Reactive Transport Modeling for the Proposed Dewey Burdock Uranium In-Situ Recovery Mine, Edgemont, South Dakota, USA

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Abstract In-situ recovery (ISR) mining extracts uranium by enhanced dissolution and mobilization of solid-phase uranium in sandstone aquifers. Geochemical changes that occur due to the ISR mining process are important for local groundwater users, regulatory agencies, and other stakeholders to understand in order to evaluate the potential effects on surrounding groundwater quality during and after mining. Reactive transport modeling is being used at the proposed Dewey Burdock ISR mine to simulate the geochemistry of: 1) uranium roll-front deposition; 2) current groundwater conditions; 3) mining processes; 4) post-mining restoration; and, 5) long-term groundwater quality after restoration. This modeling uses groundwater flow coupled with rock/water interations to understand geochemical changes during each stage. Conceptually, uranium roll-fronts are formed as oxygenated, uranium-rich groundwaters enter reducing zones where uranium minerals precipitate to form uranium ore. Through geologic time, the groundwater flow direction and incoming groundwater geochemistry can change, which may or may not alter the uranium roll-front deposit. During the mining process, oxygen and a complexing agent (such as carbon dioxide) are added to oxidize, solubilize, and remove the uranium. Post-mining, the mining solution is removed, and reducing agents may be added to re-precipitate uranium. Longer term geochemistry depends upon the remaining solid-phase minerals, their reactivity, and the composition of the incoming groundwater. All of these processes are highlighted through the use of a simple three-dimensional reactive transport model (groundwater flow and geochemistry). While this research focuses specifically on the proposed Dewey Burdock uranium ISR site near Edgemont, South Dakota, the procedures described are generally applicable to any proposed uranium ISR mine.

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

Introduction

Background information on the formation of sandstone-hosted uranium roll-front deposits and predictive modeling strategies can be found in Johnson *et al.* (2010). The proposed Dewey Burdock in-situ recovery (ISR) mine near Edgemont, South Dakota (USA) is being used for this study; however, the techniques discussed in this paper are applicable to similar sites. As such, the figures in this paper focus on the techniques, approaches, and results, not site specific geology.

Reactive Transport Modeling

Reactive transport modeling for this paper uses PHAST (Parkhurst *et al.* 2010). PHAST uses a relatively simple groundwater flow code coupled with PHREEQC (Parkhurst and Appelo 1999) to calculate geochemical conditions at each time step. For this paper, the groundwater flow velocities and mass balances for the solid phase are still generic, as well as the time. Site specific data will be added as the project progresses. Figures 1 through 8 are the most relevant slides that show geochemical processes and are a subset of a full twenty step animation. In these figures numerical dispersion does exist (actual dispersion is set to zero) due to the large time steps. This dispersion may be representative of actual conditions, but still needs to be evaluated further. Subsequent refinement of flow velocities and solid phase concentrations will include improved time stepping to avoid artificial dispersion. The model domain size is also generic and has been run in three dimensions, but the figures only represent two dimensions. Flow is always from left to right and cooler colors (blue, teal, and green) are lower concentrations and warmer colors (yellow, orange, and red) are higher concentrations (figs. 1 – 8). Concentration units are also generic.

Simulations

Uranium roll-fronts are formed as groundwater containing oxygen and dissolved uranium move into a zone with solid phase reductants (organic carbon and/or pyrite). This results in the precipitation of a reduced uranium mineral, such as uraninite (fig. 1). The initial geochemistry in these simulations start with pyrite, no uraninite, and no uranium or oxygen in the groundwater. Groundwater with uranium and dissolved oxygen are added to the model domain, which progressively consumes pyrite and forms a uraninite ore deposit at the oxidized/reduced interface (fig. 1). Chloride has been added as a conservative tracer (fig. 1).

