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EXPERIMENTAL RELATIONSHIP BETWEEN THE SPECIFIC RESISTANCE OF A
HEPA FILTER AND PARTICLE DIAMETERS OF DIFFERENT AEROSOL MATERIALS

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EXPERIMENTAL RELATIONSHIP BETWEEN THE SPECIFIC RESISTANCE OF A HEPA FILTER AND PARTICLE DIAMETERS OF DIFFERENT AEROSOL MATERIALS

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ABSTRACT

The increase in pressure drop across a HEPA filter has been measured as a function of the particle mass loading using two materials with different particle morphologies. The HEPA filter media chosen, is identical to the filter media used in the Airborne Activity Confinement System (AACS) on the Savannah River Reactors. The velocity through the test filter media was the same as the velocity through the AACS media, under normal operating flow conditions.

Sodium Chloride challenge particles were generated using an atomizer, resulting in regularly shaped crystalline forms. Ammonium chloride aerosols were formed from the gas phase reaction of HCl and NH₄OH vapors resulting in irregular agglomerates. In both cases, the generation conditions were adjusted to provide several different particle size distributions. For each particle size distribution, the mass of material loaded per unit area of filter per unit pressure drop for a given filtration velocity (1/Specific resistance) was measured.

Theoretical considerations in the most widely accepted filter cake model predict that the mass per unit area and per unit pressure drop should increase with the particle density times the particle diameter squared. However, these test results indicate that the increase in the

mass loaded per unit area per unit pressure drop, for both materials, can be better described by plotting the specific resistance divided by the particle density as an inverse function of the particle density times the particle diameter squared .

1. INTRODUCTION

An Airborne Activity Confinement System (AACS) is used in each of the reactors at the Savannah River site (SRP) to provide for the capture and confinement of accidentally released radioisotopes. Figure 1 presents a schematic description of the AACS [1]. The purpose of the moisture separator (first filter) is to remove the water droplets and any other large aerosol particles before they can be deposited in the High Efficiency Particulate Air (HEPA) filter. The HEPA filter is designed to remove all particles from the gas stream with efficiencies of at least 99.97% [2]. The final component of the filter compartment is a carbon bed. The purpose of the carbon bed is to remove more than 99.9% of the elemental iodine vapors from the exhaust gas [3].

The purpose of this research was to characterize the HEPA filter media material. Part of this characterization was to measure the pressure drop characteristics of the HEPA filter material as a function of the aerosol mass loading. Particle size effects were studied by generating different particle size distributions and measuring the pressure drop and the amount of mass collected on the filter. An experimental apparatus was set up based on filter characterization work described in earlier work [4]. The particle size is an experimental variable since there is uncertainty in the particle size distribution that may be released into the AACS. The filter media was chosen to be identical with the SRP filter material. However, the filter size was chosen to be 47 mm in diameter in order to facilitate laboratory handling and analysis and to minimize the total mass of particles that are needed to be aerosolized. To account for the difference in filtration area, the gas flow rate was scaled such that the velocity through the filter medium was the same for both plant filters and laboratory filters. The gas viscosity is expected to be similar to that encountered at SRP by using air at 25°C.

