ISSUES OF AQUIFER LEAKAGE IN IN-SITU URANIUM MINING

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ABSTRACT

Regulatory agencies require operators of uranium in-situ mines to demonstrate that there is adequate hydraulic confinement of the ore zone aquifer by upper and lower strata of low permeability. The purpose of the regulation is to prevent the migration of potentially hazardous lixiviant out of the ore zone aquifer, or to assure its subsequent return should it penetrate the confinement. In most cases, the ore zone is not totally confined. There is some leakage or hydraulic communication between the ore zone aquifer and its confining beds. The potential for leakage does not necessarily mean that mining by in-situ methods is environmentally hazardous. Generally, leakage tends to disintensify the pressure field between injection wells and the production well, causing lixiviant travel distances and times to be greater. However, natural features of the production aquifer usually alleviate this situation. These features include the limited vertical extent of the ore zone within the production aquifer, and stratification of the production aquifer. The impact of leakage can further be reduced by the design of the operational features such as well spacing, pumping and injection rates, and partial screening of wells. This paper demonstrates the simulated effect of leakage on a hypothetical in-situ leach operation with three different magnitudes of confinement leakage. A fourth case examines the effects of stratification of the ore zone aquifer upon the flow pattern and lixiviant travel times.

INTRODUCTION

One of the conditions which must be satisfied for in-situ uranium mining to be feasible is confinement of the uranium hosting aquifer. Aquitards, the confining beds which provide this confinement, usually are slightly permeable, and have considerably higher capacity to store water than the aquifers which they isolate. Thus, the aquitards do not provide total impermeable confinement; they have the ability to conduct water, release water from their storage and interact with aquifers they contact. In this paper, leakage is considered to originate from a source bed overlying the aquitard; the aquitard serves only as a path of fluid transmission, but not as a source of water.

At the onset of pumping a single well in a confined aquifer, most water comes from depressurization of the aquifer itself. As the pumping time progresses, contribution from confining beds in the form of leakage becomes an increasingly significant source of the well's water, and the aquifer acts as a drainage gallery. Such an aquifer is termed "leaky", although, in fact, it is the aquitards which are leaky. Drawdowns in leaky aquifers are less than what would be expected in totally confined aquifers, because of the additional source of water. Thus, gradients towards the production well are reduced. Figure 1 illustrates the difference between drawdown in leaky and non-leaky aquifers.

When the leakage is assumed to be derived from a source bed overlying the uranium hosting aquifer, the magnitude of leakage is commonly characterized by a leakage factor B, which is a comparison between the resistance to flow in the aquitard to resistance to flow in the aquifer. The leakage factor is quantified by the following relationship:

$$B = (Tb'/K')^{1/2} \; [L]$$

where T = transmissivity of aquifer $[L^2/t]$

b = thickness of aquitard [L]

K' = vertical hydraulic conductivity of aquitard [L/t]

If the leakage factor is high, the influence of leakage on the aquifer response to pumping is small. Conversely, a low value of the leakage factor indicates a high influence of leakage upon the aquifer response.

In the mining phase of an in-situ operation, the leakage tends to lengthen the time needed for lixiviant breakthrough from injection to pumping wells. Similarly, during the restoration phase, leakage will lengthen the time required for the lixiviant to be retracted from contacted sections of the aquifer. This happens as a result of reduced hydraulic gradients between the injection and pumping wells.

This paper shows that in most situations where confining beds of permeability lower than the aquifer they isolate are present, the leakage has a negligible effect on in-situ mining. If the leakage is locally high, the mine operator may still be in a position to mitigate its effect by modification of the operational factors over which he has control.

Additionally the beneficial effect of aquifer stratification in controlling lixiviant flow patterns is demonstrated. Since the aquifer stratification may act as "confinement-within-the aquifer", the desirability to adequately quantify this phenomenon has been addressed.

