

RESPIRATORY PARTICULATE FILTRATION BY DANIEL A. JAPUNTICH

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ABSTRACT

The purpose of this paper is to familiarize the lay reader with examples of inhalable particles and how respiratory filtration works to remove them from the air.

Topics addressed are: Particles in the air, particles in the lungs, filtration capture mechanisms and filtration efficiency versus particle size. Comparisons are made of silica dust, lead fume, and asbestos and how they are captured in a fibrous filter.

INTRODUCTION

The purpose of this paper is to familiarize the lay reader with examples of inhalable particles and how respiratory filtration works to remove them from the air. When references are cited, they represent excellent examples of a great body of work that has gone on for fifty years. In the past few years the results of this research have been incorporated into the field of filter design, and this is reflected in the content of the references supplied.

PARTICLES IN AIR

Imagine an adult red blood cell. Most of us have seen one under magnification in a microscope, in a photograph, or on a video screen. It's a familiar object with an average diameter of 7.5 microns (a micron is one millionth of a meter). Giant ragweed pollen is about 16 microns diameter or twice as big as a red blood cell. Cigarette smoke is about .15 microns average size, about 40 times smaller than a red blood cell. The approximate range of .2 to 15 microns is called inhalable, depending upon the prevailing definitions. It is this range of sizes against which respiratory filters are expected to perform. Because of this wide range of sizes, it is only logical that different outside forces will affect the particles to different degrees depending upon the size range in which they lie.

The shape of particles can affect their behavior in air. Particles which have non-spherical, irregular shapes will settle differently from spheres. Particles with greater density behave differently from particles with lesser density even though their shapes are similar. Surface characteristics can affect particle behavior when density and shape are similar. Electrostatic charge can affect particle to particle

attraction, agglomeration rates and physical adhesion to surfaces.

Some properties or mechanisms which govern the behavior of particles in the air are:

Sedimentation

Particles of significant mass are affected by gravity and fall through the viscous air reaching a terminal velocity, or settling velocity. Turbulence and convection currents in a moving airstream may not be enough to support them as they fall. For heavy particles above 3 microns diameter, sedimentation can be the dominate mechanisms affecting their behavior.

Inertia

If a moving airstream changes direction particles with enough inertia will cross the stream sideways, sometimes to impact on the nearest obstacle. How much a particle moves out of its former path in a change of airflow direction depends on its size, shape, density, and speed. In order to simplify our understanding of how aerosol particles having these different properties behave, "pseudo" particle sizes have been developed. Aerodynamic diameter is the diameter of a water sphere (density = 1) with the same settling velocity as the particle. For example, a heavy particle of 4.3 microns diameter with a density of 4 g/cm³ would have the same aerodynamic diameter as a sphere of water 8.6 microns diameter with a density of 1 g/cm³ because they fall with equal terminal velocities through the viscous air. Stokes diameter is the diameter of a sphere with the same density and settling velocity as the actual particle. These "pseudo" diameters provide a means of labeling the behavior of irregularly shaped particles.

Industrial hygienists typically use the aerodynamic diameter as the measure of what a particle of that dynamic size will do if it enters the body. Below .5 microns, however, particles no longer have enough inertia to move through air, and the aerodynamic diameter is usually replaced by the actual physical diameter.

Diffusion

Air molecules are constantly moving and randomly colliding due to their kinetic energy. In a random system, however, a good share of these molecules may move in the same general direction at the same time. If a particle is placed in the way of these molecules, they will move that particle a distance out of its previous direction. A measure of this movement is the diffusion coefficient.

Particles with large diffusion coefficients are constantly

moving within a moving airstream: upstream, cross-stream and downstream. Although this phenomenon greatly affects particles below .3 microns, particles up to 1 micron can also be affected to a lesser degree.

The power of diffusion on particles is shown by the speed by which cigarette smoke can leave its thermal convection currents and fill a room in a matter of minutes.

Particle physical characteristics can affect diffusion as well as sedimentation and inertia. For example, a crocidolite asbestos fiber with an aerodynamic diameter of .8 microns will fall through the air the same as a sphere of water of .8 microns diameter even though it may be .3 microns in diameter and 3 microns long. The asbestos fiber, however, will have a diffusion coefficient the same as a sphere of water of .54 microns diameter (Gentry, et al, 1983).

PARTICLES IN THE LUNGS

The human body "breathing apparatus" is not an efficient filter. A majority of the particles entering the lungs are breathed out again. The capture of particles entering the lungs is dependent on the particle characteristics and the breathing rate and capacity of the lungs. Above 5 microns the nasal and oral cavities take out particles by impaction and sedimentation with better than 75% efficiency. Also, exhalation is always much less efficient than inhalation. The following table is a representation of the available data (Heyder et al, 1980) (Miller et al, 1979) (Lippman et al, 1983). on the greatest percent capture of particles deleterious to health in the pulmonary region of the lungs for mouth inhalation breathing:

<u>Particle Diameter</u>	<u>% Capture Of Harmful Particles in the Lung</u>	<u>Predominate Capture Mechanism</u>
3 microns, aerodynamic	70%	Impaction
2 microns, aerodynamic	50%	Impaction, Sedimentation
1 micron, aerodynamic	35%	Sedimentation
.5 micron, aerodynamic	25%	Sedimentation, Diffusion
.2 micron, physical	27%	Diffusion

Not every particle that penetrates a protective respiratory device, as shown in this example, is captured in the lungs. Depending on the particle size, 30 to 75 percent of

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the particles will be breathed out again.

RESPIRATORY FILTERS

The most common particulate filters are of two types: absolute and non-absolute. Absolute filters contain pores which are smaller than the particles to be removed. Their main mechanism is screening of the particles. They are expensive, have high flow resistances and clog rapidly.

The common respiratory filters are non-absolute and contain pore sizes many times greater than the particles to be removed. Such filters may be 70 to 99% air by volume. Their main filtration mechanisms take into account how particles behave in moving airstreams. By placing many small fibers in the path of moving particles, small particles can randomly intercept and large particles can impact these small fiber targets. By using smaller and smaller fibers for the same weight and thickness of filter mat, a large fiber surface area is presented for particle capture by diffusion and impaction. The addition of electrostatic charges to the fibers and particles also greatly enhances particle capture.

Non-absolute fibrous filters are presently the most economical means for respiratory filtration. They can be designed to achieve particulate removal efficiencies approaching absolute filters with very low flow resistances. These low flow resistances can be maintained over a wide range of particle loadings.

FILTRATION-CAPTURE MECHANISMS

In an absolute liquid filter, as particle size is reduced an abrupt change in filtration efficiency occurs as the particle diameter reaches the pore size diameter of the filter. This is not true for air filtration even for absolute filters. In air, combinations of capture mechanisms occur at different flowrates and particle sizes to make the use of specially designed, non-absolute, very low flow resistance filters possible. Each of these mechanisms and their combinations, which make up the total filtration efficiency, are well understood. In general, the ability of researchers to predict the initial filter efficiency with accuracy on laboratory test aerosols is good (Lee and Liu, 1980)(Lee and Liu, 1982).

To simplify the visualization of the different capture mechanisms, imagine a fiber lying perpendicular to a moving airstream as in Figures 1-4. A good analogy is that the airstreams are lanes on a superhighway, and an obstacle occupying more than one lane has been placed across the path of traffic. Each capture mechanism describes the probability with which a certain vehicle will collide with the obstacle.

Interception Capture

Interception is the only capture mechanism in which particles do not deviate from their original streamline paths as shown in Figure 1. As the streamlines approach a fiber, they split and compress as they go around the fiber and rejoin on the other side. If a particle moving along these streamlines comes within one particle radius of the surface of the fiber, it is captured. As particle size increases and occupies more than one streamline, capture becomes more probable. In our vehicular analogy, a car with the inability to change lanes (rush hour traffic) would end up becoming part of the obstacle depending upon its size with respect to the obstacle.

Sedimentation Capture

Sedimentation affects only large particles (2 microns and above). It is a contributor to capture efficiency only at low flowrates. As shown in Figure 2, the particle is affected by gravity, a force completely external to the filter fiber, and crosses the streamlines to be captured by the fiber. One could imagine a car, affected by a large magnet on one side of the road, crossing lanes and becoming part of the obstacle. The inhalation airflow deflects particles into the filter from their settling paths in the environment.

Inertial Impaction Capture

When a particle with sufficient inertia encounters an abrupt change in streamline direction as shown in Figure 3, it will cross the streamlines and impact into the fiber. The inertia of the particle depends on its size, density, speed, and shape. In our analogy, a large flat-bed truck loaded with iron pipes could be moving towards our obstacle at too high a speed. The driver would find that the force of inertia is a powerful one as the truck becomes part of the obstacle which small vehicles can easily pass around in their proper lanes.

Diffusion Capture

Smaller particles are constantly in motion due to bombardment by air molecules. As shown in Figure 4, the particles can randomly cross the streamlines and their probability of touching the fiber as they pass is greatly enhanced as their diffusive activity increases. This random motion of the particle is dependent on its size and the temperature of the air. Its chances of capture are greatly enhanced by a high residence time near a fiber (low flow rates) and the availability of fibers in its path. On the super-highway, a driver with an alcohol blood level well above prescribed limits would randomly change lanes while moving in one general direction. The chances of being captured by interception are increased.

Electrostatic Capture

Electrostatically charged particles and/or electrostatically charged fibers can greatly affect particle capture. In our analogy one can imagine magnets of different strengths and poles in both the vehicles and the obstacle. Electrostatics enhances the other capture mechanisms, especially diffusion and interception.

Combinations

Vehicle capture in the design of a super-highway is not the goal of designers. To minimize such dangers the speed, weight, and size of vehicles and their control ability are taken into consideration. At high speeds a small, heavy car has the same control problems as a large truck of the same mass. The sum total of possible capture mechanisms and their interactions are more important than the close analysis of each.

For a large heavy particle the combination of inertial impaction and interception is important. For a large, light particle, diffusion and direct interception are important. For a very small particle, diffusion prevails. If each total capture mechanism is calculated to determine its degree of contribution to capture, then a theoretical filtration efficiency may be calculated from the sum of these contributions representing a first approximation of the filter performance. Empirical testing of actual filter performance and comparison with the theoretical results yield parameters which relate to filter structure, filter design, and other "real world" respiratory protection device concerns.

PARTICLE ADHESION

With the flows and particle sizes encountered with respiratory filtration, a particle touching a fiber or a captured particle, remains captured. Van der Waal's forces, London forces, and electrostatic forces exert amazing particle-to-fiber attraction on contact so that particles cannot be dislodged in normal use. While high relative humidities are of little value in affecting submicron aerosol filtration efficiency, the formation of a liquid meniscus between the particles and fibers assures adhesion.

FILTRATION EFFICIENCY VERSUS PARTICLE SIZE

When the fiber used in the explanation of the capture mechanisms is joined by other fibers to create a maze of a certain average porosity and thickness, the different mechanisms of filtration will combine at different particle sizes to affect total filtration performance. The capture mechanisms of sedimentation, interception, and inertial impaction combine effectively to remove the particles above .6

microns. The flow rates through respiratory filters at only a few centimeters per second let diffusion play its part very effectively below .1 microns.