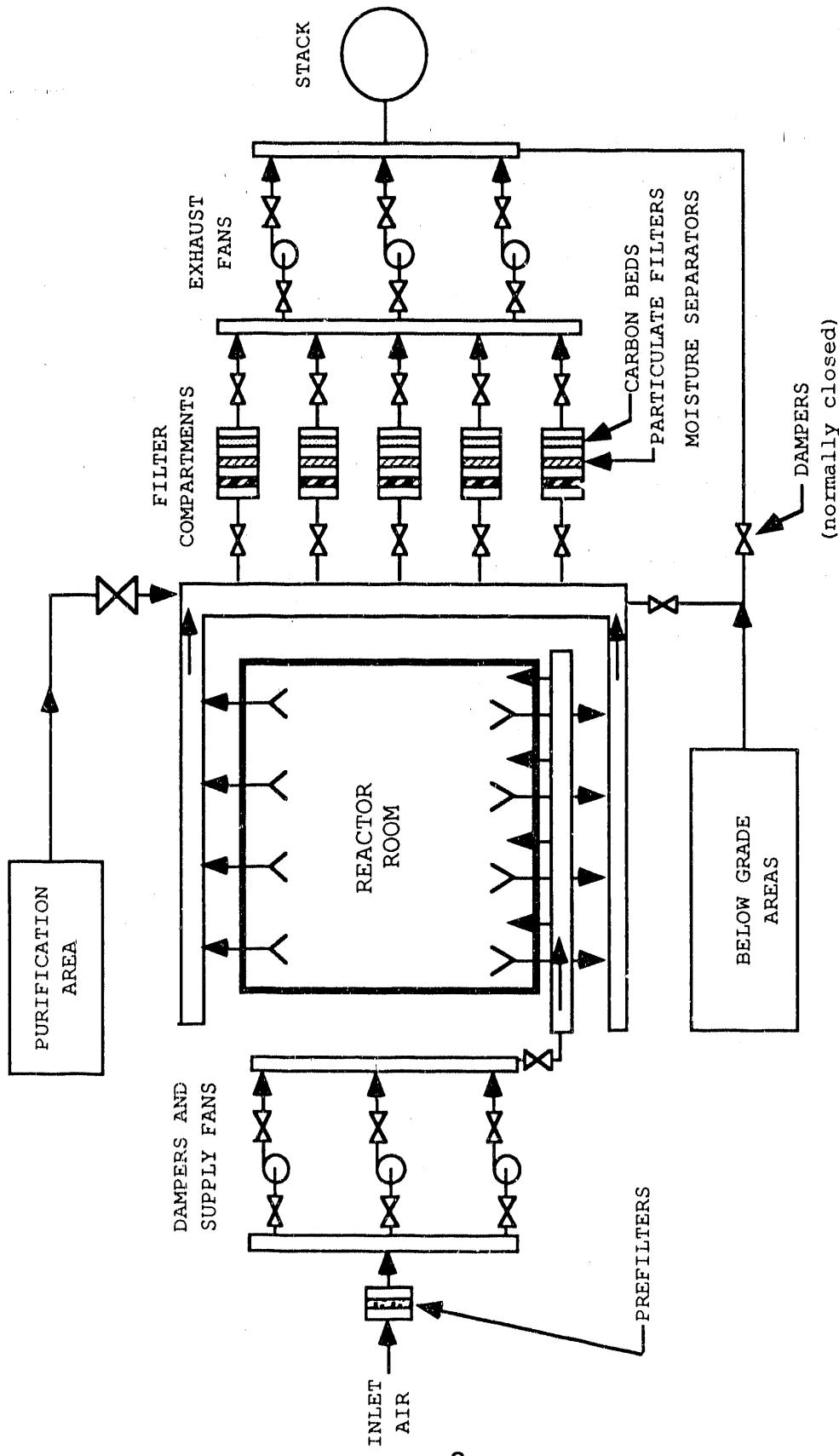


Figure 1. Schematic of the Airborne Activity Confinement System (AACS)

Particle shape effects were studied by choosing two different aerosol materials using different particle generation techniques. The two aerosol materials chosen to investigate the particle shape and density effects on the mass loading of a filter, were Sodium Chloride and Ammonium Chloride. The sodium chloride was generated by nebulizing a liquid solution of sodium chloride in water, then drying the droplets to form solid, primarily cubic crystals. The ammonium chloride was generated from the gas phase reaction of HCl and NH₄OH vapors. This process resulted in dry ammonium chloride particles with irregular agglomerated shapes, which should be more representative of the shape of the aerosol. That might be found in the event of a high temperature release into the AACs.

2. THEORY

A general model describing the increase in pressure drop as a function of mass loading can be found in a variety of sources [5,6]. For high levels of particle mass loadings on filters, it is generally accepted that the total pressure drop across the filter can be written as the sum of the pressure drop across the clean filter plus the pressure drop across the filter cake due to particle loading.

$$\Delta P = \Delta P_0 + \Delta P_p \quad (1)$$

For the range of pressure drops under consideration in these tests, the gas flow through the filter is laminar, allowing equation (1) to be rewritten in terms of the gas velocity.

$$\Delta P = K_1 V + K_2 V M/A \quad (2)$$

where

V = gas velocity through the media

M/A = particle mass loading per unit area.

The constant K_1 depends on the filter structural properties such as the porosity and thickness of the filter. K_2 is a constant for a given set of particle and cake parameters such as the particle size and cake porosity. This simple model assumes that the particles are solid. Liquid droplets are more difficult to model due to factors such as the wettability of the filter media and the surface tension and viscosity of the liquid. Obviously there is no cake formation with liquid droplets.

