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Aerosol Penetration of Leak Pathways – An Examination of the Available Data and Models

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Abstract

Data and models of aerosol particle deposition in leak pathways are described. Pathways considered include capillaries, orifices, slots and cracks in concrete. The Morewitz-Vaughan criterion for aerosol plugging of leak pathways is shown to be applicable only to a limited range of particle settling velocities and Stokes numbers. More useful are sampling efficiency criteria defined by Davies and by Liu and Agarwal.

Deposition of particles can be limited by bounce from surfaces defining leak pathways and by resuspension of particles deposited on these surfaces. A model of the probability of particle bounce is described. Resuspension of deposited particles can be triggered by changes in flow conditions, particle impact on deposits and by shock or vibration of the surfaces.

This examination was performed as part of the review of the AP1000 Standard Combined License Technical Report, APP-GW-GLN-12, Revision 0, “Offsite and Control Room Dose Changes” (TR-112) in support of the USNRC AP1000 Standard Combined License Pre-Application Review.

CONTENTS

1.	INTRODUCTION	11
2.	EXPERIMENTAL STUDIES	19
2.1	Leak Pathway Idealizations	19
2.1.1	Capillary Flow	20
2.1.2	Orifice Flow	22
2.1.3	Flow in Slots	23
2.1.4	Concrete Cracks	23
2.1.5	Gasket Leaks	29
2.2	Individual Experimental Studies	31
2.2.1	Experiments with Capillaries by Mitchell and Coworkers	31
2.2.2	Capillary Tests by Nelson and Johnson	36
2.2.3	Tests of Depleted Uranium Dioxide Flow Through Capillaries	37
2.2.4	Rockwell Tests on Capillary Flow	45
2.2.5	Tests with Orifices	47
2.2.6	Lewis Tests of Particle Transport Through a Slot	62
2.2.7	Mosley et al. Tests of Aerosol Transport Through a Slot	64
2.2.8	Liu and Nazaroff Tests of Aerosol Flow Through Slots	67
2.2.9	Tests with Cracked Concrete	70
2.2.10	Tests of Leakage from a Flow Stream	75
2.2.11	Multiple Bend Geometry Tests	77
2.2.12	Tests of Leakage Through Containment Penetrations	77
2.2.13	Containment Leak Tests	78
2.3	Turbulent Deposition of Particles	79
2.3.1	Friedlander and Johnstone	81
2.3.2	Montgomery and Corn	82
2.3.3	Wells and Chamberlain	83
2.3.4	Liu and Agarwal	84
2.3.5	El-Shobokshy	85
2.3.6	Lee and Gieseke	85
2.3.7	Shimada et al.	86
2.3.8	Sehmel	87
2.3.9	Postma and Schwendiman	88
2.3.10	Ilori	89
2.3.11	Muyshondt et al.	90
2.3.12	Forney and Spielman	91
3.	THEORETICAL INVESTIGATIONS	93
3.1	Laminar Flow Conditions	93
3.2	Chen Yu Method for Deposition by Multiple Mechanisms	97
3.3	Turbulent Flow Conditions	101
3.4	Other Considerations	105
4.	CONCLUSIONS	109

5.	REFERENCES	111
	Appendix A: DERIVATION OF THE STOKES NUMBER	117
	Appendix B: TABULATED DATA ON TURBULENT DEPOSITION OF AEROSOL PARTICLES IN SMOOTH TUBES	121

FIGURES

Figure 1. Data Cited by Morewitz [1982] for His Simple Correlation.....	12
Figure 2. Data Cited by Vaughan [1978] for His Simple Correlation.	12
Figure 3. Regimes for Aerosol Transport in Sampling Devices.....	15
Figure 4. Commercial Aerosol Sampling Device Characteristics in Terms of Agarwal and Liu Sampling Regimes.	15
Figure 5. Sampling Efficiency Data [Yoshida <i>et al.</i> , 1979] and the Agarwal and Liu “Pretty Good” Sampling Regime.	16
Figure 6. Leak Pathway Idealizations.....	19
Figure 7. Crack Dimensions.	26
Figure 8. Cracks Produced in Concrete by Predominantly Membrane Stress.....	27
Figure 9. Concrete Cracks Produced by Membrane and Shear Stress at a Penetration.....	28
Figure 10. Size Distribution of Glass Sphere Aerosols Used in Tests by Mitchell and Coworkers.	33
Figure 11. Flow Through Capillaries Exposed to Glass Sphere Aerosol.	33
Figure 12. Number of Particles that Emerged from Capillaries After 2 Hours.	34
Figure 13. Comparison of Probability Density Function for the Number Distributions of Aerosol Input and Exiting from a 5 cm long 70 μ m Capillary.....	34
Figure 14. Flow Characteristics of Capillaries Used by Sutter <i>et al.</i> [Owzarski <i>et al.</i> , 1979].....	39
Figure 15. Comparison of Observed Transmission of Uranium Dioxide Powder Through Capillaries in Tests Reported by Sutter <i>et al</i> with Transmission Expected if Penetration Through Capillaries was 100%.....	43
Figure 16. Comparison of Observed [Sutter <i>et al.</i> , 1980] Uranium Dioxide Powder Leakage Through Orifices Plotted Against the Expected Leakage Assuming 100% Particle Penetration of the Orifice.	47
Figure 17. Lewis [1995] results for aerosol flow through a 0.1 mm slot at a pressure differential of 10 kPa.	62
Figure 18. Results of Tests by Mosley <i>et al.</i> [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 2 kPa Differential Pressure	65
Figure 19. Results of Tests by Mosley <i>et al.</i> [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 5 kPa Differential Pressure	65
Figure 20. Results of Tests by Mosley <i>et al.</i> [2001] for aerosol transport through a slot 0.5 mm high, 433 mm wide, and 102 mm deep at a 10 kPa Differential Pressure	66
Figure 21. Results of Tests by Mosley <i>et al.</i> [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 20 kPa Differential Pressure	66
Figure 22. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 9.4 cm deep at a 2 Pa Differential Pressure	68
Figure 23. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 9.4 cm deep at a 10 Pa Differential Pressure	68
Figure 24. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 4.3 cm deep at a 10 Pa Differential Pressure	69
Figure 25. Data from Liu and Nazaroff for Aerosol Flow Through a slot 1.0 mm high and 9.4 cm deep at a 10 Pa Differential Pressure	69

Figure 26. Penetration of Uranine Particles Through a 67.2 μm Crack in Concrete [Gelain and Vendel, 2008].	74
Figure 27. Carrié and Modera [1998] on the Variation in Slot Height Due to Aerosol Accumulation from Transverse Flow.	76
Figure 28. Comparison of Leakage Flow of Aerosol-Laden Gas Through a Slot and a Joint [Carrié and M.P. Modera, 2002].	76
Figure 29. Turbulent Aerosol Particle Deposition Data Obtained by Friedlander and Johnstone [1957].	81
Figure 30. Turbulent Particle Deposition Reported by Montgomery and Corn [1970].	82
Figure 31. Turbulent Deposition of Tricresyl Phosphate Droplets [Wells and Chamberlain, 1967].	83
Figure 32. Turbulent Particle Deposition Data from Liu and Agarwal [1974] and from El-Shobokshy [1983].	84
Figure 33. Turbulent Deposition Velocities for Dioctyl Phthalate Droplets [Lee and Gieseke, 1994].	85
Figure 34. Turbulent NaCl Aerosol Deposition Data from Shimada <i>et al.</i> [1993].	86
Figure 35. Data on the Turbulent Deposition of Uranine Particles Obtained by Sehmel [1970].	87
Figure 36. Turbulent Aerosol Deposition Data from Postma and Schwendiman [1960].	88
Figure 37. Turbulent Particle Deposition Data Obtained by Ilori in His Thesis Research. Data Digitized from a Small Plot Published by Im and Ahluwalia [1989].	89
Figure 38. Turbulent Deposition of Oleic Acid Droplets [Muyschondt <i>et al.</i> , 1996].	90
Figure 39. Data on Turbulent Deposition of Large Particles [Forney and Spielman, 1974].	91
Figure 40. Turbulent Particle Deposition Data from Several Investigations.	92
Figure 41. Comparison of a Model of Particle Bounce Probability to Data on the Bounce of Fly Ash Particles from Filter Beds.	107

TABLES

Table 1. Glass Aerosol Deposition in a Capillary with a Pressure Differential of 40 kPa.	35
Table 2. Results of Tests by Mitchell and Coworkers.	35
Table 3. Continued Gas Flow Through Capillaries Following Plugging in Tests by Mitchell and Coworkers.	36
Table 4. Results From Tests with Sodium Oxide and Sodium Hydroxide Aerosols Reported by Nelson and Johnson [1975].	37
Table 5. Characteristics of Capillaries Used by Sutter <i>et al.</i>	39
Table 6. Flow Characteristics [Owzarski <i>et al.</i> , 1979] of Capillaries Used by Sutter <i>et al.</i>	40
Table 7. Results of Tests by Sutter <i>et al.</i> with Capillaries	41
Table 8. Parametric Values for Capillaries.	44
Table 9. Capillary Plugging Results Reported by Rockwell International [1997].	46
Table 10. Data Reported by Sutter <i>et al.</i> for Air-Sparged Uranium Dioxide Transmission Through Orifices.	48
Table 11. Parametric Values for Orifices.	61
Table 12. Some Results of Experiments by Mitchell <i>et al.</i> [1992] on the Penetration of Orifices by Nominally 7 μm glass Aerosol Particles.	61
Table 13. Results of Lewis' Test [1995] of Particle Transport Through a Slot (Best Fit Results).	63
Table 14. Results of Lewis' Test [1995] of Particle Transport Through a Slot (Data for Talc Particles).	63
Table 15. Penetration Observed in Transport of Polystyrene Latex Aerosols Through Cracks in Concrete [van de Vate, 1988].	72
Table 16. Uranine Particle Penetration of Cracks ($h = 67.2 \mu\text{m}$) in Concrete [Gelain and Vendel, 2008].	73
Table 17. Comparison of Williams Turbulent Deposition Model to Results of Tests by Nelson and Johnson.	103
Table B-1. Tabulated Data from Investigations by Forney and Spielman Using Tubes Coated with a Mixture of 75% Paraffin Oil and 25% Petroleum Jelly to Suppress Particle Bounce.	122
Table B-2. Tabulated Data from Investigations by Friedlander and Johnstone.	123
Table B-3. Tabulated data from investigations by Ilori.	124
Table B-4. Tabulated data from investigations by Lee and Gieseke.	125
Table B-5. Tabulated Data from Investigations by Liu and Agarwal.	126
Table B-6. Tabulated Data from Investigations by Montgomery and Corn.	127
Table B-7. Tabulated Data from Investigations by Muyshondt <i>et al.</i>	128
Table B-8. Tabulated Data from Investigations by Postma and Swendiman.	129
Table B-9. Tabulated Data from Investigations by Shimada, Okayama, and Asai.	130
Table B-10. Tabulated Data from Investigations by Shobokshy.	131
Table B-11. Tabulated Data from Investigations by Wells and Chamberlain.	132
Table B-12. Tabulated Data from Investigations by Sehmel.	133

1. INTRODUCTION

The phenomena associated with radioactive aerosol penetration of narrow leakage pathways have been issues of reactor safety at least since the establishment of the siting criteria in 10 CFR Part 100. The issues of aerosol leakage arise in connection with cracking of concrete containments, bypass of valves, perforation of electrical penetrations, and failure of seals such as those between the drywells and wetwells of boiling water reactors. The consequences of leakage of radioactive aerosol affect siting suitability, risk assessment and control room habitability. More recently, aerosol penetration of leak paths has been discussed in connection with dry cask storage of spent nuclear fuel and transportation of radioactive materials in casks.

Aerosol transport through narrow passages gained great visibility during the late 1970s in connection with the safety analysis of liquid metal fast breeder reactors (LMFBRs). The emphasis of these discussions was on sodium fires that produce enormous amounts of radioactive aerosol. There was, however, also some interest in aerosols produced during energetic power excursions of reactor fuel. Such events can produce quite large amounts of radioactive aerosol by vaporizing the fuel. Within this context, Morewitz [1982], Morewitz *et al.*[1979] and Vaughan [1978] provided an extraordinarily simple model to predict aerosol transport through passages:

$$\bar{m} = kD_{duct}^3 \quad (1)$$

where

- $\bar{m}$ - aerosol mass transport through a passage prior to plugging (kg)
- D_{duct} - equivalent diameter of the leak pathway (m)
- k - constant = $(5 \pm 3) \times 10^4$ (kg/m³)

Plots of data used by Morewitz and by Vaughan to support the simple correlation are shown in Figure 1 and Figure 2, respectively. Note that plugging was understood to mean obstruction of the flow pathway sufficient to filter aerosol from the gas stream. It did not mean a leak tight seal on the pathway, though especially in tests with very hygroscopic aerosol such as NaOH, leaktight plugging might be observed.

Figure 1. Data Cited by Morewitz [1982] for His Simple Correlation.

Figure 2. Data Cited by Vaughan [1978] for His Simple Correlation.

The Morewitz-Vaughan correlation is quite remarkable in its simplicity. It is independent of the hydrodynamics of flow. It is independent of the aerosol concentration or the size distribution of the aerosol particles. Furthermore, at the very high aerosol concentrations that were considered in the era (up to several hundred grams per cubic meter of gas), the predicted time for a narrow pathway to be plugged was quite short. Indeed, times for plugging are predicted to be so short that in common parlance it is even now not uncommon for the Morewitz-Vaughan correlation to be cited as a basis for arguing that aerosol transport through leak pathways can be entirely neglected!

The Morewitz-Vaughan correlation was contested almost immediately by the general aerosol community. This community has and continues to wrestle with the problem of extracting representative aerosol samples from a general atmosphere usually through narrow tubes that in the context of reactor safety look much like leak pathways. Aerosol specialists had found that criteria for adequate sampling were much more complicated than might be inferred from the simple Morewitz-Vaughan correlation.

The work of the aerosol community on adequate aerosol sampling focuses on the Stokes number of the aerosol particles. The Stokes number is the dimensionless ratio of the distance a particle will travel before it responds to the change in direction of the flow of the ambient gas to the characteristic dimension of the flow pathway.

$$Stk = \text{Stokes Number} = \frac{\rho_p C_{slip} d_p^2 V}{9 \mu_g L} \quad (2)$$

where

- ρ_p - particle density (g/cm³)
- C_{slip} - Cunningham slip correction factor (-)
- d_p - diameter of a volume-equivalent spherical particle (cm)
- V - gas velocity (cm/s)
- μ_g - viscosity of the gas (g/cm-s)
- L - character dimension of the leak path (cm)

The Stokes number is sometimes referred to as the ratio of the “stopping” distance of the particle to the characteristic dimension though it might better be referred to as the ratio of the “turning” distance of the particle to the characteristic dimension of the path. Particles with large Stokes numbers have high inertia and will be slow to respond to changes in the direction and magnitude of gas velocity. They will cross streamlines of the flow and impact the boundaries of leak paths. Based on considerations of flow fields created by sampling devices within a larger volume of aerosol-laden gas, Stokes numbers for particles and settling velocities of particles in a sampling device, the aerosol community had developed criteria for representative sampling of aerosol such that sampled particles would be representative of the aerosol in the volume of interest and negligible amounts of aerosol would deposit within the sampling device. The most restrictive of these criteria were propounded by Davies [1968].

$$Stk < 0.032$$

$$\frac{V_{setling}}{V} < 0.04 \quad (3)$$

where

$$V_{\text{settling}} = \frac{\rho_p C_{\text{slip}} d_p^2 g}{18\chi\mu}$$

g - terrestrial gravitational acceleration (cm/s²)
 χ - dynamic shape factor (vida infra)

The first of these criteria are intended to assure that when sampling from a stagnant gas, particles of all sizes are drawn into the sampling device in representative proportions and do not strike the boundaries or the surroundings of the sampling device. The second criterion is to assure that particles do not settle from the sampling flow stream by gravitational deposition. Novick [1994] has shown that data used by Morewitz and by Vaughan to develop their simple correlation were obtained in systems that violate the Davies sampling criteria

Agarwal and Liu 1980] observed that adequate sampling was obtained in some circumstances even when the Davies criteria were violated. They termed sampling in compliance with the Davies criteria as “perfect” sampling and offered a less stringent criterion that might be termed “pretty good” sampling.

$$Stk \left(\frac{V_{\text{settling}}}{V} \right) < 0.1 \quad (4)$$

The two dimensional space that is defined by the Stokes number and the settling velocity ratio can be divided into regimes as is shown in Figure 3¹. Agarwal and Liu validated their arguments about “pretty good” sampling by mapping the operating characteristics of a number of commercial aerosol sampling systems on their map of Stokes number versus relative settling velocity as shown in Figure 4. Clearly, commercial devices operate in the “pretty good” sampling regime. Prompt plugging would be unacceptable for these devices. The “plugging” regime where the Morewitz and Vaughan correlation is appropriate occurs when Stokes numbers are large and settling velocities are significant in comparison to flow velocities through the aerosol flow path.

Since publication of the Agarwal and Liu map of aerosol sampling regimes there has been a substantial effort to experimentally validate the work [Dunnet, 1992]. An example [Yoshida *et al.*, 1979] comparison is shown in Figure 5.

¹ Note that both the Davies “perfect sampling” regime and the Agarwal and Liu “pretty good” sampling regime are for sampling from a calm atmosphere

Figure 3. Regimes for Aerosol Transport in Sampling Devices.

Figure 4. Commercial Aerosol Sampling Device Characteristics in Terms of Agarwal and Liu Sampling Regimes.

Figure 5. Sampling Efficiency Data [Yoshida *et al.*, 1979] and the Agarwal and Liu “Pretty Good” Sampling Regime.