However, between these two particle size regions, diffusion and impaction are not as effective and a minimum filtration efficiency exists as shown in Figure 5. The lowest point on this curve is called the most penetrating particle size and can be predicted theoretically with good accuracy (Lee and Liu, 1980) or measured empirically in the laboratory. The weak capture mechanism effective at this minimum is an interaction between diffusion and interception. It is so predominant that it is usually listed as a separate capture mechanism. The addition of electrostatic charge to the fiber or particle directly improves both diffusion capture and this interactive mechanism in such a way as to raise the capture efficiency at the most penetrating particle size.

As an important point, most respiratory filters have a most penetrating particle size between .2 and .4 microns. This is the basis for the widely used dioctyl phthalate (DOP) test for high efficiency filters using a .3 micron particle. However, by challenging a filter with a variety of uncharged monodispersed particles in this size range or by using a heterodisperse aerosol and particle size instrumentation, the actual most penetrating particle size may be found. The filter efficiency for quality filters will always be much better with any other particle size.

Because a respiratory filter has a measurable penetration of laboratory particles in the narrow range of .2 to .4 microns, it is easy to ignore the fact that anywhere else in the wide respiratory particle size spectrum its filtration efficiency is well over 95%. It is the reduction of the entire actual work environment particulate challenge in particle number or mass that is important to protecting the worker. NIOSH Certification tests are meant to differentiate effectiveness by aiming at the highest penetration region, the worst possible case. Uncharged low density laboratory aerosols are purposefully designed to be the most penetrating particles possible for test reproducibility and resolution.

COMPARISONS OF DIFFERENT PARTICLES AND HOW THEY ARE CAPTURED

One of the basic problems with filter design is that the end use "aerosol challenge" may be very different from the laboratory test aerosol. Many particulate filter test aerosols are based on spherical particles, while in reality, actual environmental particles are of a vast variety of shapes, just as a super-highway has many different kinds of vehicles (see photos 1,2,3). Silica particles are jagged, and they agglomerate because of the ease in charging of their surfaces. Metallic fumes, on the other hand, consist of seed particle condensates which can grow and agglomerate into large

aggregates of high porosity. Although microscopy shows the shape and size of particles, it does not explain their total behavior when airborne.

Industrial filtration capture mechanisms can be modeled for different aerosol particles and combined or treated together, and a total % efficiency can be calculated for different particle sizes. Yeh and Liu (1974) and Lee and Liu (1982) are excellent examples of this technique. In order to generate the graphical examples used in this paper of the filtration of different particles the technique in Hinds (1982) was used. The addition of electrostatic capture was not done because of its complications, and the fact that it is an enhancement of the other mechanisms. Lundgren and Whitby (1965) and Brown (1979) are good examples on electrostatic technique.

SILICA DUST

Silica dust is the result of drilling, grinding, milling, or pulverizing quartz-bearing rock. The silica dust aerosol used in respirator testing is generated from a ground silica feed stock (PGS Corp.: Supersil), and in the process of sizing and dispersing the aerosol most particles greater than 2 microns are removed. As can be seen in Photo 1, silica is rough, jagged, small, but roughly "spherical".

An uncharged filter media for respiratory filtration should have many small fibers to enhance capture, have a high porosity to facilitate ease of breathing and be of a practical thickness. In this example a typical dust, mist respirator filter media is modeled theoretically and challenged with different particle sizes. Such an uncharged, theoretical respiratory filter material would have the following characteristics: fiber diameter = 2 microns, % porosity = 95%, thickness = 1 mm, after Hinds (1982). Challenging this filter with silica at a velocity of 5.3 cm/sec. gives the % efficiency versus particle size performance against silica in Graph 1. The contributions of the various capture mechanisms and their changing predominance across the particle size spectrum is shown. A minimum % efficiency does exist at around .2 microns, and above .5 microns the efficiency is greater than 99%.

Does this have anything to do with real silica air filtration? The answer is yes, since it directly relates to filters in the field. In the real world free silica is electrostatically charged, agglomerated and, in general, only a small part of dusts of other compounds. For example, quartz is only a small portion of the compounds in dusts generated by quarrying granite. In the laboratory, however, pure silica dust can be used and % efficiency curves generated on real filters.

The trends in Graph 1 are followed in laboratory filter

testing. Graphs 2, 3, and 4 are actual silica dust initial % efficiency versus particle diameter curves for three very different filters. Graph 2 is from fiberglass paper. Graph 3 is from resin-wool filter material (a typical dust, mist respirator filter) which combines electrostatic and mechanical filtration. Graph 4 is from 3M Brand Filtrete Type G-0120, an electret filter media which uses electrostatics as the principle capture mechanism. NOTE the change in % efficiency scale in Graphs 2, 3, and 4 from Graph 1.

Will the theoretical filter in Graph 1 protect the worker even though the minimum capture efficiency is 86%? The answer, again, is yes as shown in Graph 5*. If the theoretical curve (Graph 1) is applied to a pure NIOSH laboratory silica dust particle size distribution (white bars on Graph 5), only a very few particles penetrate (black bars on Graph 5). The total count % efficiency is 94.06%. Remember that 75% of these penetrating particles will be breathed out again. Each of the white bars in Graph 5 represents the number of silica particles at a certain particle diameter. If the volume of the particle at that diameter is calculated and multiplied by the density of silica (2.6 g/cm^3) the mass of that particle results. Multiplying this particle mass by the number of particles at that size range and repeating the process for each particle size range gives the total mass challenge. Repeating the process again for the penetrating particles gives mass penetration. From these two numbers a mass % efficiency of 99.76% is generated.

Does this respirator protect the worker? Yes, the Threshold Limit Value (TLV) of pure, free silica is $.098 \text{ mg/m}^3$ concentration below which a respirator is not needed. Above ten times that value a respirator cannot be worn by law (greater than $.98 \text{ mg/m}^3$). At 99.76% mass efficiency a respirator of this filter material without significant face leaks will lower the highest concentration of silica ($.98 \text{ mg/m}^3$) to $.0024 \text{ mg/m}^3$, well below the TLV. The worker is thus protected.

METALLIC OXIDE WELDING FUMES

Metallic oxide welding fumes consist of primary, small particles and complex aggregates of those particles. If a surface of metal is heated above the melting point, metal vapor is generated and chemical reactions with the air occur, mainly in the form of oxidation. The speed in growth and subsequent size of particles are based on the concentration of metal vapor and the atmospheric conditions. Tomb et al (1976) and Jarnuszkiewicz (1966) confirmed that the majority of welding fume aggregate particles sized by microscopy were below .5 microns in diameter. Iron oxide, zinc oxide and lead oxide had remarkably similar size distributions. Photo 2 shows what they saw: large aggregates of high porosity made of "seed" condensate particles of a density based on their oxide

compound. A large range of sizes of these feathery aggregates is present in any fume atmosphere.

Fume particles may be sized with two different methods. One method is to collect particles on a slide and take photos under magnification (Photo 2 for example). The dark area of each of the porous aggregates can be totaled, and each aggregate particle can be assigned an equivalent area sphere "image diameter". This image diameter conservatively estimates the size of the aggregate as a filter fiber would view it on approach for interception capture. Another method is to measure the Stokes diameter by diffusion battery sizing or electrostatic mobility sizing at the same time as the microscopy sample slide is taken so both an "image" and a "dynamic" assessment can be made. The Stokes diameter can be used to estimate how the particle behaves for impaction capture and diffusion capture.

Japuntich and Johnson (1983) characterized lead oxide fume under a variety of atmospheric conditions and found that the Stokes diameter (how the particle behaves) as measured by electrostatic mobility is much smaller than the image diameter (how the particle looks under the microscope).

An analysis into metallic fume filtration starts with the fact that these big, porous particles act like much smaller particles. This is an important point since it means that for a fume aggregate, while the interception capture mechanism is the same as for a sphere of the same image diameter, the diffusion and diffusion-interception capture mechanisms are the same as for a much smaller particle. Also, since the densities of the fume oxides ($5-9.5 \text{ g/cm}^3$) are much greater than that of laboratory test aerosol unit density spheres (1 g/cm^3), the impaction capture mechanism comes into play at much smaller particle sizes. One can imagine a very large particle approaching a filter fiber which changes course by diffusion in the same fashion as a particle many times smaller. An example of the relationship between image and Stokes diameter for lead fume is given below:

<u>Equivalent Area</u> <u>Image Dia.</u>	<u>Stokes</u> <u>Dia.</u>
.10 micron	.015 micron
.239	.045
.551	.14
.868	.24
1.35	.47
2.15	.93

The expectation from the theory of particle capture is that fume aggregates will filter efficiently in relatively open filter media since each capture mechanism comes strongly into play.

Challenging the same theoretical filter as used for silica dust with lead oxide fume gives the results shown in Graph 6. The interception capture mechanism was calculated from the microscopic image diameter distribution, and the impaction and diffusion capture mechanisms were calculated from the Stokes diameter distribution in Japuntich and Johnson (1983). The diffusion-interception interaction mechanism was calculated from a combination of both distributions.

Graph 6 shows that lead oxide fume is more easily filtered than silica dust (Graph 1). The problem with fumes is not filtration efficiency. The problem is that they clog filters and elevate the flow resistance of filters very fast when used against high mass concentrations.

It should be evident that any dense particle (with an image diameter much larger than the diameter simulating its dynamic behavior) will filter out more easily than lighter test particles with equal image and dynamic diameters. Also, consider that a large percentage of fumes are generated by arc welding, which imparts high electrostatic charges to the small particles, greatly enhancing filtration.

If the filter in Graph 6 were less efficient, the minimum % efficiency aggregate equivalent area diameter would be around .4 microns (at which the particle behaves like a .1 - .15 micron sphere).

As an example of respirator lead fume filtration, twelve 3M Brand 8710 Dust, Mist Respirators were challenged with lead fume at 32 lpm for 5 hours, 12 minutes.:

	<u>NIOSH LEAD FUME DUST, FUME, MIST SPECIFICATIONS</u>	<u>3M 8710 RESPIRATOR RESULTS</u>
TOTAL LEAD OXIDE FUME MASS CHALLENGE (16 mg/m ³ mass concentration)	160 mg	160 mg
32 LPM LEAD MASS PENETRATION	<1.5 mg	Avg.=.15 mg S.D.=.07
85 LPM FINAL INHALATION FLOW RESISTANCE (PRESSURE DROP)	<50 mmH ₂ O	>100 mmH ₂ O

This is a good example of a respirator which gives good protection against deleterious metallic oxide fumes, but under the high challenge test concentrations clogs and does not pass a different part of the government certification requirements: final flow resistance. The respirators do pass initial flow resistance specifications. Note that the 16 mg/m³ challenge concentration is 320 times the Threshold Limit Value (.05 mg/m³), and 32 times the

limit for lead fume above which respirators cannot be used. Even so, the mass % efficiencies were an average 99.9%. The NIOSH test is meant to amplify flow resistance differences in respirators under intense mass loading.

ASBESTOS

The rod-like shape of asbestos has made the study of the filtration properties of this particle difficult to model. Here is presented a proposal for an approximate filtration assessment. Because of its acicular nature, for lung deposition studies these rod-like fibers have been characterized by the aerodynamic diameter derived from particle diameter and length (John et al, 1977) (Stoeber, 1972). Using this diameter to calculate the filtration impaction capture mechanism is a worst case. The diffusion capture can be approximated by a calculated diffusion coefficient (Gentry, et al, 1983).

The interception capture mechanism is the interesting problem. A rod may approach a filter perpendicular to each filter fiber, parallel to each filter fiber, or anywhere in between.