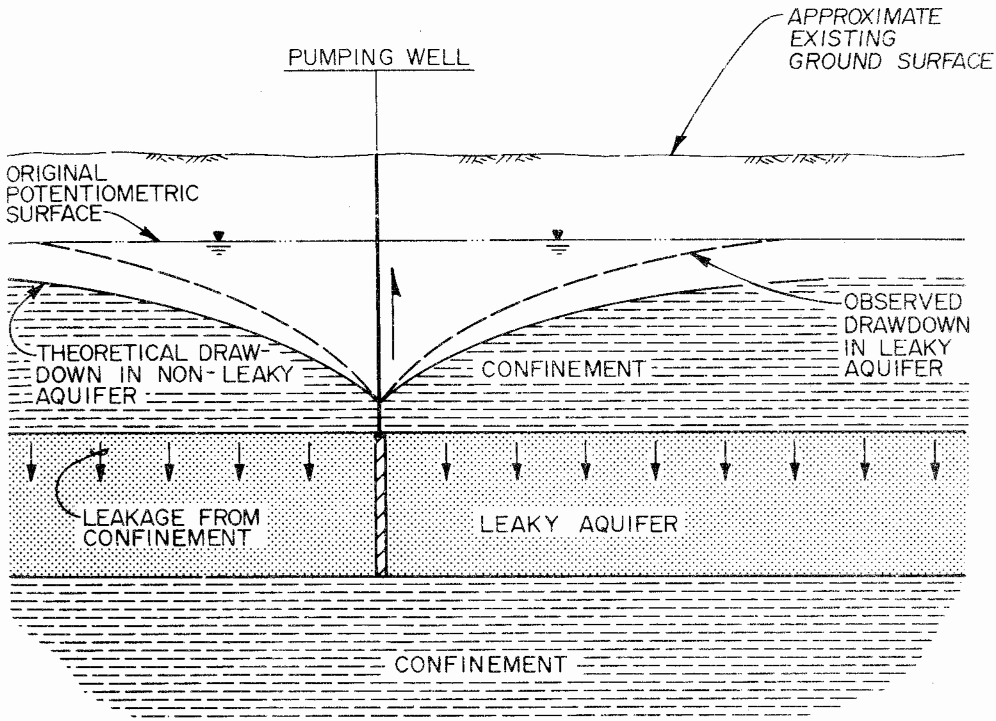


FIGURE 1

DRAWDOWNS IN LEAKY
AND NON-LEAKY AQUIFERS

COMPUTER SIMULATION

The effects of leakage were assessed by comparison of steady-state computer simulations of a hypothetical in-situ leach operation, with magnitudes of the leakage factor B, ranging from a value near infinity (representative of an ideally confined, nonleaky aquifer), to 440 meters (representative of a typical leaky system with regard to confinement thickness and permeability), through a situation where the leakage factor approaches zero (thin confinement and permeability on the order of that of the aquifer). A fourth scenario demonstrates the effect of stratification of the ore zone aquifer upon the flow pattern and lixiviant travel times.

The hypothetical operation consists of a single 15.24-meter square five-spot production cell. The mineralized section is approximately in the middle of the aquifer. The horizontal and vertical configuration of the production cell is shown on Figure 2. The pumping and injection wells are partially penetrating the 30.48-meter thick aquifer, with the screened interval of the pumping well equal to the thickness of mineralized section of the aquifer, and the screened interval of the injection wells equal to one-half of the thickness of the mineralized section. The hypothetical aquifer is horizontally isotropic with a hydraulic conductivity of 10^{-3}cm/sec, storage coefficient of 10^{-4} and porosity of 25 percent. The vertical permeability is equal to the horizontal permeability, except where noted.

