DISSEMINATION, RESUSPENSION, AND FILTRATION
OF CARBON FIBERS

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INTRODUCTION

The carbon fiber study has been structured like other atmospheric pollution problems. The source produces the material, in this case carbon fibers; the atmosphere transports and distributes them; and at the end of the chain the fibers produce effects, in this case the disruption of electrical devices. Both the source and the effects elements of this study had to be generated specifically for this problem; whereas the transportation element could be mostly adapted from other pollution studies.

For the fire plume aspect of transportation, the smoke stack models were used for the determination of the height at which the plume becomes neutrally buoyant. However, the differences between an uncontained open fire plume and an industrial smoke stack are large enough to have required some model verification testing. This work was performed at the White Sands Missile Range.

Many models exist for the cloud transport phase of the problem. These models have a large empirical data base from pollution work with gases such as sulphur dioxide from industrial sources, with liquid droplets from aerial spraying, and with solid particles such as fly ash from smoke stacks. Those models are only sensitive to the still air fall velocity of the individual particles, and have been adopted into the risk assessment studies because they have proven successful in work for the Environmental Protection Agency.

Resuspension of particles was found to be a less developed much more complex science which had developed around the need to understand soil erosion in some states and long term radioactive pollution in other states. However, what appeared applicable to round soil particles did not appear to be valid for our high aspect ratio fibers. A special series of tests was therefore conducted to monitor the resuspension of fibers from a desert land patch with a known deposition of fibers. The results of those tests led to the conclusion that resuspension was a minor problem and that the risk assessment should be based on the first-time source.

Filtration of fibers and the their entry into buildings is a subject for which models existed and only specific filter tests had to be performed. The transfer function models are essentially micro-dissemination models assuming perfect mixing of the atmosphere within the buildings.

Many organizations were involved in assembling the methodology which prescribes the path for the fibers from the source to the vulnerable equipment. This presentation contains a brief outline of the methodology used and the data developed for the four main topic areas: Fire Plume, Dissemination, Resuspension, and Filtration.

MEASURES OF FIBER POLLUTION

Typically a vulnerable electric instrument may blow cooling air over the electric circuits, and blow the fibers across contact pairs. The rate at which fibers might strike a contact pair and cause a failure is therefore proportional to the concentration of fibers in the air. In this presentation the symbol C is used for concentration. Its units are fibers/unit volume of air (f/m^3). The total risk of failure of an instrument is proportional to the exposure E, which is defined as the time-integral of the fiber concentration,

$$E = \int C \, dt \qquad\qquad f\text{-}s/m^3$$

or if the concentration C is constant for a time t, the exposure is the product of time and concentration

$$E = C \times t \qquad\qquad f\text{-}s/m^3$$

For most instruments the risk of failure is only a function of the exposure E, and it has therefore become the main measure of carbon fiber pollution.

Most detectors of fibers deposit the fibers on a surface, and the deposition density D is the number of fibers per unit area (f/m^2).

The deposition density is related to the exposure through the deposition velocity

$$D = E \times v \qquad\qquad f/m^2$$

where v is the flow velocity of the air for filter type collectors or the fibers' free fall velocity v_s for flat surfaces.

METEOROLOGY FOR DISSEMINATION

The strength of the sun's heating of the ground has the greatest influence on the turbulence of the atmosphere and on the dispersion of particles.

The sketches in Figure 1 show a smoke stack in three weather conditions. In sunny weather with low winds the radiation from the sun first heats the ground. Some of the heat is conducted to the lower few meters of the air. This stack is unstable, and the heat is distributed vertically by convection, until the atmosphere is layered at the dry adiabatic lapse rate to the height of the inversion. Typically during the heating portion of the day the temperature distribution changes from State I to State II. The convection patterns are responsible for very rapid mixing of the smoke plume in the atmosphere.

At the other end of the scale, with no solar heating the earth radiates out heat and cools. When the atmosphere is stably layered, the bottom layers will loose heat to the ground by conduction forming a stronger inversion. This atmosphere sustains no turbulence and smoke plumes mix extremely slowly. These conditions lead to the highest pollutant exposures downwind.