Fine rods in the air are affected by diffusion even when their aspect ratios (length/diameter) are large (Gentry et al, 1983). Rods large enough to settle by gravity will be randomly oriented horizontally and may not necessarily be parallel to the ground. When inhaled into a respirator filter the angular approach of these rods will be random. Once inside the filter the tortuous flow paths (Kuwabara flow field), diffusion action and the fact that one end of a rod can occupy a faster streamline than the other end ensure that the angular approach to each fiber will be random (Note: this is not true for non-fibrous capillary filters; i.e. Nuclepore filters in which a cross-section of the flow field through a hole in the filter is roughly parabolic, not like the torturous path through a system parallel cylinders).

A probability approximation of the capture position of an incoming rod to a fiber is shown by the normal distribution in Graph 7. The probabilities of a rod approaching end on (90°) or parallel (0°) to a fiber are low. The average approach angle is 45° with respect to the fiber.

Capture by interception is strongly influenced by rod length. The longer the rod, the easier the capture. An aspect ratio of 3 was chosen as the most penetrating case which still meets the U.S. Occupational Exposure Standard definition of a fiber.

Asbestos rod length and diameter also may affect the

degree of possible harm to the lungs. Pott et al (1983) state, "...many animal experiments showed that long, thin fibers have the strongest carcinogenic potential, while the carcinogenicity decreases with decreasing fiber length and increasing diameter. These relationships have been illustrated in a net hypothesis (Figure 6) (Pott 1978). The different size categories are made up by intervals of length and diameter of the fibers. Thus, they are also related to certain ranges of aspect ratios. The schematic curves, rising from the right, describe in principle the increase of the carcinogenicity of fibers with increasing length. The highest degree of carcinogenicity is defined to be 100".

By holding the aspect ratio to 3 and varying the fiber diameter to obtain different aerodynamic diameters, the % efficiency of the asbestos rods with the minimum interception capture mechanisms (worst case) may be calculated. As can be seen in Figure 6 the hypothesized most carcinogenic rods have lengths greater than three microns and aspect ratios much greater than three, so our model at an aspect ratio of 3 is quite conservative (for example, a .25 micron diameter asbestos fiber is most carcinogenic at a 20 micron length, an aspect ratio of 80). This aspect ratio of 3 and its shape factor were included in all calculations.

Graph 8 displays the calculated % efficiency of the same filter used in Graph 1 for silica and in Graph 6 for lead oxide fume at different asbestos rod angular approach position probabilities. If all the rods were lined up like guided missiles perpendicular to each filter fiber, Curve A % efficiency would result at different aerodynamic particle diameters. Curve C at 45°, however, shows the most probable % efficiency.

Using the 45° approach position for a weighted average % efficiency calculation gives the results shown in Graph 9, showing the contributions of the various capture mechanisms. On comparison with Graph 1 for silica it appears asbestos, even in the worst cases, is easier to filter than silica dust.

Photo 3 shows a photomicrograph of chrysotile asbestos, the material used in 90 to 95% of asbestos applications. "The 'curliness' of these fibers, as well as the many frayed and projecting fibers greatly increases the probability of capture or removal of these fibers by interception with a surface or with other fibers" (Ayer and Zumwalde, 1980). Other asbestos materials such as amosite and crocidolite are hard, brittle and, as in the model, more rod-like. Also, asbestos aerosols in work environments have very high electrostatic charges, greatly enhancing filtration capture over the proposed model (Jones

et al, 1983).

Does a filter made to keep out silica dust perform well against asbestos? Yes, such a respiratory material works well against asbestos. As an example, in Graph 10 the theoretical filter is challenged with an actual aerodynamic diameter asbestos particle size distribution from John (1983) (NOTE: ACTUALLY, THE FIBERS THAT MAKE UP THIS AERODYNAMIC DIAMETER DISTRIBUTION HAVE ASPECT RATIOS FROM 3 TO 30. OUR MODEL AT ASPECT RATIO OF 3 IS VERY CONSERVATIVE). As in Graph 5 for silica, the black bars are the penetration particle counts. The total % count efficiency is 98.77%, better than silica dust at 94.06%.

Weeks and Burns (1970) did mass % efficiencies of Bureau of Mines approved dust, mist respirators against respirable size asbestos fibers in high concentrations and found them more than 99.7 mass % efficient against chrysotile asbestos. In their tests, even unapproved respirators had mass % efficiencies above 97%. Of course, since workplace fiber concentration limits are in fiber count specifications, mass efficiencies are an incorrect assessment of a respiratory filter.

W. B. Johnston (1978) at the Institute of Occupational Medicine, Edinburgh, Scotland challenged 3M Brand 8710 dust, mist respirators (MSHA-NIOSH approved TC-21C-132) with two types of asbestos: UICC (International Union Against Cancer) chrysotile and crocidolite at flow rates of 30 and 90 liters per minute. Results of count efficiency by microscopy:

<u>FLOW RATE</u>	<u>CHRYSTOTILE % COUNT EFFICIENCY</u>		<u>CROCIDOLITE % COUNT EFFICIENCY</u>	
	<u>MEAN</u>	<u>S.D.</u>	<u>MEAN</u>	<u>S.D.</u>
30 lpm	99.99%	.02	99.98%	.02
90 lpm	99.99%	.02	99.98%	.03

Fiber challenge concentrations averaged 90 fibers per milliliter. Percent count efficiencies represent performance over a one hour challenge time. All particles with a diameter in the range 0.2 to 3.0 microns, which conformed to the aspect ratio of a fiber, were counted. The results indicated that the respirators preferentially filter the longer fibers (greater than 5 microns).

Most of the work on asbestos and how it affects the human lungs has been done with no respiratory protection in mind. It seems, however, that the most inexpensive, government approved respirators provide ample protection

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against asbestos, and the respiratory filtration model used in this report does support this fact.

SUMMARY

Respiratory particulate filtration technology has been presented in this paper to give an understanding of how a worker can be protected against deleterious particulates. The design of respirators is, of course, much more complicated by other factors: comfort, worker acceptance, face-fit, and manufacture cost. Added to these factors is the great cost of good quality control, which in the case of respirators is a high technology in itself, involving complicated laboratory particulate tests and strict statistical procedures. However, good respiratory particulate protection can protect the individual worker against a variety of harmful substances.

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BIBLIOGRAPHY

- Ayer, H.E. and R.D. Zumwalde (1980) "Physical and Chemical Characteristics of Airborne Fibers", Chapter 12 of Generation of Aerosols and Facilities for Exposure Experiments, K. Willeke, editor, Ann Arbor Science publishers, Ann Arbor, P. 244
- Brown, R.C. (1979) "Electrical Effects in Dust Filters," in Proceedings of the Second World Filtration Congress, London, England. Uplands Press Ltd. 1, Katharine Street, Croyden, CR9 1LB, England, PP 291-301.
- Gentry, J.W., K. Spurny, J. Schormann, H. Opiela (1983), "Measurement of the Diffusion Coefficient of Asbestos Fibers" Chapter 45 of Aerosols in the Mining and Industrial Work Environments, Vol. 2, v.A. Marple, B.Y.H. Liu, Editors, Ann Arbor Science Publishers, Inc., Ann Arbor, PP 597-612.
- Heyder, J., J. Gebhart, and W. Staulhofen (1980), "Inhalation of Aerosols: Particle Deposition and Retention", Chapter three of Generation of Aerosols and Facilities for Exposure Experiments, Klaus Willeke, Editor, Ann Arbor Science Publishers, Inc., Ann Arbor, PP 65-103.
- Hinds, W.C. (1982), "Filtration", Chapter 9 of Aerosol Technology: Properties Behavior, and Measurement of Airborne Particles, John Wiley and Sons, New York, PP 164-180.

Japuntich, D.A., and B.D. Johnson, (1983), "Characteristics of Lead Fume Aerosol Generated Under Different Conditions by an Oxygen-Natural Gas Welding Torch" Chapter 37 of Aerosols in the Mining and Industrial Work Environments, V.A. Marple and B.Y.H. Liu, Editors, Ann Arbor Science Publishers, Ann Arbor, PP 513-522.

Jarnuszkiewicz, et.al.(1966) : "Particle Size Distribution of Welding Fume Depending on the Microclimatic Conditions of the Welders Work place", Bulletin of the Institute of Marine Medicine in Gdansk, Vol. 17, 1966 (translation).

John, W., G. Reischl, D. Bettencourt, S. Goren, D. Plotkin (1977), "Anomalous Filtration of Solid Particles by Nuclepore Filters", 10th Aerosol Technology Meeting, Albuquerque, N.M.

John, W. (1983), "Sampling Technique for Airborne Asbestos Fibers" Chapter 42 of Aerosols in the Mining and Industrial Work Environments, V.A. Marple and B.Y.H. Liu Editors, Ann Arbor Science Publishers, Inc., Ann Arbor, PP 577-584.

Johnston, W.B. (1978), "An Investigation into the Performance of 3M's Disposable Respirators Types 8710 and 8800 against penetration by Airborne Asbestos", Confidential Report, Institute of Occupational Medicine, Edinburgh, Scotland.

Jones, A.D., A.M. Johnston, J.H. Vincent (1983), "Static Electrification of Airborne Asbestos Dust", Chapter 46 of Aerosols in the Mining and Industrial Work Environments, V.A. Marple and B.Y.H. Liu Editors, Ann Arbor Science publishers, Inc., Ann Arbor, P 613-632.

Lee, K.W. and B.Y.H. Liu (1980), "On the Minimum Efficiency and the Most Penetrating Particle Size for Fibrous Filters", J. Air Pollution Control Association, April, 1980, Vo. 30, No. 4, PP 377-381.

Lee, K.W. and B.Y.H. Liu (1982), "Experimental Study of Aerosol Filtration by Fibrous Filters", Aerosol Science and Technology 1:35-46.

Lungren, D.A. and K.T. Whitby (1965), "Effect of Particle Electrostatic Charge on Filtration by Fibrous Filters" I&EC process Design and Development Vol. 4:4, PP 345-349.

Lippman, M., J. Gurman, R.B. Schlesinger (1983), "Role of Particle Deposition in Occupational Lung Disease", Chapter 11 of Aerosols in the Mining and Industrial Work Environments, Vol. 1, V.A. Marple, B.Y.H. Liu, Editors, Ann Arbor Science Publishers, Inc., Ann Arbor, PP 119-138.

Journal of the ISRP

Miller, F.J., D.E. Gardner, J.A. Graham, R.E. Lee, Jr., W.E. Wilson, J.D. Bachmann (1979), "Size Considerations for Establishing a Standard for Inhalable particles", J. Air Pollution Control Association, June 1979, Vol. 29, No. 6, PP 610-615.

Pott, F. (1978), "Some Aspects on the Dosimetry of the Carcinogen Potency of Asbestos and Other Fibrous Dusts," Staub-Reinhalte. Luft 38:486.

Pott, F., W. Stober, K. Spumy (1983), "Properties of Asbestos and Other Fibrous Dusts With Regard to Their Carcinogenicity" Chapter 43 of Aerosols in the Mining and industrial Work Environments, V.A. Marple and B.Y.H. Liu Editors, Ann Arbor Science Publishers, Inc., Ann Arbor 1983, PP 585-596.

Stoeber, W. (1972), "Dynamic Shape Factors of Nonspherical Aerosol Particles," Chapter 14 of Assessment of Airborne particles, T. Mercer, D. Morrow, W. Stoeber Editors, Charlie C. Thomas, Inc., Springfield, Illinois, PP 249-289.

