Predictive Modeling Strategies for Operations and Closure at Uranium In-Situ Recovery Mines

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Abstract Uranium in-situ recovery (ISR) mining extracts uranium via enhanced dissolution of solid-phase uranium in groundwater aquifers. This changes the pre-existing groundwater geochemistry and makes uranium and other radionuclides and trace elements of concern more mobile in solution. Mined zones of aquifers often do not produce suitable drinking-water supplies, but surrounding aquifer zones can be of drinking water quality. Local groundwater users are concerned about how nearby ISR mines (either existing or proposed) might impact the quality of their water. For this research, we propose strategies for addressing the following questions: 1) How well do identified aquitards limit groundwater flow between aquifers? 2) What is the groundwater quality at the end of mining after restoration efforts are complete? and 3) What is the long-term fate and transport of any groundwater contaminants away from the mined zone? In order to address these questions, a number of predictive modeling steps should be taken to determine how surrounding groundwater quality may or may not be affected by ISR mining. First, understanding the basic hydrogeologic and geochemical system is critical. Second, predictive modeling using reactive transport models can be used to simulate future groundwater conditions (during mining and post-restoration). Third, predictive modeling can be used to evaluate how well surrounding groundwater quality is protected under the proposed mine plan design and to evaluate possible design alternatives. Fourth, model shortcomings should be evaluated to provide a reasonable range of prediction uncertainties. While these steps are generally applicable to any uranium ISR site, they will be applied and tested at a proposed uranium ISR site near Edgemont, South Dakota. The goal of this research is to provide predictive modeling strategies for better understanding the most probable fate and transport of uranium and other dissolved constituents during and after ISR operations. This information will assist mining companies, permitting agencies, and local groundwater users in making more informed decisions on final mine designs/operations and closure strategies that maximize protection of groundwater quality.

Key Words uranium, in-situ recovery, predictive modeling, reactive transport

Introduction

Sandstone-hosted uranium roll front deposits are primarily found in Tertiary age sediments throughout the western United States. Roll-front deposits form at the interface between oxidized and reduced sandstones (fig. 1). These fronts can be anywhere from a few feet to 350 feet across and are sinuous in plan view. The geochemistry associated with these deposits is complex and variable and they contain a mixture of U^{+6} minerals on the oxidized side of the front and reduced U^{+4} minerals on the reduced side of the front (Harshman 1974). Oxidizing groundwater flowing through sandstones transports uranium U^{+6} in solution down dip until reductants in the host sandstones precipitate uranium as U^{+4} minerals. Associated elements are often found distributed across the roll in zones determined by their redox potential and solubility in alkaline, oxidizing groundwater that comes into contact with pH neutral, reducing sediments at the reaction front (Deutsch 1985; Harshman 1972). Groundwater within the ore zone of roll front deposits is usually not of drinking water quality, typically containing high concentrations of uranium and its daughter products as well as elevated selenium, arsenic, lead and other dissolved constituents.

The relatively low-grade uranium in these deposits and their location in young, near-surface, permeable sandstones makes them economically mineable using in-situ recovery (ISR) mining techniques. ISR mining reverses the process which caused them to be deposited by oxidizing the roll front minerals (most commonly using oxygen and carbon dioxide). These oxidants and complexing agents are added to groundwater forming a lixiviant which is circulated through a well field developed around the rolls, oxidizing uranium from U^{+4} to U^{+6} and dissolving it into groundwater. The groundwater containing aqueous uranium (pregnant lixiviant) is pumped to the surface and the uranium is removed from solution in ion exchange tanks. Water is then recirculated

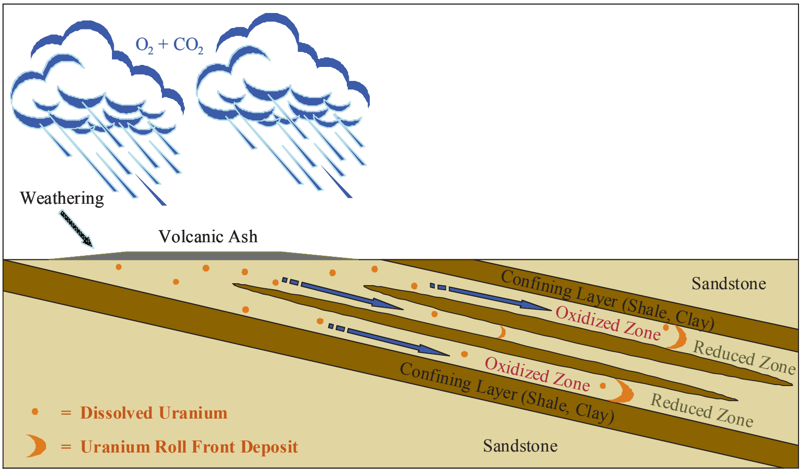

Figure 1 *Generic uranium roll-front deposit*

through the mining well field. Slightly more water is extracted than injected in order to maintain an inward hydraulic gradient preventing movement of lixiviant into portions of the aquifer not targeted for mining. The overall uranium ISR process is illustrated in Figure 2.

