

TRAVEL TIME IN GROUND WATER  
THEORETICAL BASIS

This document presents calculations of the time required for chemical species dissolved in ground water to travel from the plant to the property boundary (Indiana Street). The calculational method assumes only advective transport with no chemical/physical retardation. In order to evaluate the effects of these assumptions on the predicted travel time, this document begins with a discussion of transport processes.

TRANSPORT PROCESSES

The movement of dissolved chemical species in ground-water systems is controlled by advection, dispersion and physical/chemical reactions (e.g., Freeze and Cherry, 1979). Each of these is described below.

Advection

Advection is the bulk movement of dissolved ions with the ground water (Freeze and Cherry, 1979). Advection is generally mathematically described using Darcy's Law,

$$Q = KAi,$$

in which

- Q = Volumetric flowrate [L<sup>3</sup>/T]
- K = Hydraulic conductivity [L/T]
- A = Bulk cross sectional area [L<sup>2</sup>], and
- i = Hydraulic gradient [L/L].

In these definitions, the symbols shown in square brackets are the fundamental units of the parameters in terms of length [L] and time [T].

Darcy's Law is then rewritten using

$$Q = AV$$

in which

$$V = \text{Velocity [L/T]}$$

and all other symbols are as previously defined.

Additionally, the area is reduced to account for the actual area through which the flow occurs rather than the cross sectional area of the aquifer as used in Darcy's original

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experiments. This correction is necessary in order to calculate the velocity of the water and ions through the pores. The actual area through which the flow occurs is the area of interconnected pores, a factor generally somewhat less than the porosity of the medium that is known as the effective porosity. Thus the expression

$$Q = AV$$

is modified using

$$A_e = An_e$$

in which

$A_e$  = Effective area through which flow occurs [L<sup>2</sup>], and  
 $n_e$  = Effective porosity [L<sup>3</sup>/L<sup>3</sup>].

Thus,

$$\begin{aligned} V &= Q/A_e \\ &= Ki/n_e \end{aligned}$$

Generally these parameters are fairly well known except effective porosity. Hydraulic conductivity values are developed based on field tests and the range of values is usually averaged unless there are data to suggest the presence of a continuous zone of high hydraulic conductivity material. The hydraulic gradient is developed based on potentiometric surface measurements. The effective porosity can be determined by field tests (tracer tests) or by lab tests. In addition, the effective porosity can be estimated as less than the total porosity but not less than about 10% in porous, non-fractured media. It is my opinion that field testing for effective porosity determination (involving the injection of a foreign substance into the subsurface) is rarely warranted given that the uncertainty of the effective porosity value is only about a factor of three.

### Dispersion

Dispersion is a mixing and spreading process thought to be caused by velocity variations between water flowing in individual pores and by molecular diffusion (Anderson, 1979). The current mathematical formulation of dispersion provides a poor simulation of field behavior and the coefficient used to

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describe mechanical mixing has been found to vary with the scale of the problem. Molecular diffusion, mixing under a concentration gradient, is generally negligible except in very low velocity systems.

The effect of dispersion on the arrival time of a solute at an arbitrary point downgradient is shown diagrammatically on the Figure 1. It can be seen that dispersion causes the solute to arrive more quickly but at a reduced concentration. The solute is at half the concentration assumed in non-dispersed travel time calculations at the calculated arrival time. In addition, dispersion causes the full concentration to arrive at a later time than would be calculated for non-dispersed flow.

Because the mathematical formulation of dispersion is inadequate, I generally neglect dispersion in travel time calculations. Neglecting dispersion means that the early, low concentration arrival is not considered and that the concentration at the advected arrival time is over-estimated. This may or may not be conservative, depending on the specifics of each case.

