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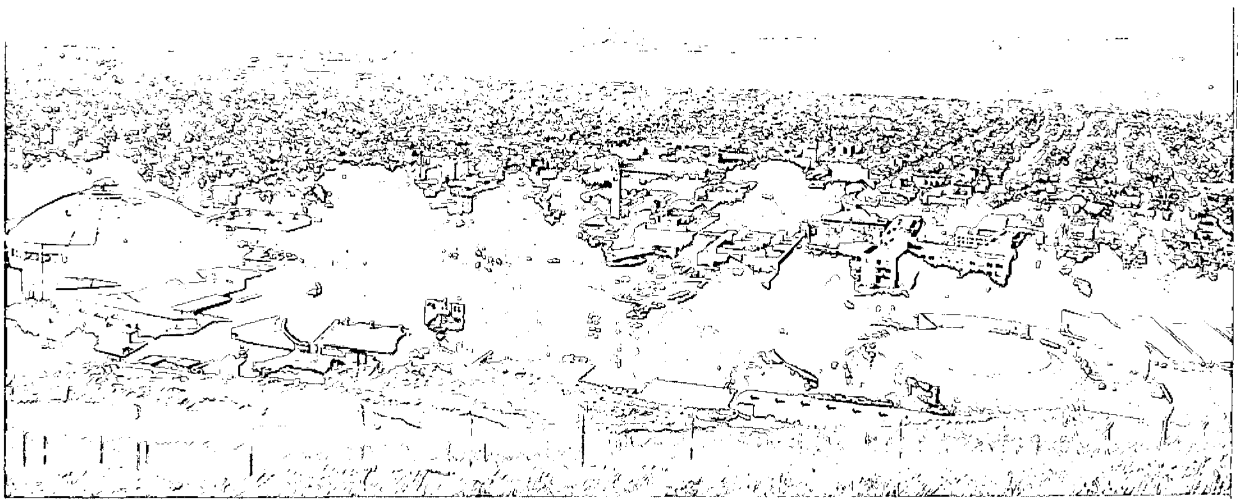

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THE EFFECTIVE DIFFUSION COEFFICIENT FOR POROUS RUBBLE

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Introduction

Each waste package in the proposed Yucca Mountain repository is to be separated from surrounded unsaturated rock by a 2-cm air gap annulus. However, if the annulus becomes filled with rock and rubble, there can exist pathways for diffusive release of radionuclides through pore liquid, even if the repository remains unsaturated. The effective diffusion coefficient for radionuclide release through pore liquid in a rubble bed depends on the porosity and moisture content of rubble material and on the geometry and contact area of individual pieces of rubble. Here we present a theoretical analysis of the effective diffusion coefficient for a bed of rubble spheres. The results give a rough indication of the magnitude of the effective diffusion coefficient, and the analysis identifies the parameters that will affect experimental measurements of mass transfer through unsaturated rubble.

Analysis

We assume that in the unsaturated environment there is no liquid film on the rubble surfaces. We consider a cylindrical waste container positioned with its axis vertical in a cylindrical bore hole, as illustrated in Figure 1. The annular gap is small compared to the borehole radius. The mass-transfer rate across the rubble bed, per unit area of porous waste-container, is given by the product of an effective diffusion coefficient D_a and the concentration difference in pore liquid across the annulus, divided by the annular thickness. Adapting an analysis of conductive heat transfer through a packed bed[1], we define

$$D_a = \frac{N_a}{N_t R}, \tag{1}$$

where N_a is the number of spheres per unit area of container surface, N_t is the number of spheres per unit distance along a waste-cylinder diameter, and R is the mass transfer resistance of a single porous sphere. Detailed geometric analysis for a simple cubic array of solid porous spheres leads to

$$R = \frac{0.53}{D_c r_c} \tag{2}$$

where r_c is the radius of the circular contact area between adjacent spheres, and D_c is the effective diffusion coefficient in intact rock. Equivalent expressions are available for other packing geometries.

Elastic spheres of radius r_0, under a contact force F, will form a circular contact area of radius r_c given by the Hertz equation[1]

$$r_c = \left[\frac{3}{4}\frac{(1-\mu^2)}{E}Fr_0\right]^{1/3}, \qquad r_c << r_0 \tag{3}$$

where E is the modulus of elasticity and μ is poisson's ratio. Here we are interested in the horizontal contact force $F = F_h$ resulting from a vertical force F_v. Experimentally, for beds of noncohesive solids $F_h/F_v = C$, where C =0.4 to 0.5. F_v is derived from the weight w of the rubble bed of height L above the rubble layer through which radial mass transfer is being calculated:

$$F_h = CS_F wLN_t = CS_F\rho_s\left(\frac{4}{3}\pi r_0^3\right)gLN_t. \tag{4}$$

where g is gravitational acceleration and S_F is a geometrical factor that depends on the packing geometry.[1]

Combining the above equations, we obtain the ratio $D_a/D_c = \Psi$:

$$\Psi = 1.714 S_F^{1/3}\left(\frac{N_a}{N_t^{2/3}}\right) r_0^{4/3}\left(\frac{4\pi gL(1-\mu^2)C\rho_s}{3E}\right)^{1/3}. \tag{5}$$