To be sure, the general aerosol community operates in a different context than did Morewitz and Vaughan when they propounded their simple correlation for plugging of leak pathways. The aerosol community is interested in the extraction of a sample over a short period of time. Plugging that could occur with protracted operation of the sampler are not of major interest. Morewitz and Vaughan were interested in the plugging of leak pathways at any time when suspended radioactive material could enter the pathway. On the other hand, the perception of aerosol concentrations and the nature of aerosols has evolved significantly since the debates over the safety of LMFBRs. It is useful to see how these changes affect the prediction of the aerosol transport and the possibility of plugging of leak pathways.

In this document some of the literature on theoretical and experimental studies of aerosol transport through leak pathways is examined. The emphasis is on data that have appeared since publication of the Morewitz-Vaughan correlation. There is a bias toward literature pertinent to the reactor safety community. The literature associated with accurate aerosol sampling is indeed huge and only those portions of that literature that point directly at the issues of interest for reactor safety are discussed. There is a growing body of pertinent literature coming from the homeland security community. This community is interested in aerosols leaking into a building rather than leaking from a building. Aerosol physics is, however, the same and this community is applying superior aerosol instrumentation to the issue of in-leakage of aerosol. The data being generated may be quite useful for validating models that are subsequently used for the reverse scenario - leakage from a building or volume. Where the literature generated by the homeland security community has been found, it has been included.

There are two broad issues associated with the leakage of aerosol. First, the aerosol must be able to enter the flow path. Second, the aerosol must be able to successfully negotiate the leak

pathway and emerge into a surroundings where the radioactivity of the particles could have consequence. The focus of this review is really on the second of these issues. There will always be some deposition of aerosol in a leakage pathway. The amount of deposition and the effects of deposits on the behavior of flow through the path including the formation of plugs are of interest. The next chapter discusses some of the experimental studies and data that are available. The third chapter of this report discusses modeling of the experiments. The final chapter summarizes and draws conclusions concerning the technology now available for predicting aerosol transport through leak paths.

2. EXPERIMENTAL STUDIES

2.1 Leak Pathway Idealizations

Experimental studies of aerosol transport through leak paths include engineering tests of actual or scaled facilities or components and laboratory tests with simpler idealized geometries. These laboratory tests are more likely to produce the controlled quantitative data that are useful for the validation of models and assessments of risk. Such laboratory tests use idealizations of real leak pathways to facilitate the modeling. Some typical idealizations of the flow paths are shown in Figure 6. Idealizations include cylindrical capillaries, orifices, annuli and slots. Some studies use combinations of these simple geometries to simulate joints.

Figure 6. Leak Pathway Idealizations.

2.1.1 Capillary Flow

By far and away the most common idealization is to treat a leak path as a straight cylindrical duct. Laboratory tests for such idealizations dominate the older literature and are particularly appropriate for the study of aerosol sampling adequacy. Cross sections of interest here are larger than 20 μm and typically smaller than about 3500 μm . For such small cross sections, laminar flow or flow approaching the transition between laminar and turbulent flow will be expected. Of course the parabolic velocity profile characteristic of laminar flow does not develop instantaneously. Usually, it is assumed that the parabolic flow profile of laminar flow develops over an entrant region of length Z given by:

$$Z = 0.05 D_h N_{\text{Re}} \quad (5)$$

where

- Z - entrance length
- D_h - hydraulic diameter = 4x flow area/wetted perimeter
- N_{Re} - Reynolds number

The isothermal flow of compressible gas through a long cylindrical capillary is given by the well-known expression [Bird, Stewart, and Lightfoot, 1960]:

$$Q^2 = \frac{\frac{RT\pi^2 D^4}{32M_w} \left[1 - \left(\frac{P_{\text{low}}}{P_{\text{high}}} \right)^2 \right]}{\ln \left(\frac{P_{\text{high}}}{P_{\text{low}}} \right) + \frac{2fL}{D}} \quad (6)$$

where

- Q - volumetric flow rate
- D - capillary diameter
- f - Fanning friction factor
- L - capillary length
- M_w - gas molecular weight
- P_{high} - inlet pressure
- P_{low} - outlet pressure
- R - universal gas constant = 83.14472 $\text{cm}^3\text{-bar/mole-K}$
- T - absolute temperature

To approximate real capillaries that do not have perfectly circular cross sections, it is common to use the hydraulic diameter, D_h , as defined above in place of the capillary diameter, D .

For smooth capillaries, the Fanning friction factors can be estimated from:

$$\begin{aligned} f &= \frac{16}{\text{Re}} & \text{for } \text{Re} < 2000 \\ f &= \frac{0.0791}{\text{Re}^{1/4}} & \text{for } 2500 < \text{Re} < 2 \times 10^5 \end{aligned} \quad (7)$$

where

$$\begin{aligned} \text{Re} & - \text{Reynolds number} = \frac{4\rho_g Q}{\pi\mu_g D} \\ D & - \text{gas density} \approx \frac{M_w P}{RT} \text{ (ideal gas law)} \\ f & - \text{gas viscosity} \end{aligned}$$

The friction factor for turbulent flow in capillaries with rough surfaces can be found iteratively from the Colebrook equation² where ε is the roughness height:

$$\frac{1}{\sqrt{4f_F}} = -2 \log_{10} \left[\frac{\varepsilon/D}{3.72} + \frac{2.51}{\text{Re} \sqrt{4f_F}} \right] \quad (8)$$

or

$$\frac{1}{\sqrt{4f_F}} = 1.1364 - 2 \log_{10} \left[\frac{\varepsilon}{D} + \frac{6.9}{\text{Re}} \right] \quad (9)$$

Some explicit formulae have also been published:

$$\frac{1}{\sqrt{4f_F}} = -1.8 \log_{10} \left[\left(\frac{\varepsilon/D}{3.7} \right)^{1.11} + \frac{6.9}{\text{Re}} \right] \quad (\text{Haaland equation}) \quad (10)$$

$$4f_F = \frac{0.25}{\log_{10} \left[\frac{\varepsilon/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}} \right]} \quad (\text{Swange-Jain equation}) \quad (11)$$

² Colebrook equation was developed for the Darcy friction factor, f_D , rather than the Fanning friction factor, f_F , used here. The two friction factors are related by $f_D = 4 f_F$

Slip flow needs to be considered when capillary diameters approach the mean free path of gas molecules. Owzarski *et al.* [1979] have discussed this issue.

2.1.2 Orifice Flow

Orifices are used to simulate punctures in metals and membranes. Adiabatic flow through orifices is described by:

$$\rho_{high} Q = C \rho_{low} A \sqrt{\frac{2P_{high}}{\rho_{low}} \left(\frac{\gamma}{\gamma-1} \right) \left(1 - \left(\frac{P_{low}}{P_{high}} \right)^{\frac{\gamma}{\gamma-1}} \right)} \quad \text{for } \frac{P_{high}}{P_{low}} < \left(\frac{\gamma+1}{2} \right)^{\frac{\gamma}{\gamma-1}} \quad (12)$$

where

- C - discharge coefficient (0.72)
- ρ_{low} - gas density at the outlet (kg/m³)
- ρ_{high} - gas density at the inlet (kg/m³)
- A - orifice cross-sectional area (m²)
- P_{low} - gas pressure at the outlet (Pa)
- P_{high} - gas pressure at the inlet (Pa)
- λ - ratio of specific heats c_p/c_v
- c_p - isobaric heat capacity (J/kg-K)
- c_v - isochoric heat capacity (J/kg-K)
- M_w - gas molecular weight (kg/kmol)
- R - universal gas constant = 8314.472 (Pa-m³/kmole-K)
- T - absolute temperature

Orifices are susceptible, of course, to choked flow.

$$\rho_{high} Q = CA \sqrt{2\rho_{high} P_{high} \left(\frac{\gamma}{\gamma-1} \right) \left(\left(\frac{P_{low}}{P_{high}} \right)^{\frac{2}{\gamma}} - \left(\frac{P_{low}}{P_{high}} \right)^{\frac{\gamma+1}{\gamma}} \right)} \quad \text{for } \frac{P_{high}}{P_{low}} > \left(\frac{\gamma+1}{2} \right)^{\frac{\gamma}{\gamma-1}} \quad (13)$$

or

$$\rho_{high} Q = CA \sqrt{\frac{2M_w}{ZRT} \left(\frac{\gamma}{\gamma-1} \right) \left(\left(\frac{P_{low}}{P_{high}} \right)^{\frac{2}{\gamma}} - \left(\frac{P_{low}}{P_{high}} \right)^{\frac{\gamma+1}{\gamma}} \right)} \quad \text{for } \frac{P_{high}}{P_{low}} > \left(\frac{\gamma+1}{2} \right)^{\frac{\gamma}{\gamma-1}} \quad (14)$$

where

Z - gas compressibility factor $\frac{PV}{RT}$

2.1.3 Flow in Slots

Baker *et al.* [1987] recommend that for slots and low pressure differentials, the flow, Q , is given by:

$$\Delta P = \frac{12\mu_g L}{wh^3} Q + \frac{\rho_g C_{discharge}}{2h^2 w^2} Q^2 \quad (15)$$

where

- ΔP - pressure differential across the leak pathway
- μ_g - gas viscosity
- ρ_g - gas density
- L - length of the leak pathway
- W - extent of the crack on the face exposed to the elevated pressure
- h - minimum crack dimension (crack height)
(note that in some analyses $2h$ is the symbol for crack height)
- Q - volumetric flow through the crack
- $C_{discharge}$ - discharge coefficient $(1.5 + n_{bend})$
- n_{bend} - number of right angle bends in the crack

A hydrodynamic instability at the exit of a slot can develop, at least in principle, even with laminar flow. [Thomas and Cornelius, 1982] This instability may be responsible for the observation that aerosol particle deposition begins near the exit plane for flow through a slot whereas in deposition usually begins at the inlet to capillaries.

2.1.4 Concrete Cracks

Cracks in concrete are often idealized as slots with rough surfaces. A variety of conventions have been developed to describe the dimensions of cracks in concrete. The convention adopted here is shown schematically in Figure 7. This figure shows a concrete block of width W_o , and thickness L_o with a crack of height h . Whether the crack is oriented horizontally, vertically or at some

angle, the minimum crack dimension perpendicular to the direction of overall flow is taken here to be the crack height.

There does not appear to be a definitive data base on concrete crack heights³. Concrete cracks produced by tensile stresses (see Figure 8.) appear to be well approximated by constant height channels or slots. Cracks produced by a combination of tensile and shear forces may be more complicated. (see Figure 9.) Rizkalla *et al.* [1983] experimented with cracks 20 to 100 μm in height. Experiments by Stegemann *et al.* [2005] involve crack heights on the order of 200 μm . Geiner and Ramm [1995] derived a model of leak flow through concrete with crack heights of 200 to 1300 μm . Rizkalla *et al.* cite work on predicting the spacings of cracks in concrete [Leonhardt, 1977] and the variations in crack heights with crack spacing [Beeby, 1979]. Work to relate cracking to an index of concrete damage is underway [Landis *et al.*, 2007]

The actual length of a crack pathway, L , can be longer than the thickness of the concrete structure, L_o . The ratio of these lengths is called the crack tortuosity:

$$\tau = \frac{L}{L_o} \quad (16)$$

Other definitions of tortuosity abound in the literature. Crack tortuosities, as defined here, are thought not to be especially high [Schlangen and Garboczi, 1996]. Gelain and Vendel [2008] found tortuosity of 1.27 for membrane stress cracks through a 10 cm concrete panel and compared this to values of 1.36 and 1.249 reported by others. Boussa *et al.* [2001] have taken a more detailed examination of cracks in concrete. They note that deviations in the crack pathway occur wherever the crack encounters large aggregate or the like. They conceive of concrete cracks being composed of short straight segments. The ends of the segments are marked by modest changes in direction. Statistical analyses of segments in cracks of various types led these investigators to suggest that angular change in direction (degrees) is normally distributed with mean zero and standard deviation between 20 and 30 degrees. They argue somewhat less persuasively that the lengths of segments are also normally distributed with mean values of 0.54 to 0.71 mm and standard deviations in the range of 0.28 to 0.40 mm. They suggest that the variations in mean and standard deviations of these measures of the segments can be related to concrete manufacture, but do not provide a useful correlation.

Meander of the crack as well as intersection with other cracks can make the crack width, W , perpendicular to the overall direction of flow much greater than the width of the concrete panel, W_o . Another type of tortuosity could be defined by the ratio of these two dimensions, though normally this is not done.

Though cracks may be approximated as constant height slots, they cannot be considered to have smooth surfaces. This complicates the prediction of flow through concrete cracks. Pan, Marchertas and Kennedy [1984] recommend the isothermal flow equation derived by Rizkalla *et*

³ In the structural mechanics literature, crack heights are sometimes termed “crack displacements or “crack opening displacements”

al. [1984]:

$$\frac{P_{high}^2 - P_{low}^2}{L} = \frac{k^n}{2} \left(\frac{\mu_g}{2} \right)^n \left(\frac{RT}{M_w} \right)^{n-1} \left(\frac{P_{low} Q_{low}}{W} \right)^{n-2} \frac{1}{h^3} \quad (17)$$

where

μ_g - gas viscosity

Q - volumetric flow through the crack

k, n - constants determined by tests with cracks

Based on tests with eight concrete specimens cracked by tensile stresses, Rizkalla *et al.* found:

$$k = 2.907 \times 10^7 \left(\frac{h}{30.48} \right)^{1.284} \quad (18)$$

$$n = 0.133 \left(\frac{30.48}{h} \right)^{0.243} \quad (19)$$

where crack heights are in meters. Alternative expressions for the flow through cracks in concrete appear in the literature, but they require parameters determined by experiment [Greiner and Ramm, 1995]. There are ongoing studies of gas and steam flow through cracked concrete [Stegemann *et al.*, 2005] that do not make the isothermal assumption adopted for the flow expression given above. Riva *et al.* [1999] has compared experimental results for air-steam flow through cracks in concrete with model predictions. These authors find the model derived by Rizkalla *et al.* to be reliable when steam condensation is not important.

Figure 7. Crack Dimensions.

Figure 8. Cracks Produced in Concrete by Predominantly Membrane Stress.

Figure 9. Concrete Cracks Produced by Membrane and Shear Stress at a Penetration.

2.1.5 Gasket Leaks

Hirao *et al.* [1993] characterize the onset pressure and temperature for leaks in hatch flange gaskets. They do not provide data on leak flow, but they do provide qualitative information on leak cross-section. The remarkable findings by Hirao *et al.* is the time at temperature required for leaks to develop in a pressurized system. This could mean that aerosol available to enter the leak will have aged and be depleted of the larger particle size material before a leak develops.

2.2 Individual Experimental Studies

Synoptic accounts of individual experimental investigations are provided in the subsections that follow.

2.2.1 *Experiments with Capillaries by Mitchell and Coworkers*

The most comprehensive response to the Morewitz-Vaughan correlation was launched in the United Kingdom in an effort by J.P. Mitchell and coworkers [Burton *et al.*, 1993; Morton and Mitchell, 1995]. The experimental studies involved flow of aerosol through capillaries 19 to 21 mm long with bores of 28 to 35 μm . Most of the experiments used nearly spherical glass spheres as the aerosol. A typical size distribution for the glass sphere is shown in Figure 10. Concentrations of the glass spheres in the source volume leading to the capillary leaks were modest in comparison to concentrations used in many of the experiments used to support the Morewitz-Vaughan correlation. Typically, these concentrations were only 1-3 g/m^3 at the start of a test and declined due to sedimentation within the source volume as the experiment progressed.

Some experiments were done with cerium oxide particles which would have modest deviations from spherical shapes.

Pressure differentials used to produce flow through the capillary leak paths were 20, 40, 60, and 80 kPa. Some results of the tests are shown in Figure 11. Results of the test at 40 kPa pressure differential are listed in Table 1. An effectiveness factor termed “penetration” is shown in this table. Penetration is the fraction of the aerosol estimated to enter the capillary (based on gas flow and aerosol concentration) that emerges from the capillary

It was found that at 20 kPa, capillaries plugged almost immediately. At a pressure differential of 80 kPa, plugging did not occur over the duration of the experiment though some fluctuations in the volumetric flow rate through the capillaries were observed. At intermediate pressure differentials, there was a slow reduction in the volumetric flow as the capillaries became plugged with aerosol. The initiation of plugging was in the entrance region of the capillaries. In the laminar flow regime of the tests done by Mitchell and coworkers, the dominant deposition mechanisms for aerosol particles are expected to be gravitational settling and diffusion to the walls. Settling and diffusion will lead to deposition if there is sufficient particle residence time in the flow pathway. It would be expected, then, that as flow velocity increases (and residence time decreases) that particle penetration would increase as long as flow remained in the laminar regime. As shown by the plot of penetration against Reynolds number (see Figure 12), this seemed to be the case in the tests done by Mitchell and co-workers.

Mitchell and coworkers employ an unusual metric termed the “standardized leak rate” (SLR) to characterize their experimental conditions. The standardized leak rate is related to the velocity of flow through the capillary by:

$$\bar{v}(m/s) = \frac{P_u^2 - P_d^2}{P_s^2} \frac{SLR}{P_u - P_d} \frac{8}{\pi D^2} = \frac{2912}{D^2(\mu m)} \quad (20)$$

where

- P_u - upstream pressure
- P_d - downstream pressure
- P_s - 100 kPa
- D - capillary inner diameter
- SLR - standardized leak rate

A leakage “efficiency”, E , is also defined that is better viewed as a figure of merit since the efficiency is not constrained to lie between zero and unity. Some results in terms of these unique quantities are shown in Table 2.