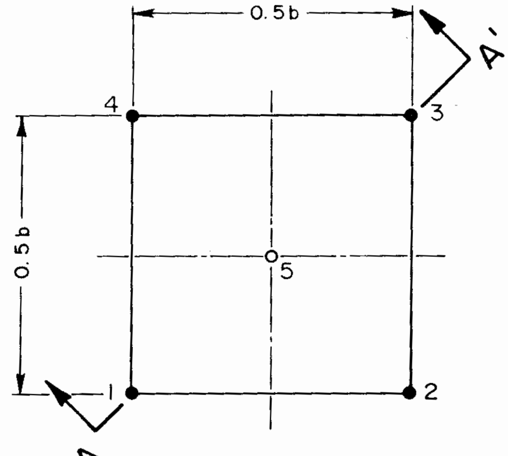
Scenario A - Impermeable Confinement

A nearly totally confined aquifer is characterized by the leakage factor, B, approaching infinity. For modeling this case, the thickness of the aquitard is assumed to be three times the thickness of aquifer, and its permeability in the range of 10^{-7} cm/sec (four orders of magnitude lower than that of aquifer). For this permeability contrast and aquifer/aquitard geometry the leakage factor is approaching infinity. Figure 3 shows the pattern of the lixiviant flow lines in the vertical direction in this aquifer after 1 year of operation. As shown, the aquifer section contacted by lixiviant extends 85 percent of its thickness, with 15 percent of the aquifer unaffected by lixiviant. The maximum distances traveled by the lixiviant away from the pattern in the horizontal plane is approximately one half of the aquifer's thickness. The potential for uncontrollable excursions in the vertical and horizontal directions appears minimal. The average arrival time for flow particles at mid-screen in the horizontal plane to arrive at the production well is 32 days.

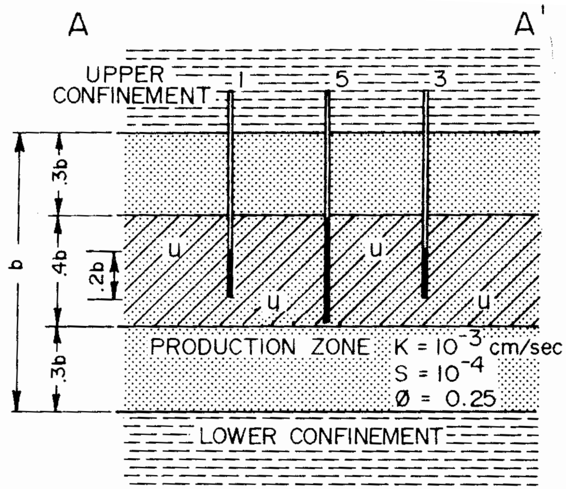
Scenario B - Leaky Confinement

This is the most realistic case. Aquitards interact with the aquifer by contributing some recharge to the aquifer depending on pressure differential and the aquitard's permeability.

As illustrated on Figure 4, the thickness of overlying aquitard is assumed to be three tenths of the aquifer thickness, or 9.1 meters. The aquitard



PLAN VIEW



CROSS SECTION A-A' (TYP.)

LEGEND:

- ● INJECTION WELL
- ○ PRODUCTION WELL
- ┃ WELL SCREEN

WELL DESIGNATION	FLOW RATE, l/min. (+ = INJECTION) (− = PRODUCTION)
1	+ 19
2	+ 19
3	+ 19
4	+ 19
5	- 78

FLOW RATES DURING MINING

FIGURE 2
FIVE-SPOT PATTERN AND AQUIFER CROSS SECTION FOR COMPUTER SIMULATIONS

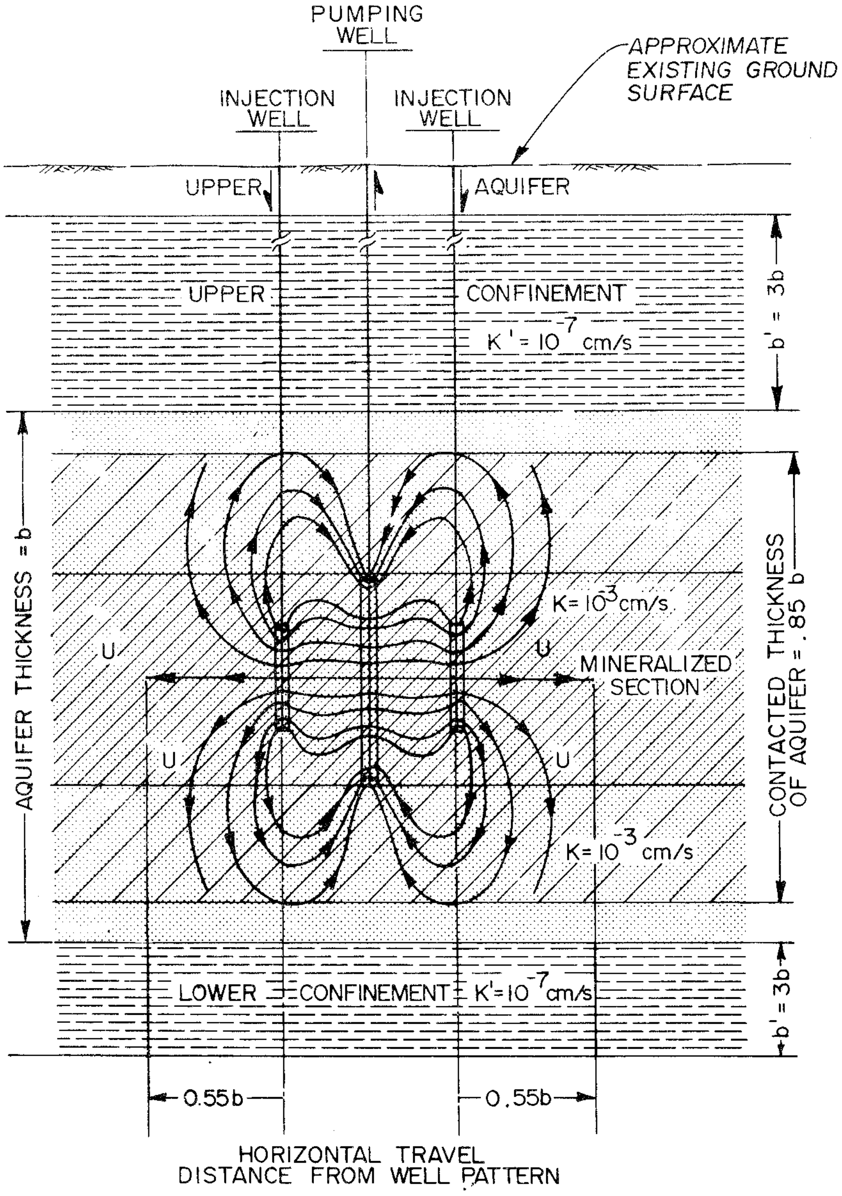


FIGURE 3

SCENARIO A

IMPERMEABLE CONFINEMENT

B = →∞

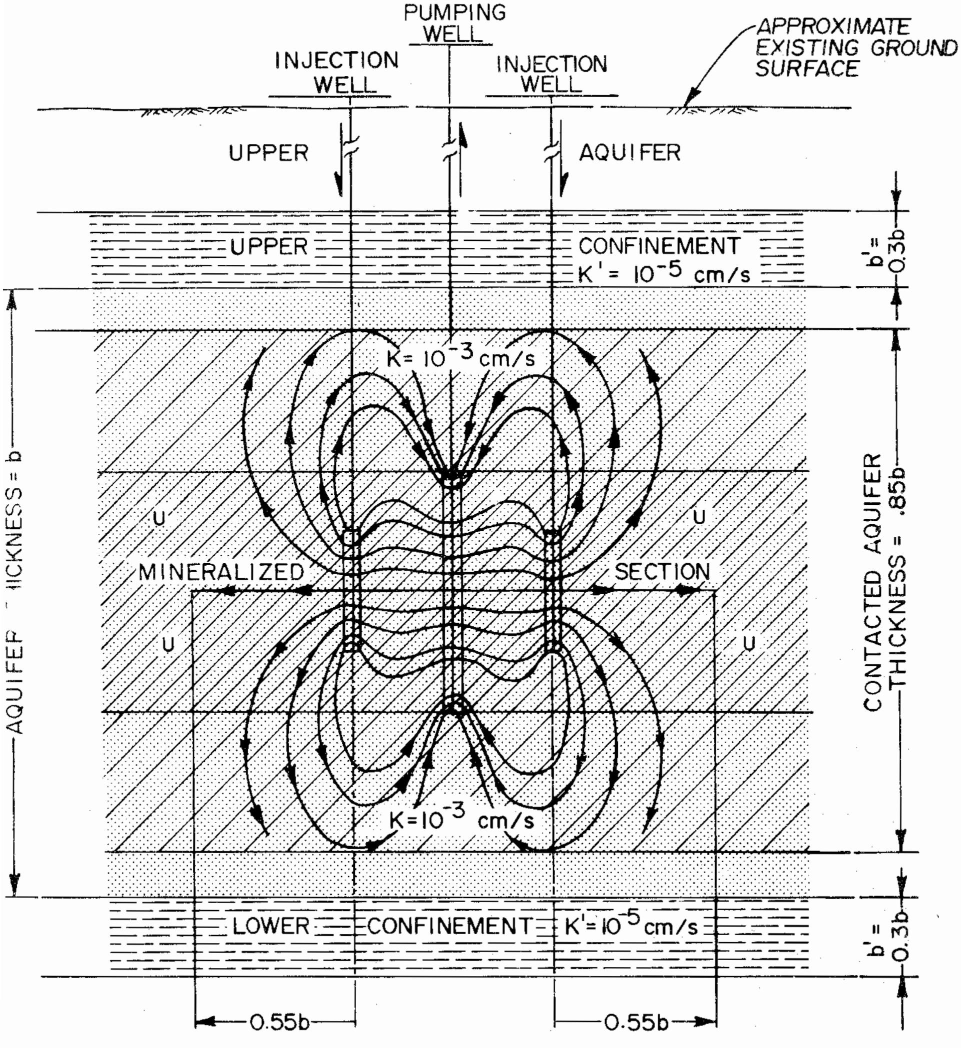


FIGURE 4

SCENARIO B

LEAKY CONFINEMENT

B= 134 m (440 ft.)

permeability is two orders of magnitude lower than the aquifer's permeability, or 10^{-5}cm/sec. The permeability contrast and aquifer/aquitard geometry renders the leakage factor B = 134 meters. This value is commonly encountered in in-situ leach operations in Wyoming. Figure 4 shows that this leakage has a negligible effect on the configuration of lixiviant flow lines, contacted thickness of aquifer, and lixiviant travel distances. The average arrival time for flow particles at mid-screen in the horizontal plane to arrive at the production well is approximately 33 days; only a matter of one day longer than for the nonleaky case. The thickness of aquifer contacted by lixiviant and maximum distances traveled by the lixiviant away from the pattern in the horizontal plane remains unchanged.

Scenario C - Thin and Highly Permeable Confinement

This scenario is examined to show that lixiviant movement can be controlled to prevent its contact with overlying and underlying strata, as well as from traveling away from the pattern to distances where its retrieval during restoration would be impossible.

The situation is shown on Figure 5. The confinement thickness is only five percent of the aquifer's thickness, and its permeability is 10^{-4} cm/sec, one order of magnitude less than that of the aquifer. The value of the leakage factor B is 17.4 m. Flow lines show the tendency to depart from the production cell. This is a result of weakening of the source/sink potential between the pumping and injection wells by the leakage contribution from confinement.

