Transport of Particles Through Gas Leaks — A Review

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TRANSPORT OF PARTICLES THROUGH GAS
LEAKS -- A REVIEW

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TABLE OF CONTENTS

	<u>Page</u>
<u>INTRODUCTION</u>	1
<u>SUMMARY</u>	1
<u>ATTENUATION DUE TO DEPOSITION BY MOLECULAR DIFFUSION</u>	2
<u>TURBULENT IMPACTION</u>	7
<u>GRAVITATIONAL SETTLING</u>	8
<u>ENHANCED DEPOSITION DUE TO PARTICLE CHARGE</u>	12
<u>EXPERIMENTAL OBSERVATION OF PARTICLE LEAK RATES THROUGH VERY SMALL CHANNELS</u>	14
<u>LEAKAGE FROM THE BULK POWDER</u>	19
<u>CONCLUSIONS</u>	23

TRANSPORT OF PARTICLES THROUGH GAS LEAKS -- A REVIEW

INTRODUCTION

Knowledge of the variables which determine to what degree a fine powder will be carried through a small opening is needed in many practical problems. Perhaps one of the most practical is that of screening and filtration, in which the mesh size of the screen and the fiber diameter and packing density of the filter are fundamental determinants of the efficiency of the system for transmitting particles. Particle size distribution and other physical properties of the powders are also important parameters. Another area in which estimates of particle transport in passageways is required is that of release of toxic solids through leaks in containers under various routine and accident conditions. Sampling of particles through small diameter tubing and the passage of particles through air channels in respiratory systems of man and animals are other examples of systems in which the fraction of particles transmitted must be known.

The particular area of interest for the current study is leakage of particles from high integrity containers for shipping plutonium oxide powders. It is the purpose of this document to review information which has been developed in the literature relative to particle transport through very small apertures. The scope is generally restricted to studies in which the particles are fine powders ($< 20 \mu\text{m}$ maximum diameter) and the smallest dimension of the opening is less than about $500 \mu\text{m}$ (0.5 mm).

SUMMARY

This literature review has shown that relatively few studies have been undertaken to determine either theoretically or experimentally the rate at which particles may be transported through narrow passageways. Deterrent to experimental investigation is the difficulty in measurement of the very small quantity which must be measured and the large number of variables upon which leak rate depends.

The principal mechanisms for removing particles in channels are diffusion, gravitational settling, turbulent impaction, and electrostatic scattering. Each mechanism is discussed and the relative importance of these controlling parameters shown with some typical results tabulated. Experimental results are presented, but few represent the exact case under consideration. Studies of particle flow in capillaries give some insight into bulk particle transport through vertical holes under gravity. These studies qualitatively support the view that bridging across an opening under a pressure differential will effectively seal holes much larger than the particles. The need for parametric studies is evident.

ATTENUATION DUE TO DEPOSITION BY MOLECULAR DIFFUSION

Several authors have studied the deposition of particles in passing through narrow channels or small diameter tubes under laminar flow conditions. The deposition is controlled by the particle diffusion coefficient, the length of the passageway, and the flow rate of gas through the passage. The early study of Townsend^[1], with additional work by Gormley and Kennedy^[2], and Thomas^[3,4], provided the calculational methods for this problem. For the most part the diffusion battery, which is an array of many parallel rectangular or circular channels, was used to characterize sizes of very small particles, or to infer the diffusion coefficient if the sizes were known by another means.

Sinclair, Countess, Liu, and Pui, verified the equation of Thomas:^[5]

$$f_{\alpha} = 0.819 \exp(-3.65 \alpha) + 0.097 \exp(-22.3 \alpha) + 0.032 \exp(-57 \alpha) \\ + 0.027 \exp(-123 \alpha) + 0.025 \exp(-750 \alpha) \quad (1)$$

in which

$f_{\alpha} = \frac{n}{n_0}$ = the fraction of entering particles which pass through the battery

n = concentration at exit end

n_0 = concentration at inlet

$\alpha = \pi D \ell / q$

D = particle diffusion coefficient, cm^2/sec

q = volume flow rate per tube, cm^3/sec

Fuchs notes that when α is very small, the basic assumptions that the concentration falls continuously along the axis and from the axis to the periphery are not realized.^[6] Gormley and Kennedy proposed a presumably more accurate expression for f_{α} for low values for α .

$$f_{\alpha} = 1 - 2.56\alpha^{0.667} + 1.2\alpha + 0.177\alpha^{1.333}. \quad (2)$$

Equation (1) and Equation (2) give nearly identical values for f_{α} for α less than about 0.1. For larger values, the Equation (1) is the more reliable.