The value of K_1 for the filter material tested in this work can be found by measuring the clean filter pressure drop as a function of gas velocity. The value of K_1 was measured previously and is given as $7.97 \times 10^2 \text{ g/cm}^2 \text{ s}$. The value of K_2 can be determined both theoretically and experimentally. The theoretical analysis first assumes that the layer of particles forming the cake is comprised of isolated spheres far enough apart so the flow around one sphere does not interfere with the flow around a neighboring sphere (i.e., the porosity of the cake, ϵ , approaches one) and that the Reynold's number, is less than one, then Stoke's Law can be applied to determine K_2 .

$$K_{\text{Stokes}} = (18 \mu) / (C D^2 \rho) \quad (3)$$

where

μ = gas viscosity

ρ = particle density

D = particle diameter

C is the Cunningham slip correction factor given as:

$$C = 1 + \lambda/D [2.514 + 0.80 \exp(-0.55 D/\lambda)] \quad (4)$$

where λ is the mean free path of the gas. For air molecules at standard conditions the mean free path, λ , is $0.066 \mu\text{m}$.

In real situations the spheres touch causing the flow around each sphere to be affected by its neighboring spheres, hence the porosity no longer approaches 1. In order to account for a real solution of K_2 :

$$K_2 = R K_{2\text{Stokes}} \quad (5)$$

At least two different researchers have developed methods of defining resistance factor R [7]. The work of Kozeny and Carman led to a semi-empirical equation that determines the resistance factor to be:

$$R = 2 K_{ck} (1 - e)/e^3 \quad (6)$$

where the empirical constant K_{ck} is equal to 4.8 for spheres and 5.0 for irregular shapes. Leith and Allen [6] state that Equation (6) should not be used if $e > 0.7$.

Alternatively, Rudnick and First [8] developed an equation for R derived from theory and thus does not have an empirical constant as in Equation (6). This equation is given as:

$$R = [3 + 2(1 - e)^{5/3}] / [3 - 4.5 (1 - e)^{5/3} - 3(1 - e)^2] \quad (7)$$

Both methods of determining R require a knowledge of the porosity of the particle cake. However, the porosity can only be determined with experimental measurements of the thickness of the deposited cake and the total mass of particles in the cake. R can also be calculated directly from the experimental data without a thickness measurement by combining Equations (1),(2),(3) and (5) to give:

$$R = A C \rho D^2 (\Delta P - \Delta P_0) / 18 \mu V M \quad (8)$$

3. EXPERIMENTAL SETUP

The sodium chloride aerosol was formed using standard liquid atomization techniques with subsequent drying and dilution. The particles were sampled from a chamber using 47 mm filters and sized using a cascade impactor. This system is described in more detail by Novick,

et al. [9].

The ammonium chloride aerosol was formed from a gas phase reaction of hydrochloric acid (37%) and ammonia hydroxide (29.5%). The reaction results in the precipitation of ammonium chloride aerosol. The size of the aerosol can be changed by controlling the total vapor concentration and residence time in the reaction or mixing chamber. Upon exiting the mixing chamber, the aerosols are diluted in the sampling

vessel to prohibit the condensation and coagulation processes from further altering the particle diameter. Sampling was again carried out using 47mm filters and sizing was performed with cascade impactors. A schematic of the experimental system for the ammonium chloride tests is given in Figure 2. Regardless of aerosol material or generation technique, the aerosol particles were collected on a 47 mm filter until a desired precision drop was obtained across the filter. The flowrate through the filter was held constant and chosen to produce the same media velocity as is commonly found in full scale HEPA filters, typically 2.45 to 3.0 cm/s.

Final test pressures of 500, 1000, 1500, and 2000 Pascals (2,4,6 and 8 inches of water) were chosen to cover the range of normal HEPA filter operation. Upon reaching the specified test pressure, the mass of material collected was determined by analytic balance and by measuring the conductivity of the solution that resulted from washing the filter. Measurements between tests were found to be reproducible to within about 10%.

4. RESULTS

The results of the pressure drop versus mass loading measurements are given in Figure 3 for some of the different particle diameters of sodium chloride tested. Figure 4 presents the results for some of the ammonium chloride tests. The slopes of the curves in Figures 3 and 4 can be interpreted, using Equation 2, to be equal to the specific resistance, K_2 , times the gas velocity, V , at the face of the filter medium.

