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²⁰₂₁ **7.1 INTRODUCTION**

Solute dispersion refers to the spatial spreading of a solute plume over time. The spreading is essentially a mixing and consequent dilution of the solute plume with the resident fluid, as depicted in Figure 7.1. Consideration of dispersion is critical to understanding gas-phase transport in porous media.

Many transport principles that were originally developed to describe behavior in saturated porous media, and later for unsaturated water flow, can also be readily



Figure 7.1. Spreading of a solute plume from an instantaneous point source. (A) Two-dimensional spatial "snapshots" (concentration versus x-y coordinates) as a function of time (t). (B) Temporal breakthough curves (concentration versus time) as a function of distance along axis of flow (x)

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1 applied to the transport of gases in unsaturated systems, including the concepts of 2 dispersion. However, any rigorous or quantitative analysis of gas-phase systems 3 requires consideration of the unique complexities of unsaturated systems and the 4 properties of gases themselves. For example, unsaturated porous media have air-5 filled porosities that may vary both spatially- and temporally, and depend on such 6 factors as soil-water content and particle-size distribution. Gas-phase diffusion coeffi-7 cients are generally four to six orders of magnitude larger than aqueous-phase values, 8 and in contrast to water, gases are significantly affected by pressure-temperature rela-9 tionships. Gases experience slip-flow along pore walls, often termed the Klinkenberg 10 effect, while water does not. In the following discussion, the authors use the terms 11 "gas" and "vapor" interchangeably, while the term "solute" refers very broadly to the 12 gas/vapor of interest.

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14 **7.2 THEORY** 15

16 7.2.1 Diffusion

Dispersion includes diffusive and mechanical mixing components. Gas-phase diffusion is often assumed to be dominated by molecular diffusion, the random spreading of a solute along concentration gradients over time, described here by a one-dimensional Fick's second law:

(7.1) $\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2}$

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where C is the gas concentration (M·L⁻³), t is time (T), D is the binary diffusion 25 coefficient in air $(L^2 \cdot T^{-1})$, and x is the distance along the axis of flow (L). For molec-26 ular diffusion, molecule-molecule collisions are the only type of collisions that occur, 27 implying a system without walls. In some cases, more complex gas-phase diffusion 28 processes may also occur, including viscous, Knudsen, and nonequimolar diffusion 29 (e.g., Scanlon et al., 2000). The former two processes occur due to the presence of pore 30 walls and consequent molecule-wall collisions (Cunningham and Williams, 1980), 31 while the latter requires both the presence of walls and a multicomponent gas (i.e., 32 a mixture). Such conditions are present in porous media and may lead to deviations 33 from Fick's law (e.g., Sleep, 1998). Baehr and Bruell (1990) report that high vapor 34 pressures, such as those achieved near organic liquid sources, also cause deviation 35 from Fick's law. In accordance with the bulk of the literature, this chapter will focus 36 on molecular diffusion (e.g., assuming a system without walls), while other diffusion 37 processes are discussed in detail elsewhere. 38

Diffusion is a solute-dependent component of dispersion, due to the relationships among average kinetic energy, velocity, and molecular mass. At a given temperature the average kinetic energy of all gases will be equal and described as:

$$\begin{array}{l} 42\\ 43\\ \end{array} (7.2) \qquad E_k = \frac{3}{2}kT = \frac{1}{2}mv_{\rm rm}^2 \end{array}$$

1 where k is Boltzmann's constant $(J \cdot K^{-1})$, T is temperature (K), m is the solute mass 2 (M), and v_{rms} is the root-mean-square velocity of the gas particles $(L \cdot T^{-1})$. Thus, 3 given thermal equilibrium and consequent equal kinetic energy, lower molecular 4 weight gases will exhibit higher average velocities relative to higher molecular weight 5 gases. This higher velocity translates into larger diffusion coefficients and larger 6 contributions to overall dispersion.