These formulations can be used with assurance that the fraction of particles transported through a channel will be as predicted provided the following conditions are met.

- As stated, the equations are for a single particle size. The frequency distribution would have to be known and each size increment considered as a separate problem.
- Particles larger than 0.1 μm have such small diffusion coefficients, D , that in many cases there will be no attenuation through the leak path.
- Particles touching the wall surfaces are retained with 100% efficiency and do not re-entrain.
- Electrical charges are such that no electrostatic deposition occurs.
- Gas flow must be laminar. Turbulent flow will tend to enhance deposition in the passage.
- Channels should be much larger than the largest particle present. Particles adhering could drastically affect flow.

A few examples will illustrate the significance of Brownian diffusion deposition to loss of very small particles in traversing a narrow channel. Equation (1) shows that loss to the wall is wholly dependent on flow rate, rather than leak diameter for circular holes, hence, only the leak rate and length of passage need be significant.

In Table I is shown some calculated fractions of particles passing through air leaks of the given magnitude.

TABLE I

FRACTION OF PARTICLES PASSING THROUGH A CIRCULAR PASSAGE
1 cm IN LENGTH (BASED ON EQUATION 1)

Particle Diameter $d_p, \mu m$	Diffusion Coefficient, D cm^2/sec	Fraction Passing Through Leak		
		$Q = 10^{-2} \text{ cm}^3/sec$	$Q = 10^{-3} \text{ cm}^3/sec$	$Q = 10^{-4} \text{ cm}^3/sec$
0.01	5.2×10^{-4}	0.45	0.00	0.00
0.04	3.6×10^{-5}	0.88	0.55	0.01
0.10	6.8×10^{-6}	0.96	0.83	0.38
0.20	2.2×10^{-6}	0.98	0.91	0.66
0.40	8.3×10^{-7}	0.99	0.96	0.81

Browning and Ackley^[7] derived two equations for estimating the "decontamination factor" for a small passageway through which an air stream containing particles was leaking. These equations account for the diffusion of particles and the volume rate of air leaking, which in turn, is a function of the pressure drop across the leak. Their equations for circular and rectangular cross section channels are the following:

For circular:

$$\log_{10} \text{ D.F. } = 0.0867 + 203.2 \frac{\mu D \ell^2}{\Delta P b^4}. \quad (3)$$

For rectangular:

$$\log_{10} \text{ D.F. } = 0.0386 + 39.35 \frac{\mu D \ell^2}{\Delta P b^4}. \quad (4)$$

D.F. = decontamination factor or the ratio of the number of particles entering the channel to the number penetrating.

μ = viscosity of air, poise.

D = diffusion coefficient of particle in air, cm^2/sec .

ℓ = length of leak, cm.

ΔP = pressure drop through leak, dynes/cm^2 .

d = diameter of cylindrical leak.

b = smallest dimension of rectangular leak.

In Figures 1 and 2 are reproduced the results of Browning and Ackley's calculations for various particles and leak sizes for a leak passage length of 1 inch (2.5 cm).

These equations and Figures 1 and 2 have not been corroborated throughout the range of values shown. A point check for a particle diameter of $0.1 \mu\text{m}$ showed satisfactory agreement with the prediction of Equation (1) and a gas leak rate for a $10 \mu\text{m}$ diameter hole, 2.5 cm long, given by:^[3]

$$L = 3810 \frac{d^3}{\ell} - 323 \frac{d}{\eta} \left[(P_u^2 - P_d^2) + \sqrt{\frac{T}{M}} (P_u - P_d) \right], \quad (5)$$

in which

L = gas leak rate atm. cm^3/sec

a = leakage hole length in cm

ℓ = leakage hole diameter, cm

P_u = upstream pressure, atm.