Between the two extremes there is the neutrally buoyant atmosphere with little or no heat flux. These conditions usually occur after the passage of fronts in strong winds under overcast skies. The turbulent mixing under such conditions is due to the turbulence accompanying the wind. The mixing is faster than in stable weather, but slower than in unstable weather.

For dissemination analysis stability indices have been developed. The Pasquill-Gifford stability classes for the three main weather conditions are shown in Figure 1. Cloud spread angles have been empirically determined for each of these classes.

PLUME MODELLING

Figure 2 shows a schematic view of a smoke cloud rising from the site of a large pool fire. When the gases are hot and buoyant the fire plume is extremely turbulant and mixes rapidly with ambient air until it reaches neutral buoyancy. The thermal buoyancy in that phase dominates the spread and rise of the clouds, and special fire plume models have been developed to predict the height and the spread of the fire plume to the point at which it becomes neutrally buoyant, that is the "stabilization point".

Beyond the stabilization point the meteorology determines the spread of the drifting smoke cloud. The Gaussian dissemination models have been developed to predict the exposure patterns downwind. The fire plume models and the dissemination models are matched together at the stabilization point.

FIRE PLUME MODELS

The fire plume models are based on material contained in a paper by G. A. Briggs (1970) presented at the Second International Clean Air Congress.

Although the model was developed for smoke plumes from industrial exhaust stacks, it provides good estimates of the stabilization parameters for the concentrated liquid-fuel pool fires of interest here.

The model is sensitive to the stability of the atmosphere and the logic changes between stable and unstable atmospheres.

In stable temperatures for instance the stabilization height is given as

$$H \approx 2.9 \sqrt[3]{F/u.s}$$

Where F is the total heat flux, u is the wind velocity and s is the potential temperature gradient.

The size of the cloud is determined by the entrainment of air and in most cases the diameter grows linearly with height so that

$$D = 0.6 \, H$$

DISSEMINATION MODELLING

The most appropriate dissemination models for a risk assessment are the Gaussian Dissemination Models.

In these models the material is given the Gaussian bell-shaped distribution shown in Figure 3. As the cloud drifts downwind it grows in diameter depending on the instability of the atmosphere. The growth angles have been determined empirically from many observations of smoke plumes.

As the cloud grows and drifts downwind it will begin to intercept both the ground and the inversion as shown in Figure 4. Inasmuch as the growth is dependent on the turbulence in the layer between the ground and the inversion, the models are refined not to allow the cloud to grow through the inversion, but to reflect back the pollutant into the layer between ground and inversion. At the same time particles will deposit on the ground at a rate dependent on particle concentration and their fall velocity. Empirical data show that reflection of 70% of the particles from the ground provides exposure patterns consistent with the fall velocity of the particles.

Figure 5 shows two typical exposure patterns. The lines of constant exposure are termed "isopleths". In the stable atmosphere the spread of the cloud is narrow, but high exposure levels may persist for up to 100 km. In the unstable atmosphere the spread of the cloud is wide, but does not persist for the same distances.

The deposition rate anywhere in the affected area is dependant on the concentration and the fall velocity

$$\dot{D} = C \times V_s$$

The total deposition at one point is

$$D = V_s \int C \, dt = V_s \times E$$

and the total deposition over the entire area is

$$\int D \, dA = V_s \int E \, dA$$

or

$$N = V_s \int E \, dA$$

where N is the total number of particles in the pollutant cloud. This equation indicates that the fire and meteorological conditions only affect the distribution of the exposures, the total area coverage however is determined by the amount of material in the source.

If the material could be uniformly distributed at exposure levels E over an area A , then we have the simple relation

$$N = V_s E A$$

Figure 6 is a parametric plot of the area covered to an exposure E as a function of the mass of single fibers in the source. As an example, the worst case analyzed in the risk assessment represented a source of 375 kg of single fibers. The plot shows that this amount of fibers could cover a whole city to an exposure of 5×10^5, or five city blocks to an exposure of 10^8. The damage potential from such a release will be discussed in the next presentation.