For a mining time of 1 year, equal to the operation times of Scenarios A and B, the lixiviant travel distance away from the pattern in the horizontal direction is equal to 60 percent of the aquifer's thickness. The lixiviant contacts 90 percent of the aquifer's thickness; those values are less than 10 percent higher than for Scenarios A and B, where perfect or adequate confinements were present. Control on the lixiviant movement in such a situation is more difficult to maintain and the economy of mining may be questionable. The most severe impact of leakage is observed in the average lixiviant breakthrough time of 71.6 days, approximately twice that of Scenarios A and B. This increase in travel time was manifested to the greatest extent by increased travel times along the streamlines sweeping the largest areas. This reinforces the concept that under such conditions, leakage effects can be mitigated by using a smaller well spacing.

Scenario D - Stratified Ore Zone Aquifer

The situation depicted in Scenarios A, B and C addressed mining in aquifers where vertical permeability is equal to horizontal. This constituted a "worst case" situation. Normally, sedimentary aquifers encountered at in-situ mining sites have a greater capacity to transmit flow in the horizontal than in the vertical direction. To demonstrate the effects of such anistropy, Scenario C (highly permeable confinement) was remodeled with a vertical permeability of 1/10 of the horizontal permeability of the ore zone aquifer. The results, shown of Figure 6, reveal a greatly reduced limit of vertical movement. The maximum lixiviant travel distance in the