Domestic and agricultural groundwater users proximal to ISR mines are concerned about the impact of uranium ISR mining on local groundwater quality. Current research is addressing those concerns by looking at the following questions: 1) How well do identified aquitards limit groundwater flow between aquifers? 2) What is the groundwater quality at the end of mining after restoration efforts are complete? and 3) What is the long-term fate and transport of any groundwater contaminants away from the mined zone?

Predictive Modeling Strategies

In order to address the above questions, a number of steps can be taken to determine how surrounding groundwater quality may or may not be affected by ISR mining. These steps use predictive modeling to follow the mining process through operations and closure and long-term natural attenuation. While these steps are generally applicable to any ISR site, they will be applied and tested at a proposed uranium ISR site near Edgemont, South Dakota. Site data will be used for model calibration as available. In addition, data from legacy uranium ISR sites (Hall 2009) are also

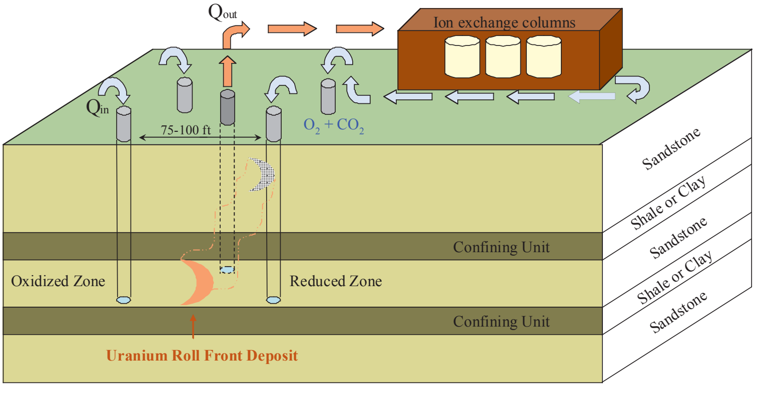

Figure 2 *General uranium ISR mining process*

being used to supplement understanding of ISR mining dynamics. This includes a comparison of pre-mining baseline compared to post-mining/restoration geochemistry.

First, a conceptual model must be established to understand the basic hydrogeologic and geochemical system, based on available data and professional expertise. Such a conceptual model includes information such as groundwater flow direction, boundary conditions, along with current groundwater and solid-phase geochemistry.

Second, predictive modeling using numerical reactive transport models can be used to simulate future groundwater conditions (during mining, restoration, and post-restoration). This requires the coupled simulation of groundwater flow and geochemical reactions using such models as PHT3D (Prommer 2002), which simulates groundwater flow using MODFLOW (Harbaugh and others 2000) and geochemistry using PHREEQC (Parkhurst and Appelo 1999). In any reactive transport modeling, input data linking the solid-phase mineralogy to the groundwater quality is very important to understand the rock-water interaction. For predictive modeling purposes, the collection of solid-phase geochemistry before mining is required. For final model calibration, post-mining solid-phase geochemistry is optimal. Theoretical reactive transport simulations of uranium ISR mining have been examined (Davis and Curtis 2007); however, field applications have been limited.

Third, predictive modeling can be used to evaluate the impact on surrounding groundwater quality under the proposed mine plan design and to evaluate possible design alternatives. Since many uranium ISR-ameneable deposits occur within sandstones that are drinking water aquifers outside of the ore zone, protection of groundwater quality is of great importance. Predictive reactive transport modeling provides a tool for evaluating potential impacts on surrounding groundwater quality based on initial mine plans. This is part of the second modeling strategy discussed above, but more importantly, alternate well field design and possible restoration procedures can be evaluated before finalizing any mine operation and closure plans.

Fourth, model limitations should be evaluated to provide a reasonable range of prediction uncertainties. This step involves the evaluation of uncertainties in the model input parameters, such as geologic layering (Johnson and Friedel 2009) and water chemistry. For example, the integrity of the confining zone should be evaluated based on any uncertainty in geologic logs and