Tomb, T.F., H.N. Treaftis, A.J. Beckert II (1983), "Quantifying the Efficiency of the Coal Mine Personal Respirable Dust Sampler for Sampling Oxide Fumes", American Industrial Hygiene Assoc. Journal August, 1983, PP 459-463.

Weeks, J. and A.F. Burns (1970), "Performance of Dust Respirators Against a Fibrous Dust", American Industrial Hygiene Assoc., Journal, June, 1970, PP 290-293.

Yeh, H.C. and B.Y.H. Liu (1974), "Aerosol Filtration by Fibrous Filters," J. Aerosol Science, 5, 191-217.

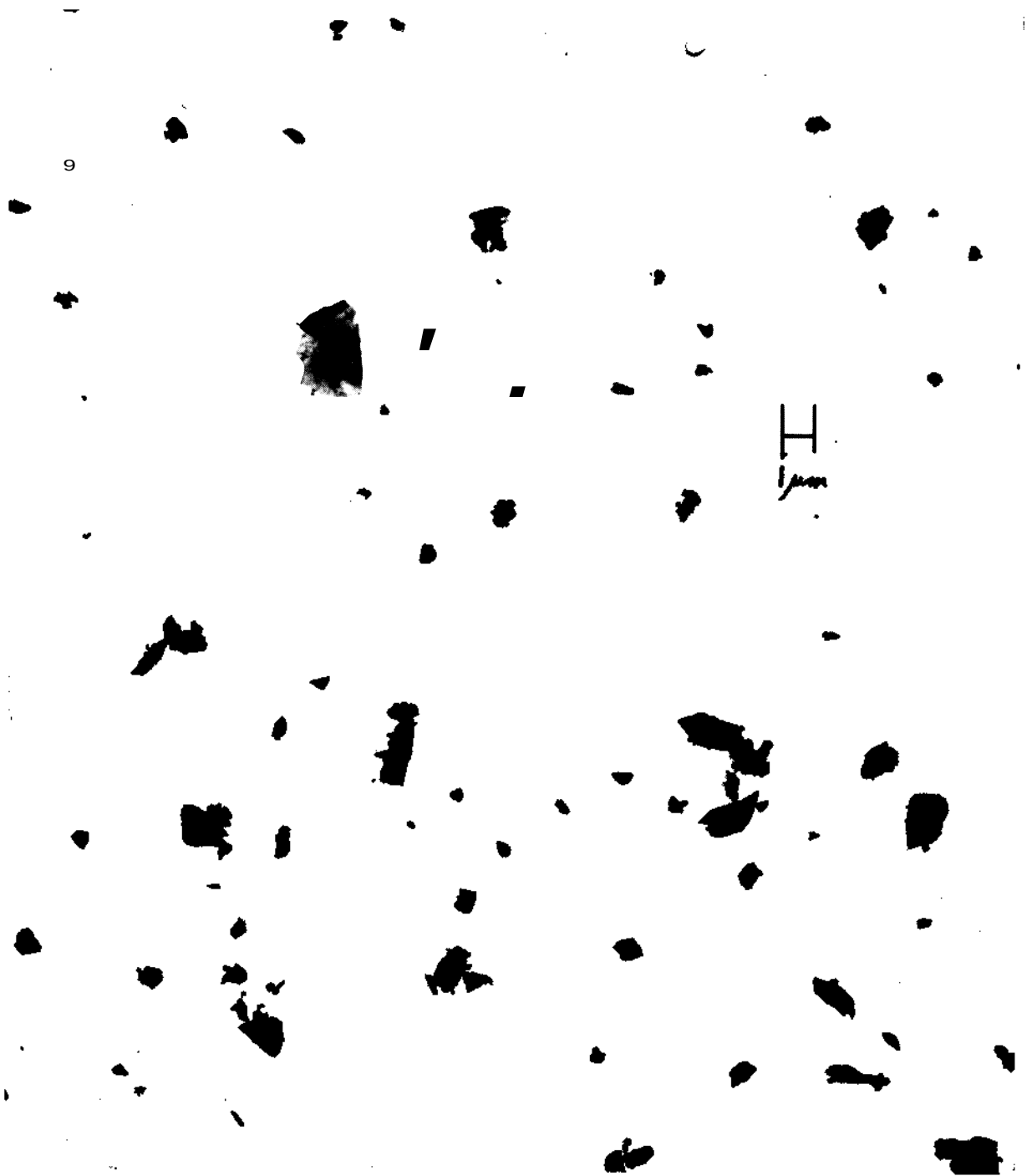


PHOTO 1. SILICA DUST 5000X

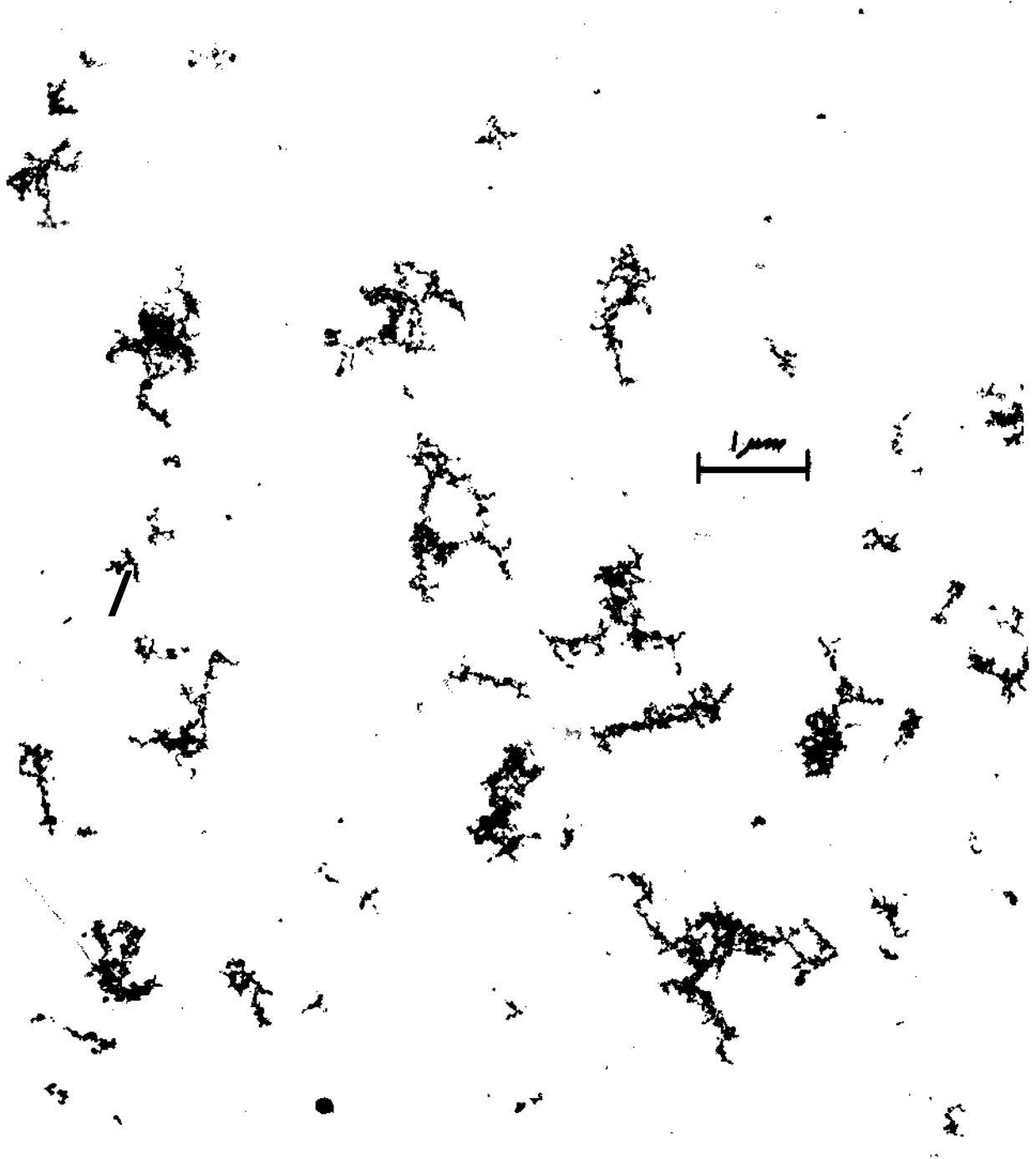


PHOTO 2. LEAD OXIDE FUME 19,800X