Assuming a simple cubic array of spheres, $S_F = 1$. For tuffaceous rock[2] $\rho_s = 2.4 \times 10^{-3}$ (kg/cm^3), $\mu = 0.14$, and $E = 2.67 \times 10^6$ (N/cm^2). We obtain $\Psi = 0.0021$ for a layer 2 cm below the top of the rubble, and $\Psi = 0.013$ for a layer 480 cm below the rubble top. Thus, the effect of the limited contact area of spherical rubble particles is to reduce the effective diffusion coefficient by a factor of 80 to 500 below that of intact rock. The effective diffusion coefficient can be about two-fold greater for body-centered-cubic and face-centered arrays of rubble spheres. In a separate paper[3] submitted for this proceeding, we illustrate the effect of diffusion through a rubble bed on the release rate of plutonium from a waste package in unsaturated rock.

Conclusion

The foregoing analysis identifies the parameters that will affect the effective diffusion coefficient in unsaturated rubble. For experimental measurements of the effective diffusion coefficient, the compaction forces on the rubble bed should be measured. For an idealized cubic array of spherical rubblized tuff, the effective diffusion coefficient may be several orders of magnitude below that of intact rock.

References

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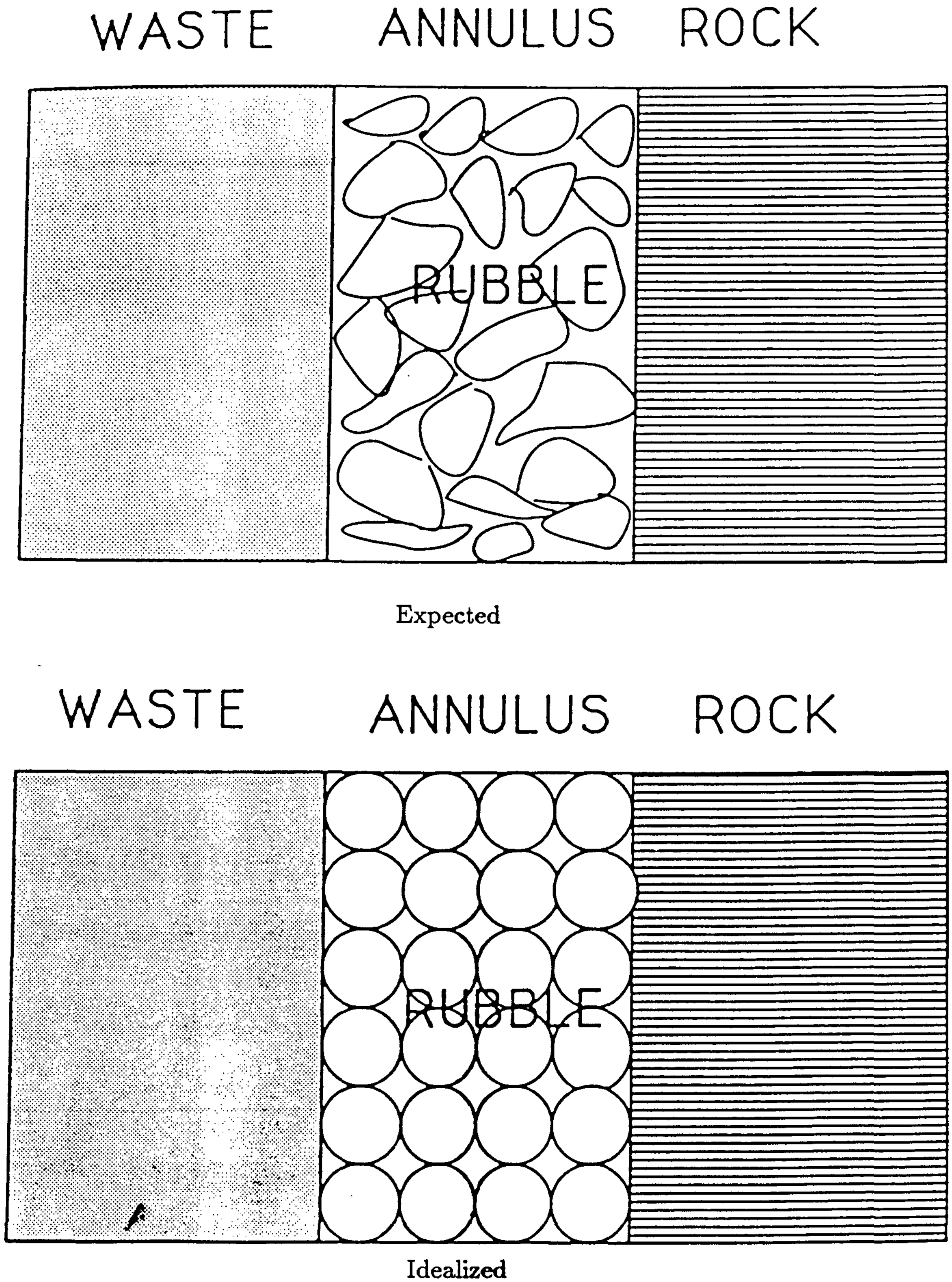

Fig. 1. Expected and idealized geometry of rubble in the waste-rock annulus.

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