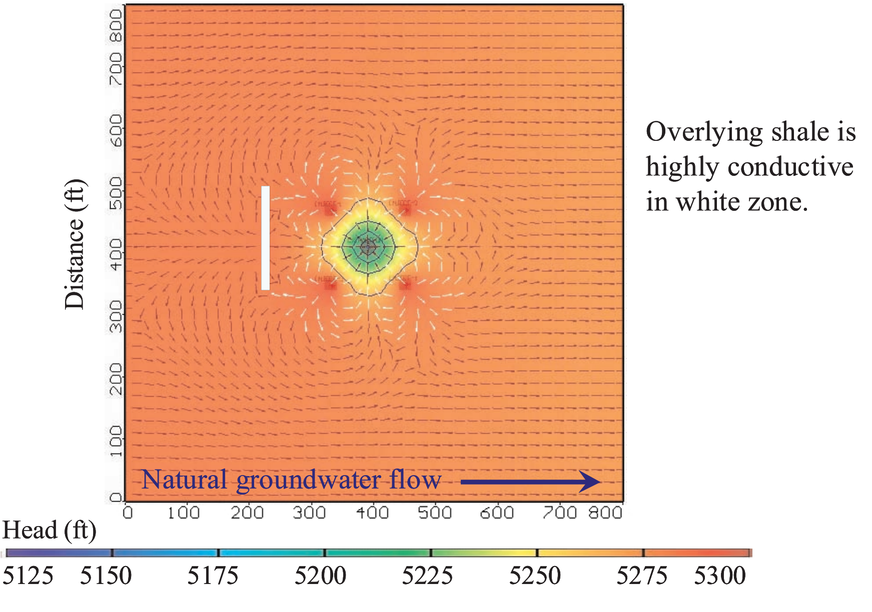

Figure 3 *Alternate conceptual model in mining zone with discontinuous confining layer, in plan view. Four injection wells and one central pumping well during mining. Discontinuity could be caused by thinning of the confining layer*

can be tested using multiple geologic conceptual models (fig. 3). In addition, any predicitions of long-term contaminant transport should provide adequate prediction uncertainties based on the uncertainties of the input data. Multiple conceptual models provide a range of potential groundwater quality impacts. This provides valuable feedback for the collection of additional data, which can assist in reducing uncertainty in future models.

Regulatory Perspective

The U.S. Environmental Protection Agency Region 8 (EPA) Underground Injection Control (UIC) Program is tasked with evaluating applications from uranium ISR mining companies for Class III injection well permits (lixiviant injection). EPA is tasked under the Safe Drinking Water Act (SDWA) with establishing permit requirements that protect underground sources of drinking water. For mining to proceeed, EPA must issue an aquifer exemption permit, which permanently exempts the mineable portion of the aquifer as a future source of drinking water under the SDWA.

Often times, private drinking water wells exist near the permit boundary of proposed ISR sites. Detailed modeling of potential fate and transport of any mobilized contaminants within and around the ore bodies is needed to evaluate the effects of nearby uranium ISR mining. The EPA is interested in evaluating predictive modeling strategies in general, with application and testing to be completed for this research at the prosed site in South Dakota. These strategies will provide information for environmentally protective decision-making that will benefit the EPA, state environmental and natural resource departments, and the Nuclear Regulatory Commission. These agencies are all tasked with regulating different aspects of uranium ISR projects, including groundwater protection and restoration.

Summary

This research effort will provide a procedure for using predicitve modeling strategies to understand the effects of uranium ISR on surrounding aquifers. These strategies will be generic for any uranium ISR mine, but will be applied to a current site in South Dakota that is in the permitting phase. This research will provide information to the EPA, mining companies, the public, and other stakeholders with specific strategies for understanding and modeling subsurface hydrogeology and geochemistry. Overall, the presented set of modeling strategies can assist a variety of stakeholders in making informed decisions for final mine designs, operations, and closure plans that maximize the protection of groundwater quality.

References

Davis, J.A., and Curtis, G.P. (2007) Consideration of geochemical issues in groundwater restoration at uranium in-situ leach mining facilities. NUREG/CR-6870, U.S. Nuclear Regulatory Commission, 86 p.

Deutsch, W.J., Martin, W.J., Eary, L.E., Serne, R.J. (1985) Methods of Minimizing Groundwater Contamination From In-Situ Leach Uranium Mining - Final Report: NUREG/CR-3709, PNL-5319, RU, 88 p.

Hall, S. (2009) Groundwater restoration at uranium in-situ recovery mines, south Texas coastal plain. U.S. Geological Survey Open-File Report 2009—1143, 32 p.

Harbaugh, A.W., E. R. Banta, M.C. Hill, and M.G. McDonald (2000) MODFLOW-2000, the U.S. Geological Survey modular groundwater model — User guide to modularization concepts and the Groundwater Flow Process. U.S. Geological Survey Open-File Report 00-92, 121p.

Harshman, E.N. (1972) Geology and Uranium Deposits, Shirley Basin Area, Wyoming, U.S. Geological Survey Professional Paper 745, 82 p.

Harshman, E.N. (1974) Distribution of elements in some roll-type uranium deposits, Formation of Uranium Ore Deposits—Proceedings of a Symposium; Athens, 6—10 May, 1974, p. 169—183.

Johnson, R.H., and Friedel, M.J. (2009) Factoring uncertainty into restoration modelling of in-situ leach uranium mines. U.S. Geological Survey Open-File Report 2009-1024, 25 p.

Parkhurst, D.L. and Appelo, C.A.J. (1999) User's guide to PHREEQC (Version2)—A computer program forspeciation, batch-reaction, one-dimensional transport, and inversegeochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99—4259, 310 p.

Prommer, Henning (2002) A reactive multicomponent transport model for saturated porous media, User's manual version 1.0. Contaminated Land Assessment and Remediation Research Centre, The University of Edinburgh, UK, 141 p.