P_d = downstream pressure, atm.

T = gas temperature, K°

M = molecular weight of the gas

η = viscosity of gas, centipoise.

The fraction of particles retained in a narrow channel when laminar flow prevails can be significant as judged by Table I and Figures 1 and 2. Although particles larger than $0.1 \mu\text{m}$ have very small diffusion coefficients, they may diffuse to the wall for very small flow rates because of the relative long transit time through the leak and the short travel distance to the wall. Experimental confirmation of wall loss by diffusion for channels of the dimensions of interest in this study was not disclosed in the

FIGURE 1

Decontamination Factors Resulting from Diffusional Deposition of Particles in Cylindrical Leaks in Reactor Containment Vessels [6]

FIGURE 2

Decontamination Factors Resulting from Diffusional Deposition of Particles in Rectangular Leaks in Reactor Containment Vessels [6]

literature reviewed. The theory is well-founded and experimental measurement for larger channels does confirm the calculation given by equation (1).

TURBULENT IMPACTION

Particles in turbulent flow will be lost to the walls of a channel by eddy transport. The degree of deposition will be determined by the turbulence and the inertial properties of the particles. Such deposition is described by the equation:^[7]

$$\frac{C}{C_0} = e^{-\frac{4K\ell}{V_a d}} \quad (6)$$

in which C_0 = the entering concentration
 C = the concentration at a distance ℓ from the entrance
 ℓ = distance from the entrance to exit, cm
 V_a = average velocity in tube, cm/sec
 d = diameter of the tube, cm
 K = deposition velocity, cm/sec.

For other than circular tubes, the equation is:

$$\frac{C}{C_0} = e^{-\frac{PK\ell}{AV_a}} \quad (7)$$

in which P = perimeter of the leakage path
 A = cross sectional area of leakage path.

The deposition velocity, K , must be known or estimated to evaluate the deposition in the leak path. Many experiments have been carried out to determine the correlation of K with important parameters, which are particle size, Reynolds Number, and surface roughness.^[10,11] None of the experimental data includes the range of the hole diameters as small as considered in this study. Laminar flow ($Re < 2000$) will occur in most cases considered in this study. If the terminal settling velocity were used in the

absence of a better defined deposition velocity, a minimum wall loss would be calculated. Experimentally determined values are not available for very small leaks.

GRAVITATIONAL SETTLING

The equation for gravity settling in a circular tube with laminar flow is as follows [12,13]:

$$F = \frac{2}{\pi} (\alpha\beta + \sin^{-1} \beta - 2\alpha^3\beta) \quad (8)$$

in which F = the fraction of particles transported without deposition.

$$\alpha = \left(\frac{3\ell u_t}{8V_a R} \right)^{1/3}$$

$$\beta = \sqrt{1 - \alpha^2}$$

ℓ = length of path, cm

u_t = terminal settling velocity, cm/sec

V_a = average flow velocity, cm/sec

R = radius of leak channel, $\frac{d}{2}$, cm

Thomas demonstrated the validity of this equation experimentally using 1.3 μ m diameter particles transported in a 49 m long tube of 1.02 cm diameter [14]. His results are shown in Figure 3, in which is plotted E_s , the fraction deposited, $(1-F)$ as a function of μ_s , which is defined as

$$\mu_s = \alpha^3 = \frac{3\ell u_t}{8V_a R} = \frac{0.589\ell u_t d}{Q},$$

in which Q = the flow rate in cc per sec and other terms are as previously defined.

The broken line shown in Figure 3 has the equation

$$E_s = 1.40 \mu_s \quad (9)$$

and represents a good approximation for deposition from zero to 0.7, or for μ_s ranging from 0 to 0.5.

The significance of gravity settling in very small circular channels can be illustrated by a few calculations shown in Table II.

