Tracer Testing to Evaluate Tailing Pile Hydrogeologic Characteristics to Support Closure and Reclamation

Craig Divine[1], Adam Griffin[2], Lee Christoffersen[3], Jeff Gillow[1], Kelli Preston[1], Phil DeDycker[1]

[1]*ARCADIS U.S., Inc., 630 Plaza Drive, Highlands Ranch, Colorado, 80129, USA, Craig.Divine@arcadis-us.com, Jeff.Gillow@arcadis-us.com, Kelli.Preston@arcadis-us.com, Phil.DeDycker@arcadis-us.com*
[2]*ARCADIS U.S., Inc., 1100 Olive Way, Suite 800, Seattle, Washington, USA Adam.Griffin@arcadis-us.com*
[3]*OTEK Australia Pty Ltd, Level 1, 79 Hay St, Subiaco, WA, 6008, Australia, lchristoffersen@otek.com.au*

Abstract Applied tracers have been widely used for site characterization in natural hydrogeologic systems; here, we provide examples of their utility in elucidating complex flow patterns within heterogeneous tailings matrices and in the development of engineered approaches to mitigate tailing-water interactions and support reclamation. We present several examples where applied tracers, such as fluorescein, bromide, and sulfur hexafluoride (SF_6), were injected into legacy tailings and their transport behavior was characterized by arrival at nearby wells. These examples demonstrate the potential value of applied tracer studies in understanding, managing, and reclaiming mill tailings and reducing their potential to pollute groundwater.

Keywords water management, tailings, tracers, characterization, reclamation

Introduction

Mine and milling operations result in waste rock and tailings that require management throughout the life cycle of the mine. In the case of mill tailings, the materials have undergone significant physicochemical alteration relative to the natural ore. In addition, the deposition of tailings creates geologic heterogeneities and complex hydrogeologic conditions. Tailings are typically transported in a slurry form to a tailings impoundment. In subaerial disposal, tailings are then discharged into the impoundment through spigots or other discharge points. This process results in a succession of overlapping deltas (Vick 1990) and is similar to natural depositional settings. Coarser tailings (sands) settle from suspension close to the point of discharge, creating beaches, while finer tailings (slimes) are carried into the interior of the impoundment and tend to settle in the standing water of the decant pond. In some operations, tailings are cycloned prior to deposition to mechanically separate the sands and slimes, increasing the relative proportion of slimes tailings deposited in the impoundment. The separated sand tailings are often used to construct the embankment of the impoundment (*e.g.* USEPA 1994).

The deposition of tailings slurry creates significant vertical and horizontal heterogeneity in geotechnical and hydraulic properties throughout the impoundment. Sands and slimes tailings exhibit considerable variability in permeability (*i.e.* hydraulic conductivity), density, plasticity, compressibility, consolidation, shear strength, and stress parameters, which influence the design, stability, and drainage of the impoundment (Vick 1990). Vertical and horizontal variability in hydraulic conductivity is the primary consideration for the evaluation and management of seepage; layers of relatively high permeability sands are interbedded with relatively low permeability slimes, creating a complex hydrogeological regime (USEPA 1994). Ultimately, water flow and geochemical interactions are driven by the hydrogeological conditions in the tailings storage facility. The direction and quantity of seepage flow is controlled by the vertical and horizontal heterogeneity of hydraulic conductivity created by interbedded sands and slimes tailings. The movement of seepage is dominant in the relatively high permeability sands, which create preferential flow paths that may or may not be laterally as well as vertically continuous. Seepage flow can also be affected by hydraulic properties of the impoundment foundation and underlying aquifer, which determine the level of saturation and hydraulic connection between the impoundment and the aquifer (Vick 1990). Understanding both the hydraulics and geochemistry of tailings seepage is important for effective mitigation as well as management. For example, mitigation options for tailings sometimes include accelerating geochemical reactivity by manipulation of the water flow in a pile or decreasing reactivity of the tailings through introduction of chemical amendments.

Tracer testing techniques are well developed for characterizing natural hydrogeologic systems and are uniquely powerful for understanding flow characteristics and quantifying transport parameters and subsurface properties (*e.g.* Divine and McDonnell 2004). Applied tracers, which are defined as non-natural constituents that are intentionally introduced into the aquifer, are an especially powerful investigation tool for understanding the hydraulic behavior of an injected reagent at the remediation scale. Although tracers have frequently been used in hydrogeology for many decades, the application of tracers has only recently emerged as a best practice for understanding and characterizing solute transport to support groundwater remediation system design (Nelson and Divine 2005). In these applications, tracer testing, can reveal the heterogeneous nature of the aquifer, and support remediation system designs which maximize the efficiency of treatment areas. This paper illustrates the practical use of applied tracers to understand flow and hydrogeologic characteristics of tailings storage facilities, and to support the design and operation of seepage control and mitigation strategies.

