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#### AQUIFER RESTORATION AT URANIUM IN SITU LEACH SITES

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#### ABSTRACT

In situ mining of uranium involves injection of a leaching solution (lixiviant) into an ore-bearing aquifer. Frequently, the ground water in the mined aquifer is a domestic or livestock water supply. As the lixiviant migrates through the ore body, uranium and various associated elements such as arsenic, selenium, molybdenum, vanadium and radium-226 are mobilized in the ground water. Aquifer restoration after in situ mining is not fully understood. Several methods have been developed to restore mined aquifers to pre-mining (baseline) quality. Commonly used methods include ground water sweeping, clean water injection, and treatment by ion exchange and reverse osmosis technologies.

Ammonium carbonate lixiviant was used at one R&D in situ mine. Attempts were made to restore the aquifer using a variety of methods. Efforts were successful in reducing concentrations of the majority of contaminants to baseline levels. Concentrations of certain parameters, however, remained at levels above baseline six months after restoration ceased. Relatively large quantities of ground water were processed in the restoration attempt considering the small size of the project (1.25 acre). More thorough characterization of the hydrogeology of the site may have enhanced the effectiveness of restoration and reduced potential environmental impacts associated with the project.

This paper presents some of the findings of a research project conducted by the Mineral Resources Waste Management Team at the University of Idaho in Moscow, Idaho. Views contained herein do not reflect U.S. Nuclear Regulatory Commission policy.

#### Introduction

In situ mining of uranium in the United States is regulated by the U. S. Nuclear Regulatory Commission (NRC) or by state agencies under agreements with the NRC. To obtain a license from the appropriate agency for commercial production of uranium by in situ mining, a Research and Development (R&D) project must first be undertaken. An essential part of a successful R&D project is demonstrating the feasibility of restoring affected aquifers to pre-mining or "baseline" quality following mining.

Aquifer restoration is not fully understood and it is often more difficult and time consuming than predicted at the beginning of an in situ project. The purpose of this paper is to examine some of the problems encountered in restoring the mined aquifer at one R&D project with the objective of transferring this information to other sites so that similar problems elsewhere can be avoided.

In Situ Mining - What's Involved

Uranium in situ mining begins with identification of an ore body which ideally is isolated by impermeable strata. A mining solution (lixiviant) such as sodium bicarbonate and hydrogen peroxide is injected into the ore body through wells. Recovery consists of removal of the complexed uranium from solutions pumped from the ore body through recovery wells. Figure 1 shows plan views of typical R&D mine well fields. Uranium ore bodies mined by this technique occur in permeable sandstone units; the hydrostratigraphy at these sites typically consists of interbedded sandstones, siltstones and clays with coarse channel sand and gravel lenses of variable extent. Williams, Osiensky, Anastasi and Rogness (1984) provide a detailed discussion of the hydrogeological aspects of in situ mining.

In situ mining greatly reduces the types of environmental impacts usually associated with open-pit and underground uranium mining. Large quantities of waste rock and mill tailings are not generated because the uranium is removed from the ore body in situ. The potential for significant adverse impacts exists, however, in terms of contaminating

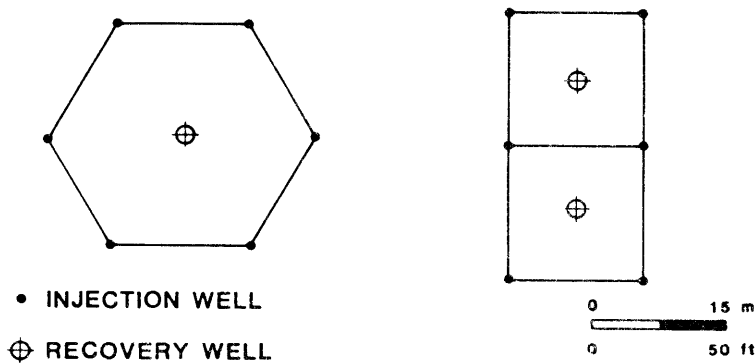


FIGURE 1. TYPICAL R&D WELL FIELD CONFIGURATIONS

potable ground water supplies. Theoretically, once the uranium has been recovered, water quality in the mined portion of the aquifer can be returned to baseline conditions. In reality, efforts to restore mined aquifers to baseline conditions have not been successful at many in situ mines.