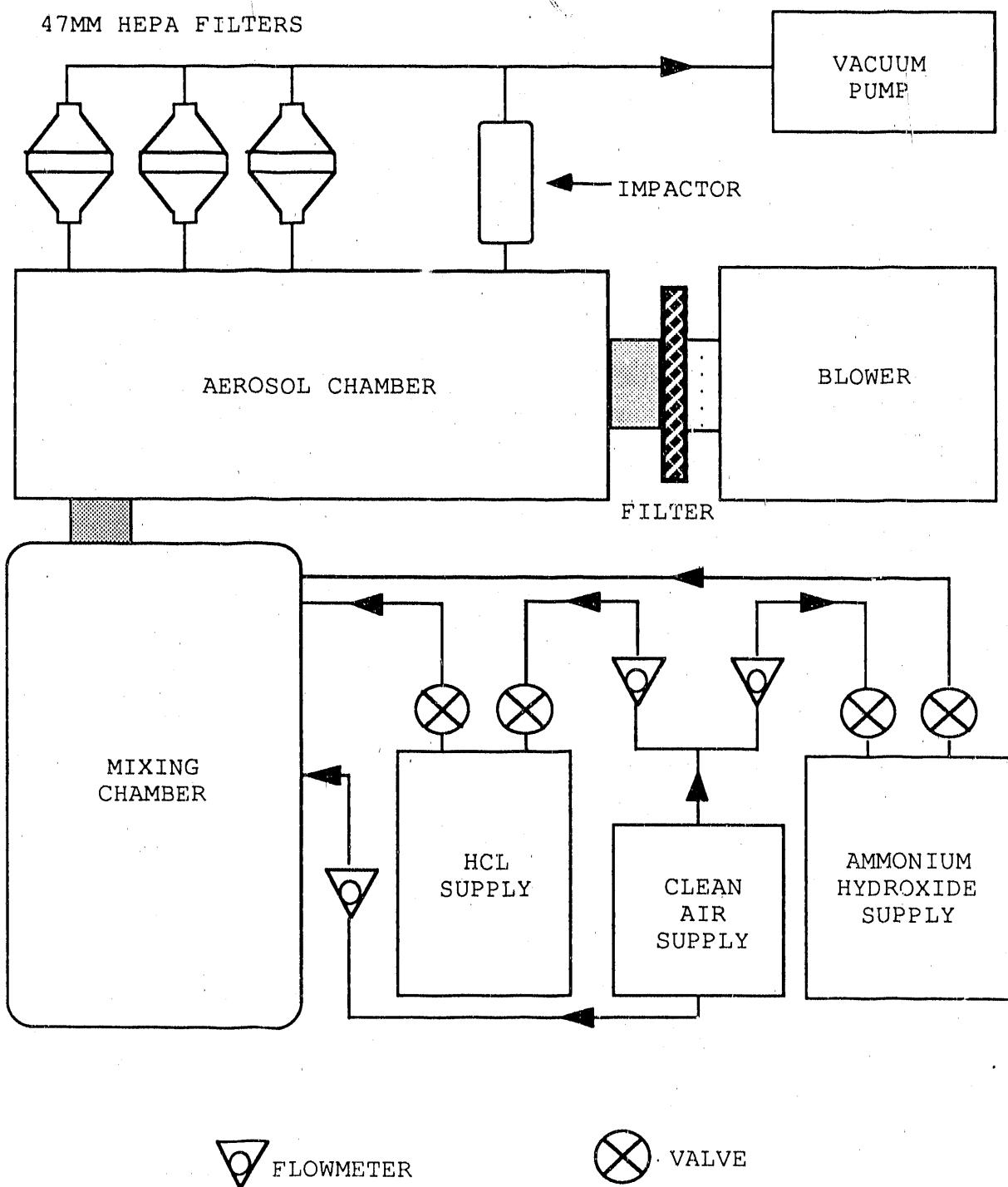


Figure 2. Schematic of the experimental setup for Ammonium Chloride aerosol tests.