PHOTO 3. CHRYSOTILE ASBESTOS 1200X

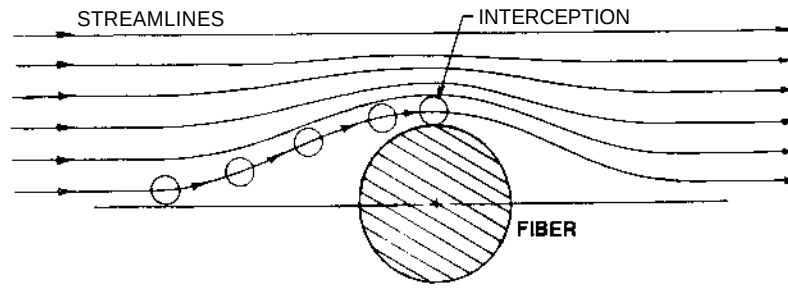


FIGURE 1. INTERCEPTION CAPTURE MECHANISM

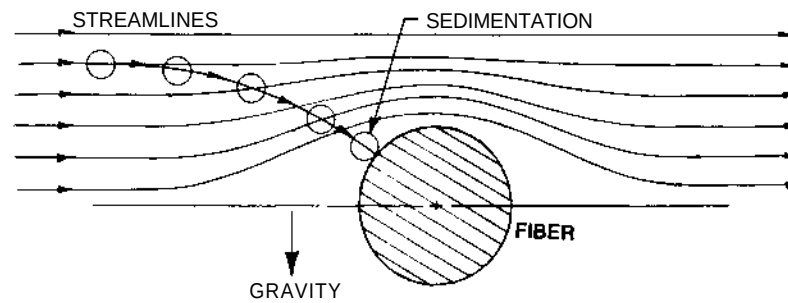


FIGURE 2. SEDIMENTATION CAPTURE MECHANISM

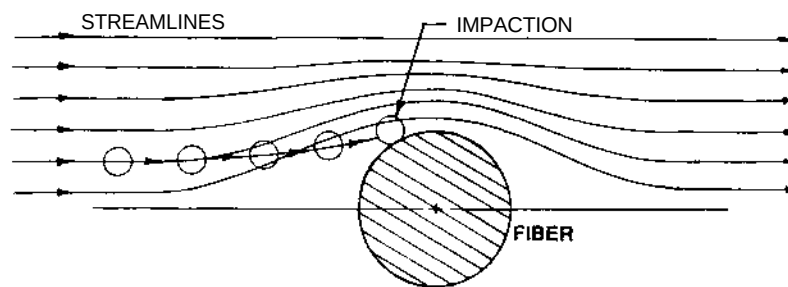


FIGURE 3. IMPACTION CAPTURE MECHANISM

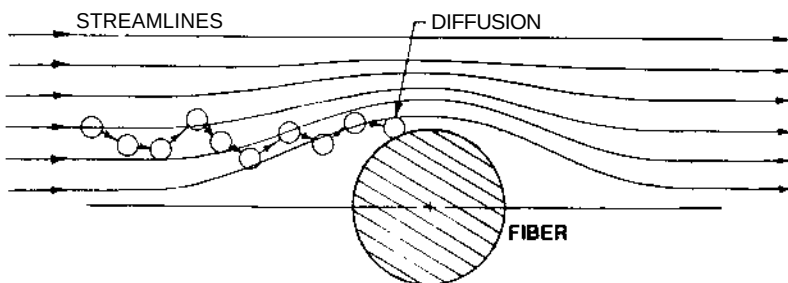
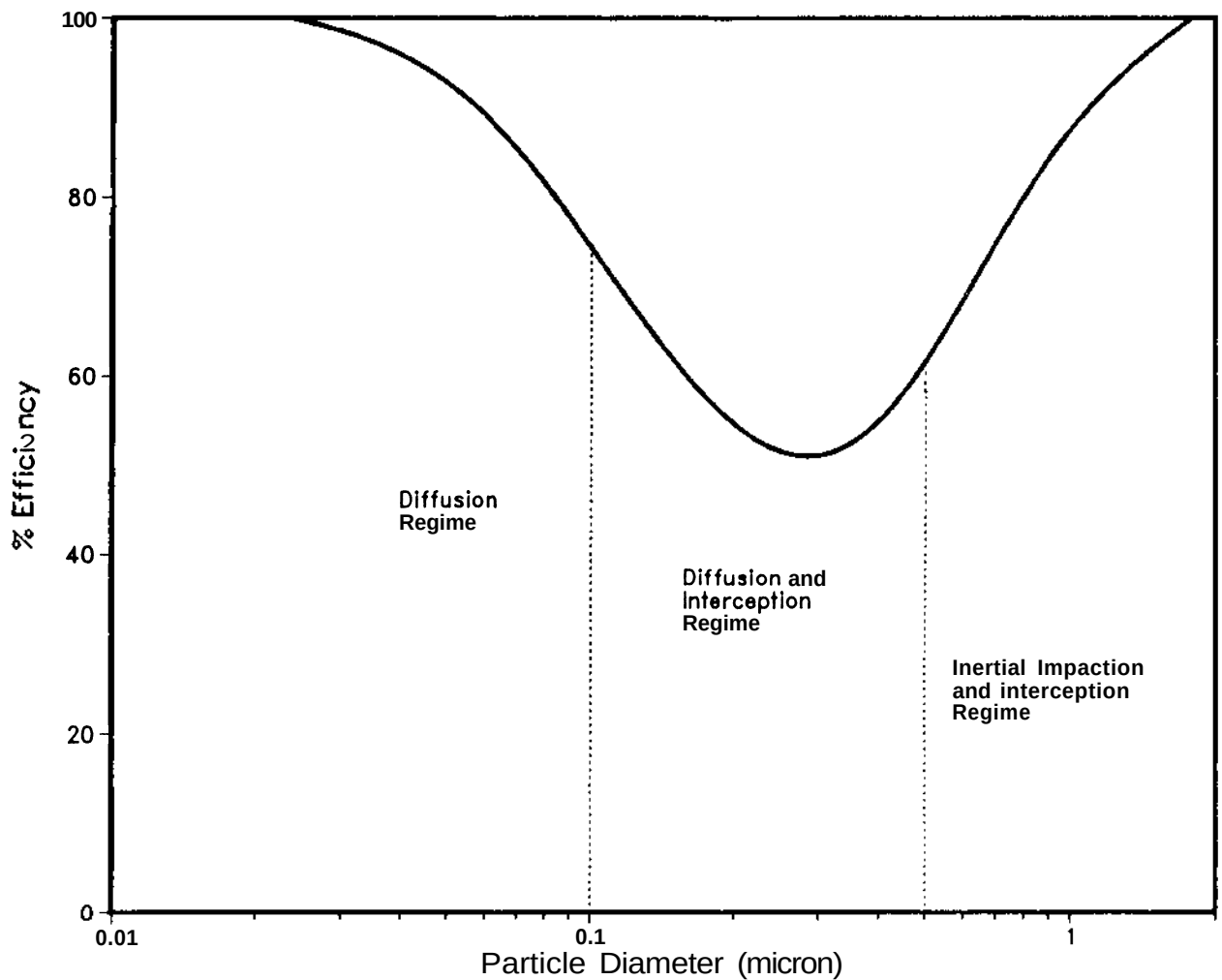


FIGURE 4. DIFFUSION CAPTURE MECHANISM

FIGURE 5. Schematic Filter Efficiency vs. Particle Size
Illustrating the Different Filtration Regimes
after Lee & Liu (1980)



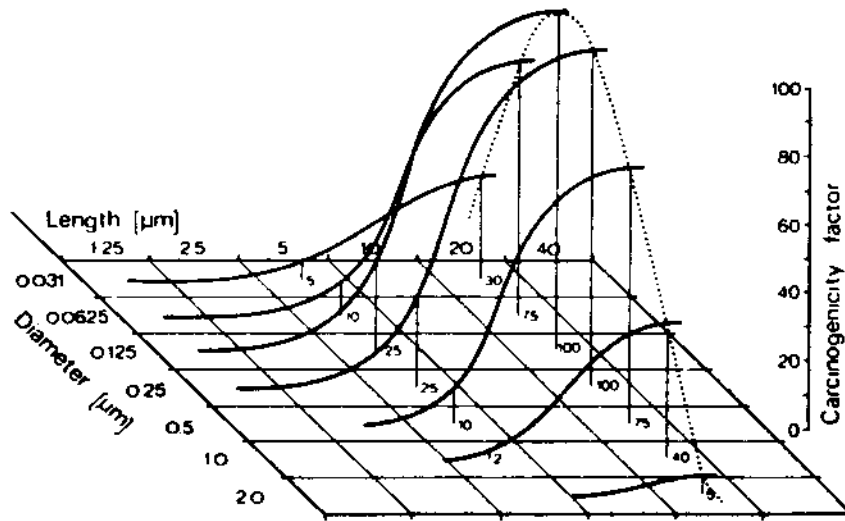
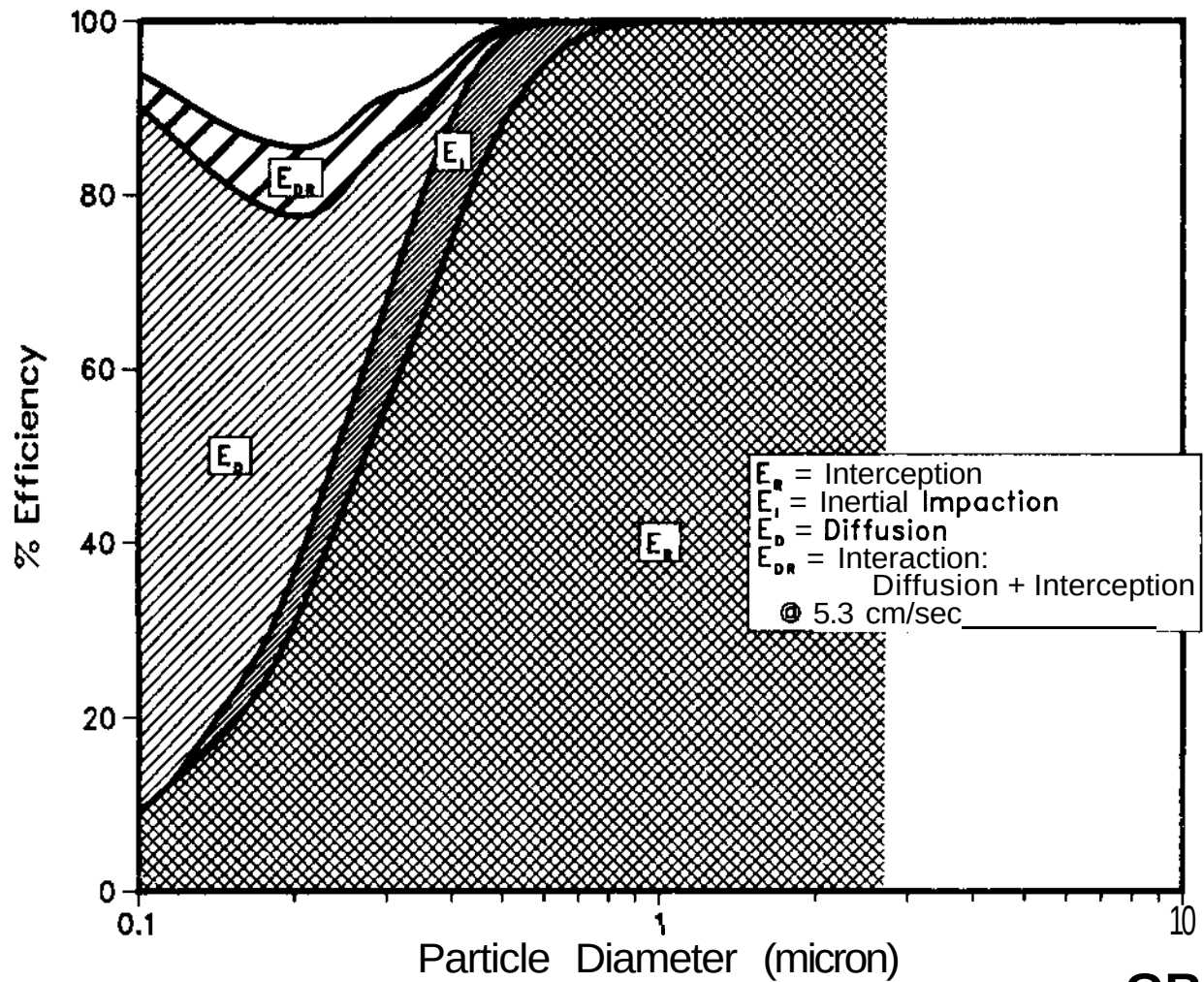