7 Diffusion processes often dominate transport in low permeability zones, such as 8 within aggregates or fine-textured lenses. In the case of volatile organic compounds 9 (VOCs), the occurrence of diffusion can both aid and present additional challenges 10 to remediation efforts. Specifically, the larger spatial distribution of the VOC caused 11 by diffusion may increase the probability of detecting the VOC in the subsurface, 12 such that a remediation plan can be implemented. Conversely, it is this same diffusion 13 process that is often largely responsible for the transport of VOCs in the vadose-zone to 14 the water table resulting in groundwater contamination (e.g., Lupo, 1989). Moreover, 15 contaminant diffusion can influence the fate of contamination in a system by altering 16 its bioavailability. Diffusion largely governs gas-exchange between the atmosphere 17 and soil, including the exchange of carbon dioxide and oxygen, and atmospheric 18 pollutants, such as fluorocarbons (Weeks et al., 1982). Jury et al. (1991) estimate that 19 only 0.5%, 1%, 0.1%, and 7-9% of the overall subsurface gas exchange is induced by 20 temperature and barometric pressure changes, wind, and precipitation, respectively. 21 Thus, they conclude that diffusion is the primary gas transport mechanism in soil systems. Little et al. (1992) review the critical role diffusion plays in transporting 22 23 subsurface VOCs into homes and buildings.

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²⁵ 7.2.2 Mechanical Mixing

27 Mechanical mixing is a solute-independent component of dispersion, governed by the 28 physical properties of the porous medium and carrier gas velocity. Mechanical mixing 29 is a lumped term, incorporating a number of sources of velocity variations that result 30 in solute mixing and dilution. Such velocity variations may be caused by (A) non-31 uniform velocity profiles along the cross section of individual pores (e.g., velocities 32 are higher in the center of the pore relative to near-wall velocities); (B) distributions in 33 pore sizes (e.g., large pores promote higher velocities than smaller pores); and (C) the 34 tortuosity of flow paths, as shown in Figure 7.2. The effective pore-size distribution 35 and tortuosity are influenced by the presence of soil-water. At larger scales, dispersion 36 may be caused by the presence of lenses of material with different permeabilities. 37 Larger-scale differences in permeability may further influence capillary forces and 38 the resultant large-scale water saturation, although much less is known about large-39 scale mechanical mixing processes (Freeze and Cherry, 1979; Selker et al., 1999). 40 Because the magnitude of mechanical mixing depends on the degree of heterogeneity, 41 it is expected that the magnitude of gas-phase dispersivity will be proportional to the 42 system-scale as has been demonstrated for aqueous-phase dispersion (Pickens and 43 Grisak, 1981; Gelhar et al., 1992).



9 Figure 7.2. Schematic of sources of pore-scale velocity variations resulting in mechanical mixing:
 (A) Velocity variations within a single pore due to wall-effects; (B) Pore-size distributions; (C) tortuosity
 effects

13 7.2.3 Dispersion Coefficient and Peclet Number

Gas-transport in porous media is often described using an advection-dispersion equation (A-D Equation), as described in more detail elsewhere. In a one-dimensional A-D equation, the effects of dispersion are represented by the longitudinal dispersion coefficient, D (L²·T⁻¹), defined as:

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$$(7.3) \qquad D = D_{\rm a}\tau + \alpha v$$

20 21

where D_a is the binary molecular diffusion coefficient in air (L²·T⁻¹); τ is the tor-22 23 tuosity factor defined between 0 and 1 and inversely proportional to the tortuosity 24 of the gas phase in the porous medium (dimensionless); α is the gas-phase longitudinal dispersivity, a measure of the physical heterogeneity of the media (L); and 25 v is the average linear velocity of the gas $(L \cdot T^{-1})$. The first term on the right-hand 26 27 side of Equation 7.3 represents the solute-dependent diffusive contributions to disper-28 sion, while the second term represents the mechanical mixing dispersion component. 29 Transverse dispersion also occurs and is described by a transverse dispersion coeffi-30 cient; however, under most conditions transverse dispersion is observed to be much 31 less significant than longitudinal dispersion and is not considered further here.