FIGURE 3

Comparison of Experimental Data with Theoretical Gravity Settling Equation

TABLE II

GRAVITATION DEPOSITION OF UNIT DENSITY SPHERICAL PARTICLES IN A CIRCULAR CROSS SECTION CHANNEL 1 cm LONG.

(Entries in table are fraction of entering particles deposited.)

d_p μm	u_t cm/sec	$Q \rightarrow$ $d \leftarrow$	Leak Rate, Q , cc/sec, and Leak Diameter, d , cm				
			2×10^{-8} 1×10^{-4}	8×10^{-5} 1×10^{-3}	5.9×10^{-3} 3×10^{-3}	7×10^{-1} 1×10^{-2}	56 3×10^{-2}
0.1	8.63×10^{-5}		0.36	8.89×10^{-4}	3.6×10^{-5}	1.01×10^{-6}	3.81×10^{-8}
0.5	1.00×10^{-3}		1.00	0.013	4.19×10^{-4}	1.18×10^{-5}	4.42×10^{-7}
1.0	3.50×10^{-3}		--	0.80	1.46×10^{-3}	4.11×10^{-5}	1.54×10^{-6}
5.0	7.77×10^{-2}		--	1.00	3.26×10^{-2}	9.16×10^{-4}	3.43×10^{-5}
10	3.06×10^{-1}		--	--	1.28×10^{-1}	3.60×10^{-3}	1.35×10^{-4}

From entries in Table II the critical dependence on leak rates, particle diameter, and channel diameter is clearly seen. Particles of density greater than 1 will settle at correspondingly higher rates. A particle of density 10 will settle essentially 10 times as rapidly as a particle of density 1. Gravitational settling for particles smaller than 0.5 μm entering leaks larger than 10 μm will deposit to a relatively small extent. Larger particles will deposit very significantly in leaks of a few tens of micrometers in diameter. Particles up to 10 micrometers in diameter should not deposit to a significant extent in channels 100 μm or larger in diameter. In the example shown combinations of flow rate, hole diameter, and leak rate are specially selected values and transport of particles should be calculated for individual cases.

For rectangular cross section channels the fraction deposited is given by: [15]

$$f = \frac{\ell u_t W}{Q} = \frac{\ell u_t}{V_h} \quad (10)$$

in which

ℓ = length of channel

u_t = settling velocity of particle

W = width of the channel

Q = gas flow rate in channel

h = height of channel.

One assumption made in deriving equation (10) is that the velocity in all parts of the cross section is constant. (plug flow). This will not be realized in real flow systems. In Table III are shown some calculated depositions for the same flow rates assumed in Table II, but with square rather than round horizontal channels. Equation (10) was used in these calculations for a 1 cm long channel.

Comparison of entries in Table II and Table III show that the deposition in a square channel whose width is equal to the diameter of a round channel will be slightly greater in the square channel for a given flow (but not equal average velocity). The small difference shows the relative unimportance of the assumption

TABLE III

GRAVITATIONAL DEPOSITION OF UNIT DENSITY SPHERICAL PARTICLES IN A RECTANGULAR CROSS SECTION CHANNEL 1 CM LONG
(Entries in Table are fraction of particles deposited.)

d_p , μm	u_t cm/sec	Q W	Leak Rate, Q , cc/sec and Leak Width, W , cm				
			2×10^{-8} 1×10^{-4}	8×10^{-5} 1×10^{-3}	5.9×10^{-3} 3×10^{-3}	7×10^{-1} 1×10^{-2}	56 3×10^{-2}
0.1	8.63×10^{-5}	0.43		1.1×10^{-3}	4.39×10^{-5}	1.23×10^{-6}	4.62×10^{-8}
0.5	1.00×10^{-3}	1.00		1.2×10^{-2}	5.08×10^{-4}	1.43×10^{-5}	5.36×10^{-7}
1.0	3.50×10^{-3}	--		4.4×10^{-2}	1.79×10^{-3}	5.00×10^{-5}	1.88×10^{-6}
5.0	7.77×10^{-2}	--		--	3.95×10^{-2}	1.11×10^{-3}	4.16×10^{-5}
10	3.06×10^{-1}	--		--	1.56×10^{-1}	4.37×10^{-3}	1.64×10^{-4}

of parabolic velocity distribution in the circular tube as compared with the assumption of "plug" flow in the derivation of the much simpler equation (10). (The average velocity in the square channel will be smaller than in the circular tube by the ratio of $\pi/4$. Thus a higher deposition would be anticipated for equal flow in the square channel.)