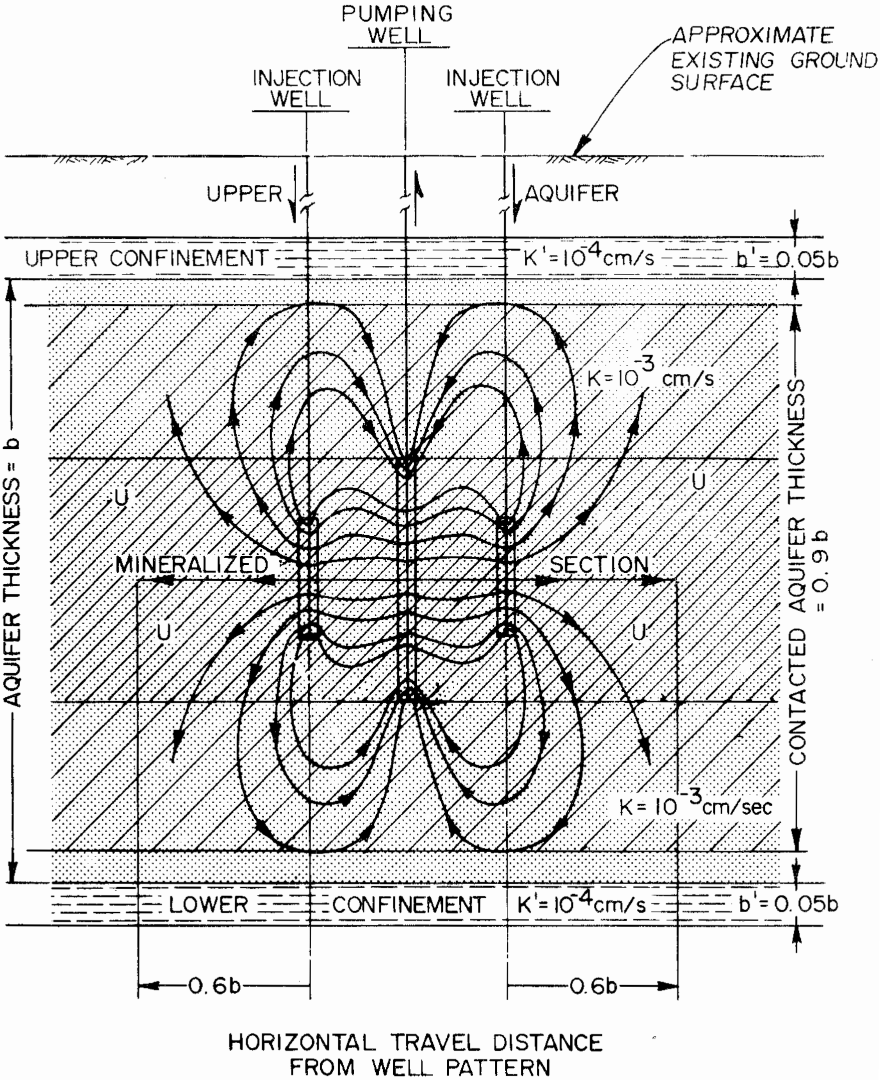


FIGURE 5

SCENARIO C

THIN AND HIGHLY PERMEABLE CONFINEMENT

B= 17.4m (57 ft.)