The efficiency of aerosol penetration would be expected to depend on aerosol particle size. The distribution of particle sizes that emerge from a capillary should differ, then, from that entering the capillary. A comparison of particle size distributions input and emerging from a 70 μm diameter capillary reported by Mitchell, Edwards and Ball [1990] are shown in Figure 13. Evidently, losses during flow through the capillary are predominantly from the smaller particle size portion of the distribution. This is indicative, of course, of a diffusive particle deposition process.

An important result from the test by Mitchell and coworkers is that very frequently capillaries could become plugged with respect to aerosol transport, but gas flow would continue. Some examples are shown for 30 μm capillaries in Table 3. The aerosols used in the tests were, of course, not radioactive. In the case of reactor accidents with radioactive aerosols plugging the pathways, deposits would be heated by decay energy. Continued flow of gas over the deposits raises the possibility that more volatile radionuclide might evaporate from the deposits and be carried through the passage.

Figure 10. Size Distribution of Glass Sphere Aerosols Used in Tests by Mitchell and Coworkers.

Figure 11. Flow Through Capillaries Exposed to Glass Sphere Aerosol.

Figure 12. Number of Particles that Emerged from Capillaries After 2 Hours.

Figure 13. Comparison of Probability Density Function for the Number Distributions of Aerosol Input and Exiting from a 5 cm long 70 µm Capillary.

Table 1. Glass Aerosol Deposition in a Capillary with a Pressure Differential of 40 kPa.

time (s)	Aerosol concentration (g/m³)	Penetration (-)	Mass deposited in time interval (mg)
600	1.33	1	0
1200	0.51	0.886	6.8×10^{-5}
1800	0.52	0.436	34.5×10^{-5}
2400	0.28	0.262	24.3×10^{-5}
3000	0.19	0.154	18.9×10^{-5}
3600	0.13	0.163	12.8×10^{-5}
3900	0.10	0	11.8×10^{-5}

Table 2. Results of Tests by Mitchell and Coworkers.

ΔP (kPa)	Aerosol concentration (g/m³)	SLR (Pa m³/s)	Particles per hour	E (-)
80	0.67	3.64×10^{-4}	2.7	1.95
60	0.71	3.26×10^{-4}	3.3	2.57
40	1.33	2.86×10^{-4}	2.73	1.48
20	3.22	1.24×10^{-4}	0.06	0.048
20	0.14	2.00×10^{-4}	0.12	1.35
20	4.24	2.57×10^{-4}	1.194	0.35
20	0.33	2.19×10^{-4}	0.45	1.96
60	0.04	8.88×10^{-4}	0.60	3.03
80	1.18	1.33×10^{-4}	3.60	4.05
100	4.3	4.10×10^{-4}	18.30	1.96

Table 3. Continued Gas Flow Through Capillaries Following Plugging in Tests by Mitchell and Coworkers.

ΔP (kPa)	SLR before plugging (Pa m ³ /s)	SLR after plugging (Pa m ³ /s)
20	2.00x10 ⁻⁴	1.19x10 ⁻⁴
40	2.86x10 ⁻⁴	2.83x10 ⁻⁴
60	3.26x10 ⁻⁴	3.28x10 ⁻⁴
80	3.64x10 ⁻⁴	3.63x10 ⁻⁴

2.2.2 Capillary Tests by Nelson and Johnson

A data set that has figured prominently in the discussions of aerosol leakage through capillaries is that reported by Nelson and Johnson [1975]. For these tests, the investigators burned 25 grams of sodium in a cylindrical chamber with inside diameter 0.61 m and length 1.48 m. The atmosphere also contained up to 8000 ppm water vapor so the aerosol was undoubtedly a mixture of sodium hydroxide and sodium oxide. Obviously, the aerosol concentration was initially very high. Gravitational deposition of aerosol within the chamber competed with flow of aerosol through vertical capillaries of various sizes and lengths. Some results obtained on aerosol penetration through the capillaries are listed in Table 4. The authors did not report aerosol particle size but appeared to understand that large particles produced by coagulation at high aerosol concentrations would be more effective in plugging the capillaries. They showed that plugging decreased with the concentration of aerosol available for input to the capillaries. Much has been made of the observed plugging of the capillaries. Equally important is the failure of capillaries to plug when only low concentrations of aerosol probably having particles with sizes too small to gravitationally sediment rapidly were left in the chamber

Table 4. Results From Tests with Sodium Oxide and Sodium Hydroxide Aerosols Reported by Nelson and Johnson [1975].

Capillary Dimensions		Aerosol Concentration (g/m ³)	Gas Flow Prior to Plugging (dm ³)	Entering Aerosol mass prior to plug (mg)	Time to plug (min)
ID (cm)	Length (cm)				
0.052	4.9	15-11	~0.06	0.65-0.9	0.125 ± 0.025
0.052	4.9	12.5-9.5	0.12	1.4 ± 0.1	2.55 ± 0.35
0.052	4.9	10-7	0.14	1.2 ± 0.2	2.3 ± 0.8
0.052	4.9	4.2-2.8	0.25	0.85 ± 0.15	3.6 ± 0.7
0.052	4.9	1.9-0.047	163	did not plug	
0.08	7.6	~5.8	0.16	~0.93	~0.3
0.08	7.6	~4.4	0.2	~0.88	1.3 ± 0.2
0.08	7.6	1.5-1.25	1.07	1.5	7.0 ± 0.5
0.08	7.6	0.26-0.17	5.55	1.3	26 ± 5
0.08	7.6	0.13-0.0001	57	did not plug	
0.107	3.8	2.1-3	5.5	14.3	
0.107	7.6	0.75-1.6	17	19.4	
0.107	3.8	0.7-0.4	19.75	9.5	
0.107	7.6	20-25	29	did not plug	
0.107	7.6	0.14-0.0001	1550	did not plug	
0.132	3.8	9.8-9.0	10	92	
0.132	7.6	6.2-1.3	30.5	95	
0.157	7.6	18-15	3.5	58	
0.157	7.6	21-8	68	did not plug	

2.2.3 Tests of Depleted Uranium Dioxide Flow Through Capillaries.

Sutter *et al.* [1980] have examined the transport of depleted uranium dioxide powders through capillaries with internal diameters of 48, 78, 114.3, 182, 229, and 275 μm . Characteristics of the capillaries measured by Owzarski *et al.* [1979] are listed in Table 5. Flows through the capillaries as functions of pressure are provided in Table 6 and shown in Figure 14.

The particles in the uranium dioxide powder had mean sizes of 1 μm but were extensively aggregated. The powders were dispersed with a low velocity gas flow through a bed so that concentrations were controlled in the test rather than decaying rapidly due to gravitational settling within the generation volume. No effort was made to characterize the size distribution of the airborne material, but mass concentrations were measured. Aerosol concentration were very much lower than those used in other investigations. Consequently, aerosol growth by coagulation probably does not complicate the interpretation of the results. Tests were done with the leak paths above and below the powder bed. Only tests with leaks above the powder bed are of interest for the purposes of this work. Some of the data reported by Sutter *et al.* are shown in Table 7. The uranium dioxide that penetrated the capillaries in the tests is plotted in Figure 15 against the mass of uranium expected if there was 100% penetration. The diagonal line in this plot is indicative of perfect agreement between observations and expectations based on 100% penetration.

Sutter *et al.* found two regimes of behavior depending on the dimensional metric Φ :

$$\Phi = \ln A \sqrt{\Delta P} \quad (21)$$

where

A - leak area (μm)²
 ΔP - pressure difference (psig)

The two regimes are:

- $\Phi < 10.5$

For this regime a maximum of 46 μg of particulate material passed through the leaks.

- $\Phi > 10.5$

Leakage in this regime could be correlated by the expression:

$$\ln(m_{\text{UO}_2}) = a + b_1 \ln A + b_2 \sqrt{\Delta P} \pm t_{1-\alpha/2}(N-3) \frac{\text{std. error}}{\sqrt{N-3}} \quad (22)$$

where m is the mass of uranium dioxide in μg that leaks and $t_{1-\alpha/2}(n)$ is the critical value of the Student's t-statistic for a confidence of 100 (1 - α)% and n degrees of freedom. Parametric values for capillaries are listed in Table 8.

Table 5. Characteristics of Capillaries Used by Sutter *et al.*

Capillary Label	Length (cm)	Inside Diameter (μm)	Roughness
1-50	2.54	48	0.087
2-75S	0.762	78	0.028
100S	0.762	114.3	0.028
100B	2.85	114.3	0.028
150S	0.767	182	0.014
150A	2.54	189	0.014
150B	2.63	176	0.014
200S	0.759	228	0.0043
200B	2.61	231	0.0043
250S	0.782	276	0.0044
250A	2.62	274	0.0044
250B	2.69	274	0.0011

Figure 14. Flow Characteristics of Capillaries Used by Sutter *et al.* [Owzarski *et al.*, 1979].

Table 6. Flow Characteristics [Owzarski et al., 1979] of Capillaries Used by Sutter et al.

ΔP (psig)	Flow Through the Indicated Capillary in cm ³ /minute					
	1-50	2-75 S	100 S	100 B	150 S	150 A
1		3.7	8	3.2	57	16
2		4.3	14	7.1	87	38
3		6.5	22	12.5	121	61
4		7.7	29	15	145	82
5		13	444	19	180	101
10		30	83	37	295	182
20	1.1	58	133	77	475	325
30	4.0	83	180	130	640	425
40	6.5	107	235	165	780	530
50	16	130	275	195	900	640
60	22	146	340	215	1020	740
70	33	165	365	245	1180	840
80	39	195	405	265	1360	940
90	42	205	450	310	1520	1040
100	45	225	490	325	1640	1150
1000	400	2100	4800	2840	14600	10500

Table 7. Results of Tests by Sutter *et al.* with Capillaries

Test # (Capillary Label)	Capillary Diameter (μm)	Chamber Pressure (psig)	Test Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)	UO2 Transmitted (μg)
14(250A)	274	500	30	5400	2×10^{-4}	30.4 ± 9.1
15(150A)	189	1000	10	10500	0.012	1280 ± 660
26(150B)	176	500	30	5600	4	720 ± 330
28(200B)	231	500	10	20000	0.01	2690 ± 1100
34(250A)	274	30	30	1180 (plugged)	3×10^{-5}	2.4 ± 1.6
37(250B)	274	30	60	520	2×10^{-4}	5.9 ± 1.8
41(150S)	182	1000	10	14600	1×10^{-3}	212 ± 64
43(150S)	182	500	30	5600	2×10^{-3}	290 ± 87
44(150B)	176	30	60	520	4×10^{-4}	12.4 ± 3.7
45(150S)	182	30	60	640	5×10^{-4}	18.0 ± 5.4
50(100B)	99	1000	10	3140	3×10^{-3}	87.8 ± 26
52(100B)	99	1000	10	400	2×10^{-3}	6.2 ± 1.9
54(100B)	99	500	30	195	0.0007	4.07 ± 1.7
55(250S)	276	1000	10	38800	0.02	9210 ± 360
57(1-50)	48	500	30	195	4×10^{-3}	25 ± 7.5
58(250S)	276	500	30	13300	2×10^{-3}	675 ± 200

Table 7, Continued.

Test # (Capillary Label)	Capillary Diameter (μm)	Chamber Pressure (psig)	Test Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)	UO2 Transmitted (μg)
60(200S)	228	30	60	4800	5×10^{-5}	13 ± 3.9
61(1-50)	48	30	60	4	0.04	8.75 ± 2.6
62(100S)	97	1000	10	4800	5×10^{-4}	22.3 ± 6.7
63(200S)	228	1000	10	25300	2×10^{-5}	3.95 ± 1.8
65(2-75S)	78	1000	10	2100	2×10^{-3}	33.7 ± 10
67(1-50)	48	1000	10	400	0.04	143 ± 43
69(200S)	228	500	30	8000	0.01	3340 ± 1300
70(100B)	99	500	30	1560	8×10^{-5}	3.8 ± 1.8
71(250S)	276	30	60	1650	2×10^{-3}	217 ± 65
73(100B)	99	30	30	180	1×10^{-3}	4.96 ± 1.8
78(250S)	276	100	30	4500	1×10^{-3}	188 ± 56
84(1-50A)	48	100	30	1150	2.6×10^{-5}	0.877 ± 0.27
86(150B)	176	100	30	1150	1.3×10^{-5}	0.462 ± 0.27
87(200S)	228	100	30	2430	1.4×10^{-5}	1.04 ± 0.31
88(150S)	182	100	30	1640	7×10^{-3}	320 ± 43
89(1-50A)	48	100	30	45	4.9×10^{-4}	0.655 ± 0.27
95-1(250B)	274	30	60	1200	1.2×10^{-4}	8.55 ± 2.6
95-2(250S)	274	30	60	1650	6.6×10^{-6}	0.652 ± 0.27
96-1(150B)	176	30	60	520	2.8×10^{-5}	0.883 ± 0.27
96-2(150S)	182	30	60	640	2.5×10^{-4}	9.65 ± 2.9
97-1(250B)	274	1000	10	31880	9.5×10^{-6}	3.02 ± 0.9
97-2(250S)	276	1000	10	38800	0.04	15800 ± 2100
98-1(150B)	176	500	30	5600	6×10^{-3}	959 ± 140
98-2(150S)	182	500	30	7400	1×10^{-3}	267 ± 37

Figure 15. Comparison of Observed Transmission of Uranium Dioxide Powder Through Capillaries in Tests Reported by Sutter *et al* with Transmission Expected if Penetration Through Capillaries was 100%.

Table 8. Parametric Values for Capillaries.

Parameter	Capillary
a	-17.9875
b1	2.1658
b2	0.1170
N	37
std. error	1.1379
R2	0.6634

2.2.4 Rockwell Tests on Capillary Flow

Rockwell International [1977] reported results of aerosol plugging capillaries as a function of capillary diameter, capillary length and pressure differential. These results, extracted from graphs, are shown in Table 9. Aerosols were sodium oxide and sodium carbonate. Particle size information was not given, but in light of the rather high concentrations, it would be expected that particles would be rather large ($\sim 10\text{ }\mu\text{m}$). Without particle size information there is rather little that can be done with these data aside from developing correlations of the type proposed by Morewitz and Vaughan. An interesting feature of the tests is the observation that plugging differed in capillaries with sharp opening than in capillaries with rounded openings.

Table 9. Capillary Plugging Results Reported by Rockwell International [1997].

ΔP (kPa)	Capillary diameter (cm)	Capillary Length (cm)	Aerosol Concentration (g/m³)	mass passing through prior to plugging (mg)
3.45	0.108	3.8	14-16.5	1.4
6.93	0.108	3.8	14-16.5	6.9
12.5	0.108	3.8	14-16.5	15
13.6	0.108	3.8	14-16.5	49
27.2	0.108	3.8	14-16.5	107
3.45	0.132	5.1	6-10.5	0.25
3.45	0.132	15.2	6-10.5	0.49
3.45	0.132	10.1	6-10.5	1.5
3.45	0.132	20.4	6-10.5	2.4
3.45	0.132	17.9	6-10.5	3.9
2.9 to 6.9	0.041	5.0	1.3-1.7	13
2.9 to 6.9	0.059	5.0	1.3-1.7	15
2.9 to 6.9	0.059	5.0	1.3-1.7	23
2.9 to 6.9	0.108	5.0	1.3-1.7	70
2.9 to 6.9	0.108	5.0	1.3-1.7	70
2.9 to 6.9	0.108	5.0	1.3-1.7	83

2.2.5 Tests with Orifices

Sutter *et al.* [1980] also examined the flow of uranium dioxide powder through orifices using an apparatus similar to that used for their studies of capillaries (see Section 2.2.3). Their results for upward flow are shown in Table 10. They observed no profound tendency for orifice plugging. Observed uranium dioxide leakage through the orifices is plotted in Figure 16 against the leakage that would be expected for 100% penetration of the orifices. Sutter *et al.* analyzed their data on the leakage of uranium dioxide powder through orifices using the same model that they used for the analysis of leakage through capillaries (see Section 2.2.3) and derived the parameters (see Table 11

Mitchell *et al.* [1992] also examined the penetration of nominally 7 μm glass beads through orifices 19.3 to 106 μm in diameter. Like Sutter *et al.*, these authors used a fluidized bed technique to produce aerosol, so concentrations were controlled. Their results are listed in Table 12. The authors observed no plugging save for some partial plugging of the 20 μm orifice. They concluded that their results were consistent with those of Sutter *et al.*

Figure 16. Comparison of Observed [Sutter *et al.*, 1980] Uranium Dioxide Powder Leakage Through Orifices Plotted Against the Expected Leakage Assuming 100% Particle Penetration of the Orifice.