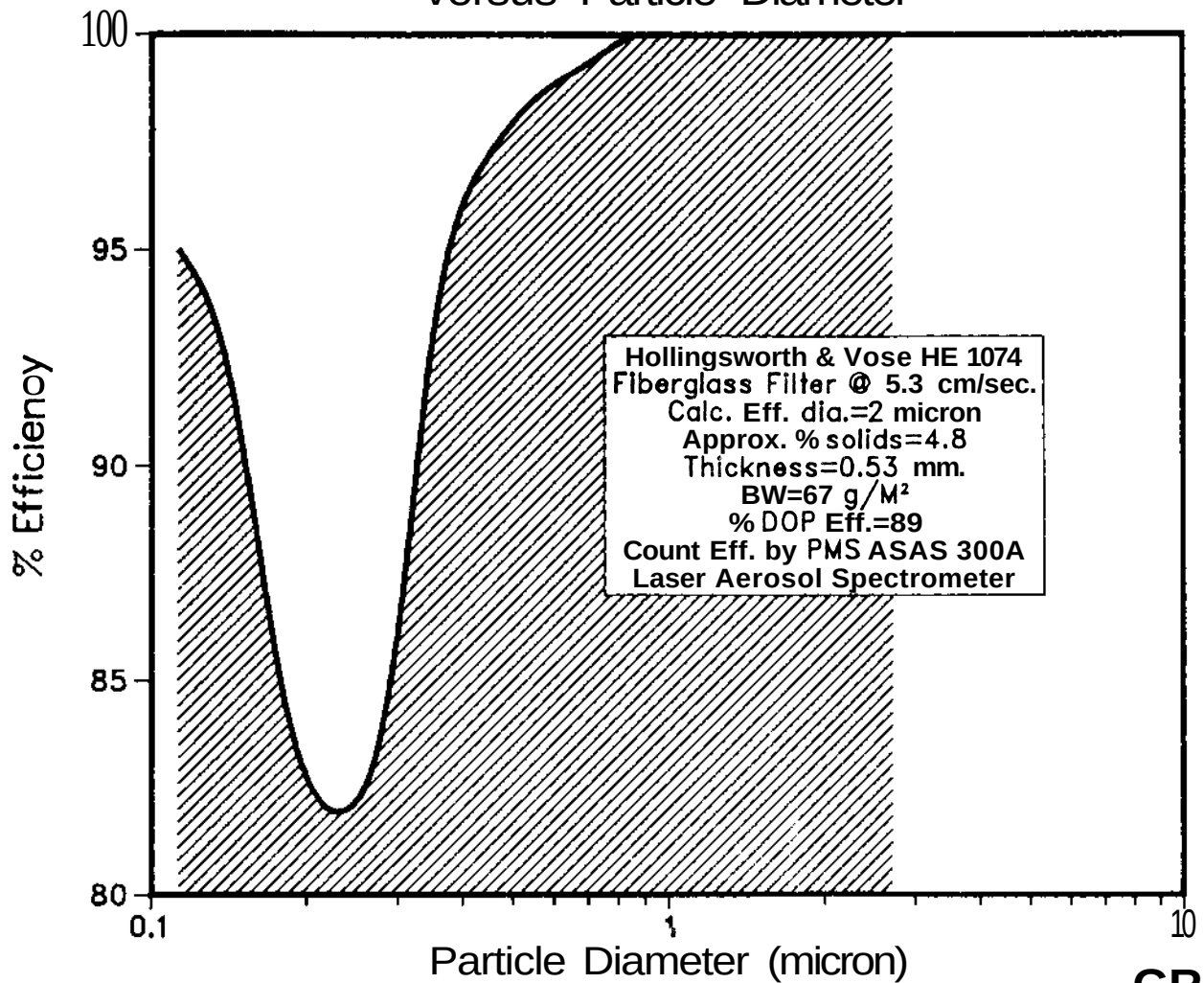
FIGURE 6. HYPOTHESIS OF A 'CARCINOGENICITY FACTOR' EXPRESSING THE CARCINOGENIC POTENTIAL OF A FIBER AS A FUNCTION OF SIZE (BASED ON PRELIMINARY DATA). THE THREE DIMENSIONAL MODEL REQUIRES THE FIBER SIZE TO BE SUBDIVIDED INTO MANY SIZE CLASSES ACCORDING TO LENGTH AND DIAMETER OF THE FIBER. FROM JOHN (1983)