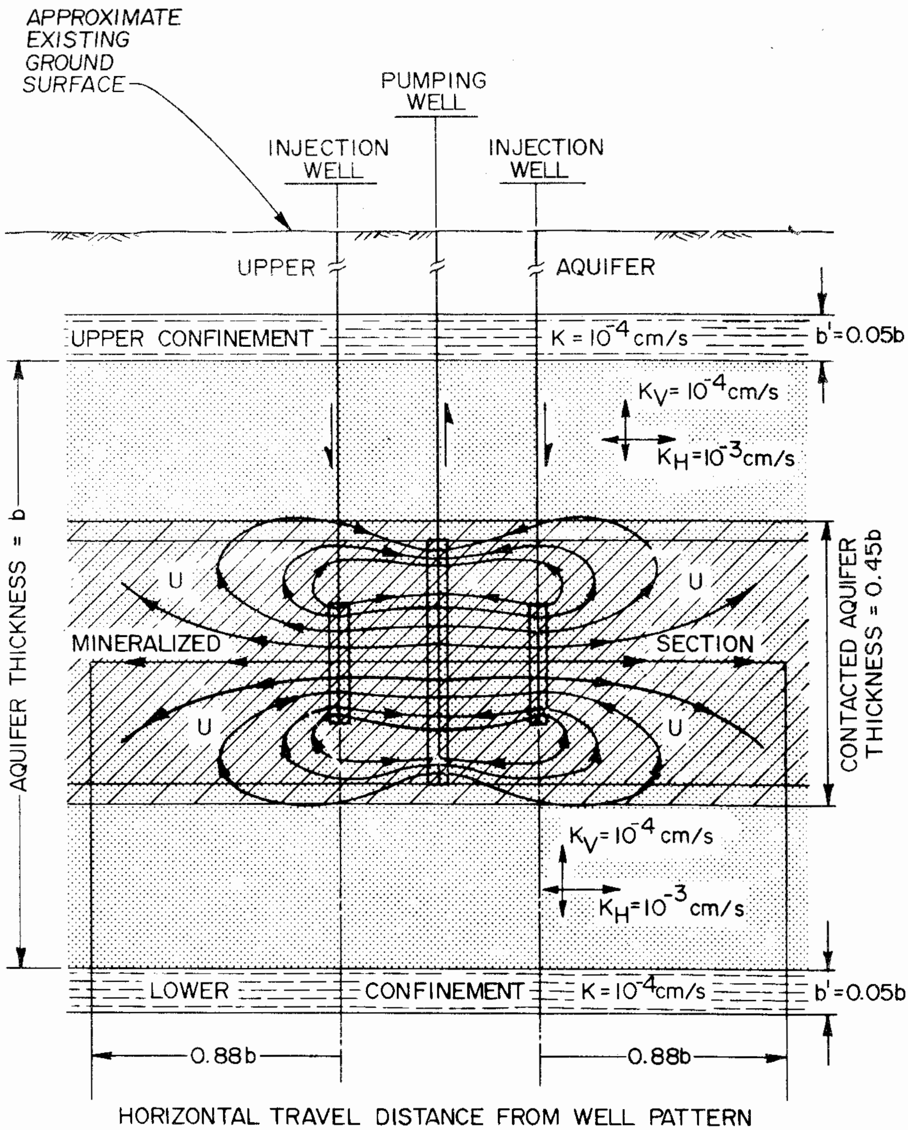


FIGURE 6

SCENARIO D

STRATIFIED ORE ZONE AQUIFER

B=17.4 m (57 ft.)

vertical direction outside the mineralized section is less than 5 percent of the aquifer thickness, approximately 40 percent less than in the case of nearly ideal confinement. The average travel time for particles in the horizontal plane to arrive at the production well is 5 days. The travel time is six times shorter than for cases A and B despite their numerically higher leakage factors. This suggests that permeability contrasts are worthy of investigation during aquifer testing for in-situ mining. The maximum lixiviant travel distance outside the well pattern in the horizontal plane at mid-screen is 88 percent of the aquifer's thickness, which is 30 percent greater than the departures for Scenarios A and B. This reflects the tendency for lixiviant to move laterally as opposed to vertically.

SUMMARY AND CONCLUSION

The scenarios presented for lixiviant flow behavior in response to various magnitudes of leakage are no doubt gross simplifications of "real life" situations faced by mine operators. Their purpose is not to downgrade the role of adequate confinement; it rather is to show that leakage, however high, does not necessarily prevent mining by the in-situ method.

Leakage to the aquifer from which uranium is mined may affect the in-situ leach process if the vertical permeability of the confining units is not significantly less than the vertical permeability of the mineable horizon itself. Natural factors which have an influence on lixiviant flow patterns, and which tend to make this requirement less significant during both mining and aquifer restoration phases are stratification (layering) of permeability within the aquifer, and positioning of the mineralized zone of the aquifer with respect to the confining beds.

The operational factors which may govern the flow pattern include:

- rate of over-pumping
- pumping/injection rates
- spacing of pumping and injection wells
- time of operation
- screened interval

The operator has no control over the natural factors affecting lixiviant flow; nevertheless, through the right combination of operating factors he may be able to demonstrate to the regulatory agencies the feasibility of mining via the in-situ method even if natural conditions are not overly favorable. The results of the computer simulations, which are based on data acquired during exploration as well as on data supported by referenced sources, can also serve as a guide as to the required level of complexity of the hydrogeological testing for regulatory permitting. If preliminary modeling shows a possibility of lixiviant contacting the confinement, the hydraulic properties of the confinement should be addressed in detail. If modeling demonstrates that lixiviant will be confined to the mineralized section and separated from other aquifers by thick and virtually impermeable confining beds, less complex tests on the nature of the aquifer/aquitard interaction may prove satisfactory for permitting agencies. In any case, aquifer/aquitard testing, data interpretation, and presentation of results should be carried out according to conditions existing at the site, as well as to proposed operational factors.