An important stipulation in the derivation of equations (8), (9) and (10) is that the channel be horizontal. In the extreme cases, vertical up or vertical down, no deposition will occur. In intermediate positions, where θ is the angle, the channel centerline makes with the horizontal, the terminal settling velocity can be resolved into components along the direction of flow and perpendicular to the direction of flow. The vector additions would permit the deposition to be calculated if the corrected average velocity along the channel centerline, V_θ , and the component of settling velocity $(u_t)_\theta$ to the wall are used in equations.

Thus,

$$(u_t)_\theta = u_t \cos \theta \quad (11)$$

centerline above horizontal

$$(V)_\theta = V_a - u_t \sin \theta \quad (12)$$

centerline below horizontal

$$(V)_{-\theta} = V_a + u_t \sin \theta \quad (13)$$

The calculation of deposition for non-horizontal orientation of the leak channel under the assumption of parabolic flow in circular cross section channels should be reasonably approximated by adjusting u_t and V_a as indicated in equations (11), (12), and (13). The literature search revealed no experimental verification of gravitational deposition in non-horizontal channels.

ENHANCED DEPOSITION DUE TO PARTICLE CHARGE

Charged particles can be readily collected in an intense electrical field, which is the principle upon which electrostatic precipitators are based. In the absence of an electric field, deposition of unipolarly charged aerosols moving in a channel may be enhanced by mutual repulsion, which can be termed electrostatic scattering. For a monodisperse, unipolarly charged aerosol, Fuchs

presents an equation for the changing concentration as the aerosol moves through a channel.^[16]

$$\frac{C_o}{C} = 1 + \frac{4 \pi q^2 B C_o \ell}{V_a} \quad (14)$$

in which

C_o = entering concentration

C = exiting concentration

q = charge per particle

B = particle mobility = D/KT

ℓ = length of channel

V_a = average velocity in the channel

In Thomas's experimental study, results of which are shown in Figure 3, p. 9, no significant difference in deposition was noted between particles charged with 37 electrons and those charged with 4. In studies to determine the relative deposition of unipolar vs. neutral aerosols in pushing through a long tube, Wehner, Sehmel, Schwendiman, and Harter found insignificant difference in deposition.^[17] Garrity,^[18] calculated some base cases for diffusional deposition of uncharged particles in long channels, then calculated the same cases, except for particles carrying a single positive charge.* The cases calculated by Garrity were selected to represent a leakage through rather small but quite long passageways and are not representative of acceptable leaks from shipping containers. The aerosol considered was monodisperse particles of uranium dioxide. The carrying gas was xenon moving through the channel at 8 cm per second. The inlet concentration was 10^8 particles per cc. Various pressure differentials across the leak, particle sizes, and leak lengths were chosen so that the exponent in the diffusion equation for circular cross section channels, Δ , was changed from a base case to four times, and ten times the base case.[†]

Results of Garrity's calculations are shown in Table IV.

* The author's statement "... if all particles were assumed to carry a positive charge, ..." on p. 3-4-22 is interpreted to mean each particle carried a single charge.

† Δ in Garrity's diffusional deposition equation is 0.25α of equation 1, p. 2.

TABLE IV
ELECTROSTATIC DEPOSITION
BASE CASE CALCULATIONS AND PARAMETRIC VARIATIONS

	(a) Diffusion only				(b) Electrostatic Scatter, only	
	Δ (cylinder)	$d_p, \mu\text{m}$	$d_{\text{hole}}, \mu\text{m}$	Deposition length, ℓ , cm	$\frac{C}{C_o}$	$\frac{C}{C_o}$
Base Case:	0.0577	1	100	153	0.36	0.037
4 x Base Case:	0.2308	0.39	71	306	0.028	0.0094
10 x Base Case:	0.577	0.17	56	482	0.0017	0.0038

Although the theoretical considerations for deposition resulting from electrostatic scattering indicate that this mechanism could contribute to the deposition of particles, there appears to be little experimental information to confirm these calculations. To our knowledge, combined diffusional and electrostatic scattering has not been addressed either theoretically or experimentally.