Table 10. Data Reported by Sutter *et al.* for Air-Sparged Uranium Dioxide Transmission Through Orifices.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
2	200	1000	20	16400	8×10^{-3}
3	100	1000	10	2100	7×10^{-3}
4	125	500	30	4300-4800	0.01
5	200	500	30	6200	7×10^{-3}
6	61	1000	10	2100	3×10^{-3}
7-1	22	500	10	111	0.05
7-2	23	500	30	133	3.8×10^{-3}
7-3	20	500	60	94	6.5×10^{-3}
7-4	23	500	120	140	7.1×10^{-4}
8	20	1000	10	210	6×10^{-3}
9	33	1000	10	580	6×10^{-3}
10	61	500	30	1000	2×10^{-3}
11	38	500	30	470	2×10^{-3}
12	20	500	30	94	0.02
13	200	1000	10	22000	0.02
17	200	30	60	1000	1×10^{-3}
18	100	30	60	245	4×10^{-3}
19	66	30	60	80	4×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
20-1	33	500	10	350	5×10^{-3}
20-2	43	500	30	435	3×10^{-3}
20-3	33	500	60	285	6×10^{-4}
20-4	38	500	120	470	3×10^{-4}
21	200	500	30	6400	7×10^{-5}
22-1	33	500	30	350	1×10^{-3}
22-2	43	500	30	435	2×10^{-3}
22-3	33	500	30	285	1×10^{-3}
22-4	38	500	30	470	9×10^{-4}
24-1	22	500	30	111	2×10^{-3}
24-2	20	500	30	94	2×10^{-3}
24-3	23	500	30	140	1×10^{-3}
24-4	23	500	30	133	3×10^{-3}
25-1	66	500	30	1100	2×10^{-3}
25-2	61	500	30	1000	3×10^{-3}
25-3	65	500	30	1200	2×10^{-3}
27-1	66	500	10	1100	4×10^{-4}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
27-2	61	500	30	1000	2×10^{-4}
27-3	65	500	60	1200	2×10^{-4}
29-1	22	1000	10	275	0.01
29-2	23	1000	10	275	3×10^{-3}
29-3	20	1000	10	210	0.01
29-4	23	1000	10	290	2×10^{-3}
30-1	22	1000	10	275	3×10^{-3}
30-2	23	1000	20	275	7×10^{-4}
30-3	20	1000	30	210	2×10^{-3}
30-4	23	1000	60	290	3×10^{-4}
31-1	22	30	10	10	0.07
31-2	23	30	30	10.3	0.03
31-3	20	30	60	9.5	0.02
31-4	23	30	120	14.5	6×10^{-3}
32	43	30	60	20	0.01
33-1	22	30	30	10	$< 3 \times 10^{-3}$
33-2	23	30	30	10.3	4×10^{-3}
33-3	20	30	30	9.5	$< 3 \times 10^{-3}$

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
33-4	23	30	30	14.5	7×10^{-3}
35-1	33	30	30	28	0.01
35-2	43	30	30	22	5×10^{-3}
35-3	33	30	60	24	2×10^{-3}
35-4	38	30	120	39	5×10^{-3}
36	22	30	60	10	7×10^{-3}
38-1	33	30	60	39	2×10^{-3}
38-2	43	30	60	33	1×10^{-3}
38-3	33	30	60	35	0.01
38-4	38	30	60	39	0.02
40-1	66	1000	10	2300	2×10^{-3}
40-2	61	1000	10	860	2×10^{-3}
40-3	65	1000	10	1760	0.004
42-1	66	1000	10	200	0.01
42-2	61	1000	30	1450	0.001
42-3	65	1000	60	2400	1×10^{-3}
46-1	33	1000	10	695	2×10^{-3}
46-2	43	1000	20	840	6×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
46-3	33	1000	30	580	6×10^{-4}
46-4	38	1000	60	920	6×10^{-4}
47-1	33	1000	10	695	5×10^{-3}
47-2	43	1000	10	840	2×10^{-3}
47-4	38	100	10	920	7×10^{-4}
48-1	66	30	30	80	3×10^{-3}
48-2	61	30	60	88	3×10^{-4}
48-3	65	30	120	109	9×10^{-4}
49-1	66	30	57	80	3×10^{-3}
49-3	65	30	57	109	4×10^{-3}
51-1	100	1000	15	7100	2×10^{-3}
51-2	125	1000	30	500	2×10^{-3}
51-3	100	1000	40	5800	1×10^{-3}
42-1	66	1000	10	200	0.01
42-2	61	1000	30	1450	0.001
42-3	65	1000	60	2400	1×10^{-3}
46-1	33	1000	10	695	2×10^{-3}
46-2	43	1000	20	840	6×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
56-3	100	500	60	3100	3×10^{-4}
59-1	100	500	30	3060	5×10^{-5}
59-2	125	500	30	4500	8×10^{-4}
59-3	100	500	30	3100	6×10^{-4}
64-1	100	30	30	245	7×10^{-3}
64-2	125	30	60	365	2×10^{-3}
64-3	100	30	120	245	6×10^{-4}
66-1	100	30	60	245	2×10^{-4}
66-2	125	30	60	365	2×10^{-3}
66-3	100	30	60	245	3×10^{-3}
68-2	200	1000	10	22000	0.01
68-3	200	1000	10	22000	0.01
72-1	200	500	10	12200	0.01
74-1	200	500	30	12200	0.01
74-2	310	500	30	11200	7×10^{-3}
75	100	100	30	640	1×10^{-3}
76-1	200	1000	10	4000	0.04
76-2	310	1000	30	22000	0.07

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
77	61	100	30	225	2×10^{-3}
79-1	200	30	60	1000	5×10^{-3}
79-2	310	30	60	960	2×10^{-4}
79-3	200	30	60	1000	2×10^{-3}
80	22	100	30	25	9×10^{-3}
81	43	100	30	77	2×10^{-3}
82-1	200	30	30	1000	2×10^{-3}
82-3	200	30	90	1000	4×10^{-4}
83	274	100	30	3463	6×10^{-6}
85	200	100	30	2300	1×10^{-3}
90-1	231	500	30	16080	4×10^{-6}
90-2	276	500	30	20000	0.02
91-1	100	100	10	640	1.1×10^{-3}
91-2	125	100	30	900	7.7×10^{-4}
91-3	100	100	60	638	3.9×10^{-4}
92-1	100	100	30	640	4.5×10^{-4}
92-2	125	100	30	900	2.2×10^{-5}
92-3	100	100	30	638	1.1×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
93-1	66	100	10	255	3×10^{-4}
93-2	61	100	30	225	1×10^{-4}
93-3	65	100	60	265	1×10^{-4}
94-1	66	100	30	255	1.3×10^{-4}
94-2	61	100	30	225	5.3×10^{-4}
94-3	65	100	30	255	3.0×10^{-4}
96-3	200	30	60	1000	2.8×10^{-4}
98-3	200	500	30	11000	3×10^{-3}
101-1	22	100	30	25	0.01
101-2	23	100	30	29	3.5×10^{-3}
101-3	20	100	30	22	2.2×10^{-3}
101-4	23	100	30	32	2.5×10^{-3}
103-1	22	100	10	25	0.013
103-2	23	100	30	29	3.8×10^{-3}
103-3	20	100	60	22	9.5×10^{-4}
103-4	23	100	120	32	4×10^{-4}
104-1	200	1000	10	18800	0.03
104-2	200	1000	10	22300	8×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
106-1	33	100	30	74	1.5×10^{-3}
106-2	43	100	30	77	1.3×10^{-3}
106-3	33	100	30	64	2.4×10^{-3}
106-4	38	100	30	106	1.4×10^{-3}
107	23	1000	10	220	1.4×10^{-3}
108	38	1000	10	998	3.8×10^{-4}
109	23	1000	10	30	0.013
110	38	1000	10	57	0.012
111	65	1000	10	660	8.0×10^{-3}
112	100	1000	10	3650	3.0×10^{-3}
113	200	1000	10	18500	0.03
114	23	500	30	35	2.7×10^{-3}
115	38	500	30	270	5×10^{-4}
116	65	500	30	320	8.6×10^{-4}
117	100	500	30	2250	3.6×10^{-4}
118	200	500	30	10800	2×10^{-3}
119	23	100	30	42.5	8.9×10^{-4}
120	38	100	30	28	3.3×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
121	65	100	30	195	1.4×10^{-3}
122	100	100	30	415	1.1×10^{-3}
123	200	100	30	2260	1.6×10^{-3}
126	38	30	30	28	4.2×10^{-3}
127	65	30	30	98	7.6×10^{-4}
128	100	30	30	120	8.3×10^{-3}
129	200	30	30	860	6×10^{-3}
130	23	1000	10	15.2	0.018
131	38	1000	10	385	1.6×10^{-3}
132	61	1000	10	690	5.0×10^{-3}
133	100	1000	10	335	0.03
134	200	1000	10	19200	8×10^{-3}
136	23	500	plugged		
137	38	500	30	230	9.5×10^{-4}
138	65	500	30	1020	4.7×10^{-4}
139	100	500	30	680	3.1×10^{-3}
140	200	500	30	10300	2×10^{-3}
141	20	100	plugged		

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
142	33	100	30	19	3.4×10^{-3}
143	65	100	30	165	6.6×10^{-4}
144	100	100	30	370	1.8×10^{-3}
145	200	100	30	2300	1.3×10^{-3}
148	38	30	30	35	8.2×10^{-4}
149	100	30	30	177	5.5×10^{-4}
150	65	30	30	98	1.6×10^{-3}
151	200	30	30	870	3.5×10^{-4}
190	20	1000	30	1300	1.6×10^{-4}
191	226	500	30	13100	3.6×10^{-3}
192	89	1000	30	12400	1.1×10^{-4}
193	111	500	30	2150	1.9×10^{-3}
194	32	1000	30	660	4.3×10^{-4}
195	226	500	30	11400	3.7×10^{-3}
196	89	1000	30	2200	1.1×10^{-3}
197	226	30	30	1000	6.8×10^{-3}
199	22	500	30	370	3.5×10^{-4}
200	89	500	30	3360	4.6×10^{-4}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
201	111	1000	30	7100	2.8×10^{-3}
202	22	1000	30	690	3.2×10^{-4}
203	22	30	30	28	0.011
204	190	1000	30	22000	3.3×10^{-3}
205	190	500	30	11000	2.1×10^{-3}
206	32	30	30	24	6.8×10^{-3}
207	226	1000	30	28000	3.4×10^{-3}
208	190	30	30	940	3.5×10^{-3}
210	32	500	30	275	5.4×10^{-4}
211	89	30	30	235	2.3×10^{-3}
212	226	1000	30	25200	4.0×10^{-3}
213	111	500	30	3060	0.033
214	190	30	30	1000	1.0×10^{-3}
215	32	500	30	285	4.1×10^{-4}
216	89	500	30	3100	2.2×10^{-4}
218	111	30	30	245	0.014
219	226	500	30	12200	4.6×10^{-3}
220	32	1000	30	580	1.9×10^{-3}

Table 10, continued.

Test #	Orifice Diameter (μm)	Chamber Pressure (psig)	Duration (min)	Air Flow (cm^3/min)	Aerosol Concentration (g/m^3)
221	22	30	30	28	2.4×10^{-3}
222	190	500	30	11000	2.5×10^{-3}
223	111	1000	30	7100	4.5×10^{-3}
224	22	1000	30	695	5.8×10^{-4}
225	226	30	30	1000	0.024
227	190	1000	30	2200	0.018
228	32	30	30	24	2.7×10^{-3}
229	89	1000	30	5500	1.2×10^{-3}
230	22	500	30	350	6.5×10^{-4}
231	89	30	30	245	2.7×10^{-3}
250	111	30	30	245	4.1×10^{-4}
251	111	100	360	640	4.6×10^{-3}
252	111	100	360	640	1.0×10^{-4}
253	111	100	30	870	1.6×10^{-3}
255	111	100	1440	700	3.0×10^{-4}
256	111	100	1440	700	1.0×10^{-4}
261	111	100	30	795	4.1×10^{-3}
262	111	100	30	695	1.5×10^{-3}
263	111	100	360	625	4.8×10^{-4}

Table 11. Parametric Values for Orifices.

Parameter	Capillary
a	-14.1959
b1	1.7906
b2	0.1095
N	91
std. error	0.8718
R2	0.8262

Table 12. Some Results of Experiments by Mitchell *et al.* [1992] on the Penetration of Orifices by Nominally 7 μm glass Aerosol Particles.

orifice			Aerosol Concentration (Particles/m^3)	Leak Rate (particles per hour)
Bore (μm)	Length (μm)	Discharge Coefficient		
106	102	0.47	482×10^6	2.05×10^6
41.8	102	0.35	291×10^6	1.30×10^6
37.6	102	0.46	69×10^6	0.966×10^6
32.2	102	0.43	214×10^6	0.625×10^6
20.5	229	0.47	26×10^6	0.233×10^6
20.5	102	0.39	29×10^6	0.090×10^6
19.3	50.9	0.45	62×10^6	0.0745×10^6
20.0	25.4	0.47	43×10^6	0.0123×10^6
21.3	12.7	0.51	281×10^6	0.227×10^6
21.2	509	0.54	88×10^6	0.349×10^6

2.2.6 Lewis Tests of Particle Transport Through a Slot

Lewis [1995] obtained penetration data for various sizes of particles passing through a slot. Particles included talc, fumed silica, precipitated silica, aluminum oxide, titanium dioxide, and Arizona road dust. The slot was 0.1 mm high and 40 mm long. The differential pressure in the tests was 10 kPa. Penetration data were fit to a quadratic polynomial in particle size. What Lewis termed “best fit” results from a variety of tests are shown in Table 13. Results from tests with talc are shown in Table 14. These results are plotted in Figure 17. The size-dependent data are particularly useful for code validation.

Figure 17. Lewis [1995] results for aerosol flow through a 0.1 mm slot at a pressure differential of 10 kPa.

Table 13. Results of Lewis' Test [1995] of Particle Transport Through a Slot (Best Fit Results).

d_p (μm)	Penetration (-)	d_p (μm)	Penetration (-)
1.0	0.985	3.46	0.621
1.0	0.935	4.0	0.554
1.5	0.918	4.0	0.521
1.5	0.9	4.5	0.442
2.0	0.86	4.5	0.412
2.0	0.859	5.0	0.315
2.48	0.797	5.0	0.297
2.48	0.794	5.5	0.175
3.0	0.730	5.5	0.173
3.0	0.715	6.0	0.053
3.46	0.647	6.0	0.029

Table 14. Results of Lewis' Test [1995] of Particle Transport Through a Slot (Data for Talc Particles).

d_p (μm)	Penetration (-)	d_p (μm)	Penetration (-)
1.0	0.481	2.29	0.600
1.10	0.842	2.68	0.695
1.20	0.642	3.09	0.543
1.31	0.974	3.46	0.636
1.50	0.736	4.34	0.499
1.60	0.751	4.64	0.284
1.70	0.811	5.89	0.330
1.90	0.478	6.29	0.001

2.2.7 Mosley *et al.* Tests of Aerosol Transport Through a Slot

Mosley *et al.* [2001] reported on the transport of aerosol having aerodynamic mean diameters of 0.05 to 5 μm through a horizontal slot 0.508 mm high, 433 mm wide and 102 mm deep. The slot was made with aluminum sides so surface roughness was quite small. Data were collected with an aerodynamic particle sizer (APS) and an electrical low pressure impactor (ELPI). Some results are shown in Figure 18 through Figure 21. Penetration increases with increasing differential pressure over the range of 2 to 20 kPa. Model predictions shown in the figures were based on considering only diffusion and gravitational sedimentation. The efficiencies of these deposition processes were taken to be additive, so:

$$P_{\text{overall}} = P_{\text{grav}} P_{\text{diff}} \quad (23)$$

where

P_{overall} - overall penetration of the slot

P_{grav} - penetration if only gravitational sedimentation

$$= 1 - \frac{V_{\text{settling}} L}{2hV}$$

P_{diff} - penetration if only diffusion

$$= \exp\left[\frac{1.967\eta_p L}{h^2 V}\right]$$

h - crack height

The agreement between experimental results and predictions of the simple model is quite noteworthy. Particle sizes examined and hydrodynamic conditions span sufficient range to test well diffusion and gravitational settling models for laminar flow.

Figure 18. Results of Tests by Mosley *et al.* [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 2 kPa Differential Pressure

Figure 19. Results of Tests by Mosley *et al.* [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 5 kPa Differential Pressure

Figure 20. Results of Tests by Mosley *et al.* [2001] for aerosol transport through a slot 0.5 mm high, 433 mm wide, and 102 mm deep at a 10 kPa Differential Pressure

Figure 21. Results of Tests by Mosley *et al.* [2001] for Aerosol Transport Through a Slot 0.5 mm High, 433 mm Wide, and 102 mm Deep at a 20 kPa Differential Pressure

2.2.8 Liu and Nazaroff Tests of Aerosol Flow Through Slots

Liu and Nazaroff [2001; 2003] also reported on aerosol penetration of plots. They constructed slots of a variety of materials including aluminum, brick, concrete and various kinds of wood. Slot heights were 0.25 and 1.0 mm. The flow path lengths (slot depth) were 4.3 and 9.4 cm. Differential pressures were 4 and 10 kPa. Potassium chloride aerosol particles produced by atomizing solutions were used as aerosols. Particles were charge neutralized after drying by irradiation with ^{85}Kr . Particle size data were collected with an aerodynamic aerosol particle sizer (APS), and electrostatic aerosol analyzer, EAA, and a condensation nuclei counter (CNC). Results for aluminum slots are shown in Figure 22 through Figure 25. As with the Mosley *et al.* data, these results are extraordinarily useful for the development and validation of models. Liu and Nazaroff were able to predict results of the experiments with a simple model accounting for diffusion and gravitational settling. This model is discussed further in connection with the discussions of theoretical analyses.

Nazaroff Liu 0.25 mm x 9.4 cm 2 Pa

Figure 22. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 9.4 cm deep at a 2 Pa Differential Pressure

Liu Nazaroff 0.25 mm x 9.4 cm slot 10 Pa

Figure 23. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 9.4 cm deep at a 10 Pa Differential Pressure

Figure 24. Data from Liu and Nazaroff for Aerosol Flow Through a slot 0.25 mm high and 4.3 cm deep at a 10 Pa Differential Pressure

Figure 25. Data from Liu and Nazaroff for Aerosol Flow Through a slot 1.0 mm high and 9.4 cm deep at a 10 Pa Differential Pressure

2.2.9 Tests with Cracked Concrete

Tests of aerosol transport through cracked concrete specimens were reported by van de Vate [1988]. For these tests, penetration was defined as:

$$P = \frac{\text{number of particles exiting a pathway}}{\text{number of particles entering a pathway}} \quad (24)$$

where

- $\bar{m}$ - aerosol mass transport through a passage prior to plugging (kg/m³)
- D_{duct} - equivalent diameter of the leak pathway (m)
- k - constant = $(5 \pm 3) \times 10^4$ (m³/kg)

Monodisperse polystyrene latex sphere were used as aerosol particles. Cracks in the concrete varied in width up to 0.25 mm. Some results are shown in Table 15. Results of the tests were correlated by:

$$-\ln P = (2.8 \pm 1.7) \times 10^{-3} Q^{1.8 \pm 0.07} d_p^4 C_{slip}^2 \quad (25)$$

where

- P - penetration
- Q - volumetric flow through the crack (cm³/s)
- d_p - particle diameter (μm)
- C_{slip} - Cunningham slip correction factor

In contrast to the experiments by Mitchell and coworkers, these tests showed that penetration decreased with increasing pressure drop across the crack. Van de vate concluded that crack flow was in the transition between laminar and fully developed turbulent flow whereas tests by Mitchell and coworkers all involved laminar flow. Gelain and Vendel [2008] suggest that because of roughness, flow in concrete cracks makes a transition from laminar to turbulent for Reynolds numbers between 5 and 10.