Methods

Case Study 1: Tracer Tests to Support in situ Uranium Phosphate Precipitation Pilot Test Design

A pilot-scale field testing program (Pilot Test) was implemented in the tailings impoundment, targeting the dissolved uranium phases in the tailings porewater. Specifically, the pilot test was intended to evaluate the efficacy of sodium tripolyphosphate (STPP) as a phosphate source. STPP, which consists of linear chains of phosphate ions, has been evaluated by the Department of Energy (DOE) to treat uranium in groundwater through *in situ* application. Because STPP hydrolyzes over time, it can be transported in groundwater systems more widely than orthophosphate, which is immediately available to react. The primary objective of the Pilot Test was to evaluate the effectiveness of STPP at immobilizing uranium *in situ*. Tracer testing was conducted at two locations (the well network for Test Area 1 and Test Area 2 are shown in Fig. 1 below) prior to STPP injection to characterize the injection and hydraulic parameters of the impoundment in the Pilot Test area. Specifically, the tracers were intended to characterize the reagent distribution areas, flow directions and rates, and solute transport characteristics. Test Area 1 was located in an area of the tailings that is predominately fine material and slimes, while Test Area 2 was located in an area with a much greater sand content.

Conservative (*i.e.* non-reactive, non-sorbing) tracers were injected into the injection wells (*e.g.* wells labeled INJ1 ES10 in Fig. 1). Two tracers were used concurrently: bromide (as potassium bromide) as a quantitative tracer and the dye tracer fluorescein (as sodium fluorescein) as a visual tracer for field confirmation of tracer arrival. Approximate injected concentrations of bromide and fluorescein for both areas were 500 mg/L and 5 mg/L, respec-

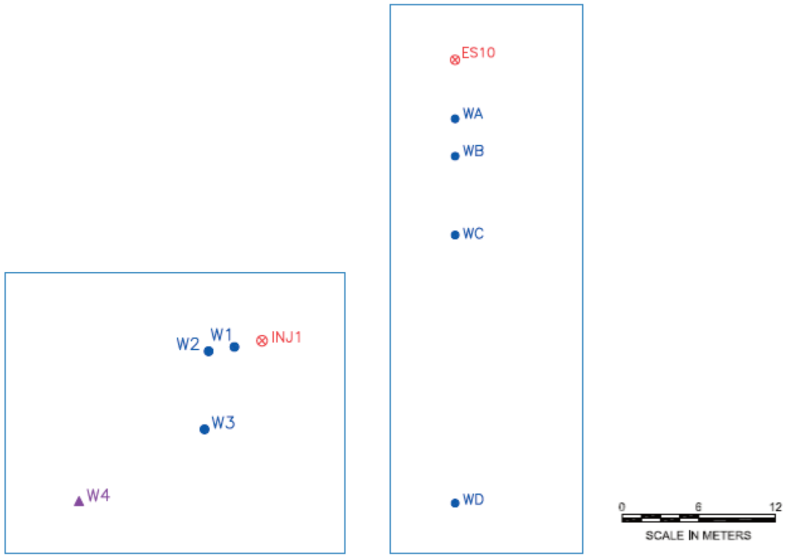

***Fig. 1** Well networks for Test Area 1 (left) and Test Area 2 (right). Red labels are the injection wells and blue labels are monitoring wells.*

tively. In Test Area 1, 17,000 L of tracer solution were injected at an approximate injection rate of 11.4 L/min, and in Test Area 2, a total of 83,000 L tracer solution were injected an approximate rate of 34.1 L/min. Post-injection monitoring extended after the tracer injections and continued for more than two months at Test Area 1 and more than seven months at Test Area 2.

Case Study 2: Tracer Test to Evaluate Performance of Tailings Flushing Program

A flushing and recovery approach has been applied to the tailings from a former uranium mill to reduce the long-term potential loading to the underlying aquifer. The flushing program involves the injection of clean water into the tailings and the subsequent extraction of pore water using a network of interconnected injection and extraction wells. In many areas, uranium areas have decreased substantially and therefore a tracer test was conducted to confirm treatment performance and better understand fluid flow behavior in the tailings. Specifically, the tracer test was designed to characterize the hydraulic connectivity and solute transport processes within tailings.

The study was designed to utilize a dissolved gas as a tracer, as opposed to more common tracer materials such as salts or dyes. A key advantage of using dissolved gas as a tracer is that it can be injected for an extended period of time with little field oversight, so a much larger volume of water can be dosed; additionally, many dissolved gas tracers have very low analytical detection limits resulting in a large "signal-to-noise" ratio. Sulfur hexafluoride, the selected tracer, is a non-toxic, inert gas and has been used for more than 20 years in applied studies (*e.g.* Wilson and Mackay 1993).