EXPERIMENTAL OBSERVATION OF PARTICLE LEAK RATES THROUGH VERY SMALL CHANNELS

The literature search identified a rather small number of studies which have considered the question of the fractional transport of particles from an air space through very small leaks. In this section, these studies are described and the results summarized. In all research reported, we were unable to identify any study which could be called a parametric study. Most observations were for a rather specific set of circumstances, and frequently the particles were not well characterized. The conditions were selected to correspond to an estimate of conditions to be experienced following a reactor accident.

Witherspoon and Postma^[19] reported experiments on the leakage of fission products in the Containment Systems Experiment. Leaks were fabricated as small orifices, or valves were used which were made to leak. Gas leak rates were quite high, 1 liter per minute. Table V shows a summary of their data.

TABLE V

SUMMARY OF PENETRATION OF ARTIFICIAL LEAKS
BY IODINE AND CESIUM AERSOLS^[19]

<u>Nature Of Leak</u>	<u>Radionuclide On Particle</u>	<u>Leak Rate ℓ/min</u>	<u>Overall Decontamination Factor for Air- borne Activity</u>
Valve leak with inlet flush with wall	Iodine	Run A-5 1.0	8.1
		Run A-16 1.0	10.8
	Cesium	Run A-5 1.0	> 112
		Run A-16 1.0	> 1500
Valve leak with inlet probe extending into chamber	Iodine	Run A-11 1.0	3.6
		0.1	4.1
	Cesium	Run A-11 1.0	> 130
		0.1	> 537
	Iodine	Run A-16 0.5	3.1
		1.6	22
	(overall 3.73)		
	Cesium	Run A-16 0.5	96
		1.6	51
	(overall 81)		
Small pinhole leak in orifice on end of tube extending into chamber	Iodine	Run A-16 1.6 start	3.8
		0.7 end	
	Cesium	Run A-16 1.6 start	4.9
		0.7 end	
(during sampling period ranged from 0.25 to 77.5)			
Leakage from 8" butterfly valve	Iodine	Run A-16 1.0	34
	Cesium	Run A-16 1.0	210

Nelson, et al^[20] measured the fraction of sodium oxide aerosol which would pass through a crack in a concrete plug. The data are reproduced in Table VI. In Figure 4 is shown the decontamination factor as a function of crack dimensions. These crack dimensions are much larger than the leak dimensions under consideration for a leakage of 10^{-3} cc/sec.

Nelson and co-workers have performed more recent experiments to measure the leakage of sodium oxide aerosols through prepared cracks or capillary tubing.^[21, 22, 23, 24] Sodium oxide aerosols of average aerodynamic diameter of 3 to 5 μm at concentrations ranging from a fraction of a microgram per cc to 18 $\mu\text{g/cc}$ were sampled through capillaries ranging from 0.052 cm (520 μm) to 0.157 cm (1570 μm). Capillary lengths were from 4.9 to 7.6 cm. When the aerosol was dry (1300 ppm water, R.H. of about 5%), the capillaries did not plug for long test periods. When the humidity was adjusted to 8000 ppm, plugging of the capillaries occurred in times ranging from 0.1 min to 41 min. These tests show the importance of the aerosol properties, but are not directly applicable to the very small leaks under consideration. They do support a generalization that small leaks can be readily plugged with aerosol particles of much smaller dimension than the diameter of the leaks. The authors don't give explicit decontamination factors for the air passing through the leak up to the time of plugging, but they do indicate that the plug acts as a filter. In the case of sodium oxide, the researchers observed that when humidity of the leak gas was relatively high, the sodium hydroxide plug in the channel would dissolve and droplets would be ejected intermittently.^[24]