Gelain and Vendel [2008] have very recently reported on the penetration of uranine particles through artificial cracks 67.2 μm high in 10 cm thick concrete panels. Their data are listed in Table 16 and plotted in Figure 26. They considered both diffusion and gravitational settling in their modeling of the results. They also considered inertial impaction at the inlet to the crack. The overall penetration is given by:

$$P_{total} = P_{diff} P_{grav} P_{inertial} \quad (26)$$

$$P_{diff} = 0.914 \exp[-2.8278\Theta] + 0.0531 \exp[-32.147\Theta] + 0.01528 \exp[-93475\Theta] + 0.00681 \exp[-186805\Theta] \quad (27)$$

$$P_{grav} = 1 - \frac{V_{settling} L}{Vh} \quad (28)$$

$$P_{inertial} = \frac{1}{1 + 85.9 Stk^{1.24}} \quad (29)$$

where

$$\Theta = \frac{8DL_w}{3Qh} \quad (30)$$

$$D = \frac{C_{slip} kT}{3\pi\mu_g D_{particle} \chi} \quad (31)$$

where

D - particle diffusion coefficient

A brief discussion of particle diffusion coefficients is provided in Appendix A to this document. The model of diffusion used by Gelain and Vendel is taken from the work of Bowen *et al.* [1976]. The inertial deposition model is from Regtuit *et al.* [1990] (See also [Eleftheriadis and Colbeck, 1992].)

Table 15. Penetration Observed in Transport of Polystyrene Latex Aerosols Through Cracks in Concrete [van de Vate, 1988].

ΔP (kPa)	d_p (μm)	Q (cm^3/s)	Penetration (-)
3	0.48	145	0.8
3	0.82	145	0.8
3	1.1	145	0.5
3	2.0	145	0.11
6	0.48	250	0.75
6	0.82	250	0.6
6	1.1	250	0.2
6	2.0	250	0.008
9	0.48	350	0.65
9	0.82	350	0.45
9	1.1	350	0.07
9	2.0	350	0.005

Table 16. Uranine Particle Penetration of Cracks (h = 67.2 μm) in Concrete [Gelain and Vendel, 2008].

Particle diameter = 1.1 μm		Particle diameter = 0.8 μm		Particle diameter = 0.6 μm	
Flow (cm^3/s)	Penetration (± 0.11)	Flow (cm^3/s)	Penetration (± 0.12)	Flow (cm^3/s)	Penetration (± 0.11)
51.5	0.11	85	0.57	110	0.168
51.5	0.20	85	0.35	110	0.247
111.4	0.43	85	0.30	110	0.081
134.2	0.47	128.4	0.38	230	0.255
164.6	0.48	128.4	0.44	230	0.337
183	0.30	128.4	0.64	230	0.182
236.2	0.38	171	0.71	230	0.277
390	0.21	171	0.51	230	0.359
600	0.19	260	0.46	230	0.197
341	0.480	260	0.49	230	0.305
341	0.334	260	0.52	230	0.382
380	0.501	348	0.53	230	0.182
380	0.572	360	0.33	295.3	0.435
380	0.452	360	0.44	295.3	0.510
455	0.518	475	0.36	295.3	0.354
455	0.592	500	0.51	305	0.421
455	0.466	505	0.39	305	0.505
		603	0.25	305	0.348
		606	0.23	330	0.439
		630	0.41	330	0.515
		502	0.502	330	0.365
		502	0.569	341	0.408
		502	0.427	519	0.423
		518.5	0.452	519	0.497
		518.5	0.523	519	0.349
		518.5	0.381	613	0.487
				613	0.554
				613	0.412

Figure 26. Penetration of Uranine Particles Through a 67.2 μm Crack in Concrete [Gelain and Vendel, 2008].

2.2.10 Tests of Leakage from a Flow Stream

Most of the data cited here are for aerosol leaking from a relatively calm gas volume. Carrié and Modera [1998; 2002] examined leakage of aerosol through a slot perpendicular to a flowing stream of aerosol-laden gas (This is the so-called “transverse flow problem”). The motivation of the investigators appears to have been the investigation of aerosols for sealing leaks in duct systems. The aerosol they used was acetate-acrylate vinyl polymer which they described as “sticky”. (At the microscopic scale of aerosol surface interactions dominated by van der Waals forces, the concept of “sticky” is difficult to quantify.) The aerosol had mass median diameters of 3 to 7 μm . The aerosol was injected into a 15 cm duct that could bent through a 3 mm high, 40 mm long slot. Gas flows were 12500 cm^3/s to 55500 cm^3/s at pressure differentials of 20, 40, 60 and 80 Pa. The aerosols, of course, could not all follow stream lines of the flow redirection through the slot. Many would impact on the downstream wall of the slot causing the slot to narrow. An example of the change in slot thickness as a function of time is shown in Figure 27. In subsequent tests [Carrié and Modera, 2002], the authors investigated transverse flow of aerosol-laden gas through slots and joints. Some results are shown in Figure 28.

Figure 27. Carrié and Modera [1998] on the Variation in Slot Height Due to Aerosol Accumulation from Transverse Flow.

Figure 28. Comparison of Leakage Flow of Aerosol-Laden Gas Through a Slot and a Joint [Carrié and M.P. Modera, 2002].

2.2.11 Multiple Bend Geometry Tests

Morewitz *et al.* [1979] reported results of especially complicated geometry test involving about 12 bends. Typical flow pathways in the test were 0.125 cm and 0.079 cm wide. Results of the four tests were:

Test 1

Aerosol composed of a mixture of sodium oxides and sodium carbonate at a concentration of 15 to 20 g/m³ and a differential pressure of 6.9 kPa were used. The system plugged in about 5 minutes. A total of 0.217 m³ gas passed through the system and carried 3 to 4 grams of aerosol.

Test 2

A similar test with 500 g/m³ sodium oxide/ sodium carbonate aerosol and a differential pressure of 280 kPa lead to plugging in about 6 seconds. Only 0.003 grams of aerosol having a means size > 6.8 :m passed through the system.

Test 3

A test with uranium oxide aerosol at 900 g/m³ plugged the system in about 1.5 minutes. Gas flow through the system amounted to 0.012 m³ STP and carried 0.45 g uranium dioxide.

Test 4

A repetition of test 3 with uranium dioxide aerosol at 230 g/m³ lead to plugging in about 5 minutes. Gas flow through the system was 0.013 m³ STP. About 0.015 g of uranium oxide aerosol was carried through the system.

2.2.12 Tests of Leakage Through Containment Penetrations

Watanabe *et al.* [unpublished] described results of an integral test of aerosol leakage through boiling water reactor containment penetrations. A large model BWR containment was heated. The atmosphere of the containment was contaminated with CsI aerosol. At 553 to 593 K, leakage was detected in a low voltage electrical penetration. The pressure differential across the penetration at the time leakage was detected was about 7 kPa. The aerosol concentration within the model was about 0.08 g/m³. The aerosol had a mass median aerodynamic diameter of about 1.4 :m. At the outlet side of the penetration aerosol concentrations were 0.003 to 0.005 g/m³. With time, the decontamination of aerosol-laden gas passing through the electrical penetration increased by about a factor of 3.

Continued heating of the model containment lead to leakages in the flange gasket when temperatures reached 803 to 633 K. Post test examination showed that the gasket on the flange had developed cracks up 10 mm wide. Decontamination factors for aerosol-laden gas passing through these cracks was found to vary between 10 and 30.

For neither the electrical penetration leakage nor the flange gasket leakage are their data on the size dependence of decontamination. Consequently, extrapolating the integral test results to other situations is difficult.

2.2.13 Containment Leak Tests

Hilliard and Postma [1981] reported results obtained in a series of large scale containment leak tests. For these tests, deliberate leaks were introduced that passed 0.1 to 1.0 liters of aerosol-laden gas per minute. The authors defined an “attenuation factor”, A_f to be:

$$A_f = \frac{\text{mass passing through the leak}}{\text{mass entering the leak pathway}} \quad (32)$$

They considered leakage of cesium particles and iodine in both gaseous and particle form. The cesium particles had aerodynamic settling diameters of 10-17 μm in the early stages of the tests. The mean settling diameters were between 3 and 10 μm in the late stages of the test. The geometry of the leak path was quite complicated and included a needle valve, so analysis of the tests would be challenging. They reported attenuation factors at 2 and 24 hours. But, these attenuation factors apparently included the effect of condensation in a volume beyond the needle valve and the subsequent heat up of the condensate to dryness. The authors reported that ~96% of the iodine and ~99% of the cesium were retained in the heated volume as a nonvolatile residue as though most of the iodine and cesium had successfully negotiated passage through the leak and the needle valve only to be trapped in condensate.

2.3 Turbulent Deposition of Particles

Many of the experiments described in the previous section of this report have been analyzed assuming the flow is laminar and the primary deposition mechanisms are gravitational for larger particles and diffusive for smaller particles. Turbulent flow conditions can develop especially in flow through cracks in concrete where surface roughness can trigger turbulence. Turbulence introduces a new mechanism for the deposition of aerosol particles. This mechanism is a very local phenomenon. Aerosol deposition is not usually analyzed in terms of “penetration”. Rather, turbulent particle deposition is usually considered in terms of a deposition velocity V_d . The deposition velocity relates the particle flux, in terms of either mass or particle number, to the particle concentration in the gas phase, again either in terms of mass concentration or number concentration:

$$\frac{1}{A} \frac{dN}{dt} = V_d C \quad (33)$$

where

V_d - deposition velocity
 C - particle concentration

In early work on turbulent aerosol deposition, it was assumed that the deposition velocity could be correlated with flow conditions via some function of the Reynolds number. Experimental evidence has shown there to be a confounding between the flow conditions and the particle properties. It is now common to correlated the deposition velocity with the particle relaxation time, τ . The particle relaxation time is defined and discussed in Appendix A. Dimensionless quantities used in the correlation are:

$$V_d^+ = \frac{V_d}{u^*} \quad (34)$$

$$\tau^+ = \frac{\tau \rho_g (u^*)^2}{\mu_g} \quad (35)$$

where

u^* - friction velocity

For flow through smooth cylindrical channels, the friction velocity is found from:

$$u^* = V \sqrt{\frac{f}{2}} \quad (36)$$

$$f = \frac{0.0791}{\text{Re}^{1/4}} \quad (37)$$

$$\text{Re} = \frac{D_{\text{path}} \rho_g V}{\mu_g} \quad (38)$$

where

D_{path} -diameter of cylindrical pathway

Where the flow pathway is not perfectly cylindrical, it is common to use the hydraulic diameter as discussed above in Section 2.1.

Turbulent deposition data of interest for common idealizations of cylindrical leaks involves deposition on smooth surfaces. (Concrete cracks are, of course, an exception.) A vast amount of data has been gathered on turbulent deposition in such pathways. Most has been from experiments larger than those of interest for leaks from reactor containment buildings, but the dimensionless correlation of deposition velocity and particle relaxation time makes it possible to apply these data. The objective here is to accumulate this data base, at least, to an appreciable extent.

The experimental data base has been reviewed many times [Parker *et al.*, 2008; Papavergos and Hedley, 1984; and especially Sippola and Nazaroff, 2002]. Consequently, only very brief descriptions of important experimental studies are provided in the subsections that follow. To avoid too much more disruption of the flow of the text, tabulated values of the dimensionless deposition velocity and dimensionless particle relaxation times derived from the experiment data are collected in Appendix B.

2.3.1 Friedlander and Johnstone

The experimental studies conducted by Friedlander and Johnstone [1957] is usually considered the work that initiated 50 years of investigation of turbulent deposition of aerosol. Prior investigations had been reported, but Friedlander and Johnstone provided a mechanistic interpretation of their experimental observations. The experiments were done with a variety of particles in vertical tubes of various types. Data derived by digitizing plots in the Friedlander and Johnstone publication are shown in Figure 29. These data are now considered to be of primarily historical significance though they are occasionally still cited in the validation of theoretical models of turbulent deposition.

Figure 29. Turbulent Aerosol Particle Deposition Data Obtained by Friedlander and Johnstone [1957].

2.3.2 Montgomery and Corn

Montgomery and Corn [1970] examined turbulent deposition of uranine-methylene blue aerosol ($\rho = 1.5 \text{ g/cm}^3$) in a horizontal pipe 15.405 cm diameter. They did attempt to charge neutralize the aerosol using electron guns. The data they obtained are shown in Figure 30. These data are concentrated in the regime where the dimensionless deposition velocity begins to rapidly increase with increases in the particle relaxation time.

Figure 30. Turbulent Particle Deposition Reported by Montgomery and Corn [1970].

2.3.3 Wells and Chamberlain

Wells and Chamberlain [1967] reported data on the deposition of tricresyl phosphate droplets (density = 1.16 g/cm^3). They used a vertical, copper duct with flow downwards. The deposition surface was a brass rod 1.27 cm in diameter within the 3.81 cm diameter duct. Their data shown in Figure 31 are concentrated in the regime of dimensionless droplet relaxation times where the dimensionless deposition velocity passes through a minimum.

Figure 31. Turbulent Deposition of Tricresyl Phosphate Droplets [Wells and Chamberlain, 1967].

2.3.4 Liu and Agarwal

Widely considered a definitive study, the data obtained by Liu and Agarwal [1974] are frequently used to substantiate theoretical models of turbulent deposition of aerosols. The data were obtained using olive oil particles (density = 0.92 g/cm³) tagged with uranine. The experiments were done with a vertically oriented glass tube 1.27 cm in diameter. Air was the gas phase in these tests. Results of the tests are shown in Figure 32. There is a sharp rise in the dimensionless deposition velocity for values of the dimensionless particle relaxation time of 0.2 to about 10. Thereafter, the dimensionless deposition velocity slowly decreases with increases in the dimensionless particle relaxation time. This slow decrease is thought to be real and not an artifact of particle bounce.

Figure 32. Turbulent Particle Deposition Data from Liu and Agarwal [1974] and from El-Shobokshy [1983].

2.3.5 El-Shobokshy

El-Shobokshy [1983] was most concerned about the effects of low levels of surface roughness on turbulent deposition of particles. He did do experiments with glass surfaces he took to be completely smooth. The experiments involved a glass duct with an internal diameter of 0.8 cm. Flow was downward through this duct. The aerosol were fluoroscene ($\rho = 1.5 \text{ g/cm}^3$). The aerosol were charge neutralized with ^{85}Kr irradiation. Data obtained in the study for glass pipes were digitized from a small plot and are shown in Figure 32 along with the data from Liu and Agarwal.

2.3.6 Lee and Gieseke

Lee and Gieseke [1994] reported data on the deposition of dioctyl phthalate droplets (density = 0.986 g/cm^3) in pipes with diameters of 0.767 cm and 0.622 cm (see Figure 33). The pipes used in the tests were very long and had ten 90° bends that may have affected particle deposition. The aerosol were charge neutralized by irradiation with ^{85}Kr . Data are concentrated in the range of particle relaxation times where deposition velocities pass through a minimum. The results of Gieseke indicate higher deposition velocity in this region than do results of other investigators.

Figure 33. Turbulent Deposition Velocities for Dioctyl Phthalate Droplets [Lee and Gieseke, 1994].

2.3.7 Shimada *et al.*

Shimada *et al.* [1993] reported data on the deposition of extremely fine aerosol particles (0.01 to 0.043 μm) (see Figure 34). Unfortunately, the composition of the particles is not stated in their publication. Based on other work by the authors [Kuyama *et al.*, 1984], it suspected that the particles are sodium chloride (density = 2.165 g/cm^3). The experiments were done with a horizontal copper pipe (ID = 0.6 cm) using air as the gas phase. The investigators did charge neutralize their aerosol. Reynolds numbers for the flow velocity went up to $\sim 50,000$.

Figure 34. Turbulent NaCl Aerosol Deposition Data from Shimada *et al.* [1993].

2.3.8 Sehmel

Sehmel [1970] undertook a monumental effort to characterize the deposition of uranine particles in vertical aluminum tubes. The focus of the effort was on the practical issues of particle deposition in ventilation ducts and, consequently, there were pipe joints and the like that complicate interpretation of the experiments. In some of the tests, the pipe surfaces were coated with a grease to inhibit particle bounce. The bulk of the data shown in Figure 35 is very scattered. Some of the complication comes no doubt from particle deposition by means other than turbulence brought about by the rather “industrial” design. Particle bounce and resuspension of deposited materials may also have contributed to the scatter.

Figure 35. Data on the Turbulent Deposition of Uranine Particles Obtained by Sehmel [1970].

2.3.9 Postma and Schwendiman

Postma and Schwendiman [1960] reported on the deposition of ZnS (density = 4.093 g/cm^3) and glass particles from turbulent flow in 1.905 cm polished stainless steel tubes and 2.54 cm aluminum tubes (see Figure 36). It appears likely that the tubes were oriented horizontally.

Figure 36. Turbulent Aerosol Deposition Data from Postma and Schwendiman [1960].

