	5366 (22.7 °C)	1.1	2.2
12000	4127 (23 °C)	0.9	2.2
10000	1574 (21.2 °C)	1	2.2

Table 3. Properties of polymer solutions with 400 ppm NaCl.

Alluvium sediment (sieved to remove >4mm particles for ease in packing columns) collected was from the INL site packed into 2" (4.8 cm) ID x 15" (37.8 cm) long plexiglass cylindrical columns at dry bulk densities similar to in situ conditions at the INL. The sediment was packed slightly moist (approximately 4 wt% water) to achieve the desired bulk density, using a soil tamper to uniformly pack the column. Desired soil mass was calculated using Equation 1 (Stephens, 1995).

$$\rho_d = \frac{M_t - M_c}{(1 + \theta_g) * V_t} \quad (\text{Eq. 1})$$

where  $\rho_d$  is the dry bulk density (g/cm<sup>3</sup>),  $M_t$  is the total mass of the packed column prior to saturation (weight of column, water and soil),  $M_c$  is the column mass (g),  $\theta_g$  is the gravimetric moisture content (mass water/mass dry soil), and  $V_t$  is the total column volume (cm<sup>3</sup>).

Initial volumetric moisture content was calculated from gravimetric moisture content using Equation 2.

$$\theta_v = \theta_g * \frac{\rho_d}{\rho_w} \quad (\text{Eq. 2})$$

where  $\theta_v$  is the volumetric moisture content (volume of water / total column volume) and  $\rho_w$  is the density of water (g/cm<sup>3</sup>).

Sample porosity of the packed columns was determined from Equation 3.

$$\phi = 1 - \left( \frac{\rho_d}{\rho_p} \right) \quad (\text{Eq. 3})$$

where  $\phi$  is the column porosity (ml pore volume / ml total column volume) and  $\rho_p$  is the particle density assumed to equal 2.65 g/cm<sup>3</sup> (particle density of quartz sand)

The soil column properties for two replicate soil columns are listed in Table 4.

The soil columns were saturated with INL synthetic groundwater using IV pumps at 200 ml/hr flux (Figure 2). The columns were considered saturated after 1 pore volume water injection based on observations of water potential along the length of the column (measured using tensiometers). Full saturation (was not achieved due to entrapped air. However, the degree of saturation was representative of typical field saturation values (70-80%) in vadose zone sediments (Stephens, 1995). One column was used as a standard (column 1) to measure soil column



Properties	column 2	column 1
initial wt% moisture content (g water/g dry soil)	0.042	0.039
dry bulk density (g/cm <sup>3</sup> )	1.50	1.64
calculated porosity (ml/ml)	0.44	0.39
initial volumetric moisture content (ml/ml)	0.22	0.20
column volume (cm <sup>3</sup> )	687.44	693.16
pore volume (cm <sup>3</sup> )	302.47	305.00
Saturated volumetric moisture content (ml/ml)	0.32	0.35

Table 4. Measured and calculated properties for repacked soil columns

hydraulic conductivity in the absence of polymer injection and the other column was used to measure the reduction in hydraulic conductivity as a result of polymer injection. Preliminary column tests were conducted to determine the optimum polymer concentration (1, 1.2, or 1.5 wt%) and injection flux rates.

The column tensiometers were used to monitor column pressures over time to determine optimum shut-in times. Once the optimum polymer solution and flux rate were identified and a column was uniformly injected without significant soil disturbance, the column was shut-in (i.e. the end caps were sealed) and the polymer was allowed to swell. After one week, a falling head permeability test method was used to measure hydraulic conductivity. The conductivity was compared to a replicate soil column (column 1) to determine the degree of permeability reduction due to polymer swelling. The columns were instrumented with tensiometers connected to a datalogger to monitor column pressure during polymer reaction with the sediments. The polymer solution was injected into the bottom of the columns using an IV pump. Samples were collected every 0.25 PV to monitor solution pH, density, and electrical conductivity.



Figure 2. Experimental set-up for 1D column polymer tests.

The polymer solution that exhibited the best results was the 1.5 wt% Carbopol 981 dissolved in a 400 ppm NaCl solution adjusted to pH 2.1 (pre-injection) at a flux rate of 300 ml/hr. Polymers at lower concentrations did not result in observable reductions in hydraulic conductivity. The 1.5 wt% polymers injected at lower flux rates resulted in premature column clogging (ie, not able to uniformly propagate the polymer through the entire length of the column). The optimal shut-in time was determined to be approximately one week based on changes in column pressure as the polymers reacted with the soil and began to swell.

The measured reduction in hydraulic conductivity was 43% ( $1.11 \times 10^{-3}$  cm/sec in polymer injected column;  $2.57 \times 10^{-3}$  cm/sec in non-injected column). The columns were dissected after the tests were conducted to examine changes in matrix structure and cohesiveness. Polymer fibers were visible throughout the column and the sediment was considerably more cohesive than the non-injected column (Figure 3). The results of these bench and column studies were used to design a layered sandbox experiment.