Membrane filters with average pore size from millimicrometers to several micrometers are used in many applications where high efficiency removal of particles is required. These membranes are very thin, of the order of 50-100 μm , yet Lindeken^[25] has shown 5 μm pore size filters to be very efficient for collecting submicron natural radioactive aerosols. Face velocities may be chosen to favor diffusional deposition of very small particles. The relatively long leak pathway present in these filters would be even more

TABLE VI
Experimental Test Data^[19]

Parameters	Porous Alundum Crucible	Concrete Specimen				
		1	2	3	4	3'
Diameter (in.)	1.5	2	2	2	2	2
Thickness (in.)	1/16	1.5	1.5	1.5	1.5	1.5
Initial Flow at 5 psig (ℓ/min)	25	1.2	11.2	24	24	1.3 x 10 ⁻³
Flow at 5 psig After Test (ℓ/min)	-	1.2	10	1.4	12.5	<10 ⁻⁴ *
Type of Leak [†]	Porous	Crack	Crack and Orifice	Crack	Crack and Orifice	Porous
ΔP Across Specimen During Test (psig)	<0.5	5	0.5 to 1	2.5	2.5 to 4	3
Crack Width (mil)	None	~1.8	~3.8 to 4.5	~5	~5 to 6.3	None
Reduction [§] Factor for Sodium Oxide (Ai)	4 x 10 ⁴ *	>10 ⁵ *	5.5 x 10 ³	2.5 x 10 ³	150	>5 x 10 ³ *
Reduction [§] Factor- Agglomerated I ₂ ^[3]	>10 ³ *	-	-	-	-	-

* Limit of detection
† Type of flow characterized by $A = \frac{g_C b^3 \ell (P_u - P_d)}{128 \mu x}$

in which Q = flow rate

b, x = d cross sectional dimensions of crack, b - width, x - breadth of crack

ℓ = length of crack, inlet to outlet

P_u = upstream pressure

P_d = downstream pressure

μ = viscosity of gas

g_C = dimensional constant

§ Ratio of sodium or agglomerated I₂^[3] entering concrete as crucible to that on membrane filter.
Ai initial reduction factor

FIGURE 4

Aerosol Reduction Factor vs. Crack Width^[17]

favorable to diffusional deposition. Increased filter efficiency with loading is generally observed. One example is shown in reference ^[26]. Whatman 41 which is a relatively porous filter showed an increase in efficiency for 0.365 μm particles from 75% to 97% in a 30-minute period of use. The concentration of the aerosol sampled was 0.5 mg/m^3 .

Filters, per se, are only qualitatively analogous to leaks through a simple capillary or very narrow passage. The average pore of a filter diameter represents in a rough way the diameter of a leak passage; however, the impaction and interception experienced by a particle in traversing a porous medium is quite different than for a straight channel of equivalent diameter.

LEAKAGE FROM THE BULK POWDER

In considering the location of a gas leak with respect to the contents of a container, it is readily apparent that the bulk powder may completely cover the leak. When the leak geometry is favorable and driving force and/or vibration sufficient, particles may be forced or shaken through the gas leak path. The driving force may be internal pressure or a gravitational force, either static (as in an hourglass) or dynamic, such as centrifugal force from spinning the container. Under appropriate conditions, particles could be jetted or vibrated through the passage. Particles of much smaller diameter from the leak diameter may bridge and clump, effectively blocking the entrance to the passage of even very small particles. When the leak minimum dimension is somewhat smaller than the largest particles present, the leakage of particles would be extremely small, since the probability would be high that the leak would quickly be blocked by a single particle. (More likely, the leak would be blocked by aggregates of smaller particles, thus making the transport of significant number of particles from the bulk powder through such a leak very unlikely.)

The literature search was directed towards articles on the movement of powders through small apertures. Some titles were investigated which seemed pertinent to the study at hand. These were studied and abstracted; however, in almost every case, the

articles addressed problems of bulk flow of powders from hoppers of various configurations, rather than the problem of leaks through "very small" apertures or passageways.

The information abstracted from the reports of interest (if not directly applicable) to the problem of flow through leaks is discussed in this section.