2.3.10 Ilori

Ilori has obtained data on turbulent deposition of particles as part of his thesis research (T.A. Ilori, Turbulent deposition of aerosol particles in pipes”, Ph.D. Thesis, University of Minnesota, 1974). These data have not been published in a more accessible source. Data shown here (see Figure 37) were obtained by digitization of a small plot published by Im and Ahluwalia [1989].

Figure 37. Turbulent Particle Deposition Data Obtained by Ilori in His Thesis Research. Data Digitized from a Small Plot Published by Im and Ahluwalia [1989].

2.3.11 Muyshondt *et al.*

Muyshondt *et al.* [1996] looked at the deposition of oleic acid droplets (density = 0.933 g/cm³) from turbulent gas flow in tubes of diameter from 1.3 to 10.2 cm (see Figure 38). These tubes are, of course, much larger than leak paths of interest here, but the data do permit extension of the correlations of deposition velocity to higher values of the particle relaxation time.

D_{pipe} indicates the pipe diameter.

D_{part} indicates the aerosol particle diameter.

Figure 38. Turbulent Deposition of Oleic Acid Droplets [Muyshondt *et al.*, 1996].

2.3.12 Forney and Spielman

Forney and Spielman [1974] examined the deposition of lycopodium spores (mean diameter = 30.9 μm ; density = 0.65 g/cm^3), ragweed pollen (mean diameter = 19.5 μm ; density = 0.48 g/cm^3) and pecan pollen (mean diameter = 48.5 μm ; density = 0.94 g/cm^3) from turbulent flow in vertically oriented cylinders with internal diameters of 1.3, 1.78, 2.54, 3.12, 3.65, and 4.4 cm (see Figure 39). The particles they used were, of course, far larger than aerosols that are of interest for the purposes of reactor accident analyses. The large particles do allow the data base for turbulent deposition of particles to be expanded.

Forney and Spielman encountered severe particle bounce problems at values of the dimensionless particle relaxation time in excess of about 10. They attempted to counter the tendency for particles to bounce off the tube walls by coating these walls with petroleum jelly is widely done in the aerosol field. This helped, but did not eliminate particle bounce. The investigators found that a mixture of 75% paraffin oil and 25% petroleum jelly sufficiently suppressed particle bounce for their purposes.

Blue squares are data for Lycopodium spores.
 Light blue triangles are data for Pecan pollen particles.
 Green circles are data for ragweed pollen particles

Figure 39. Data on Turbulent Deposition of Large Particles [Forney and Spielman, 1974].

An overall plot of several of the data sets discussed above is shown in Figure 40. Data extend over about 7 orders of magnitude in the value of the dimensionless particle relaxation time. The dimensionless deposition velocity decreases with increasing relaxation time in the regime where diffusion is an important process for bringing particles into contact with the surfaces. When the dimensionless relaxation time reaches a value of about 0.1, the dimensionless deposition velocity increases quite abruptly even in the logarithmic scale of the plot to a maximum at a relaxation time of about 30. There is a slow decrease in the deposition velocity with increases in the

relaxation time beyond that maximum. There are theoretical reasons to think that this slow decrease is a manifestation of the turbulent process and not the product of particle bounce [Sipolla and Nazaroff, 2002].

Figure 40. Turbulent Particle Deposition Data from Several Investigations.

3. THEORETICAL INVESTIGATIONS

Particles that enter leak pathways are susceptible to several processes that can lead to deposition. The processes listed by van de Vate in his studies of aerosol leakage through concrete cracks are:

- Diffusion
- Electrophoresis
- Thermophoresis
- Diffusiophoresis
- Gravitational settling
- Inertial impaction and interception

To this list, Williams [1994] would add advection and turbophoresis. Van de Vate [1988] has assessed the importance of each of the mechanisms within the context of aerosol transport through cracked concrete. He is able to discount thermophoresis and diffusiophoresis despite the pressure drop across the leak path. Diffusion, including where applicable turbulent diffusion, gravitational settling and inertial impaction, again where applicable, emerge as the dominant mechanisms of aerosol deposition.

Since publication of the Morewitz-Vaughan correlation, there has been substantial theoretical work on aerosol transport. Much of the pertinent work has been directed at accounting for the simplicity of the empirically derived correlation. (Earlier theoretical work has been well reviewed by Schwendiman and Sutter [1997].) Deposition data show a strong variation between laminar and turbulent flow conditions. Modeling activities also divide naturally between these two flow regimes.

3.1 Laminar Flow Conditions

The utility of rather simple flow models for aerosol deposition from laminar flows through leak pathways has been demonstrated by results reported by Mosley *et al.* [2001] and by Liu and Nazaroff [2003] and discussed in Section 3. Both of these teams of investigators have assumed that deposition is dominated by diffusion and gravitational settling. They assume further that these processes operate independently so that the overall penetration is given by the product of penetrations achieved by either mechanism alone:

$$P_{overall} = P_{diff} P_{grav} \quad (39)$$

Were inertial impaction important in the tests these investigators examined, its effects could be included as a third term in the product on the right hand side of this equation. Both sets of investigators use the Fuchs model for the penetration that will be achieved in the face of just gravitational settling: where:

$$P_{grav} = 1 - \frac{V_{settling} L}{hV} \quad (40)$$

where

- $V_{settling}$ - settling velocity of the aerosol particle
- L - depth of the leak passage diameter of the leak pathway (m)
- h - height of the leak passage (note that some analysts use 2h as the leak height)
- V - flow velocity through the leak

To model penetration when only diffusion leads to particle deposition, Mosley *et al.* use the expression:

$$P_{diff} = \exp\left(\frac{1.967\eta_p L}{(h/2)^2 V}\right) \quad (41)$$

where

- η_p - particle diffusion coefficient = $\frac{kTC_{slip}}{3\pi\mu_g d_p}$
- k - Boltzmann constant
- C_{slip} - Cunningham slip correction factor
- d_p - particle diameter

Liu and Nazaroff, on the other hand, use [De Marcus and Thomas, 1952]:

$$P_{diff} = 0.915 \exp(-1.885\phi) + 0.592 \exp(-22.3\phi) + \exp(-152\phi) \quad (42)$$

where

$$\phi = \frac{4\eta_p L}{h^2 V} \quad (43)$$

Liu and Nazaroff related pressure differential across the slots used in their test to volumetric flow using an equation by Baker [1987]:

$$\Delta P = \frac{12\mu_g L}{wh^3} Q + \frac{\rho_g C_{discharge}}{2h^2 w^2} Q^2 \quad (44)$$

where the discharge coefficient is given by

$$C_{discharge} = 1.5 + n_{bend} \quad (45)$$

and where

n_{bend} - number of right angle bends in the crack

For diffusive deposition, Schwendiman and Sutter [1977] prefer:

$$P_{diff} = 0.819 \exp(-3.65\phi) + 0.097 \exp(-23\phi) + 0.032 \exp(-57\phi) + 0.027 \exp(-123\phi) + 0.025 \exp(-750\phi) \quad (46)$$

which has been validated by Sinclair *et al.* [1976] For small values of ϕ (< 0.1), some prefer the Gormley and Kennedy expression [1949]:

$$P_{diff} = 1 - 2.56\phi^{0.667} + 1.2\phi + 0.177\phi^{1.333} \quad (47)$$

Differences in the detailed expressions for penetration when diffusion is the only process leading to diffusion do not make large differences in the predictions for experiments since the fraction of particles subject to rapid diffusive deposition is small typically.

Schwendiman and Sutter also note the expressions derived by Browning and Ackley [1963] for the decontamination factor (DF) – the reciprocal of penetration) associated with flow through circular and rectangular channels:

- circular channel

$$\log_{10} DF = 0.0867 + 203.2 \frac{\mu_g \eta_p L^2}{\Delta P D^2} \quad (48)$$

- rectangular channel

$$\log_{10} DF = 0.0386 + 39.35 \frac{\mu_g \eta_p L^2}{\Delta P h^4} \quad (49)$$

Han [2007] has considered aerosol deposition from laminar flow in concrete cracks. He has adopted the description of the crack pathway as a series of straight segments bounded by small curves. Most of the particle retention he considers occurs at the bends in the flow pathway. He takes the fraction of particles depositing in the bend to be:

$$f_d = \alpha \left(1 - \frac{4.5 \mu_g h}{\theta u_{\max} \rho_p d_p^2} \right) \quad (50)$$

where

- f_d - fraction of particles deposited in the bend
- α - sticking probability of a particle hitting a surface
- θ - angle (radians) of bend
- $u_{\max}$ - maximum velocity in the parabolic gas velocity profile
- ρ_p - material density of the particle
- d_p - diameter of a spherical particle of equivalent volume

For turbulent flow conditions that are commonly encountered when gas flows through cracks in concrete, McFarland *et al.* [1997] recommends the fraction of particles retained in a bend to be given by:

$$f_d = 1 - 0.01 \exp \left(\frac{4.61 + a \theta Stk}{1 + b \theta Stk + c \theta^2 Stk^2 + d \theta^2 Stk} \right) \quad (51)$$

where

$$a = -0.9526 - 0.0568 \delta \quad (52)$$

$$b = \frac{-0.297 - 0.0174 \delta}{1 - 0.07 \delta + 0.0171 \delta^2} \quad (53)$$

$$c = -0.306 + \frac{1.895}{\sqrt{\delta}} - \frac{2.0}{\delta} \quad (54)$$

$$d = \frac{0.131 - 0.0132 \delta + 0.000383 \delta^2}{1 - 0.129 \delta + 0.0136 \delta^2} \quad (55)$$

$$\delta = \frac{2R_{bend}}{h} \quad (56)$$

$$Stk = \frac{C_{slip} \rho_p d_p^2 V}{9\mu_g h \chi} \quad (57)$$

and where

R_{bend} - radius of the bend in the flow path

3.2 Chen Yu Method for Deposition by Multiple Mechanisms

Many of the models of aerosol deposition in leak pathways treat the deposition by multiple mechanisms as independent processes. The overall penetration is simply the product of penetration that would be produced if each mechanism operated alone. The efficiencies of deposition (logarithms of penetration) are simply additive. This works well when diffusion and gravitational deposition are the only important mechanisms since these mechanisms are most effective on distinct portions of any real aerosol size distribution. Inertial deposition, on the other hand, operates on particles that are also affected by one or the other of diffusion or gravitational settling. The efficiencies of deposition are not simply additive. Logically, a proper method for combining efficiencies is:

$$\varepsilon_{overall} = 1 - (1 - \varepsilon_1)(1 - \varepsilon_2) = \varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2 \quad (58)$$

where ε_1 and ε_2 are the efficiencies of each process when it operates alone.

Chen and Yu [1993] argue that a better way to combine efficiencies of two mechanisms is:

$$\varepsilon_{overall} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 - (\varepsilon_1 \varepsilon_2)^2} \quad (59)$$

Similar, but more complicated, expressions are provided for three mechanisms:

$$\varepsilon_{overall} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 - (\varepsilon_1 \varepsilon_2)^2 - (\varepsilon_1 \varepsilon_3)^2 - (\varepsilon_2 \varepsilon_3)^2 - (\varepsilon_1 \varepsilon_2 \varepsilon_3)^2} \quad (60)$$

Chen and Yu also provide expressions for the efficiencies of aerosol deposition by diffusion and gravitational sedimentation in plug and parabolic flows:

Sedimentation - slug flow [Yu *et al.*, 1977]

$$\varepsilon = \frac{2}{\pi} \left[\sin^{-1} \left(\frac{4}{3} f \right) + \frac{4}{3} f \sqrt{1 - \frac{4}{3} f} \right] \quad (61)$$

where

$$f = \frac{3LV_{\text{settling}}}{4DV} \quad (62)$$

Sedimentation - parabolic flow [Pich, 1972]

$$\varepsilon = \frac{2}{\pi} \left(2f \sqrt{1 - f^{2/3}} - f^{1/3} \sqrt{1 - f^{2/3}} \right) \quad (63)$$

Diffusion - slug flow [Ingham, 1975]

$$\varepsilon = 1 - 4 \sum_{n=1}^3 \frac{1}{\lambda_n^2} \exp(-\Delta_d \lambda_n^2) - \left(1 - 4 \sum_{n=1}^3 \frac{1}{\lambda_n^2} \right) \exp \left[\frac{8\sqrt{\Delta_d/\pi}}{1 - 4(1/\lambda_1^2 + 1/\lambda_2^2 + 1/\lambda_3^2)} \right] \quad (64)$$

where

$$\Delta_d = \frac{4\eta_p L}{VD^2}$$

η_p - particle diffusion coefficient = $\frac{kTC_{\text{slip}}}{3\pi\mu_g d_p}$

k - Boltzmann constant

and η_p is the particle diffusion coefficient and λ_n is the n^{th} zero of the zero-order Bessel function.

Diffusion - parabolic flow

$$\varepsilon = 1 - 0.819 \exp(-3.66\Delta_d) - 0.0976 \exp(-22.31\Delta_d) - 0.0325 \exp(-57\Delta_d) - 0.0509 \exp(-49.96\Delta_d) \quad (65)$$

Chen and Yu draw a distinction between fully developed laminar flow with a parabolic gas velocity profile across the pathway and plug flow where the gas velocity profile is flatter. In real capillaries, gas entering a capillary will have a velocity profile approximating the flat profile of plug flow more or less depending on details of the inlet. This velocity profile will evolve over the entry length to become parabolic. Mass (and heat transfer) is somewhat slower from fully developed laminar flow with a parabolic velocity profile than it is in plug flow. The somewhat faster mass transfer in the inlet region to a capillary may be one of the reasons that aerosol deposition is often seen to begin at the entrance to a capillary.

3.3 Turbulent Flow Conditions

Williams [1994] has written comprehensively on turbulent deposition of particles in leak paths. Ramsdale and Dunbar [1986] have also addressed this issue. Both studies arrive for practical reasons to the Liu and Agarwal [1974] model of turbulent deposition of aerosol:

$$v^+ = \frac{v_d}{u^*} = \begin{cases} 6 \times 10^{-4} & \text{for } \tau_+ < 12.9 \\ 0.1 & \text{for } \tau_+ > 12.9 \end{cases} \quad (66)$$

where

- v_d - particle deposition velocity
- u^* - friction velocity = $V\sqrt{f/2}$
- f - friction factor

and

$$\tau = \frac{\rho_d d_p^2}{18\mu_g} \quad (67)$$

$$\tau_+ = \frac{\tau \rho_d (u^*)^2}{\mu_g} \quad (68)$$

This leads to the prediction that above a critical particle diameter, the deposition velocity is independent of particle size and from there the Morewitz-Vaughan correlation can be derived. Williams goes on to discuss how a growing deposit of aerosol affects flow and subsequent deposition of particles. He compares his model predictions to results of experiments by Nelson and Johnson [1975]. An example comparison is shown in Table 17. Parozzi *et al.* [2005] have developed a computer code patterned after the analyses by Williams.

Sippola and Nazaroff [2002] have reviewed masterfully the modeling of turbulent deposition of aerosol particles. They consider both empirical models fit to experimental data and more mechanistic modeling. For the purposes of reactor accident analysis, empirical modeling is most suitable. Mechanistic modeling of turbulent particle deposition is still a work in progress. Sippola and Nazaroff suggest:

$$v_d^+ = \begin{cases} f(S_c, \tau^+) & \text{for } f(S_c, \tau^+) < 0.18 \\ 0.18 & \text{for } f(S_c, \tau^+) \geq 0.18 \\ \frac{2.6}{\sqrt{\tau^+}} \left(1 - \frac{50}{\tau^+}\right) & \text{for } \tau^+ > 270 \end{cases} \quad (69)$$

where

$$f(S_c, \tau^+) = \frac{0.063}{S_c^{2/3}} + 3.5 \times 10^{-4} (\tau^+)^2 \quad (70)$$

$$Sc = \frac{\mu_g}{\rho_d D_{part}} \quad (71)$$

and where

D - particle diffusion coefficient (see Appendix A)

Table 17. Comparison of Williams Turbulent Deposition Model to Results of Tests by Nelson and Johnson.

Experiment						Model Prediction			
Inside diameter (cm)	Length (cm)	aerosol conc. (g/m ³)	gas flow (cm ³)	Plug Mass (mg)	Plug time (min)	Plug time (min)	gas flow (cm ³)	Plug Mass (mg)	
0.052	4.9	15-11	60	0.65-0.9	0.1-0.15	0.46	120	1.48	
0.052	4.9	12.5-9.5	120	1.3-1.5	2.2-2.9	0.54	140	1.48	
0.052	4.9	10-7	140	1.0-1.4	1.5-3.1	0.7	180	1.48	
0.052	4.9	4.2-2.8	25	0.7-1.0	2.9-4.3	1.7	440	1.48	
0.052	4.9	1.3-0.9	1500	1.4-1.9	25	5.4	1400	1.48	
0.052	4.9	1.9-0.047		no plug					
0.08	7.6	5.8	160	0.93	0.3	1.58	960	5.4	
0.08	7.6	4.4	160	0.88	1.1-1.5	2.1	1300	5.4	
0.08	7.6	1.5-1.25	1070	1.5	6.5-7.5	6.65	4100	5.4	
0.08	7.6	0.26-0.17	5600	1.3	21-31	42.7	26000	5.4	
0.08	7.6	0.130.0001		no plug					
0.107	3.8	0.75-1.6	5500	14.3	10-14	3.65	5200	11.2	
0.107	7.6	0.4	17000	19.4	33-36	9.6	11300	12.8	
0.107	3.8	0.7	20000	9.5	39	16.8	24200	11.1	
0.107	7.6	20-2.5		no plug					
0.107	7.6	0.14 0.0001		no plug					
0.132	3.8	9-9.8	10000	92	23-24	1.15	2700	19.1	
0.132	7.6	1.3-6.2	31000	95	39-41	3.5	6700	23.6	
0.157	7.6	15-18	3500	58	4	0.9	2600	38.4	
0.157	7.6	8-21		no plug					

3.4 Other Considerations

Much of the discussion of the theoretical and experimental aspects of particle deposition in leak pathways has been based on the presumption that a particle impacting a surface will be retained permanently on that surface. This need not be the case. Particle can bounce off surface and particles deposited on surfaces can resuspend in the flow. Bounce has afflicted many attempts to measure turbulent deposition of solid particles when measures were not taken to suppress bounce such as coating surfaces with grease or oil. (Liquid droplets appear less susceptible to bounce but they are not immune.) Particle resuspension was observed in tests done by Mitchell and coworkers as discussed in Section II.B of this report. It appears that Van de Vate may have observed resuspension in tests of aerosol retention in cracks in concrete.