### Case History

At one R&D in situ mine, a lixiviant of ammonium carbonate and hydrogen peroxide and/or oxygen was used in two small well fields (Anastasi, 1984). The first well field consisted of 12 wells and occupied approximately 0.25 acre surface area; mining operations were conducted for about 6 months. When the ore body was exhausted, lixiviant was withdrawn and transferred to a second well field consisting of approximately 20 wells and occupying approximately 1.0 acre. The ore body at the second well field was mined for about 9 months. Following mining operations, the ammonia concentration in the ore-zone aquifer was over 700 mg/l in the first well field and over 3,000 mg/l in the second. Consequently, restoration was geared toward ammonia removal.

Numerous attempts were made to restore water quality in the ore-zone aquifer at the mine to baseline conditions. Restoration of the first well field commenced with transfer of lixiviant to the second well field. A total of about  $3.5 \times 10^6$  l ( $9.2 \times 10^5$  gal) of solution, or about 5.4 pore volumes, were pumped from the first well field ore zone. This procedure produced a partial ground water sweep of the mined area. Ground water sweeping is a hydraulic method of restoration which removes contaminated ground water from the mined portion of the aquifer and replaces it with fresh ground water from surrounding portions of the aquifer. A general improvement in ground water quality resulted from this procedure. Ammonia concentrations were reduced to about 420 mg/l, however this concentration was still well above baseline. A more complete ground water sweep was impractical because no evaporation ponds had been constructed at the site to contain the quantity of water which would be produced by an extended ground water sweep.

Clean water recirculation with treatment by cation exchange was employed subsequent to the lixiviant transfer. The purpose of this additional effort was to reduce the concentrations of ammonium ( $\text{NH}_4^+$ ) and uranium in the ground water. In this water treatment method, solutions were pumped from the ore zone, run through two ion exchange columns (one for uranium removal and one for ammonium removal) and reinjected into the ore zone. However, the lower pH water injected into the ore zone dissolved calcium from the host sandstone; increased calcium concentrations resulted in the displacement of ammonium and hydrogen ions by calcium in the cation exchange resin and in the production zone clays. This series of chemical changes resulted in an increase in ammonia concentration in the aquifer from 420 to 630 mg/l. This method was abandoned after about  $2.8 \times 10^6$  l ( $7.5 \times 10^5$  gal) of water were treated by cation exchange. It is noteworthy that this procedure increased the ammonia concentration rather than decreased it; some lessons obviously can be learned from this experience.

Reverse osmosis technology was utilized next for restoration of the first well field. In this method of water treatment, solutions were pumped from the ore zone and run through a system which utilizes membranes to concentrate dissolved constituents into a waste stream. The resultant cleansed water was reinjected into the ore zone. This method was used for only 33 days. About 6.5 pore volumes of water were treated by reverse osmosis.

Removal of ammonia by air stripping was the final method of restoration used at the first well field. Sodium and/or potassium was added to ground water produced from the well field to promote the volatilization of ammonia. The water then was circulated through an air stripping column to aid dispersion of ammonia to the atmosphere. The treated water was reinjected into the ore zone following this procedure. Air stripping was discontinued when ammonia levels apparently had stabilized at 25 mg/l. Approximately 26 pore volumes were circulated through the air stripping column and subsequently reinjected.

A summary of the restoration efforts conducted at the first well field is presented in Table 1. A total of over 42 aquifer pore volumes (7 million gallons) of ground water were removed or treated in the attempts to restore the first well field. Although these efforts reduced significantly the concentration of ammonia in the aquifer, water quality data for a six month post-restoration stability period indicates that average concentrations of TDS, ammonia, arsenic, selenium, vanadium,  $^{226}\text{Ra}$  and pH exceeded baseline or Wyoming Department of Environmental Quality Class I (Domestic) standards. Table 2 presents a summary of these data.