At the Dewey Burdock site, the current groundwater in the roll-front area does not contain any dissolved oxygen. Because of this, these roll fronts

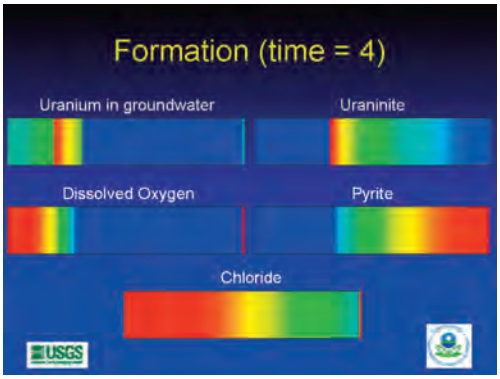

Figure 1 *Initial uranium roll-front formation. Flow is from left to right.*

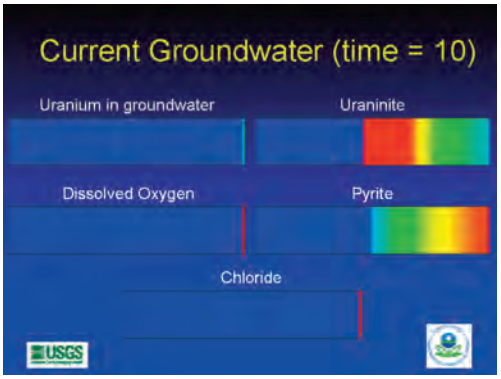

Figure 2 *Uranium roll front with current groundwater conditions. Flow is from left to right.*

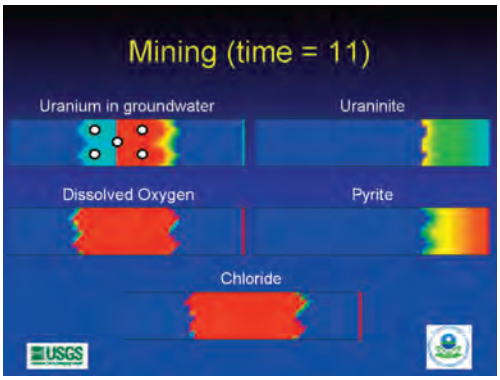

Figure 3 *Five-spot ISR mining with oxygen and carbon dioxide. Flow is from left to right.*

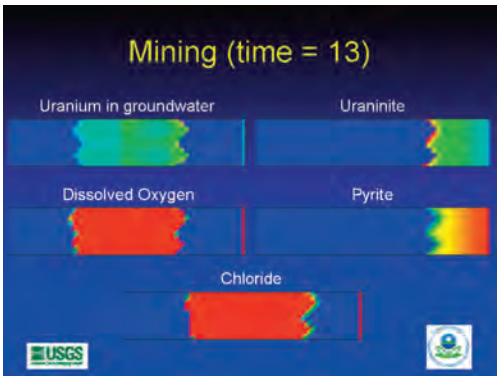

Figure 4 *End of mining with lower uranium concentrations in solution. Flow is from left to right.*

are probably not being formed at the present. To simulate pre-mining conditions, groundwater with no dissolved oxygen was transported through the model domain. The result is a solid phase uraninite roll front associated with pyrite on the solid-phase reduced side and uranium and dissolved oxygen are not found in solution (fig. 2).

Uranium in-situ mining is simulated using a leach solution with oxygen and carbon dioxide. The resulting oxidation makes uranium soluble and the carbon dioxide creates a complexing agent. A five-spot well pattern is simulated with a center pumping well and four surrounding injection wells (fig. 3). In the ore zone, the result is elevated concentrations of uranium in the groundwater where the ore zone is being mined and uraninite and pyrite are completely removed (fig. 3). Once mining is complete (fig. 4), uranium in solution is much lower and the mined area has high dissolved oxygen and chloride.

During the restoration phase, the existing well field is used to flush out the mining solutions from the groundwater. This process was simulated as water with low dissolved consitutent concentrations, but with 50 ppb residual uranium (figs. 5 and 6). In one simulation, oxygen was left in the restoration fluids (fig. 5) and in another simulation, oxygen was kept at zero (fig. 6). At this stage, reductant addition to help precipitate uranium could be simulated, but was not completed for this paper.