32 Diffusion coefficients (in air) are typically obtained from the literature. The tor-33 tuosity factor is estimated using empirical literature correlations incorporating total 34 and air-filled porosity (Penman, 1940; Currie, 1961; Millington and Quirk, 1961; Millington and Shearer, 1971; Sallam et al., 1984; Karimi et al., 1987; Shimamura, 35 36 1992; Moldrup et al., 1996; Schaefer et al., 1997; Poulsen et al., 1998). The product 37 of the diffusion coefficient and the tortuosity factor is often termed the effective dif-38 fusion coefficient, D_a^* . The reduction in D_a^* relative to the diffusion coefficient in air 39 is due to the presence of the solid-phase media, resulting in smaller cross-sectional 40 area available for diffusion, the tortuosity of the gas pathways, the presence of disconnected or "dead-end" pores, and at least in dry porous media, the geometry of the 41 42 pores, as influenced by particle shape (Currie, 1960). Thus, D_a^* decreases in response 43 to the presence of soil-water or greater bulk densities. Theoretically, the distribution 44 of water due to pore-size distributions also influences measured D_a^* values (Bruce

and Webber, 1953). Effective diffusion coefficients can be estimated using tortu osities (see above) or can measured directly in the laboratory (Taylor, 1949; Bruce
 and Webber, 1953; Currie, 1961; Shearer et al., 1973; Sallam et al., 1984; Johnson
 and Perrott, 1991; Barone et al., 1992; Jin and Jury, 1996; Batterman et al., 1996;
 Schaefer et al., 1997; Moldrup et al., 1998, 2000) and field (Raney, 1949; Lai et al.,
 1976; Weeks et al., 1982; Kreamer et al., 1988).

7 The longitudinal dispersivity term scales with the degree of heterogeneity of the physical system and is often measured using column-scale nonreactive tracer tests. 8 9 Gas-phase longitudinal dispersivities have been measured in laboratory porous media 10 systems and are found to range approximately between 0.2 and 2.9 cm (Popovičová 11 and Brusseau, 1997; Ruiz et al., 1999; Garcia-Herruzo et al., 2000; Costanza-12 Robinson and Brusseau, 2002). Dispersivities measured in the field tend to be 13 larger due to increased system heterogeneity. Ideally, dispersivities should be solute-14 independent and insensitive to changes in carrier gas velocity or nonequilibrium 15 effects. However, if the data analysis fails to consider all relevant transport processes, dispersivity can become a "lumped" solute-dependent parameter that no longer solely 16 17 represents physical heterogeneity of the porous medium (Costanza-Robinson and 18 Brusseau, 2002).

19 The Peclet number, P_e , is a dimensionless measure of the degree of dispersion 20 experienced by a solute, defined alternatively as the ratio between the advective and 21 dispersive processes or the ratio of advective to diffusive processes (Rose, 1973). The 22 former definition is more encompassing and will be used here. The Peclet number is 23 usually obtained by fitting a solute breakthrough curve with an advective-dispersive 24 solute transport model. The magnitude of the Peclet number is inversely proportional 25 to the degree of dispersion. Thus, low Peclet numbers correspond to a large degree 26 of solute spreading. The Peclet number, also termed the Brenner number (Rose and 27 Passioura, 1971), can be related to the dispersion coefficient as follows:

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$$P_e = \frac{V_I}{L}$$
 (7.4) $P_e = \frac{V_I}{L}$

where *L* is a characteristic length of the system (L). The characteristic length can be defined at small- or macro-scales (e.g., grain diameter or column length) (Rose, 1973). The specific formulation of the Peclet number varies by application and field of study. The macroscale length is used commonly in the fields of soil physics and hydrology, while grain-scale lengths are often used in engineering disciplines. Thus, caution should be exercised when interpreting absolute values of Peclet numbers or when comparing values from different studies.

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³⁹ 7.2.4 Functional Dependence of Dispersion and the Dispersion Coefficient 40

The dispersion coefficient is a function of the solute velocity, v. While the diffusion
term is independent of v, the mechanical mixing component of dispersion is proportional to velocity (see Equation 7.3). Thus, D decreases with decreases in velocity.
However, slower velocities lead to larger residence times, thereby allowing more time

1 for diffusion to occur. This results in larger magnitudes of dispersion. When velocities 2 are sufficiently large, the contribution of diffusion to dispersion will be negligible. 3 Under these conditions, while the magnitude of the *dispersion coefficient* will change 4 with changes in velocity, the magnitude of *dispersion* will be velocity-independent. 5 This is shown by consideration of the Peclet number (Section 2.3). If diffusion is 6 considered as negligible, the dispersion coefficient in Equation 7.4 can be replaced 7 with the mechanical mixing term from Equation 7.3. As shown below, this results in 8 a velocity-independent Peclet number:

9 10

(7.5)
$$P_e = \frac{vL}{D} = \frac{vL}{\alpha v} = \frac{L}{\alpha}$$

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Thus, at high velocities P_e , a measure of the magnitude of dispersion, depends solely on properties of the porous medium, as represented by the dispersivity (α) and the characteristic length of the system (*L*). Gas retention in the system (e.g., adsorption, dissolution) results in longer residence time and to an increase in apparent dispersion. However, the magnitude of the dispersion coefficient, a measure of the dispersion *per unit time*, does not actually increase (Jury et al., 1991).

