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 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
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 constituent 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).
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.

Acknowledgements
The author thanks the USGS Uranium Resources and the Environment Project and the U.S. EPA Regional Applied Research Effort grant for funding this project.

References

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.