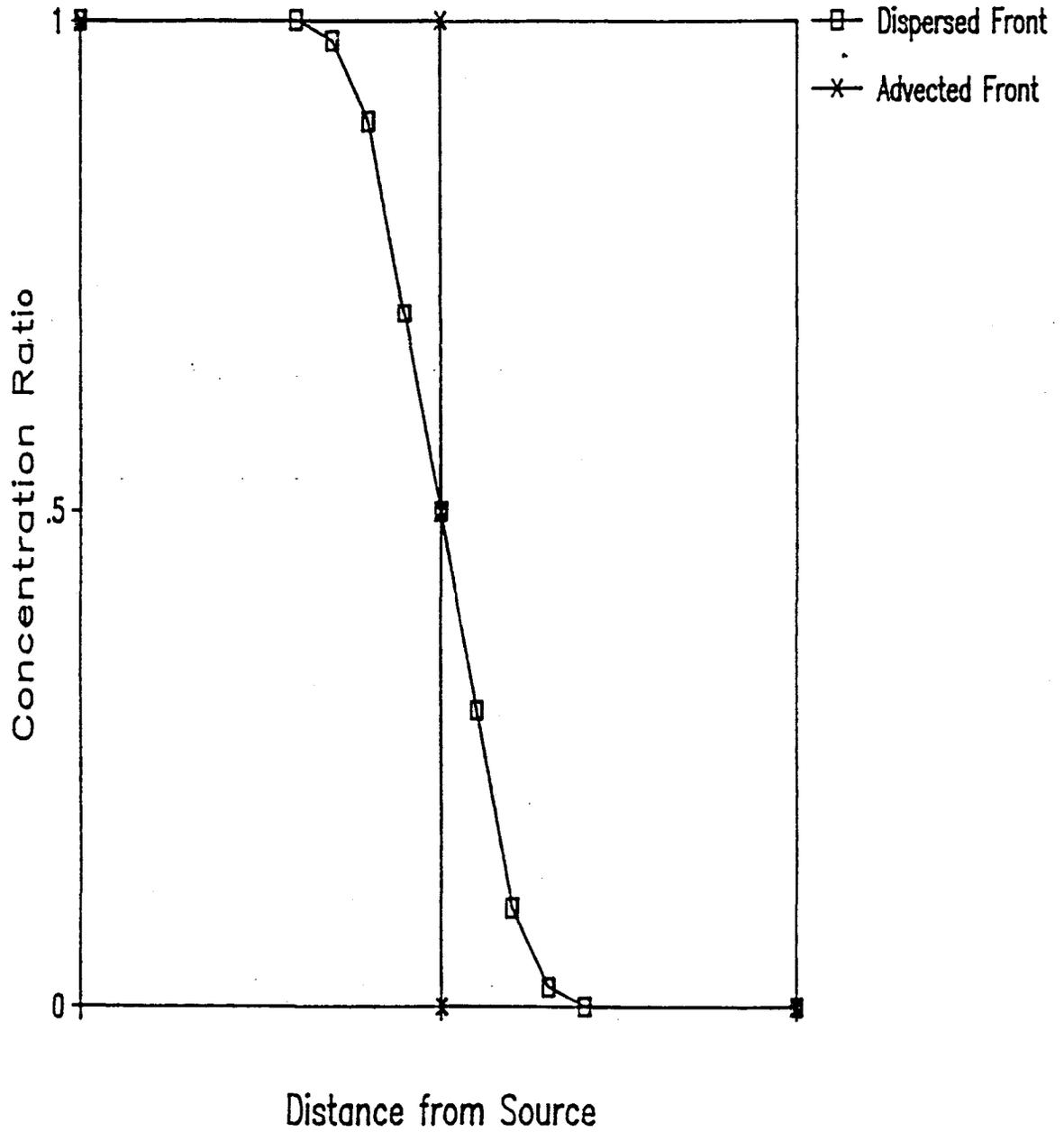
Physical/Chemical Processes

There are many physical/chemical processes than can alter ionic concentrations during transport in the subsurface. The most important of these are as follows.

1. Dilution -- simple mixing of different waters without chemical transformation. Dilution ratios can be estimated by comparing the recharge area impacted by the source to the rest of the recharge area.
2. Ion exchange -- the adsorption of ions onto solids (generally clays) because of preferred valence and size or under concentration gradients, with consequent release of the ions that were adsorbed (Hem, 1985).
3. Precipitation -- controlled by oxidation/reduction conditions and pH, precipitation of metals with simple salts and oxide/hydroxides is perhaps the most important retardation mechanism (see Markos, 1979 or Hem, 1985, for an explanation of these

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Figure 1. Advection/Dispersion Diagram



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processes). The lack of significant metal contamination at the plant is probably due to both the low solubility of the radionuclides and other metals coupled with co-precipitation of any metals that do get into solution.