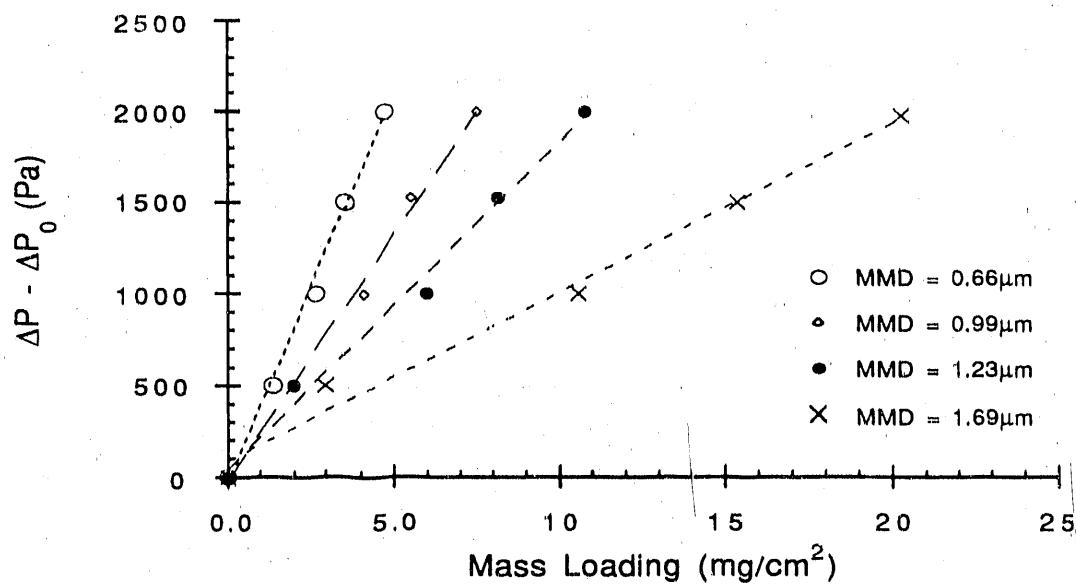


Figure 3. Net increase in pressure drop as a function of mass loading for different particle size distributions of NaCl aerosol.

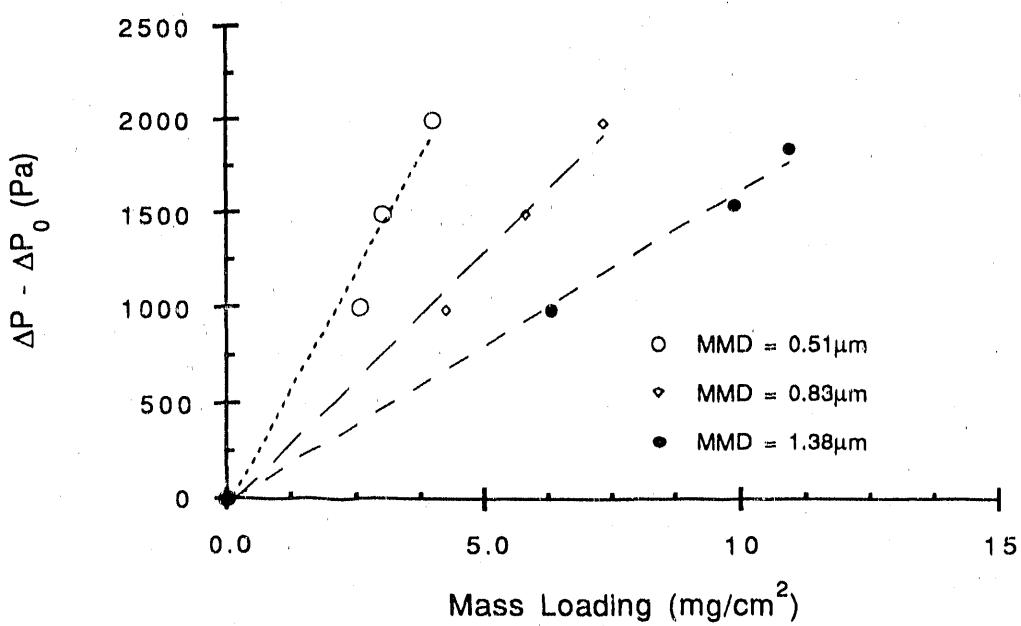


Figure 4. Net pressure drop as a function of mass loading for different particle size distributions of Ammonium Chloride.

As suggested by the theoretical evaluation of K_2 , the slope of the curve for every particle diameter tested, divided by the gas velocity, is plotted against the inverse of the particle density times the square of the diameter in Figure 5. The mass median diameter is used since the mass loading on the filter is the quantity of interest.