An important issue in uranium in-situ recovery mining is the groundwater quality post-mining and the potential for long-term natural attenuation. For longer-term groundwater quality, inflowing water of similar composition to the groundwater found at the Dewey Burdock site was added (calcium sulfate water with no dissolved oxygen). For restoration that left behind dissolved oxygen, the solid phase uraninite and pyrite zones continue to move downgradient and some uranium and dissolved oxygen are found in the groundwater (fig. 7). For restoration with no dissolved oxygen left behind, the movement of the uraninite and pyrite is much less and uranium is not found in solution (fig. 8).

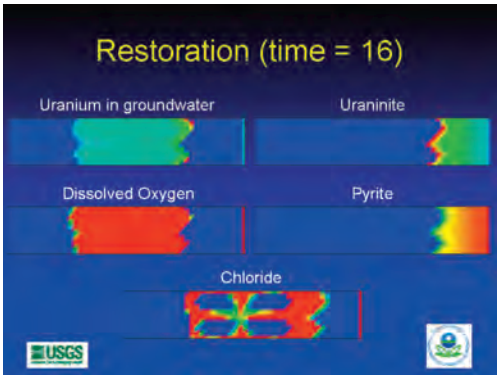

Figure 5 *Restoration with dilute water (no chloride) but some dissolved oxygen. Flow is from left to right.*

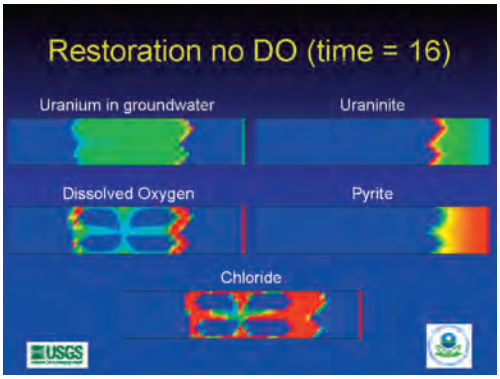

Figure 6 *Restoration with dilute water (no chloride) and no dissolved oxygen. Flow is from left to right.*

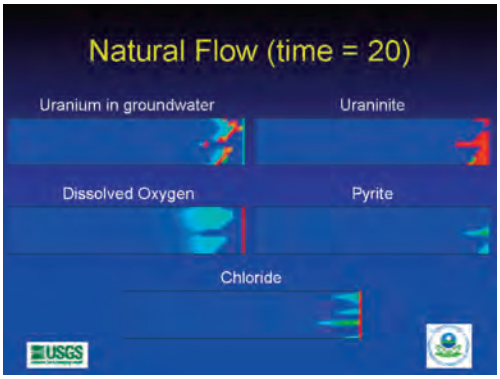

Figure 7 *Return to ambient flow after restoration that had dissolved oxygen. Flow is from left to right.*

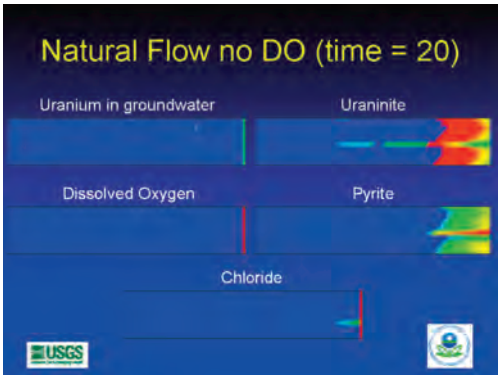

Figure 8 *Return to ambient flow after restoration with no dissolved oxygen. Flow is from left to right.*

Summary

This paper provides initial reactive transport simulations that support our conceptual understanding of uranium roll-front formation, current groundwater conditions, mining geochemistry, restoration geochemistry, and long-term groundwater quality at a uranium ISR site. These simulations are a starting point for additional refinement that will reflect detailed site conditions and can provide stakeholders with a better understanding of groundwater quality during and after uranium ISR mining.

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