The well network for the dissolved gas tracer study and subsequent rebound monitoring is shown in Fig. 2. The injection wells for the tracer study were I1, I2, I3, I4, I5, and I6; these wells continued to inject clean water at total average flowrate of 75 L/min during the tracer test while being charged with SF_6. The gas was conveyed from compressed gas cylinders to approximately five feet from the bottom of each injection well. At the end of the piping, a microporous (6 micron pore size) diffusion stone discharged the gas to improve diffusion from the gas to the aqueous phase. A total of seven 53-kilogram-cylinders of SF_6 were injected from January 21 – 31 and from March 24 – May 9, 2011. In total, approximately 3.7 ML of water were dosed with SF_6 and injected into the tailings.

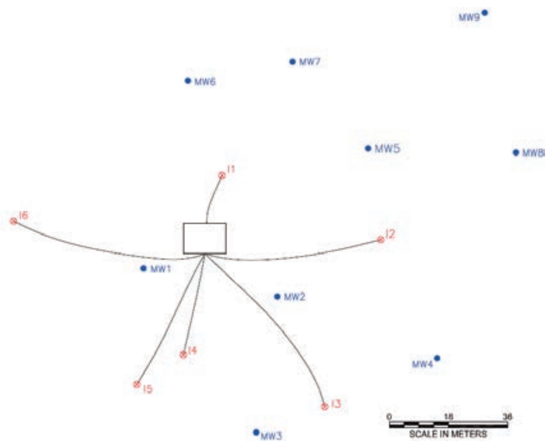

Fig. 2 *Well networks for Case Study 2. Red labels are the injection wells, blue labels are monitoring wells, and black lines depict above-ground gas conveyance piping.*

The monitoring wells were monitored for SF_6 during the tracer study to evaluate the distribution and transport of SF6 in the Rebound Evaluation area. Passive diffusion (PD) samplers, similar to those described in Divine and McCray (2004) were used to measure the concentration of dissolved gas in the pore water. PD samplers were deployed at different depths in the monitoring wells for a minimum of one week; SF_6 diffused through the membrane into the PD sampler to achieve equilibrium. The dimensionless Henry's Law constant (the concentration in gas divided by the concentration in water under equilibrium) for SF_6 is 122 at 10 °C (Wilson and Mackay 1993). During the period of active injections (January through May 2011), the PD samplers were collected weekly for analysis; after collection, new PD samplers were deployed for the next monitoring event. Information about the injection system was also recorded weekly, and included tank pressure, header gas pressure for each injection well, totalizer readings from each injection well, and the measured water flow rate at each injection well. After SF_6 injections were discontinued on May 9, 2011, the PD samplers were analyzed through January 31, 2012.

Results

Case Study 1

Tracer breakthrough curves for Test Area 1 and Test Area 2 are included below as Figs. 3. The breakthrough curves illustrate bromide concentration data versus time (elapsed since injection), where the concentration data has been normalized to the injected concentration. The results of were very different in the two test areas due to the different hydrogeologic characteristics. In Test Area 1, (slimes-dominated), a relatively low maximum injection rate was achieved with a hydraulic and response only observed at W1. Tracer response at W1, which is approximately 1.7 m away from the injection well (INJ1), was observed after the injection of 6,800 L. Based on this response, the estimated mobile porosity (the pore space where the majority of flow occurs) was calculated assuming a cylindrical distribution to be approximately 4 % in this area. Based on the tracer washout rate from INJ1, flow velocities were estimated to be less than 0.5 m per day, based on water levels and the minimal tracer response in wells W1, W2, and W3, the flow direction was interpreted to be toward the north and northeast.

In Test Area 2 (sands), a much higher injection rate was observed, indicating much higher average hydraulic conductivity of the tailings. Based on the lack of observed tracer response at WA after the injection of 83,000 L, the estimated mobile porosity in this pilot test area is greater than 8 %. Post-injection tracer monitoring confirmed the arrival of tracer solution at monitoring wells WA, WB, and WC, all at normalized concentrations greater than 0.1. These results confirmed the southerly flow direction and implied relatively high flow velocities of about 1 m per day or greater. Based on these results, both areas were determined to be adequately permeable for the implementation of the STPP Pilot Test.