Inspection of Equation 7.3 shows that the diffusion contribution to *D* is solutedependent, while that of mechanical mixing is not. Thus, the magnitude of dispersion will vary as a function of the solute when diffusion provides a significant contribution, with lower molecular-weight gases exhibiting greater dispersion. Conversely, dispersion will be solute-independent for larger velocities, when mechanical mixing dominates dispersion.

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7.3 LABORATORY INVESTIGATIONS

27 287.3.1 Variables Affecting Diffusion

29 The magnitude of diffusion and its contribution to overall dispersion depends on 30 properties of the solute and porous medium, as well as transport parameters, such 31 as carrier velocity, as noted above. Ehlers et al. (1969) found diffusion contributions 32 to gas-phase dispersion be directly and inversely related to temperature and bulk 33 density of the medium, respectively. Others have reported similar bulk-density or 34 total-porosity effects on diffusion rates (Taylor, 1949; Sallam et al., 1984; Karimi et 35 al., 1987; Shimamura, 1992; Abu-El-Sha'r and Abriola, 1997). Lower bulk densities 36 correspond to larger pores and less tortuosity; thus, these results are consistent with 37 the discussion above.

At soil-water contents higher than 4 to 5% (wt), Ehlers et al. (1969) found soilwater content did not influence effective diffusion coefficients, although the technique used could not differentiate between gas-phase and aqueous-phase diffusion. Thus, at higher water contents, the expected decrease in gas-phase diffusion was likely offset by increased aqueous-phase diffusion. Karimi et al. (1987) examined the role of soil-water content on diffusion of benzene in a simulated landfill scenario and was able to isolate the process of vapor diffusion. Increasing soil-water content in

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1 the range 8 to 11% (wt) was observed to decrease the effective benzene diffusion 2 coefficient. Similar inverse relationships between soil-water content and diffusion 3 are reported for graded (Taylor, 1949) and aggregated porous media (Millington and Shearer, 1971; Arands et al., 1997). Shimamura (1992) presented similar results for 4 5 a number of sandy soils with controlled grain-size distributions.

Taylor (1949) presented diffusion rates as a function of matric potential, a variable 6 7 that is inversely related to soil-water content. The plot of effective diffusion distance (inversely proportional to tortuosity) versus matric potential displayed significantly 8 9 less variability for the four natural and graded porous media studied, as compared to 10 the plot of effective diffusion distance versus soil-water content. Viewing diffusion 11 as a function of matric potential, incorporates both the effects of soil-water content 12 and pore- and grain-size distributions, thereby allowing more general conclusions to 13 be drawn for a variety of porous media.

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15 7.3.2 Variables Affecting Mechanical Mixing and 16

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Total Dispersion

18 The total magnitude of dispersion depends on several factors, including physical 19 properties of the porous medium, physicochemical properties of the gaseous solute, 20 and flow conditions. Edwards and Richardson (1968) measured dispersion coeffi-21 cients by varying argon velocity in a dry packed system, demonstrating that the 22 dispersion coefficient is relatively constant at low Reynolds numbers (e.g., 0.01–0.5) 23 and increases approximately linearly for higher Reynolds numbers. The Reynolds 24 number is a measure of the turbulence of flow and for the same fluid and porous 25 medium is directly proportional to average linear velocity. Thus, for the low velocity 26 experiments, the magnitude of dispersion remained relatively constant, but increased 27 linearly at higher velocities. The authors interpret this as indicating that molecular dif-28 fusion, a velocity-independent term (see Equation 7.3), dominates dispersion at low 29 velocities (e.g., low Reynolds numbers). At higher velocities, mechanical mixing, 30 which is directly proportional to velocity, dominates dispersion. Using expressions 31 similar to Equation 7.3, Edwards and Richardson (1968) define three regions of disper-32 sion: (1) low Reynolds numbers where the mechanical mixing term (in Equation 7.3) 33 is negligible; (2) intermediate Reynolds numbers where both mechanical mixing and 34 diffusion terms are significant; and (3) high Reynolds numbers where the diffusion 35 term becomes negligible. This three-region approach had been previously applied to 36 the case of saturated flow.