Figure 3. Gelled column structures.

(Note: Top left figure shows rapid reaction (clogged column), figures on the right show gelled polymers in the soil and visible fibers. The center figure shows a cohesive column after polymer injection.

A 3D layered sandbox was constructed and instrumented with ERT electrodes (Figure 4) to monitor fluid movement before and after a polymer injection, and to monitor polymer placement distribution within the layered system. When a measurable electrical resistivity contrast is developed in the subsurface due to injection of fluids, ERT can be used to monitor the movement and distribution of the fluids over time. The advantages of ERT are that the method is completely scaleable; after the system is installed the data collection is automated so that large data sets can be collected and processed. ERT data by nature are three-dimensional providing a good understanding of the system behavior.

A sandbox apparatus was constructed of clear Lexan plastic with inside dimensions of 30 cm x 60 cm x 91 cm (x, y, and z respectively). The box was instrumented with six strings of 15 electrodes each. Two strings on each of the wide faces and 1 string on each end allow full coverage of the inside of the tank. The sandbox was layered with INL alluvium and basalt bricks to simulate the heterogeneity of the INL vadose zone. The bricks simulated subsurface macro-fracture networks in the INL vadose zone. Some of the fractures were sealed with caulk, while some were left open to simulate fast pathways. The geologic layers consisted of a gravel drain layer (bottom layer), an

engineered silica sand filtering layer (next lowest layer), and alternating layers of INL alluvium and basalt bricks (Figure 4).



Figure 4. Layered sandbox instrumented with ERT electrodes to monitor water, tracer, and polymer movement in 3D.

Continuous monitoring of the system was conducted during all aspects of the experiment using electrical resistivity tomography (ERT) and inline (influent and effluent) conductivity sensors to measure tracer and polymer movement. A pre-polymer injection salt tracer (NaCl at approximately 16,000  $\mu\text{S}/\text{cm}$  electrical conductivity) was injected into a surface basin at a rate of 0.5 L / hour for approximately 10 hours while two pore volumes of INL synthetic ground water (approximately 700  $\mu\text{S}/\text{cm}$  electrical conductivity) flowed through the system to provide a sufficient hydraulic gradient to move the tracer through the sandbox. Following the initial tracer test, five pore volumes of simulated ground water were flushed through the system to remove the salt tracer, then 7 L of 1.5 wt% Carbopol 981 polymer solution (using a 400 ppm NaCl solvent) with an electrical conductivity of approximately 5000  $\mu\text{S}/\text{cm}$  was injected into the tank at a rate of 0.5 L / hr for approximately 12 hours (concurrently with a simulated groundwater injection to maintain the same hydraulic gradient as the tracer tests). The tank remained static for 2 weeks allowing the polymer to swell. A post-polymer tracer injection, identical to the pre-polymer injection, was performed to evaluate the changes in the flow regime caused by polymer emplacement.

ERT data was inverted using commercial software (EarthImager). The ERT monitoring effectively identified the tracer movement before and after polymer injections (blue colors) and the distribution of polymer placement within the tank over time. The ERT data showed little evidence of the polymer passing through the initial basalt layer, and little if any evidence of breakthrough at the bottom of the tank (Figure 5). Comparison of pre- and post-polymer injection tracer movement show that the tracer was diverted around the polymer placement within the tank (ERT data) and that the breakthrough behavior was altered (EC data). Although the initial tracer breakthrough times are similar, the peak concentration for the post test is much lower with a broader peak than observed in the initial tracer test. The tracer test comparison indicated less fingering and more uniform tracer movement in the post-tracer test compared to the initial test. The test results indicate that the polymer successfully plugged preferential flow paths (ie, macro-fractures in the basalt) forcing the tracer movement through alternate secondary pathways.