TABLE 1  
SUMMARY OF RESTORATION

<u>METHOD</u>	<u>GALLONS (<math>\times 10^6</math>)</u>	<u>PORE VOLUMES<sup>1</sup></u>	<u>TIME (days)</u>	<u>NH<sub>3</sub> (N, ppm)</u>
Ground Water Sweep	0.9	5.4	15	420
Cation Exchange	0.75	4.5	11	630
Reverse Osmosis	1.1	6.5	33	140
Air Stripping	4.4	26.0	132	25

<sup>1</sup>Restoration was expected to require treatment of 2 to 3 pore volumes by reverse osmosis, or removal of up to 20 pore volumes by ground water sweep.

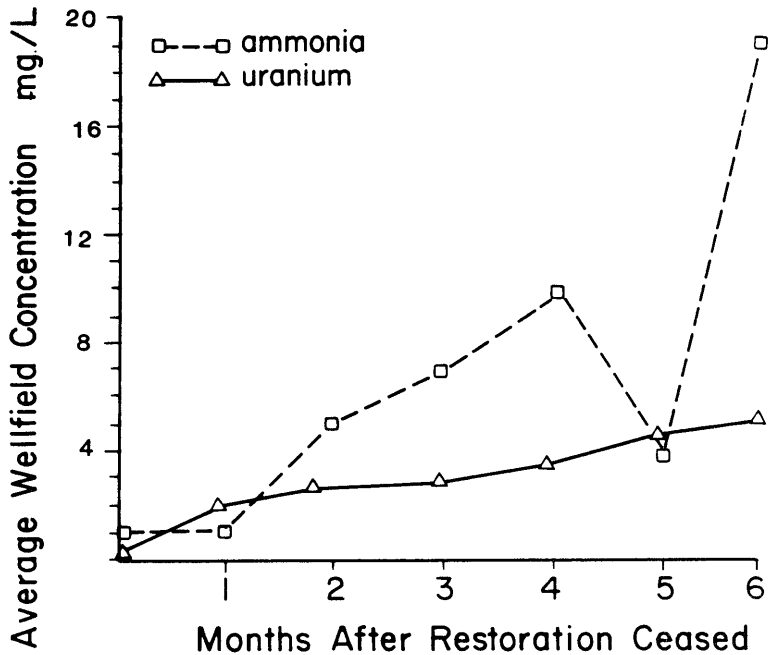
TABLE 2  
PARAMETERS NOT RESTORED TO ACCEPTABLE LEVELS

<u>PARAMETER</u>	<u>AVERAGE BASELINE<sup>1</sup></u>	<u>POST- RESTORATION<sup>1</sup></u>
Total Dissolved Solids (TDS)	414	582
pH	7.5-8.7	9.1
Ammonia	0.18	35
Arsenic	<0.02	0.335
Selenium	<0.01	0.79
Uranium	0.05	5.28
Vanadium	<0.05	0.33
Radium-226	21.6	>100
Sulfate	159	252

<sup>1</sup>Values in mg/ℓ except pH (standard units) and Radium-226 (pCi/ℓ)

Restoration of the second well field began with air stripping for ammonia removal. Over 12 pore volumes of ground water were treated; ammonia levels were reduced from about 3400 to 185 mg/ℓ. A ground water sweep was then initiated subsequent to the acquisition of an NPDES surface discharge permit for release of withdrawn water. Approximately 1.6 pore volumes of ground water were removed from the ore zone, circulated through ion exchange columns to reduce contaminants to levels prescribed by the permit, and discharged to the surface. Overall ground water quality was improved and ammonia levels dropped to 120 mg/ℓ following this restoration work. After the ground water sweep, air stripping was employed again to reduce ammonia. An additional 5.6 pore volumes of water were treated and reinjected during this time. Ground water sweeping was conducted again to reduce further the concentrations of ammonia and other contaminants. Approximately  $7.5 \times 10^5$  ℓ ( $2.0 \times 10^5$  gal) of fresh water pumped from an aquifer overlying the ore zone were injected into the ore zone near the end of this last phase of restoration of the second well field in a final attempt to reduce ammonia concentrations in localized areas.