4. Complexing -- complexing of metals with bicarbonate and sulfate anions can be an important mechanism for keeping the metals in solution as hybrid molecules under either electrostatic or covalent bonding (Garrels and Christ, 1965; Stumm and Morgan, 1970). The complexes then move with nearly the mobility of the anion, although the metal concentrations that can be kept in solution by this mechanism are generally low.
5. Volatilization -- generally associated with the direct transformation of dissolved organic compounds in ground water to the gaseous phase as a result of high gas/liquid partitioning coefficients apparently associated with the high vapor pressures, low molecular weights and low solubilities of the organic compounds (Thompson and Marrin, 1987). Although volatilization of organic compounds is well documented, the process generally does not significantly retard the movement of an organic plume. Other compounds may also volatilize, notably carbon dioxide and methane.
6. Radioactive Decay -- the disintegration of unstable atoms by the emission of ions, electrons and short wavelength electromagnetic radiation (Adamson, 1973). As can be seen in Table 1, the half-lives of the compounds of interest are generally long enough that the process is not an important retardation mechanism.
7. Biologic Transformation -- many organic and some inorganic compounds can be transformed by microorganisms to produce energy and gases of CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>, H<sub>2</sub>S, N<sub>2</sub>, NH<sub>3</sub> and NO (EPA, 1987). Microbial processes can significantly retard the movement of dissolved organic compounds and nitrogen species.

The above described physical and chemical processes (with the exception of dilution) have potentials to occur that are generally described by equilibrium constants. Thus, it is

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Table 1. Half-lives of Selected Radionuclides

<u>Radionuclide</u>	<u>Half-life (years)</u>
Tritium	12.4
Pu-238	92
-239	$2.4 \times 10^4$
-240	$6.6 \times 10^3$
-242	$5 \times 10^5$
U-234	$2.4 \times 10^5$
-235	$7.1 \times 10^8$
-238	$4.5 \times 10^9$

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Note:

Data from Davis and DeWiest (1966) and O'Connor (1974).

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possible to evaluate which process is most likely to occur and even to predict theoretical concentrations at equilibrium. However, the time required for equilibrium to be achieved is unknown. This means that the importance of the processes in each specific flow system can not be predicted without extensive field data. Because of these uncertainties, it is often assumed that all constituents of interest are conservative (non-retarded) and neglect physical/chemical reactions. This is clearly conservative in the engineering sense.

PREDICTION OF TRAVEL TIME

As described above, it is considered appropriate and generally conservative to estimate travel time using advective transport only and to assume that the dissolved constituents are non-retarded. Flow in alluvial materials and in bedrock are discussed separately below.

Alluvial Materials

The ground-water pathway in alluvial materials for offsite flow is as follows:

- 1) from the source toward the drainages in Rocky Flats Alluvium, on top of claystone bedrock;
- 2) from the Rocky Flats Alluvium through various colluvial materials on the slopes and into the Valley Fill Alluvium; and
- 3) in the Valley Fill Alluvium toward the property boundary.

Because this is a general evaluation and the source location is unknown, the time required for flow from the source to the slope material and then down the slope to the Valley Fill Alluvium is neglected. The following considers only the transport time in Valley Fill Alluvium to the boundary.

The Valley Fill Alluvium is a gravel with some cobbles and sand. The most conductive of this material occurs in the Woman Creek drainage where it has an average (geometric mean) hydraulic conductivity of  $8 \times 10^{-4}$  centimeters per second (cm/s) and a maximum of  $3 \times 10^{-3}$  cm/s (Table 5-2 of DOE, 1988, as re-analyzed in response to EPA comments).

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Flow in the alluvium occurs in response to infiltration events, and the alluvium desaturates following the event by down-valley flow and evapotranspiration. High evaporative losses have been noted repeatedly in investigations of the Valley Fill Alluvium. Hurr (1976) notes that as much as 0.25 cubic feet per second was lost to evapotranspiration along Woman Creek during the period July to September, 1974. Both Rockwell (1986) and DOE (1988) comment on evapotranspirative losses from the valley fill alluvium, based on water level records. Six of the nine wells completed in the Woman Creek alluvium have been dry during at least some portion of the year since their construction. DOE (1988) presents water level data that are reproduced here as Figure 2, which shows that the Valley Fill Alluvium is dry at three locations from about July 1 to October 1 (3 months).

The travel time for a non-attenuated constituent to reach the property boundary in the Valley Fill Alluvium is in the range of 20 to 77 years. This is calculated as follows.

The velocity is in the range of 170 to 650 feet per year, using either the grade of the base of the alluvium or the ground surface as the gradient (both equal 0.021), an hydraulic conductivity in the range of  $8 \times 10^{-4}$  to  $3 \times 10^{-3}$  cm/s, and an effective porosity of 0.1.