Particle bounce is incompletely understood. Dahneke [1995] has discussed the normal impact of fully dense, spherical particles on a flat surface and derived an expression for the critical impact velocity necessary for particles to bounce from the surface:

$$V_{bounce} = \sqrt{\frac{2A}{m_p} \left(\frac{1}{e^2} - 1 \right)} \quad (72)$$

where

e - coefficient of restitution of the particle

A - particle-surface interaction energy

The critical velocity depends explicitly on the coefficient of restitution of the particle material and the energy of interaction with the surface material. Neither of these will be well known for the aerosols of interest in the analysis of reactor accidents. Furthermore, the bounce of particles from surfaces also depends on angle of particle impact with the surface [Xu *et al.*, 1993], surface roughness [Tsai *et al.*, 1990] and the yield strengths of both the particle material and the surface material [John, 1995].

Ellenbecker *et al.* [1980] have suggested that for real applications the concept of a critical velocity for particle bounce is not as useful as the idea that there is a probability that a particle will bounce upon impact with a surface. Further, the probability can be related to the kinetic energy of the particle based on the component of velocity normal to the gross surface geometry.

The many uncertain factors that affect bounce will in real situations have distributions of values. These distributions are unknown, of course. But, appeal to the Central Limit Theorem suggests that distributed values of important factors affecting bounce will lead to a lognormal probability of particle bounce:

$$P_{bounce} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2} y^2\right) dy \quad (73)$$

where

$$z = \frac{\ln\left(\frac{KE}{KE_o}\right)^{1/4}}{\ln \sigma} \quad (74)$$

$$KE = \frac{1}{2} m_p v_n^2 \quad (75)$$

and

m_p - particle mass

v_n - particle velocity normal to the surface

Using the data from Ellenbecker *et al.* to parameterize this model yields:

$$KE_o = 4.484 \times 10^{-14} \text{ J}$$

$$\sigma = 4.189$$

Predictions of this model are compared in Figure 41 with data for the probability of fly ash particle bounce from filter beds. Note that the data from Löffler [1974] and from Esmen *et al.* [1978] were not used in the parameterization of the model. Though the model does not conform well to any of the individual data sets, in aggregate it does appear to reflect the observations. The model predicts it to be more likely that big particles will bounce than small particles. Furthermore, it is quite difficult to have all particles of the size of interest for reactor accident to bounce. The generality of the model and certainly the parameterization of the model cannot be assured, but the approach to prediction of particle bounce appears promising. The model does not account for all pertinent phenomena. For example, there is assuredly some impact velocity that will cause particle to break and fragment rather than simply bounce [Thronton *et al.*, 1996].

Resuspension will lift particles deposited on surfaces back into the flow through the leak pathway. Resuspension of deposited aerosol has received some study in recent years [Biasi, *et al.*, 2001; Reeks and Hall, 2001]. These studies have focused on resuspension induced by sudden changes in the gas flow over the deposited particles. The investigations show that there can be a sudden large resuspension. This immediate resuspension is followed by a prolonged period of episodic, smaller resuspension events. Freshly deposited aerosol are more susceptible to resuspension than are deposits that have aged in place.

There are other mechanisms of resuspension. One of these is resuspension triggered by the impact of a particle. John and Sethi have investigated this type of resuspension produced by particles in a jet of gas directed at the aerosol deposit. They find a critical Stokes number for the impacting particles to initiate resuspension of the deposited particles:

$$\sqrt{Stk_{critical}} = 0.81 \pm 0.19 \quad (76)$$

Finally, it is known that particle resuspension can be enhanced if the substrate supporting the deposited particles vibrates or a shock wave passes through the substrate. This mechanism of resuspension and its synergism with gas flow have not been investigated extensively.

Figure 41. Comparison of a Model of Particle Bounce Probability to Data on the Bounce of Fly Ash Particles from Filter Beds.

4. CONCLUSIONS

Conclusions that can be drawn from this review of the available information on aerosol transport through leak pathways are:

- The Morewitz-Vaughan correlation for leak pathway plugging does not provide a complete description of aerosol behavior in leaks. In fact, the correlation is applicable for only a narrow portion of the range of aerosol concentrations and particle sizes of interest for the analysis of reactor accidents.
- The criteria for sampling developed by Davies and by Agarwal and Liu are more useful for assessing the susceptibility of leak pathways to plugging.
- There are abundant data available on the deposition of aerosol in idealizations of leak pathways. Data are available for capillaries, orifices, slots and cracks in concrete.
- Prediction of aerosol deposition is well developed for the conditions of laminar flow through pathways with relatively smooth surfaces. Particle deposition is predominantly by diffusion of small particles and gravitational settling of larger particles.
- Prediction of aerosol transport in laminar flow through cracks in concrete is a developing field.
- A robust base of data and models exists for predicting turbulent particle deposition in capillaries when surface roughness is not large.
- Under turbulent flow conditions aerosol deposition on surfaces may not be permanent. Particles can bounce off surfaces they impact. Deposited particles can resuspend.
- There is a growing understanding of particle resuspension as a result of changes in gas flow over deposits. Resuspension of deposited particles by particle impact and by shock or vibration is less well understood.
- It may be possible to model particle bounce from surfaces using a probabilistic model based on the kinetic energy of the particle.

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APPENDIX A: DERIVATION OF THE STOKES NUMBER

Consider an aerosol particle suspended in a quiescent gas medium and subject to gravitational force. The steady state gravitational settling velocity of the aerosol particle is given by a balance between the gravitational force on the particle and the drag force on the particle:

$$\frac{\pi}{6} D_p^3 (\rho_m - \rho_g) g = \frac{1}{2} C_D \rho_g \frac{\pi}{4} D_p^2 \frac{\chi}{C_{slip}} V_{settling}^2 = \frac{V_{settling}}{B} \quad (77)$$

where

- B - particle mobility (s/g)
- C_D - drag coefficient (-)
- C_{slip} - slip correction factor (-)
- D_p - diameter of a sphere with the same mass as the particle in question (cm)
- g - gravitational acceleration (980.665 cm/s²)
- ρ_g - gas density (g/cm³)
- ρ_m - density of the material making up the aerosol particle (g/cm³)
- $V_{settling}$ - settling velocity (cm/s)
- χ - dynamic shape factor (-)

For perfectly spherical, fully dense particles, the shape factor, χ , is equal to one. For all real aerosol particles, the shape factor is greater than one. For the particles of interest here, the slip correction factor, C_{slip} , differs little from unity.

For the Stokes regime ($Re_p < 1$), the drag coefficient is given by:

$$C_D = \frac{24}{Re_p} \quad (78)$$

$$Re_p = \frac{D_p \rho_g V_{settling}}{\mu_g} \quad (79)$$

where

- Re_p - particle Reynolds number (-)
- μ_g - gas viscosity (g/cm-s)

For larger particles and higher velocities such that the particle Reynolds number exceeds unity, the drag coefficient is given by more complicated expressions involving the Reynolds number. For algebraic simplicity it will be assumed for the purposes of this derivation that only the Stokes regime is of interest. For detailed calculations, more careful attention will have to be devoted to the drag coefficient.

Then,

$$\frac{\pi}{6} D_p^3 (\rho_m - \rho_g) g = \frac{3\pi\mu_g D_p \chi}{C_{slip}} V_{setling} \quad (80)$$

$$V_{setling} = \frac{C_{slip} D_p^2 \rho_m g}{18\mu_g \chi} \quad (81)$$

$$B = \frac{C_{slip}}{3\pi\mu_g D_p \chi} \quad (82)$$

From the Stokes-Einstein relationship and the particle mobility, the aerosol particle diffusion coefficient can be determined:

$$D = \frac{C_{slip} kT}{3\pi\mu_g D_p \chi} \quad (83)$$

where

D - aerosol particle diffusion Reynolds number (-)

The mobility conveniently relates the particle velocity to the force on the particle. Consider now the same particle subjected to a gas velocity U^∞ . The differential equation for the particle velocity, V , is:

$$\frac{\pi}{6} D_p^3 \rho_m \frac{dV}{dt} = \frac{U^\infty - V}{B} \quad (84)$$

or

$$\frac{1}{U^\infty - V} \frac{dV}{dt} = \frac{1}{\tau} = \frac{18\mu_g \chi}{\rho_m D_p^2 C_{slip}} \quad (85)$$

where

- t - time (s)
- τ - particle relaxation time (s)
- V - particle velocity (cm/s)

The particle relaxation time divided by the life time of turbulent eddies yields a dimensionless time that is useful for the correlation of turbulent deposition of aerosol particles.

The particle relaxation time multiplied by the gas velocity yields a characteristic distance of particle travel:

$$d = \tau U^\infty \quad (86)$$

This characteristic distance of particle travel can be compared to characteristic dimensions of the flow path for the particle. A plausible characteristic distance for flow in a cylindrical leak is the leak radius, $D_{cyl}/2$. The ratio of the particle characteristic travel distance and the characteristic dimension of the apparatus yields the dimensionless quantity called the Stokes number:

$$Stk = \frac{2d}{D_{cyl}} = \frac{2\tau U^\infty}{D_{cyl}} = \frac{\rho_m D_p^2 C_{slip} U^\infty}{9\mu_g \chi D_{cyl}} \quad (87)$$

Note that some prefer to use the cylinder diameter rather than the cylinder radius as the characteristic dimension of the flow path.

The Stokes number is often used for the correlation of particle deposition data due to inertial impaction. Seldom is it the only correlating variable.

APPENDIX B: TABULATED DATA ON TURBULENT DEPOSITION OF AEROSOL PARTICLES IN SMOOTH TUBES

Tabulated data on the dimensionless deposition velocity, v_d^+ , as a function of dimensionless particle relaxation time, τ^+ , as defined in the text, are provided for experimental investigations discussed in the text.

Table B-1. Tabulated Data from Investigations by Forney and Spielman Using Tubes Coated with a Mixture of 75% Paraffin Oil and 25% Petroleum Jelly to Suppress Particle Bounce.

$d_p = 30.9 \mu\text{m}$ $D_{\text{pipe}} = 1.30 \text{ cm}$		$d_p = 30.9 \mu\text{m}$ $D_{\text{pipe}} = 1.78 \text{ cm}$		$d_p = 30.9 \mu\text{m}$ $D_{\text{pipe}} = 2.54 \text{ cm}$		$d_p = 19.0 \mu\text{m}$ $D_{\text{pipe}} = 1.30 \text{ cm}$		$d_p = 19.0 \mu\text{m}$ $D_{\text{pipe}} = 1.78 \text{ cm}$		$d_p = 19.0 \mu\text{m}$ $D_{\text{pipe}} = 2.54 \text{ cm}$	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
147	0.153	27.6	0.217	28.0	0.178	101	0.230	98.6	0.406	58.8	0.139
147	0.205	27.6	0.342	35.9	0.267	101	0.120	98.6	0.321	58.8	0.126
217	0.196	27.6	0.253	59.4	0.176	101	0.239	58.8	0.139	58.8	0.195
217	0.264	27.6	0.211	59.4	0.158	101	0.0777	58.8	0.126	58.8	0.149
217	0.362	67.3	0.250	120.8	0.216	215	0.292	58.8	0.195	86.9	0.207
345	0.143	67.3	0.318	200	0.253	215	0.304			86.9	0.252
345	0.182	67.3	0.365	200	0.242					23.7	0.177
		67.3	0.417	3.56	0.0267					23.7	0.111
		107	0.226	4.89	0.113					23.7	0.110
		107	0.392	7.13	0.173						
		107	0.385	11.9	0.152						
		107	0.290	17.1	0.201						
		226	0.218	26.9	0.188						
		226	0.240	36.3	0.261						
		335	0.224	60.8	0.159						
		335	0.279	60.8	0.172						
				59.6	0.195						
				122	0.177						
				122	0.213						
				200	0.239						
				196	0.265						
				292	0.283						

Note: Data were obtained by digitizing a small graph.

Table B-2. Tabulated Data from Investigations by Friedlander and Johnstone.

0.8 μm Fe particles in 2.5 cm brass tube		0.8 μm Fe particles in 2.5 cm glass tube		1.57 μm Fe particles in 1.30 cm glass tube coated with petroleum jelly		2.63 μm Fe particles in 2.5 cm brass tube		1.81 μm Fe particles in 2.5 cm brass tube	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
0.319	7.21×10^{-5}	0.319	1.06×10^{-4}	7.68	0.0112	11.66	0.0774	1.04	0.00101
0.442	1.09×10^{-4}	0.590	6.92×10^{-5}	7.76	0.00456	6.32	0.0268	1.55	0.00153
0.621	1.72×10^{-4}	0.954	2.72×10^{-4}	7.71	0.00529	3.19	0.0189	3.09	0.00373
0.778	1.87×10^{-4}			5.70	0.00338	3.19	0.00994	5.68	0.0134
0.950	1.61×10^{-4}			3.45	0.00259	2.12	0.00430		
1.214	1.66×10^{-4}					1.21	0.00135		
1.32 μm Fe particles in 2.5 cm brass tube		0.8 μm Fe particles in 0.54 cm glass tube		1.81 μm Al particles in a 1.38 cm brass tube		0.8 μm Fe particles in a 1.30 cm glass tube		1.57 μm Fe particles in a 1.30 cm glass tube	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
0.850	9.03×10^{-4}	37.2	2.77×10^{-4}	1.50	4.83×10^{-4}	0.827	2.5×10^{-5}	1.52	5.06×10^{-4}
1.70	0.00131	83.7	0.00186	1.95	3.90×10^{-4}	0.546	9.2×10^{-5}	3.00	0.00142
3.11	0.00340	83.7	0.00405	2.71	0.00187	1.21	7.05×10^{-5}	3.65	0.00175
		83.7	0.00482	3.83	0.00114	1.16	8.0×10^{-5}	4.71	0.00155
		83.7	0.00281	5.18	0.00138	1.20	7.1×10^{-5}		
		17.2	2.99×10^{-5}	6.90	0.00366	1.67	1.06×10^{-4}		
		83.7	0.00355	9.44	0.00612	2.09	1.65×10^{-4}		
		33.0	3.4×10^{-4}	11.94	0.0112	2.24	2.1×10^{-4}		
		120	0.00463			1.20	1.13×10^{-4}		
		120	0.00637			4.36	3.77×10^{-4}		
		198	0.0241			9.30	9.97×10^{-4}		
		198	0.0233						

Note: Data were obtained by digitizing a small graph.

Table B-3. Tabulated data from investigations by Ilori.

τ^+	v_d^+
45.9	0.102
45.9	0.088
45.9	0.077
35.6	0.092
36.1	0.081
23.1	0.067
20.5	0.071
18.7	0.076
10.3	0.071
15.2	0.056
15.4	0.043
11.1	0.054
7.52	0.039
7.98	0.033
8.10	0.027
3.61	0.012
2.64	0.015
2.27	0.015
2.84	0.00897
2.56	0.00708
1.19	0.00684
0.742	0.0138
0.811	0.0119
0.799	0.00898

Note: Data were digitized from a small graph published by Im and Abluwalia.

Table B-4. Tabulated data from investigations by Lee and Gieseke.

dioctyl phthalate droplets in a 0.767 cm diameter copper pipe		dioctyl phthalate droplets in a 0.622 cm diameter copper pipe	
τ^+	v_d^+	τ^+	v_d^+
1.32x10 ⁻⁴	9.72x10 ⁻⁵	2.90x10 ⁻⁴	5.23x10 ⁻⁵
1.90x10 ⁻⁴	9.72x10 ⁻⁵	4.15x10 ⁻⁴	5.23x10 ⁻⁵
4.59x10 ⁻⁴	8.62x10 ⁻⁵	0.00101	4.17x10 ⁻⁵
0.0022	6.43x10 ⁻⁵	0.00483	1.06x10 ⁻⁴
0.00515	5.34x10 ⁻⁵	0.0113	2.08x10 ⁻⁵
0.0295	1.42x10 ⁻⁴	0.0645	6.29x10 ⁻⁵
9.05x10 ⁻⁴	9.88x10 ⁻⁵	0.00199	1.19x10 ⁻⁴
0.0013	1.11x10 ⁻⁴	0.00283	1.22x10 ⁻⁴
0.00314	5.39x10 ⁻⁵	0.0069	9.67x10 ⁻⁵
0.0151	1.55x10 ⁻⁴	0.0330	4.79x10 ⁻⁵
0.0352	1.37x10 ⁻⁴	0.0771	4.79x10 ⁻⁵
0.202	2.55x10 ⁻⁴	0.441	1.98x10 ⁻⁴
0.00726	9.88x10 ⁻⁵	0.00486	2.94x10 ⁻⁴
0.0148	2.02x10 ⁻⁴	0.00692	2.94x10 ⁻⁴
0.0227	0.0031	0.0169	3.52x10 ⁻⁴
0.0073	9.88x10 ⁻⁵	0.0807	3.23x10 ⁻⁴
0.0022	2.01x10 ⁻⁴	0.188	2.94x10 ⁻⁴
0.00317	2.15x10 ⁻⁴	1.08	5.01x10 ⁻⁴
0.00770	1.60x10 ⁻⁴	0.188	3.23x10 ⁻⁴
0.0368	4.19x10 ⁻⁴	1.08	6.60x10 ⁻⁴
0.0861	4.87x10 ⁻⁴	0.00878	9.39x10 ⁻⁴
0.492	6.75x10 ⁻⁴	0.0125	9.77x10 ⁻⁴
0.492	7.43x10 ⁻⁴	0.0305	0.00102
0.00770	1.46x10 ⁻⁴	0.274	0.00109
0.0368	1.32x10 ⁻⁴	0.341	0.00193
0.0861	4.19x10 ⁻⁴	1.938	0.00345
0.492	6.08x10 ⁻⁴	0.341	0.00216
0.0040	4.37x10 ⁻⁴	1.938	0.00399
0.0057	5.34x10 ⁻⁴		
0.0139	4.37x10 ⁻⁴		
0.0664	7.74x10 ⁻⁴		
0.155	0.00161		
0.887	0.00198		
0.155	0.00203		
0.887	0.00408		

Table B-5. Tabulated Data from Investigations by Liu and Agarwal.