Ammonia levels averaged 2.54 mg/ℓ at the end of the second well field restoration activities. A total of over 22 aquifer pore volumes (200x Million litre) were treated or removed in attempting to restore the ore zone. Although the ammonia concentration was reduced to 2.54 mg/ℓ, six months of post-restoration stability monitoring in the second well field indicated that ammonia, TDS, selenium, uranium, sulfate, pH and <sup>226</sup>Ra concentrations continued to exceed baseline and/or domestic quality standards. Furthermore, concentrations of ammonia, selenium and uranium in the second well field were observed to be increasing during the stabilization period (Figure 2).



**FIGURE 2. CONCENTRATIONS OF AMMONIA AND URANIUM AFTER RESTORATION CEASED.**

Possible Explanations for Restoration Problems

Numerous possible explanations may be offered for the problems encountered in restoration at this in situ mine. The case may be made that best practicable technology was not utilized in the restoration attempts. The absence of an evaporation pond at the site precluded conducting an extensive ground water sweep; this method has been successful at other in situ mines. Additionally, the emphasis on ammonia reduction led to reliance on the air stripping technique. While the method is effective at ammonia reduction, it does little or nothing in reducing concentrations of other dissolved contaminants resulting from in situ uranium mining. Reverse osmosis and electrodialysis water treatment techniques have been used successfully at some in situ mines to reduce the full spectrum of contaminants.

Another possible explanation of these difficulties may be that complex hydrogeological conditions at the site have complicated the restoration efforts. Leaky aquifer/aquitard systems are not uncommon at in situ mine sites. Ideally, the ore-bearing sandstone aquifer is overlain and underlain by "impermeable" shale or clay units. It is possible, however, that the aquitards at the site have sufficient hydraulic conductivity and specific storage to take lixiviant into storage during mining operations. When hydraulic gradients are reversed by restoration operations, lixiviant and dissolved constituents may bleed slowly back into the aquifer (Figure 3). This interpretation could explain the gradual increase in contaminant concentrations observed after restoration operations ceased at the mine discussed above. This phenomenon has been observed at other in situ mines also.

Heterogeneity and anisotropic conditions within the ore-zone sandstone aquifer might be complicating restoration efforts also. Complex velocity fields within the aquifer would result from such conditions, and lixiviant could migrate in preferred directions during mining along zones of high hydraulic conductivity. Additionally, lixiviant may be forced through zones of lower hydraulic conductivity under reversed hydraulic gradients induced by restoration activities. The result would be inefficient removal of lixiviant and contaminated ground water from the mined aquifer.

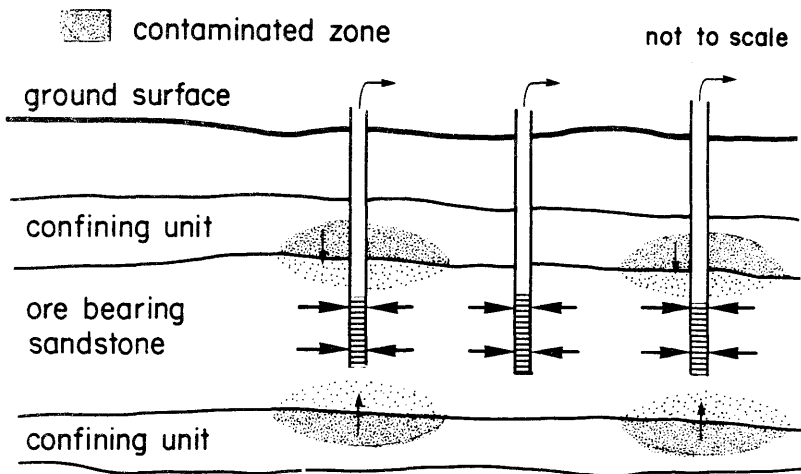


FIGURE 3. LIXIVANT RELEASED FROM STORAGE IN COMPRESSIBLE AQUITARDS.