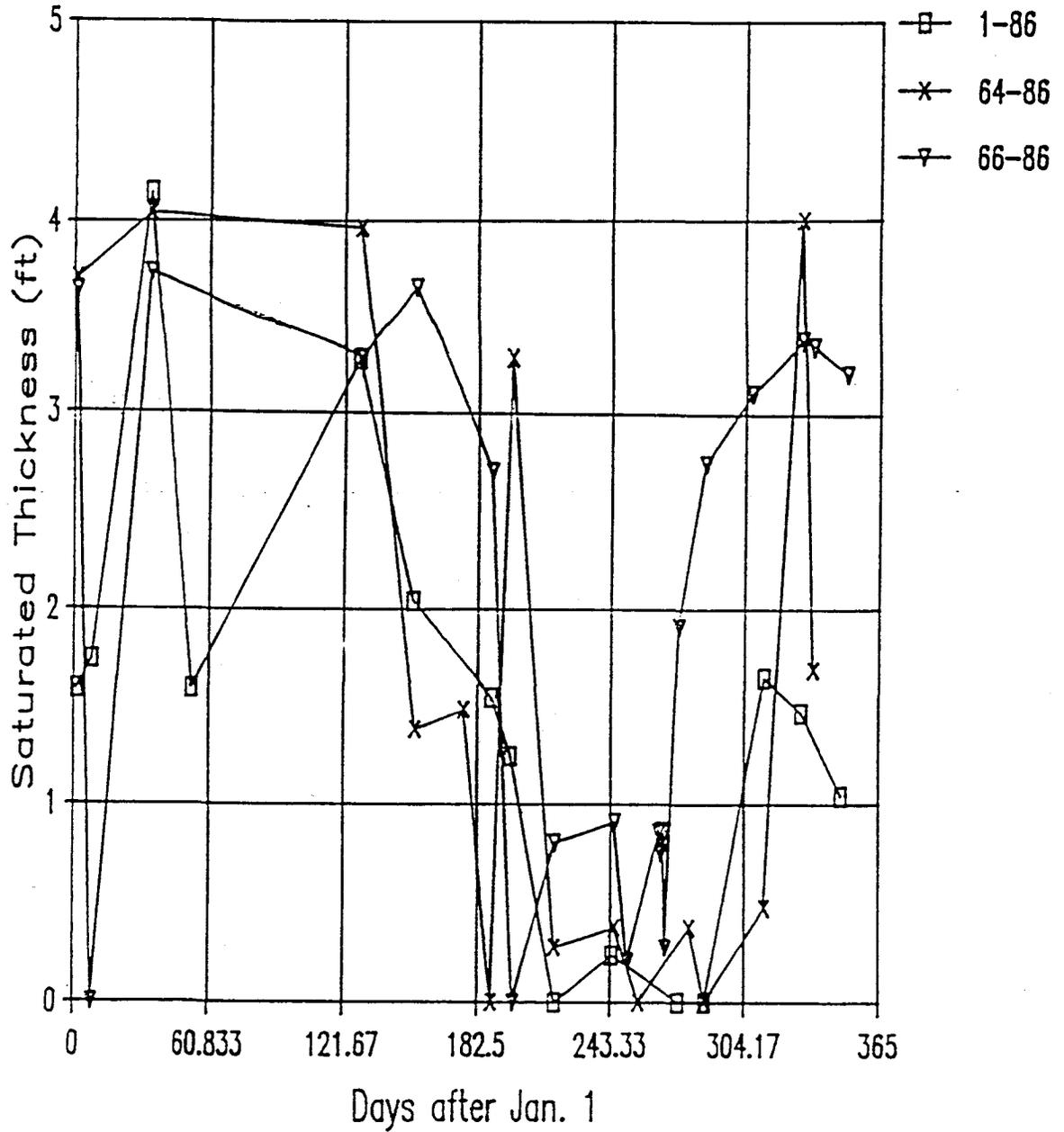
A dissolved particle travels only a portion of this distance each year because the alluvium is not saturated for the full year. Assuming that the alluvium is saturated for about three-quarters of the year, the dissolved particle would travel approximately 130 to 490 feet during the year.

The property boundary is approximately 10,000 feet from the source (distance between wells 64-86 and 1-86).