37 Popovičová and Brusseau (1997) also examined the role of carrier gas velocity on 38 the magnitude of dispersion and the relative contributions of diffusion and mechan-39 ical mixing to methane transport in a dry, homogeneous, glass-bead column. At 40 low velocities, virtually all methane dispersion was due to diffusion, while at larger 41 pore velocities, mechanical mixing contributed more than 80% of the observed dis-42 persion. Similar velocity-dependence of dispersion-contributions was observed for a 43 heterogeneous glass-bead column, and total dispersion increased relative to the homo-44 geneous system. The heterogeneous column had a macropore located in the center of

Costanza-Robinson and Brusseau

the otherwise homogeneous column. At the highest velocities in the heterogeneous
 column, rate-limited diffusion (e.g., nonequilibrium effects) between the macro- and
 micropore domains became much more significant than dispersion processes.

Garges and Baehr (1998) simulated gas-phase miscible displacement breakthrough curves using a one-dimensional advection-dispersion transport model and varying the degree of dispersion, as represented by varying Peclet numbers. The paper provides excellent plots displaying the effect of different magnitudes of dispersion on the resulting breakthrough curves. As expected, larger dispersion coefficients results in breakthrough curves with shallower slopes for both the arrival and elution waves.

10 Batterman et al. (1995) examined the influence of porous media properties and 11 the relative humidity of the gas-phase on diffusion rates and total dispersion coef-12 ficients. Effective diffusion coefficients were measured for a number of dry natural and synthetic media and were found to be consistent with predictions from empir-13 14 ical correlations (see Section 2.3). Total dispersion coefficients were measured for 15 the same media with carrier relative gas humidities ranging from 0 to 90% (gener-16 ally corresponding to very dry soils with gravimetric soil-water contents <1%). The 17 authors concluded that mechanical mixing and diffusion contributed about equally to 18 dispersion under these conditions.

19 Batterman et al. (1995) report that methane experienced greater overall disper-20 sion than did trichloroethene (TCE) in column studies performed over a range of 21 soil humidities. This trend is expected due to the much higher diffusivity of methane 22 relative to TCE. However, additional analysis shows that the difference in reported 23 dispersion coefficients for TCE and methane is too large to be explained by differ-24 ences in diffusion coefficients alone. After correcting the total dispersion coefficients 25 reported by Batterman et al. (1995) for diffusion, the absolute dispersion due to 26 mechanical mixing is almost three times greater for methane than for TCE. Theoret-27 ically, mechanical mixing should be a solute-independent term. This indicates that 28 additional transport processes were likely occurring in the experiments that were not 29 considered in the original data analysis.

30 Costanza-Robinson and Brusseau (2002) observed that the lowest molecular weight 31 compound studied, methane, had the largest diffusion contribution in a wetted homo-32 geneous natural sand system, comprising approximately 60% of the total observed 33 dispersion. For higher molecular weight compounds (e.g., difluoromethane and TCE) 34 mechanical mixing dominated dispersion, contributing between 50 and 100% of the 35 dispersion, depending on soil-water content. Relative contributions from mechani-36 cal mixing increased at higher soil-water contents due to the consequent increase in 37 tortuosity and decrease in diffusion.

The influence of specific system properties on experimentally-determined dispersivity values, including soil-water content and particle- and pore-size distributions have not been fully studied. Furthermore, laboratory-measured dispersivity values are often derived from data from nonreactive tracer tests and are assumed to be representative of dispersivities for reactive compounds under various system conditions. Because dispersivity is a measure of the heterogeneity of the physical system, this assumption is theoretically justifiable. However, for this assumption to hold in a real

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system, all relevant transport processes must be appropriately accounted for in the
 analysis. For example, if additional transport processes, such as rate-limited mass transfer are occurring, but are not considered in the data analysis, the dispersivity
 values will become lumped, solute-dependent values.