B.S. Neumann in a Chapter, Powders,^[27] discusses general properties of powders influencing their behavior in bulk. Of primary interest is powder tendency to "stick" or "flow" in hoppers and bins. An important factor in "stickiness" is the fraction of particles smaller than 10 μm . (For the materials of interest to the main objective of particle leakage through very small passageways, a large fraction of the powder will be under 10 μm .) Moisture greater than that in equilibrium with surroundings also enhanced stickiness. Powders can be made to flow by adding larger, inert particles.

Bingham and Wikoff undertook to carry out a thorough investigation of the factors influencing the flow of sand through capillaries.^[28] They did not achieve a model, but in a series of simple experiments arrived at certain conclusions regarding gravity flow of particles (sand) through capillaries. They measured the rate of flow of various size fractions taken from ordinary sand. The fine size fractions were in the range of about 120 μm to 400 μm , of much coarser sizes than considered for the particular problem of leaks in shipping containers. These authors found that increasing the "head" of powder in the reservoir decreased the flow rate. Flow increased when the capillary was lengthened. A curve showing these results is shown in Figure 5. The flow as a function of the diameter was found to be proportional to $d^{2.65}$, where d is the diameter of the capillary.

FIGURE 5
Volume of Flow of various Grades of Sand
Through Capillaries of Varying Lengths,
Time of Flow Being Held Constant

Shinohara and Tanaka proposed a model for the gravity flow of cohesive particles through an aperture of a storage vessel.^[29] They developed an equation which permits estimation of flow rate as a function of bed height, hopper dimension, and outlet diameter. According to this model, the delivery rate is not greatly affected by bed height for a wide range of heights for a given discharge diameter. Delivery rate should vary as the 2.0 to 3.5 power of the aperture diameter, which is consistent with experimental measurements.

These relationships, while of value in designing hoppers for required delivery rates, are not applicable when the particle diameter is near the aperture diameter and in cases in which the bin outlet is a relatively long capillary.

McDougall and Evans studied the influence of air-pressure difference on the gravity flow of particulate solids through an orifice.^[30] They derived a theoretical relationship based on a fluid analogy which provided a reasonable explanation for the experimentally observed effects. The theoretical flow rate is shown to be given by

$$U = \left[\frac{2g}{1 - \left(\frac{D_o}{D_c} \right)^4} \left(\frac{P_1 - P_2}{\rho_B} \right) \right]^{1/2} \quad (15)$$

It follows that the mass flow rate is $G = \phi(P_1 - P_2)^{1/2}$ in which U = linear flow rate through the orifice (16)

g = gravitational constant

D_o = orifice diameter

D_c = hopper diameter

P_1 = "pseudo pressure" just above orifice at the point of movement

P_2 = pressure applied below orifice

ρ_B = bulk powder density.

The authors derived an expression for P_1 , which was necessary to solve Equations 15 and 16 for the experiments:

$$P_1 = \frac{\rho_B D_o}{4\mu} (1 + 3\mu^2) \quad (17)$$

in which μ = coefficient of friction for the powder in shear.

The flow rate of two powders through several different orifices was measured for various applied pressures. The results could be expressed by the relationship

$$G = K D_o^m (P_1 - P)^n \quad (18)$$

m was of the order 2
and n was of the order of 0.5.

CONCLUSIONS

This review of technical literature has identified the principal mechanisms through which particles are transferred to the wall of a channel. Although theoretical and empirical relations have been used to calculate particle loss in small dimension passageways there is very little supporting experimental data to confirm the predictions. When flow passageways approach the dimension of the larger particles in an aerosol, particle trajectories to the leak entrance become important as well as the mechanisms which govern loss to the walls. The calculated loss to the walls of small channels should be confirmed with experimental measurements.

The phenomenon of bulk flow of powders through very small holes has received only limited attention. Some data leading to generalized conclusions regarding mass flow of larger particles through small diameter channels is available, but much larger particles were used. It appears that experimental data should be obtained regarding bulk flow.

The many mechanisms by which particles will be prevented from passing through a very small channel suggest that a rather small quantity would leak through. Experiments should be conducted to bear this out or otherwise show that the relationships are valid for loss through very small openings.

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