The Contribution of the Different Calculated Capture Mechanisms for Silica Dust



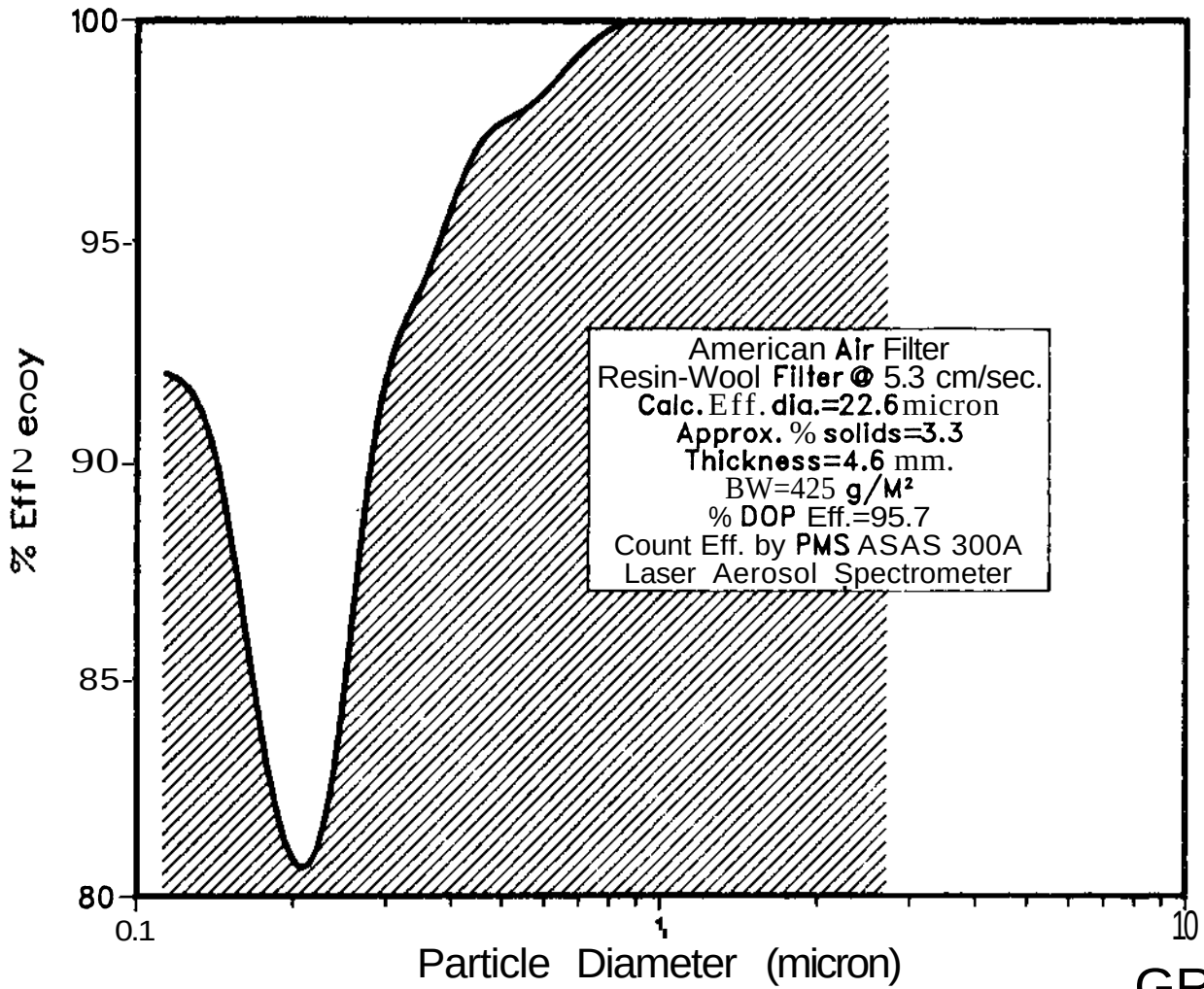
GRAPH 1

Actual Silica Dust
% Filtration Efficiency
versus Particle Diameter

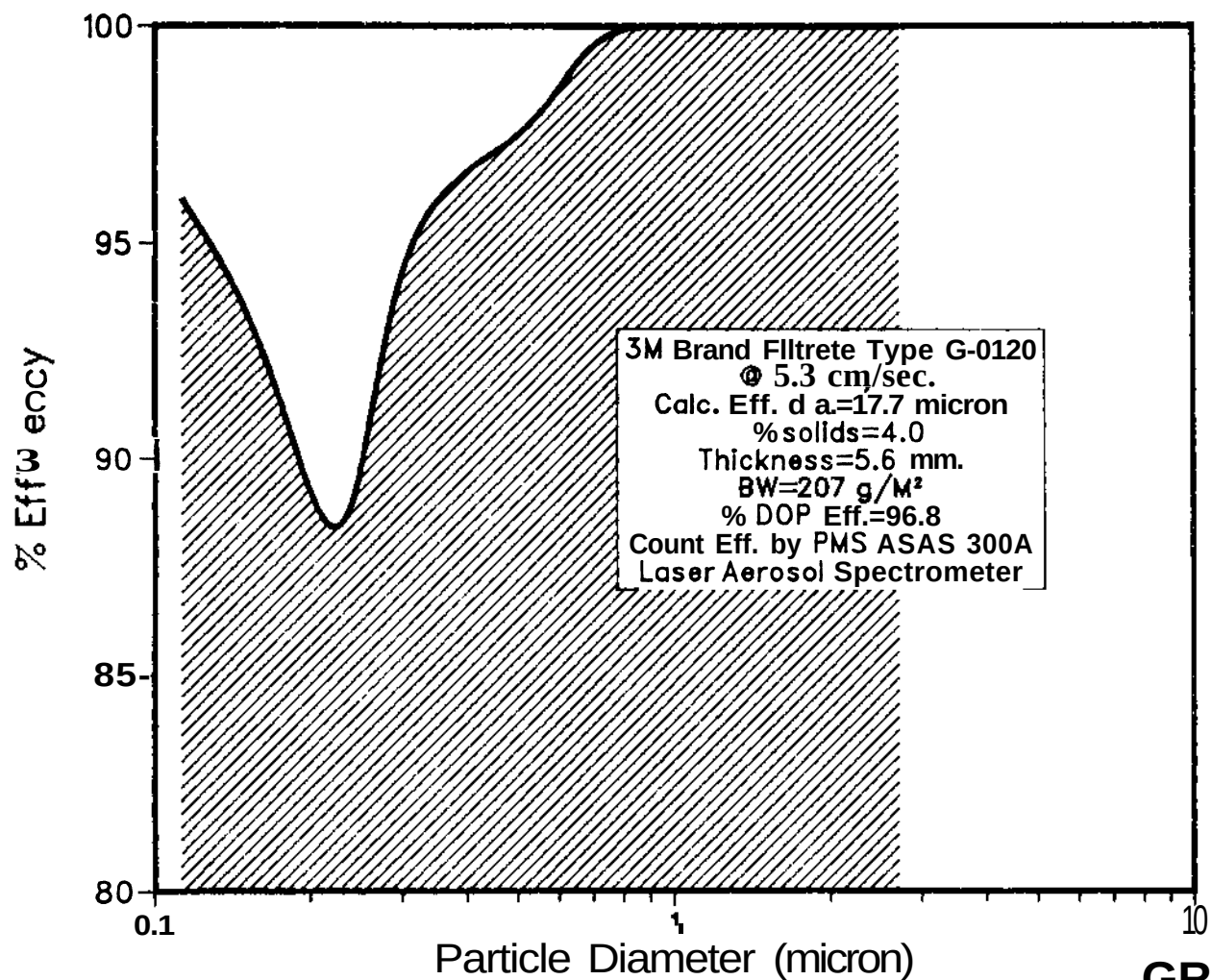


GRAPH 2

Actual Silica Dust
% Filtration Efficiency
versus Particle Diameter

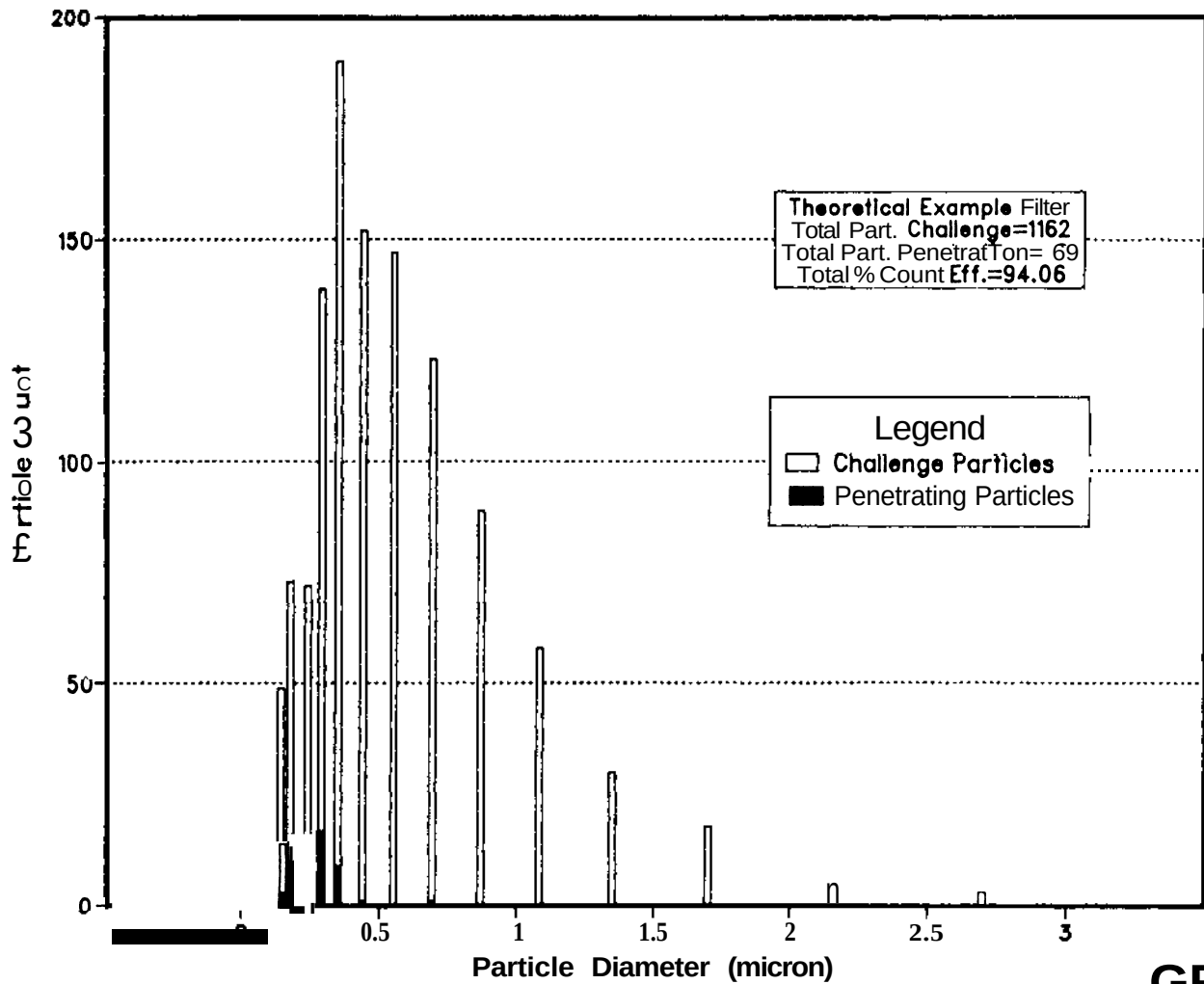


Actual Silica Dust
% Filtration Efficiency
versus Particle Diameter



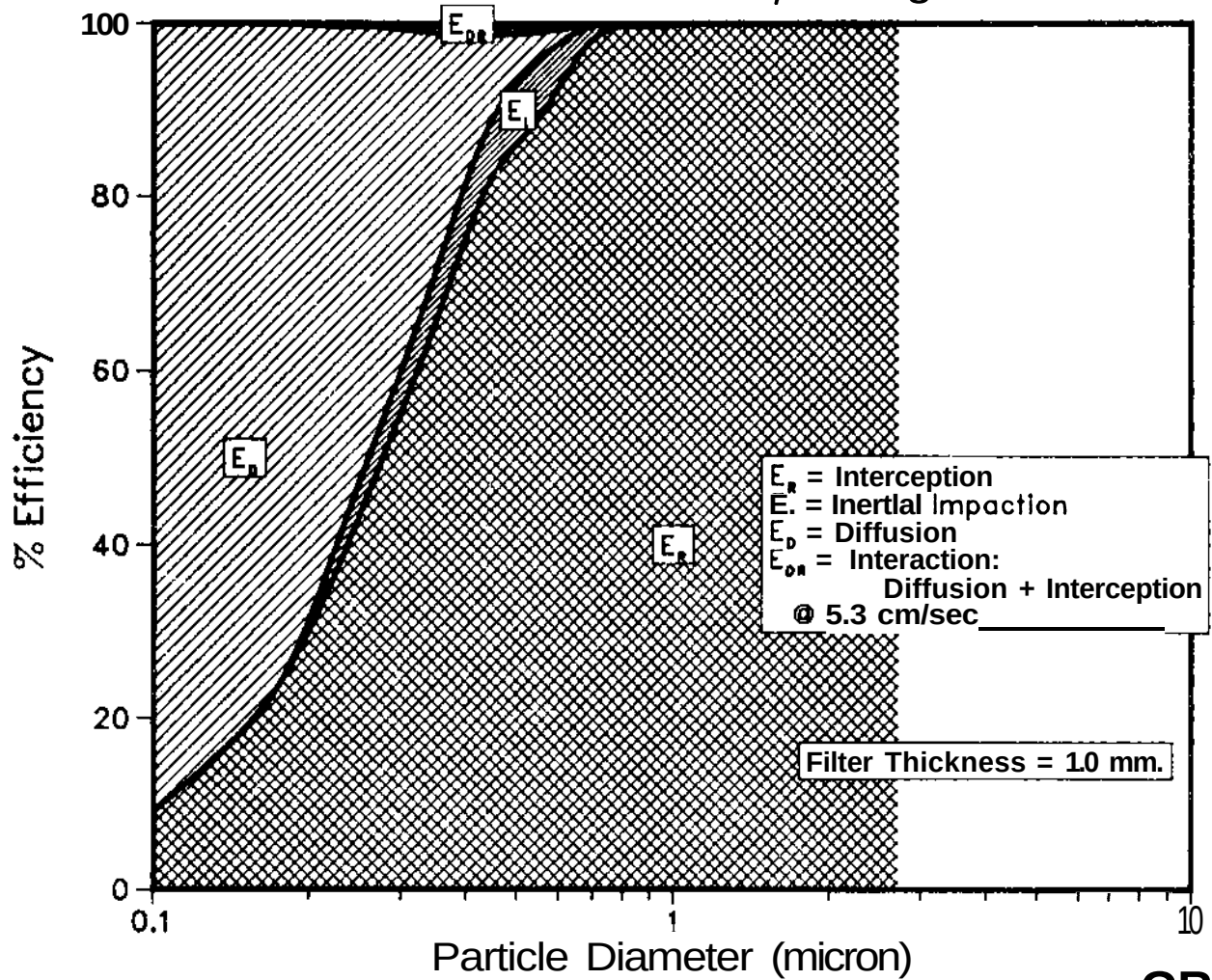
GRAPH 4

Silica Dust Challenge and Calculated
Filter Penetration Particle Count
versus Particle Diameter



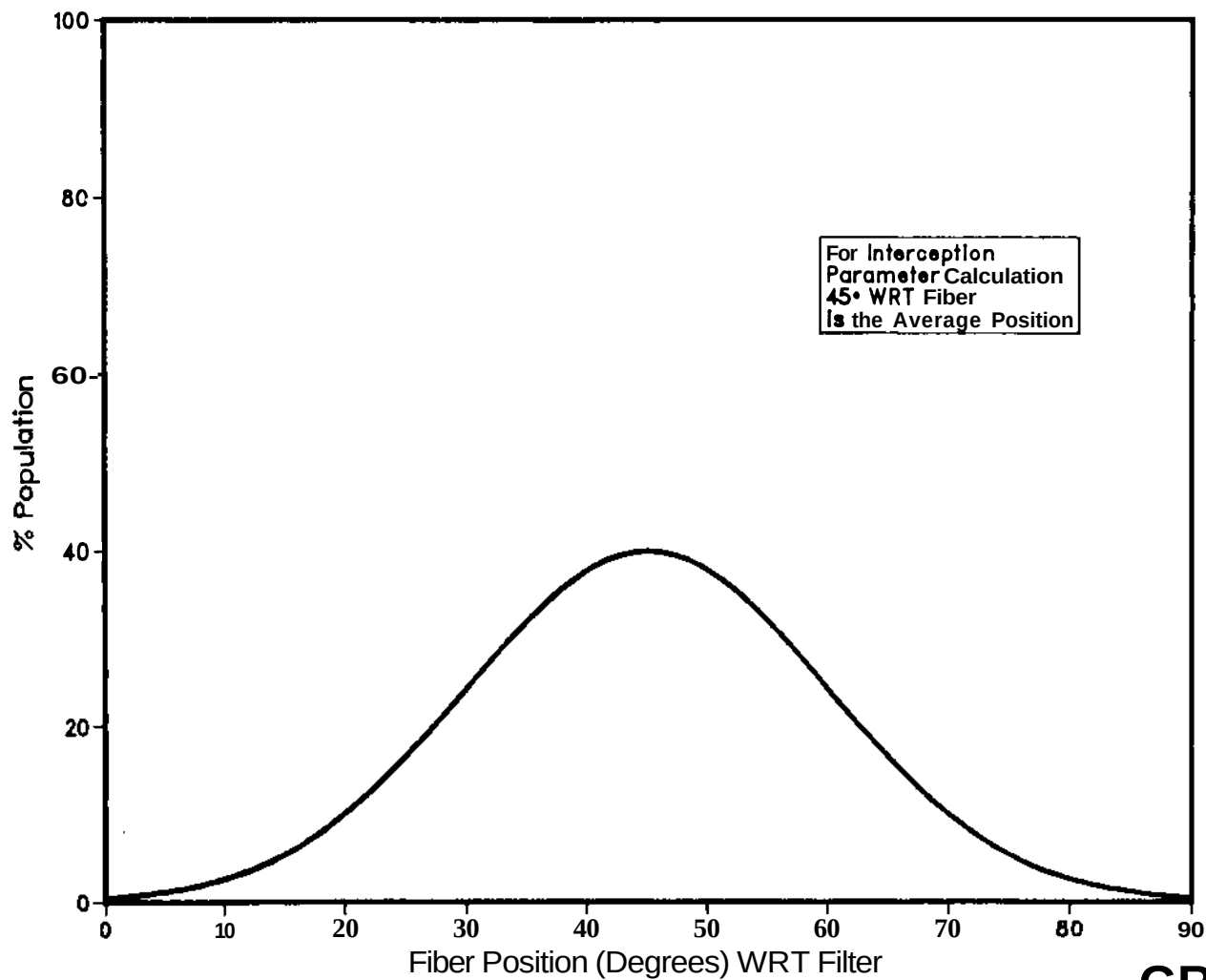
GRAPH 5

The Contribution of the Different
Calculated Capture Mechanisms
for Lead Oxide Fume $\rho=9.5 \text{ g/cm}^3$