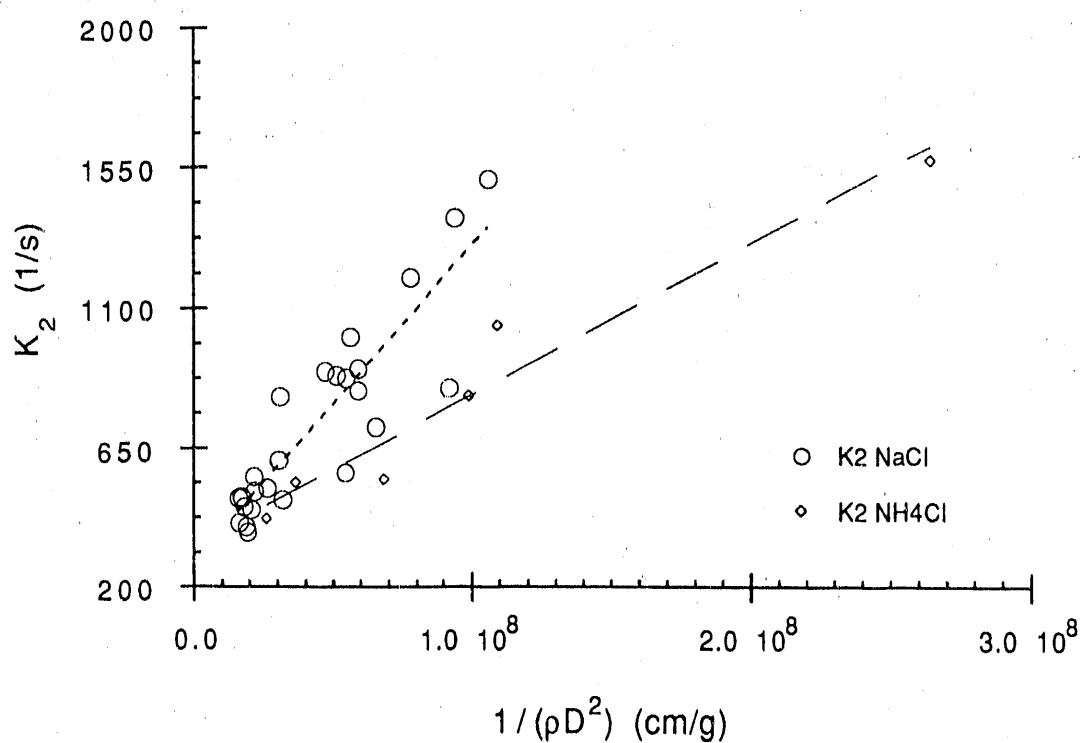


Figure 5. The measured specific resistance of the filter cakes as a function of $1/\rho D^2$ for both Sodium and Ammonium Chloride particles.

Figure 5 clearly shows that the theory does not fully account for variation in materials, unless it can somehow be accounted for in the

resistance factor R . The best empirical fit of the data is obtained when K_2/p is plotted against the inverse of the first power of the mass medium diameter as shown in Figure 6. This representation is equivalent to stating that K_2 is a linear function of $1/D^2$ and that there is no particle density dependence in the specific resistance.