τ^+	v_d^+	τ^+	v_d^+
3.74	0.00983	0.683	2.53×10^{-4}
7.83	0.0666	0.737	3.46×10^{-4}
14.0	0.108	1.10	8.13×10^{-4}
23.5	0.145	1.39	0.00133
54.5	0.138	1.47	0.00147
54.5	0.142	2.97	0.00306
58.5	0.123	5.45	0.00973
64.2	0.124	5.45	0.00986
113	0.123	6.88	0.0306
125	0.126	10.4	0.0520
195	0.132	10.6	0.0959
345	0.112	20.4	0.149
517	0.098	20.4	0.149
496	0.097	39.3	0.150
773	0.0894	45.7	0.153
0.212	6.0×10^{-5}		

Note: Data were obtained by digitizing a small graph.

Table B-6. Tabulated Data from Investigations by Montgomery and Corn.

τ^+	ν_d^+
1.60	0.0385
1.10	0.00177
1.14	9.05×10^{-4}
0.0257	8.12×10^{-4}
0.871	0.00965
0.399	5.96×10^{-4}
0.0730	4.79×10^{-4}
0.0209	1.78×10^{-4}
0.115	4.67×10^{-5}
2.88	0.00506

Table B-7. Tabulated Data from Investigations by Muysshondt et al.

10.2 cm diameter pipe		5.08 cm diameter pipe		2.54 cm diameter pipe		1.27 cm diameter pipe	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
0.983	0.00741	1.221	0.00640	67.02	0.134	0.971	0.00139
1.374	0.00852	6.444	0.0330	5.134	0.0179	2.35	0.00457
1.527	0.0107	13.09	0.0808	1.215	0.00243	7.72	0.0276
2.017	0.0126	28.86	0.146	0.258	4.62x10 ⁻⁴	0.971	0.00172
1.236	0.00564	52.37	0.163	19.55	0.107	1.84	0.00362
0.819	0.00454	0.336	0.00466	17.3	0.0993	3.22	0.00904
0.244	0.0181	2.331	0.00756	12.9	0.0695	4.91	0.0253
2.930	0.0224	5.983	0.0422	8.37	0.0434	0.812	0.00167
2.163	0.00905	11.55	0.0773	4.38	0.0149	1.69	0.00513
1.501	0.00424	20.29	0.114	4.08	0.00546	3.96	0.0230
5.236	0.0444	7.745	0.0645	3.46	0.00776	2.97	0.0160
2.300	0.0170	13.14	0.0892	2.95	0.00588	2.09	0.00918
1.254	0.00784	0.739	0.00182	1.98	0.00393	1.11	0.00166
0.349	0.00140	3.910	0.0283	1.14	0.00204		
		1.155	0.00315				
		4.723	0.0315				
		8.662	0.0606				
		19.310	0.106				

Note: The data were obtained from the authors

Table B-8. Tabulated Data from Investigations by Postma and Swendiman.

30 μm glass spheres in 2.54 cm diameter Al tube		2 μm ZnS particles in a 2.54 cm diameter Al tube		4 μm ZnS particles in a 1.905 cm diameter stainless steel tube	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
8.04	0.0049	0.0750	4.49×10^{-5}	16.6	0.0352
16.7	0.0192	0.147	5.71×10^{-5}	10.0	0.0218
27.3	0.0410	0.242	6.20×10^{-5}	6.45	0.00696
46.6	0.0723	0.353	7.95×10^{-5}	3.43	0.00232
89.8	0.135	0.600	2.54×10^{-4}	2.44	5.91×10^{-4}
228	0.316	0.741	5.98×10^{-4}	1.63	4.23×10^{-4}
265	0.333	1.04	7.82×10^{-4}	0.82	1.07×10^{-4}
		1.42	0.00183	0.49	3.64×10^{-5}
		2.11	0.00423		
		2.05	0.00607		
		2.85	0.00881		
4 μm ZnS particles in 2.54 cm diameter Al tube		2 μm ZnS particles in 1.905 cm stainless steel tube			
τ^+	v_d^+	τ^+	v_d^+		
11.1	0.0395	0.126	4.31×10^{-6}		
8.08	0.0459	0.218	1.29×10^{-5}		
7.98	0.0322	0.423	5.17×10^{-5}		
5.46	0.0155	0.900	2.99×10^{-4}		
4.11	0.0139	0.634	5.47×10^{-5}		
2.86	0.00708	1.70	7.48×10^{-4}		
2.32	0.00275	2.63	0.00223		
1.40	0.00106	4.38	0.00413		
0.925	3.39×10^{-4}				
0.567	3.16×10^{-4}				
0.285	3.57×10^{-4}				
0.284	1.30×10^{-4}				

Table B-9. Tabulated Data from Investigations by Shimada, Okayama, and Asai.

0.043 μm NaCl particles Cslip = 5.84		0.021 μm NaCl particles Cslip = 11.4		0.017 μm NaCl particles Cslip = 13.9		0.01 μm NaCl particles Cslip = 23.3	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
0.00176	1.92×10^{-6}	0.00105	4.38×10^{-6}	0.0125	9.62×10^{-6}	0.00563	2.16×10^{-5}
0.00454	2.36×10^{-6}	0.00154	5.74×10^{-6}	0.00558	7.96×10^{-6}	0.00583	1.70×10^{-5}
0.00860	2.56×10^{-6}	0.00158	6.89×10^{-6}	0.00405	7.79×10^{-6}	0.00557	1.60×10^{-5}
0.0154	2.68×10^{-5}	0.00194	4.22×10^{-6}	0.00253	9.41×10^{-6}	8.97×10^{-4}	1.45×10^{-5}
0.0240	2.58×10^{-6}	0.00289	3.86×10^{-6}	0.00184	9.70×10^{-6}	7.23×10^{-4}	1.10×10^{-5}
0.0243	3.20×10^{-6}	0.00359	4.94×10^{-6}	0.00134	6.44×10^{-6}		
0.0471	2.65×10^{-6}	0.00737	5.05×10^{-6}				
		0.00535	7.05×10^{-6}				
		0.00797	8.40×10^{-6}				
		0.0119	5.86×10^{-6}				

Note: Data were obtained by digitizing small graphs.

Table B-10. Tabulated Data from Investigations by Shobokshy.

τ^+	v_d^+
0.435	1.01×10^{-4}
0.436	1.84×10^{-4}
0.923	3.95×10^{-4}
0.944	6.52×10^{-4}
1.63	8.80×10^{-4}
3.31	0.00213
3.06	0.00312
3.33	0.00558
4.51	0.00724
4.70	0.0110
4.51	0.0110
7.21	0.0289
7.22	0.0478
12.0	0.163
1.67	0.00140

Table B-11. Tabulated Data from Investigations by Wells and Chamberlain.

0.65 μm droplets		1.1 μm droplets		2.1 μm droplets	
τ^+	v_d^+	τ^+	v_d^+	τ^+	v_d^+
5.09×10^{-4}	3.35×10^{-5}	5.73×10^{-4}	4.02×10^{-5}	0.0073	1.61×10^{-5}
0.0151	1.57×10^{-5}	5.73×10^{-4}	1.50×10^{-4}	0.213	8.80×10^{-6}
0.0516	1.24×10^{-5}	0.0120	2.74×10^{-5}	0.447	9.7×10^{-6}
0.119	2.40×10^{-5}	0.088	1.64×10^{-5}	0.871	5.0×10^{-5}
0.225	4.3×10^{-5}	0.128	1.36×10^{-5}	1.785	4.86×10^{-4}
		0.187	1.80×10^{-5}	1.932	0.0011
		0.137	2.97×10^{-5}		
		0.576	7.97×10^{-5}		

Table B-12. Tabulated Data from Investigations by Sehmel.

τ^+	ν_d^+	τ^+	ν_d^+	τ^+	ν_d^+
0.533 cm tube		1.26	2.80×10^{-5}	0.398	5.28×10^{-5}
4.62	0.0031	1.73	1.22×10^{-4}	2.09	1.80×10^{-5}
1.84	9.61×10^{-4}	3.76	6.09×10^{-4}	2.01	3.38×10^{-5}
3.94	0.00321	3.78	7.97×10^{-4}	4.18	2.07×10^{-4}
11.0	0.00752	3.17	0.00105	4.09	4.59×10^{-4}
10.2	0.0193	3.16	0.00430	4.09	7.11×10^{-4}
10.8	0.0571	4.89	0.00386	9.14	0.0051
10.5	0.0618	11.4	0.104	15.3	0.0029
0.647	1.19×10^{-5}	1.575 cm tube		15.2	0.0032
0.514	5.88×10^{-5}	9.15	0.00509	1.16	5.99×10^{-6}
4.00	7.55×10^{-5}	12.1	0.00933	1.08	8.78×10^{-6}
3.98	3.36×10^{-4}	12.1	0.0120	1.18	1.12×10^{-5}
5.36	0.00346	12.2	0.0132	1.16	2.08×10^{-5}
6.74	0.00902	19.7	0.0689	1.10	5.45×10^{-5}
10.0	0.0331	22.5	0.0697	13.1	0.0905
14.7	0.0505	29.7	0.0602	21.1	0.0961
3.66	1.08×10^{-5}	0.484	2.52×10^{-6}	3.66	4.58×10^{-4}
0.0754	2.61×10^{-5}	0.428	4.06×10^{-6}	3.63	5.40×10^{-4}
0.0749	3.31×10^{-5}	0.871	8.70×10^{-6}	3.63	8.66×10^{-4}
0.469	3.99×10^{-5}	0.450	1.32×10^{-5}	6.10	4.85×10^{-4}
1.31	5.59×10^{-5}	0.0895	3.48×10^{-5}	6.10	0.0012
1.30	2.26×10^{-4}	0.901	2.51×10^{-5}	6.10	0.0016
3.06	0.0400	0.876	3.24×10^{-5}	6.10	0.0018
3.06	0.0462	0.902	3.50×10^{-5}	9.06	0.0029

Note: Data obtained by digitizing small graphs.

Table B-12, Continued.

τ^+	ν_d^+	τ^+	ν_d^+	τ^+	ν_d^+
1.575 cm tube		7.75	0.0164	0.00195	1.44×10^{-5}
9.06	0.0040	8.75	0.0262	0.00195	1.60×10^{-5}
9.02	0.0050	8.76	0.0301	0.00161	2.66×10^{-5}
9.02	0.0080	9.56	0.087	0.00162	2.95×10^{-5}
8.98	0.0082	10.9	0.0706	0.040	7.79×10^{-6}
10.4	0.0076	15.2	0.0948	0.040	8.57×10^{-6}
10.4	0.0123	18.3	0.121	0.035	4.66×10^{-5}
14.5	0.0245	0.138	4.33×10^{-6}	0.398	7.25×10^{-6}
14.7	0.104	0.138	6.87×10^{-6}	0.398	7.95×10^{-6}
20.4	0.110	0.136	1.16×10^{-5}	0.398	4.97×10^{-6}
36.2	0.126	0.136	1.52×10^{-5}	0.172	7.55×10^{-6}
36.2	0.137	0.616	7.29×10^{-6}	1.59	3.49×10^{-5}
36.1	0.144	0.616	1.18×10^{-5}	1.59	5.28×10^{-5}
28.2	0.126	0.617	1.67×10^{-5}	1.59	1.56×10^{-4}
0.0275	4.87×10^{-6}	0.617	2.50×10^{-5}	1.60	2.61×10^{-4}
0.0278	8.62×10^{-6}	0.613	3.28×10^{-5}	0.916	4.02×10^{-6}
0.0309	1.79×10^{-5}	1.53	2.24×10^{-5}	0.914	6.69×10^{-6}
5.74	0.0033	1.53	2.54×10^{-5}	0.914	1.22×10^{-5}
5.72	0.0038	1.53	2.92×10^{-5}	0.166	6.04×10^{-6}
5.69	0.0041	3.39	8.64×10^{-4}		
5.75	0.0092	3.38	0.0016		
5.78	0.0236	3.38	0.0023		
7.78	0.0102	3.38	0.0030		
7.76	0.0127	3.38	0.0032		

Note: Data obtained by digitizing small graphs.

Table B-12, Continued.

τ^+	ν_d^+	τ^+	ν_d^+	τ^+	ν_d^+
2.926 cm tube		15.8	0.00524	7.491	0.0266
3.38	0.0107	15.8	0.00486	0.820	2.63×10^{-5}
18.8	0.0864	7.23	0.0409	1.68	5.19×10^{-4}
51.3	0.00146	7.20	0.0547	1.68	7.94×10^{-4}
32.9	0.00107	9.89	0.0763	1.68	9.97×10^{-4}
32.9	9.23×10^{-4}	3.38	0.00847	1.68	0.00150
33.0	5.93×10^{-4}	3.38	0.00573	20.3	0.00106
33.0	4.72×10^{-4}	3.39	0.00765	15.8	0.00178
33.0	3.65×10^{-4}	3.39	0.00960	15.7	0.00299
32.9	1.45×10^{-4}	2.20	6.70×10^{-4}	12.4	0.00326
51.5	1.86×10^{-5}	2.21	5.09×10^{-4}	2.99	0.00121
51.6	1.57×10^{-5}	2.24	4.28×10^{-4}	2.97	0.00180
20.3	1.26×10^{-4}	2.22	3.42×10^{-4}	2.96	0.00252
20.3	1.47×10^{-4}	2.24	1.45×10^{-4}	2.96	0.00307
50.3	2.62×10^{-4}	2.22	8.19×10^{-5}	4.50	0.00560
0.818	5.86×10^{-6}	2.25	7.66×10^{-5}	4.48	0.00408
7.48	0.0110	0.571	4.00×10^{-5}	4.48	0.00361
7.50	0.00788	0.00345	2.15×10^{-4}	4.49	0.00258
7.50	0.00697	0.00380	1.56×10^{-4}	0.00307	1.41×10^{-6}
9.78	0.0109	1.47	2.07×10^{-4}	0.00366	1.86×10^{-6}
9.79	0.00951	1.46	6.12×10^{-4}	0.00394	3.89×10^{-6}
9.67	0.00562	7.01	0.112	0.00365	1.63×10^{-5}
15.7	0.00948	5.45	0.113	0.00337	2.38×10^{-5}
15.7	0.00689	5.43	0.0784	0.290	3.19×10^{-6}

Note: Data obtained by digitizing small graphs.

Table B-12, Continued.

τ^+	ν_d^+	τ^+	ν_d^+	τ^+	ν_d^+
2.926 cm tube		3.78	0.0304	14.4	0.00725
0.263	5.05×10^{-6}	4.88	0.0324	15.8	0.00159
0.896	3.06×10^{-6}	26.4	0.0212	14.5	0.00240
0.900	7.05×10^{-6}	27.0	0.0236	15.4	9.65×10^{-4}
0.269	2.35×10^{-5}	57.2	0.0102	13.6	9.96×10^{-4}
0.583	1.16×10^{-5}	68.3	0.0134	6.80	6.18×10^{-4}
0.243	6.64×10^{-6}	89.9	0.00291	5.86	2.38×10^{-4}
0.242	8.22×10^{-6}	0.156	1.74×10^{-4}	3.80	2.41×10^{-4}
0.242	9.01×10^{-6}	0.174	1.44×10^{-4}	1.87	2.79×10^{-4}
0.821	8.18×10^{-6}	0.774	3.78×10^{-4}	2.54	9.06×10^{-5}
0.823	1.35×10^{-5}	0.855	7.77×10^{-4}	2.00	5.86×10^{-5}
1.68	4.01×10^{-4}	0.828	9.71×10^{-4}	1.28	3.28×10^{-5}
7.137 cm tube		0.825	0.00145	1.27	1.92×10^{-5}
0.371	6.64×10^{-5}	1.81	0.00309	1.16	1.43×10^{-5}
0.379	7.38×10^{-5}	1.84	0.00487	1.09	1.34×10^{-5}
0.626	2.53×10^{-5}	1.78	0.00622	1.28	8.68×10^{-6}
0.649	3.59×10^{-5}	2.32	0.00374	0.540	7.97×10^{-6}
0.660	4.34×10^{-5}	13.5	0.00873	0.155	3.06×10^{-5}
1.03	3.12×10^{-5}	13.1	0.00911	0.160	3.26×10^{-5}
1.03	3.99×10^{-5}	13.3	0.0110	0.227	5.26×10^{-5}
0.716	3.14×10^{-4}	12.9	0.0111	0.221	5.78×10^{-5}
0.720	2.79×10^{-4}	39.6	0.00178	0.228	6.85×10^{-5}
0.884	3.64×10^{-4}	42.0	0.00390	0.386	4.03×10^{-5}
0.954	6.32×10^{-4}	42.0	0.01633		

Note: Data obtained by digitizing small graphs.

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