Ultimately, Test Area 1 was selected for the subsequent STPP Pilot Test because several factors including its close well spacing, significantly smaller target reagent injection volume

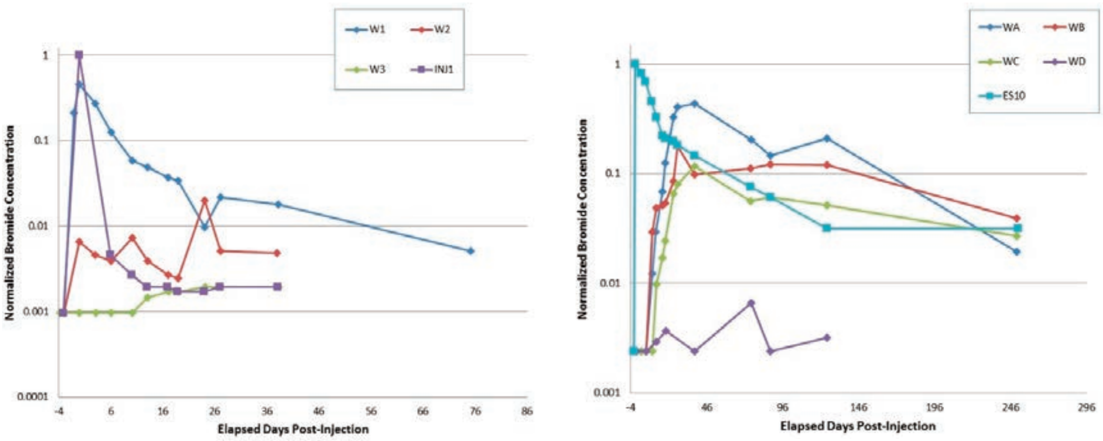

Fig. 3 *Normalized bromide tracer concentrations measured at injection and monitoring wells at Test area 1 (left) and Test Area 2(right).*

required, and lower flow velocity. Four additional monitoring wells were installed to the north and northeast of well INJ1 to further expand the monitoring well network.

Case Study 2

The SF6 tracer breakthrough curves for several monitoring wells are presented in Fig. 4. One of the most surprising observations is that the arrival of tracer was observed at four wells within 8 days of the initial tracer application and that the peak arrival of tracer occurred about 15 days after the start of the second tracer application period. These short arrival times indicate tracer transport rates were about 1–2 m per day. Based on the low average hydraulic conductivity of the tailings, and total pore space volume of the test area, the mobile porosity is very low, about 1 %. These interpretations are consistent with Cone Penetrometer Testing data collected from several nearby borings which identified thin continuous sand zones within the slimes matrix (Fig. 5). These observations imply that the flushing strategy

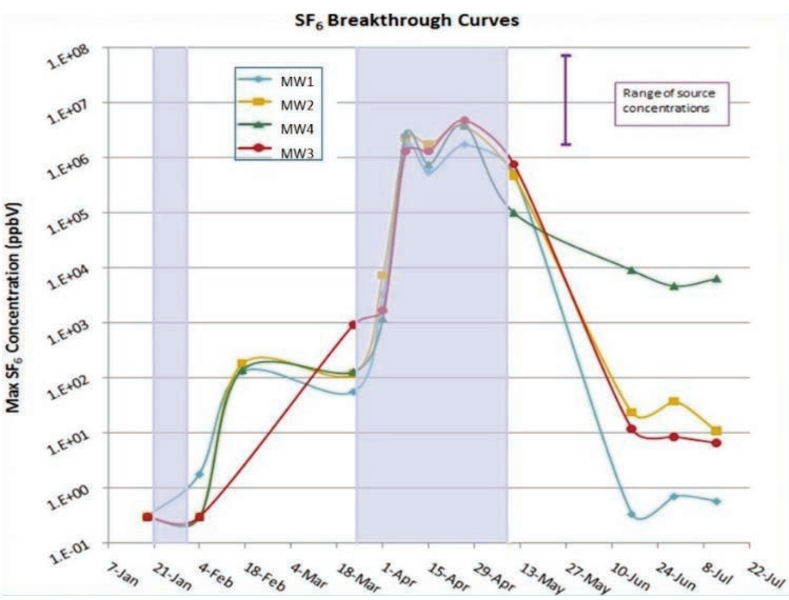

Fig. 4 *Uranium concentration and pH at downgradient monitoring wells. The shaded zones indicate time periods where tracer was continuously injected.*

can be very effective at accessing and recovering uranium and other constituents within the zones that contribute to flow and pose the most potential risk of mobilization and transport.

Another important observation is that the peak tracer concentrations were very similar to applied concentrations, even at wells located 10s of meters from the injection points. Additionally, tracer concentrations rapidly declined after the test. This behavior suggests that the diffusion-controlled solute exchange rates between the mobile porosity (flowing zones) and immobile porosity (low permeability non-flowing zones) is very low, back diffusion of uranium and other constituents after flushing may be limited.

Conclusions

The case studies presented in this paper clearly demonstrate that fluid flow in tailings materials is complex and governed by local-scale geologic structure and hydrogeologic conditions. Consequently tailings control and management strategies must be based on an appropriate understanding of fluid flow characteristics. Applied tracer testing, which is a well-developed technique for hydrogeologic investigations, is a practical and uniquely powerful for characterizing fluid flow behavior and permits direct quantification of transport parameters and other properties of tailings. This conceptual and quantitative information can be used to directly support tailings management system designs and long-term strategies.

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