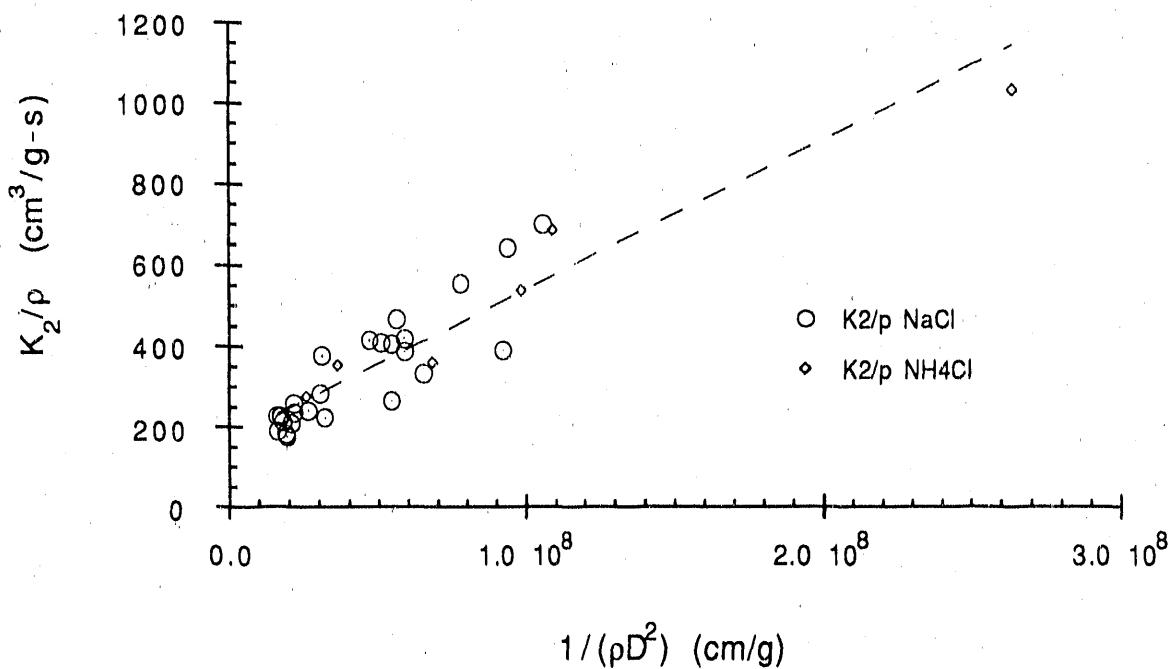


Figure 6. The measured specific resistance divided by the particle density as a function of $1/\rho D^2$ for Sodium and Ammonium Chloride cakes.

For comparison purposes, an equally good fit to the data can be obtained when K_2/p is plotted against the inverse of the particle diameter, as shown in Figure 7.

Additional work with other materials is necessary to determine the utility of this empirical relationship and to develop a modified theoretical model of the response of the pressure drop across the filter to the mass

loading of the filter.

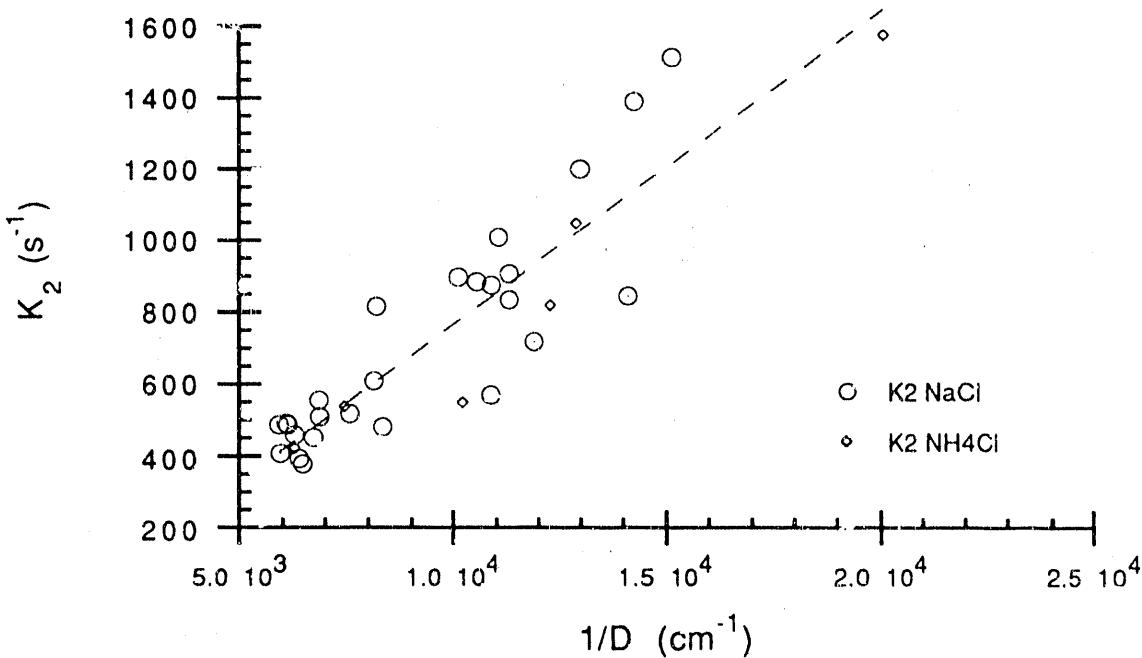


Figure 7. Measured specific resistance vs. the inverse of the particle diameter for both NaCl and NH_4Cl data

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