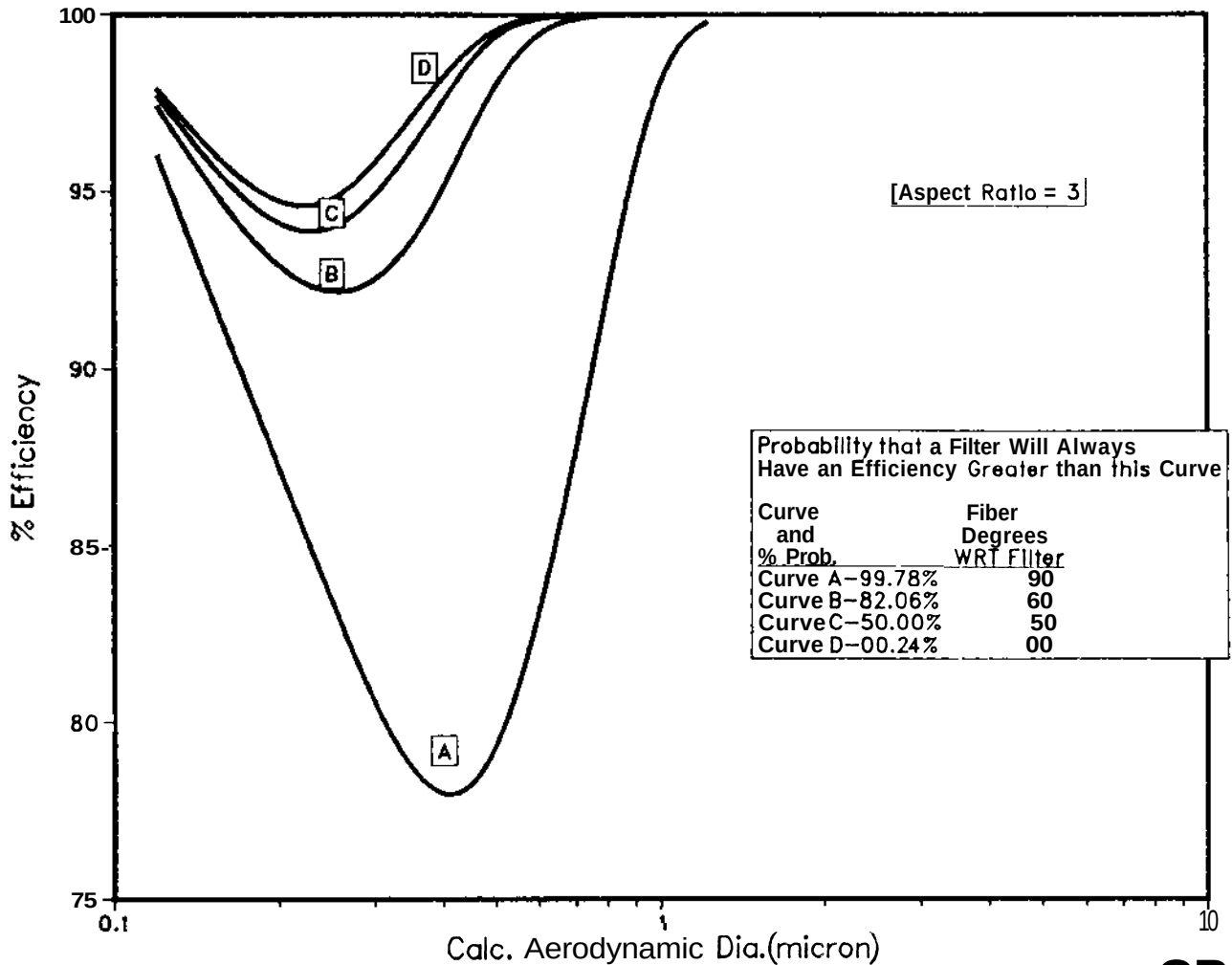
GRAPH 6

Normal Distribution Approximation of an Asbestos
Fiber Random Position (Degrees)
with respect to a Filter Fiber



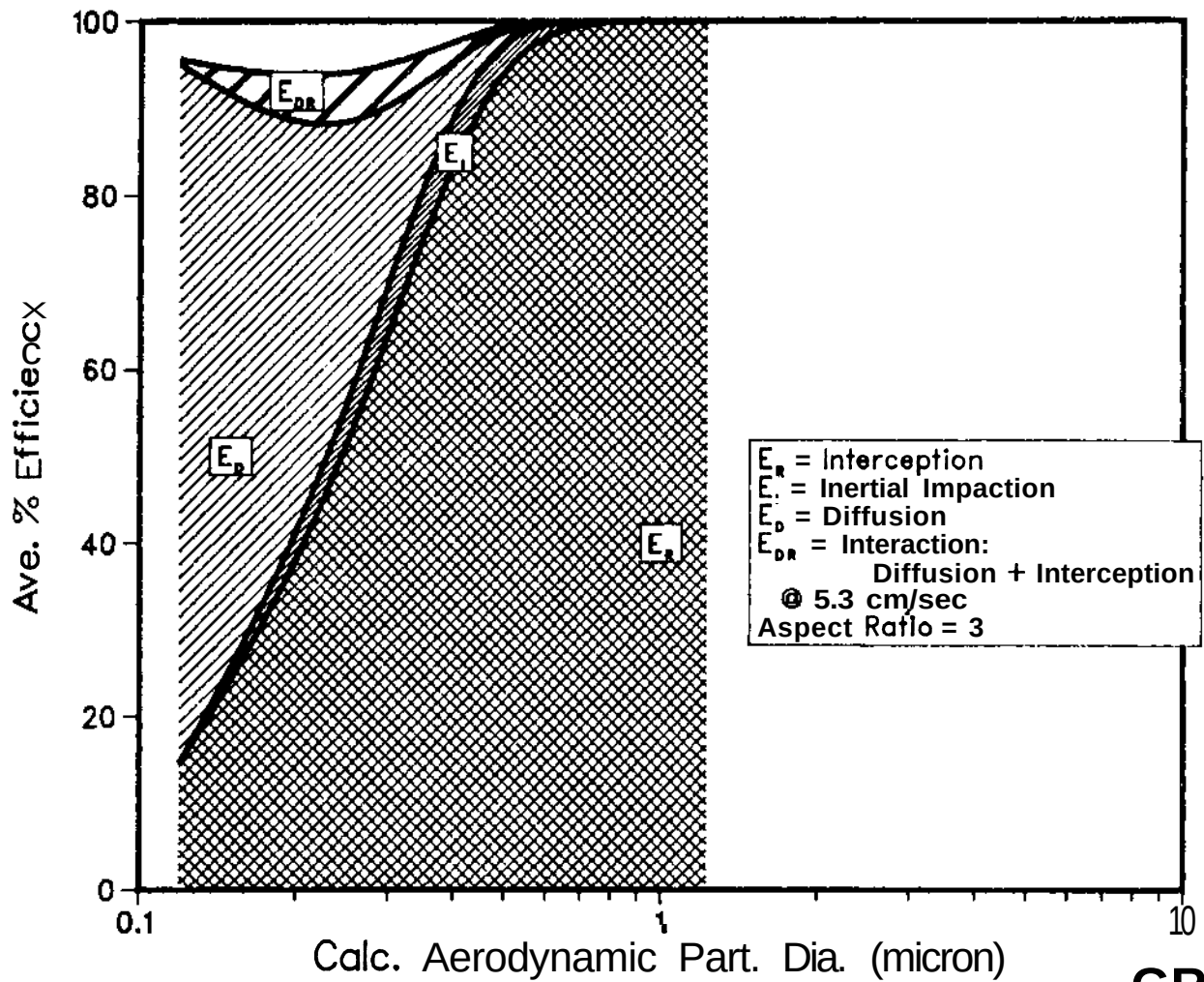
GRAPH 7

Calculated % Efficiency of Asbestos
at Different Asbestos Fiber Positions
With Respect to a Filter Fiber



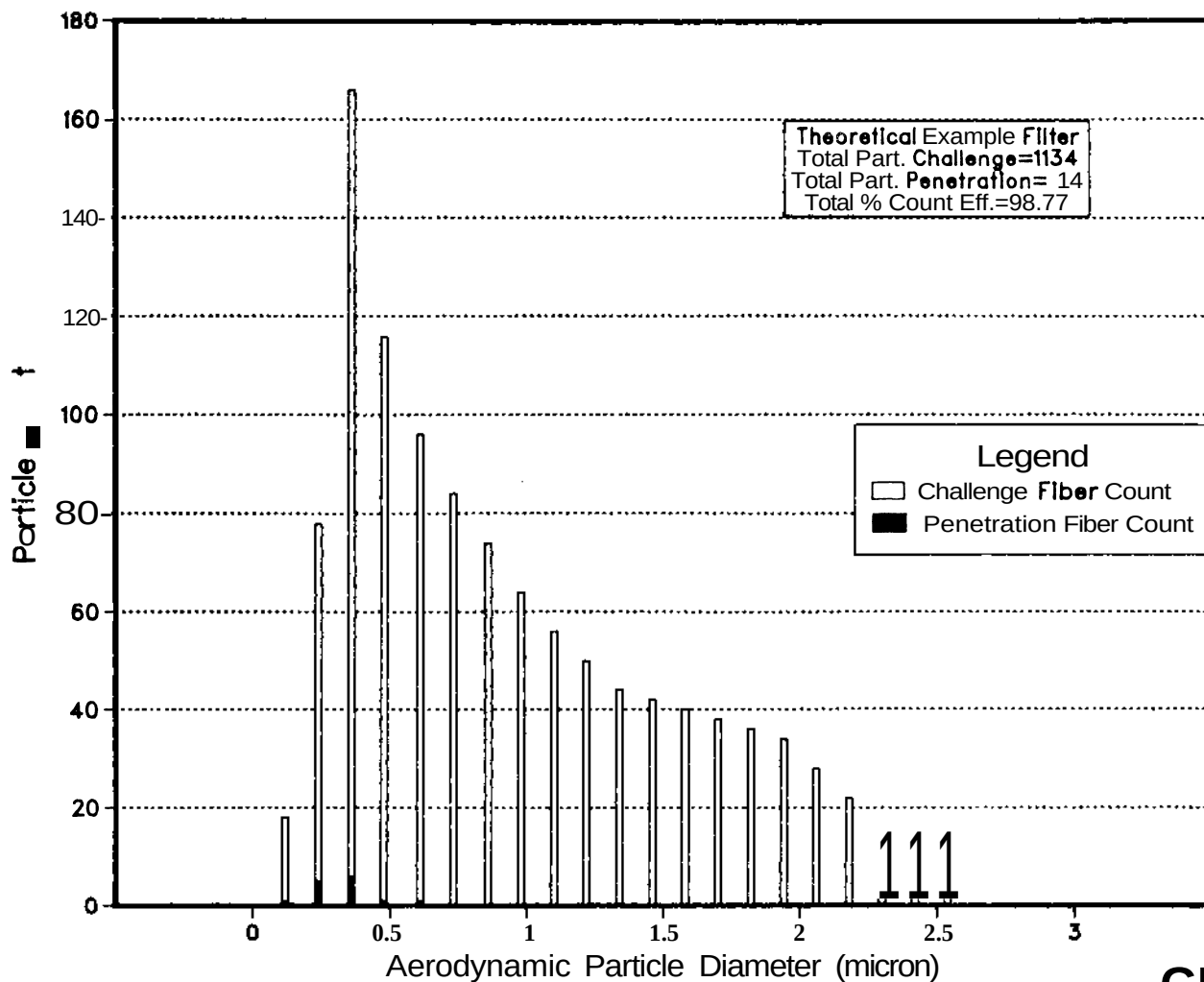
GRAPH 8

The Contribution of the Different Calculated Capture Mechanisms for Asbestos



GRAPH 9

Asbestos Challenge and Calculated Filter Penetration Particle Count versus Aerodynamic Particle Diameter



GRAPH 10