This calculation is considered conservative because the effective porosity is likely to be higher than the value used (as much as a factor of 3). Thus, the uncertainty regarding the effective porosity is more significant and tends to offset the correction for non-continuous saturation. Also, travel times are calculated for both the maximum and the average hydraulic conductivities. The travel time estimated using the average hydraulic conductivity is considered the most reasonable (77 years) because all reactive retardation

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Figure 2. Composite Hydrograph of Wells 1-86, 64-86 and 66-86



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processes are neglected in the calculations and, according to Mackay et al. (1985), the organic solvents of interest can be expected to migrate at rates two to three times slower than the ground-water velocity.

In addition, the calculation is extremely conservative because it neglects the travel time from the source to the Valley Fill Alluvium. For example, volatile organics in colluvial ground water at the 881 Hillside have moved approximately 200 feet (midway between wells 4-87 and 47-87) from the source near 9-74 in 15 to 18 years. Based on this velocity, it will require another 19 to 23 years before the organics travel the additional 250 feet to the Valley Fill Alluvium. Thus, organics from the 881 Hillside are not expected to reach the property boundary (well 1-86) for approximately 97 years (20 years in colluvium plus 77 years in Valley Fill).

Bedrock Materials

The ground-water pathway in bedrock materials is as follows:

- 1) from the source in Rocky Flats Alluvium, on top of claystone bedrock, toward a sub-cropping, permeable sandstone; and
- 2) through the dipping sandstone unit to the east toward the property boundary.

The existence of the bedrock ground-water flowpath requires several major assumptions. The most significant assumption is that the subcropping sandstone is hydraulically interconnected with other sandstone units so that a continuous hydrostratigraphic unit is formed. Detailed drilling at the Solar Ponds did not find interconnected sandstones (Rockwell, 1986); however, drilling slightly east of the plant in the vicinity of the 903 pad found a sandstone horizon that was apparently continuous for approximately 500 feet (DOE, 1987).

The hydraulic properties of the Arapahoe sandstones have been developed by on-site testing and are also available from published literature. Tests of wells on-site have yielded hydraulic conductivities ranging from  $1 \times 10^{-6}$  to  $3 \times 10^{-3}$  cm/s, consistent with the range of grain sizes and silt/clay content. The sandstones are very fine- to medium-grained, with approximately 15 percent silt and clay (Rockwell, 1986). DOE (1987) found an isolated occurrence of coarse-grained sandstone. The high end of the hydraulic conductivity range

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is in good agreement with the estimate of 0.3 to 0.4 feet per day ( $1 \times 10^{-4}$  cm/s) in Hurr (1976). Robson (1983) shows the hydraulic conductivity of the Arapahoe in the vicinity of the plant to be 0.5 feet per day ( $2 \times 10^{-4}$  cm/s), based on a test of an off-site well.

On-site determinations of gradients within single sandstone horizons have ranged from 0.02 (Rockwell, 1986) to 0.09 (DOE, 1987). Both Hurr (1976) and Robson et al. (1981) show gradients of approximately 0.03 to the east. Robson (1983) presents laboratory test results indicating an average effective porosity of 25.6 percent in the Arapahoe.

The travel time for a non-attenuated constituent to reach the property boundary in the Arapahoe sandstone is on the order of 800 years. This is calculated as follows.

The velocity is approximately 12 feet per year, using an average hydraulic gradient of 0.03, hydraulic conductivity of  $1 \times 10^{-4}$  cm/s, and an effective porosity of 0.256.

The property boundary is approximately 10,000 feet from the subcrop of the sandstone.

If the above hypothesized interconnected, continuous sandstone horizon were to exist, it would be 400 to 500 feet below ground at the property boundary, based on mapping presented in Robson et al. (1981). It is very unlikely that downgradient ground-water wells draw water from depths of 400 to 500 feet below ground, because data presented in Robson et al. (1981) indicate that adequate supplies (50 gallons per minute) can be obtained from depths of 100 to 200 feet below ground.

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SUMMARY

This document presents travel time calculations for ground-water transport of dissolved chemical species from the plant to off-site areas. The calculated travel times are as follows.

Alluvium	40 - 97 years
Bedrock	800 years

The calculations are conservative, using high values of hydraulic conductivity and neglecting travel time in the Rocky Flats Alluvium and colluvium; travel time in the colluvium was demonstrated to be significant at the 881 Hillside. In addition, the calculations neglect chemical processes (e.g., volatilization, degradation, adsorption, and precipitation) that can result in significantly longer travel time.

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