### Recommendations for Minimizing Restoration Problems

Thorough characterization of the hydrogeology at an in situ mine site is essential to ensure a successful project. Once the complexities of the hydrostratigraphy are identified, mining and restoration operations can be planned with these considerations in mind. Extensive borehole geophysical data often are not collected at in situ mines. Given the fact that numerous boreholes are drilled at a site for well installation, effort should be made to obtain several important geophysical logs from the boreholes. These data can aid greatly in delineating heterogeneities and structural discontinuities which may affect mining and restoration activities. Sophisticated hydrogeologic testing methods and data analysis techniques should be utilized to determine the existence of leakage and anisotropic conditions. Hydraulic properties of aquitards as well as aquifers should be determined by field testing at each in situ site.

Multiple well aquifer pumping tests stress relatively large portions of the hydrogeologic system under in situ conditions. Methods for evaluating leaky aquifer conditions include those described by Hantush and Jacob (1955), Hantush (1960), and Neuman and Witherspoon (1972). These methods generally utilize observation wells completed in the ore-bearing aquifer and in overlying and underlying aquitards; vertical hydraulic conductivity of the aquitards can be estimated and water supplied from leakage can be detected using these methods. Plots of drawdown data vs. time that match the Hantush and Jacob (1955) type curves usually indicate significant vertical leakage from overlying and/or underlying aquifers occurs under pumping conditions. Similarly, data plots that match the Hantush (1960) modified type curves usually indicate that water is released from storage within confining aquitards. The ability of aquitards to release water from storage under pumping conditions indicates that lixiviant may be driven into the aquitards during mining and it may bleed slowly back into the aquifer during and after restoration. Quantification of the vertical hydraulic conductivity of aquitards can give an indication of the degree to which lixiviant will infiltrate the confining units during mining. Under ideal hydrostratigraphic conditions this problem should not occur; but if confining units are compressible, permeable or discontinuous lixiviant can be stored within them or move through them to overlying or underlying aquifers where lixiviant may be stored.

The ratio of horizontal to vertical hydraulic conductivity (anisotropy) of the ore-zone aquifer may be determined by aquifer testing using the method of Weeks (1969). This method of analysis utilizes drawdown data collected from partially penetrating piezometers or observation wells near a partially penetrating pumping well and can be applied to unconfined and confined ore-zone aquifers. Knowledge of anisotropy may be used to model the expected distribution of lixiviant throughout the aquifer during mining, and restoration operations can be tailored accordingly taking such anisotropy into account.



Finally, sufficient impoundment capacity should be available to facilitate ground water sweeping. Although methods of water treatment may be utilized also, this hydraulic method has been demonstrated to be an effective means of aquifer restoration. An evaporation pond must be constructed at the site for this technique to be an option.

Unfortunately, such sophisticated hydrogeologic testing and geophysical logging techniques have not been utilized at many in situ projects in the past. Typically, hydrogeologic testing has emphasized determination of directional transmissivities of the ore-bearing aquifer in the horizontal plane (not the vertical plane) to guide placement of injection and recovery wells to maximize uranium recovery efficiency. Geophysical logging is used mainly to identify ore-bearing horizons in the host sandstones. In view of the problems associated with aquifer restoration after in situ mining as demonstrated by the preceding discussion, and in view of the obvious relationship of hydrogeologic conditions to these problems, it seems likely that thorough determination of the hydraulic properties of aquitards and of ore-zone aquifers at potential mine sites will enhance the effectiveness of restoration and benefit the in situ mining process in general. In the long run, the economics of in situ mining will be enhanced by such testing because the cost of ore-zone aquifer restoration will be reduced.

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