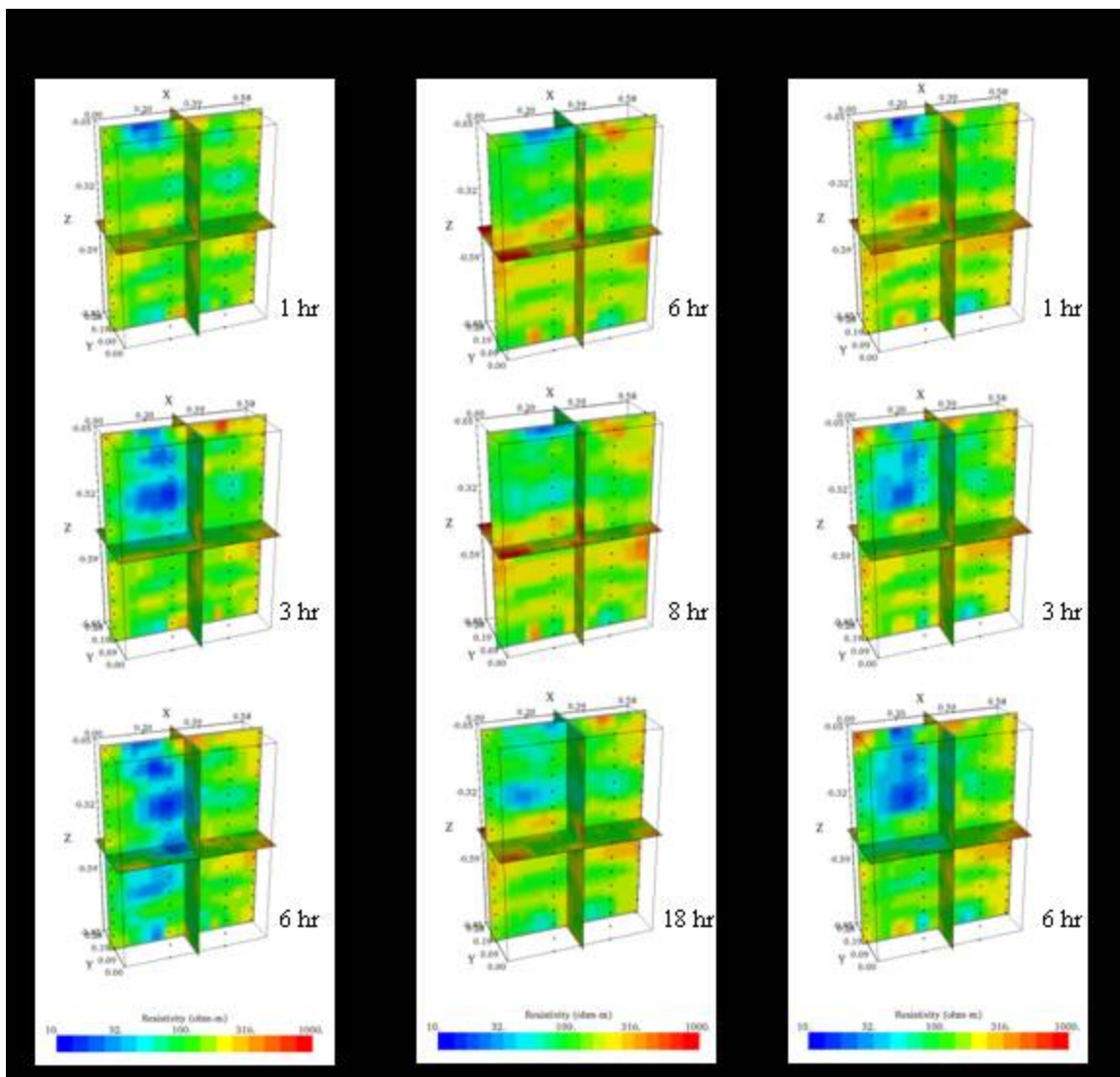


Figure 5. Inverted ERT data images showing tracer and polymer movement over time. (Note: The blue colors represent low electrical resistivity regions (i.e. tracer and polymer distribution) while the red colors represent high electrical resistivity regions. The location of the basalt layers are represented by the orange/red/yellow horizontal zones bounding the “T” cross section in the center of the images.

The results of the laboratory tests conducted at the INL support the hypothesis that pH triggered polymers can be considered as a viable injectate to create subsurface barriers for fluid infiltration in a heterogeneous geologic system. The preliminary batch and column experiments identified a polymer reagent suitable for reaction with INL sediments while the layered sandbox experiment showed that ERT technology could be used to monitor polymer placement and fluid movement through a heterogeneous system. The ERT technology also identified changes in tracer (i.e., fluid) transport behavior as a result of the polymer emplacement. Further studies are necessary to determine the impact of polymer reactions with INL vadose zone mineralogy on soil water quality before in situ demonstrations can be conducted at the INL. Future studies can utilize the INL laboratory test results to design meso-scale and field-scale demonstrations.

## CONCLUSIONS

Based on the laboratory work conducted by researchers at the INL and UT, the following conclusions can be made:

- PAA microgel technology creates a gel barrier when injected into both the INL alluvium and basalt. The resulting gel barriers were shown to be nearly impenetrable to water.
- A 1.5 wt% Carbopol 980 polyacrylic acid polymer adjusted to an initial pH of 2.1 was adequate for significantly reducing permeability in INL alluvium and basalt.
- Alluvium in the absence of an acid pre-flush allowed sufficient polymer propagation without pre-mature clogging; therefore, it is possible that an acid preflush may not be required.
- ERT is a viable methodology for monitoring polymer placement and fluid movement in the subsurface.
- ERT monitoring during 3-D sandbox experiments conducted at the INL demonstrate the feasibility of altering flow paths from the creation of low permeability polymer emplacement within a heterogeneous geologic system. The polymer adequately clogged preferential flow-pathways (i.e., fractured basalt) and diverted solute transport around a polymer-gel filled region of the sandbox.

The implication of these findings is that the pH triggered polymer technology is applicable in highly heterogeneous subsurface materials. The advantages of the polymer technology, including low cost, low environmental impact, applicability to most subsurface mineralogy, and ease of application, provide a strong foundation for in situ demonstrations at the VZRP at the INL.

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