5 Costanza-Robinson and Brusseau (2002) performed experiments to examine these 6 issues. Diffusional dispersion contributions were explicitly accounted for using prop-7 erties of the porous medium and literature tortuosity correlations and diffusion 8 constants. The total dispersion coefficient was obtained by fitting the experimen-9 tal breakthrough curves with an equilibrium, one-dimensional, transport model. The 10 difference between the total dispersion coefficient and the diffusional contributions 11 was taken as the mechanical mixing contribution. The dispersivity values calculated 12 in this manner were observed to be constant for the porous medium studied at soilwater contents ranging from 2 to 14%. This indicates that it may be appropriate 13 14 to use a single dispersivity value to represent a given porous media over a range 15 of natural conditions. Moreover, the calculated dispersivities were the same for all 16 compounds studied, which included a nonreactive (methane), a water-soluble (diflu-17 oromethane), and a water-soluble and sorbing solute (TCE). This indicates that in 18 the 2 to 14% soil-water content range, the data analysis appropriately accounted for 19 transport processes, such that the dispersivity value was a true measure of the porous 20 medium heterogeneity, rather than a solute-dependent lumped term. At soil-water 21 contents greater than 14%, dispersivities became solute-dependent, indicating that 22 additional transport processes were being lumped into the dispersivity term. The 23 authors attributed this to rate-limited diffusion of the soluble solutes through water 24 films, which was not considered in the data analysis.

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²⁶ 7.4 FIELD AND MODELING INVESTIGATIONS ²⁷

28 The relatively few experimental field investigations of gas-phase dispersion have 29 focused on diffusion. Raney (1949) and Lai et al. (1976) have presented methods for 30 measuring effective diffusion coefficients in-situ that are applicable to surface soils. 31 Weeks et al. (1982) examined the use of atmospheric pollutants, fluorocarbons F-11 32 and F-12, in measuring effective vadose-zone diffusion rates, concluding that gas-33 phase diffusion is likely the most important transport mechanism in regions where 34 groundwater recharge is small. As expected, soil tortuosity and the solubility and 35 sorption of the gases resulted in measured effective diffusion coefficients that were 36 much less than those estimated for free-air diffusion. Numerical-modeling results 37 indicated that the near-surface region had lower tortuosities, while deeper layers 38 contributed most significantly to reduced diffusion rates. Finally, Weeks et al. (1982) 39 concluded that the relative agreement between their optimized tortuosity factors and 40 tortuosity factors estimated via a number of theoretical and empirical approaches 41 lends support to the use of diffusion theory in predicting soil gas concentrations, even 42 in large-scale, heterogeneous natural systems.

43 Mathematical modeling of gas-phase transport has also focused largely on diffu-44 sional processes, citing barometric pressure gradients and consequent advection as

Costanza-Robinson and Brusseau

minimal. Mendoza and Frind (1990) demonstrate that in dilute (e.g., low vapor pres-1 2 sure) vadose zone systems, diffusion from the soil to the atmosphere results in removal of 95% and 69% of the contaminant mass from systems having gas-phase permeabil-3 ities of 1.0×10^{-11} and 1.0×10^{-10} m², respectively. At the higher permeabilities 4 other transport mechanisms, such as density-driven advection, contribute more sig-5 nificantly to gas transport. Lupo (1989) also demonstrates the importance of diffusion 6 7 in the transport of aromatic contaminants in a simulated landfill scenario. Diffusion 8 of chlorobenzene and benzene is calculated to be most critical in coarser soils and 9 under conditions of lower groundwater recharge. Similarly, Baehr (1987) reports the 10 important role diffusion plays in the transport of hydrocarbons in the vadose zone.

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¹² 7.5 SUMMARY

14 Gas-phase dispersion is caused by mechanical mixing and diffusion processes. The 15 magnitude of diffusion is inversely proportional to compound molecular weight, 16 porous media bulk density, and soil-water content and directly proportional to tem-17 perature. Under natural-gradient conditions, diffusion will likely be the dominant 18 transport mechanism. Mechanical mixing is likely to be dominant only under condi-19 tions of induced gas advection (e.g., miscible displacement experiments and soil vapor 20 extraction systems) or relatively extreme changes in barometric pressure. The mag-21 nitude of dispersion depends on the degree of heterogeneity of the physical system. 22 Experimental investigation of gas-phase dispersion has focused almost exclusively on 23 laboratory-scale systems. Understanding of gas-phase dispersion is important for con-24 taminant transport applications, as well as atmosphere-soil gas exchange processes. 25

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