RESUSPENSION OF CARBON FIBERS

Carbon fibers deposited on a surface may be resuspended by a disturbance such as wind or traffic. This phenomenon was investigated to determine if resuspension could represent a significant contribution to the carbon fiber risk.

Figure 7 shows the logic diagram for the type of surface on which fibers are first deposited. Fibers deposited on water will sink and cannot be resuspended. Fibers deposited in vegetated surfaces will fall so deep that the winds required to resuspend the particles cannot reach the particles. But fibers deposited on flat hard surfaces could be resuspended. One test series was conducted to monitor the resuspension of fibers from a desert surface. From an original source of 23 kg scattered over an area of 60 X 80 m The daily downwind fiber flux is plotted in Figure 8. The data was collected for three years. The vertical and horizontal distributions were not defined, but on the assumption that the flux was uniform over a downwind area of 1000 m^2, we can calculate a total flux of 0.1 kg of 4 mm fibers or less than 0.4% of the available total source. At the same time the average length of the captured fibers changed from an initial mean length of 7 mm to a final mean length of 1 mm, while the source material left on the ground clearly retains the initial lengths of 7 mm. The fragmentation indicates that the fibers released are broken from the clumps of source fibers, most probably by the saltation of sand particles.

Because the fraction of fibers resuspended is small, because only special areas are suitable for resuspension, and because fibers appear to be fragmented in the process of resuspension, the phenomenon of resuspension was not considered further in the risk assessment.

TRANSFER FUNCTIONS

The transfer function of a building or instrument enclosure is the ratio of internal fiber exposure to external fiber exposure.

Filtration, airflow, and settlement velocity are the parameters controlling the transfer function.

Filter tests have been carried out at the Ballistics Research Laboratories to define the filter transmission factors as a function of fiber length for many

common filter media. Figure 9 shows the results of such tests on a typical window-screen and a furnace filter. Both filters are more effective against long fibers than against short fibers. As a result the mean fiber length as well as the number of fibers are reduced by the filter.

Figure 9 shows an initial exponential fiber length distribution, and the distribution after filtration. The mean fiber length has changed from $l^* = 2$ mm to $l^* = 0.9$ mm, and the transfer function for fibers longer than 1 mm is 0.13.

Such analytical refinements have not been introduced into the risk assessment. Instead, the contractors have used the filter factors appropriate for the 2 mm mean spectrum length and have assumed that the transmitted spectrum remains exponential.

The Bionetics Corporation has tested filtration equipment from commercial aircraft. Both water separaters and air cleaners have very low transmission factors, but also cause severe fiber fragmentation. In a separate test the fragmentation of fibers was evaluated by passing 3 mm fibers through a curved duct. Figure 10 shows a schematic of the test apparatus together with the test results. At low flow speeds most fibers travel through the curved tube intact, but at fiber speeds of 11 m/s and higher virtually all fibers were fragmented into lengths less than 1 mm.

Aircraft ventilation air drawn from the compressor stages of the turbines typically would undergo many turns and much higher speeds. We have therefore assumed that fibers longer than 1 mm would be fragmented into lengths smaller than 1 mm in aircraft engines.

Models for the analysis of transfer functions have been available from previous studies. The transfer function for an enclosure can be shown to be the ratio of fiber inflow rate to the fiber loss rate.

The inflow rate is given by the airflow rate times filter transmission factor. The fiber loss rate is made up of outflow losses, losses in the recirculation filter, and losses due to fiber deposition.

Figure 11 shows the transfer function calculations for a 200 m^2 residence with open windows protected by wire screens. The calculations show that even with open windows transfer functions as low as 0.01 are to be expected.

CONCLUSIONS

The elements of the fiber transport chain have been studied. The mathematical models had been established for other pollution problems and were found to be appropriate for the carbon fiber problem.

A particular study was made to establish the possibility of resuspension. The data showed that resuspension cannot be a major contributing factor to the risk.

Filtration and fragmentation tests were run to provide the necessary data base for transfer function calculations. The data showed that filters are much

more effective than assumed in the preliminary study and that in high velocity air handling systems significant fiber fragmentation will change the fiber spectrum to shorter mean lengths.
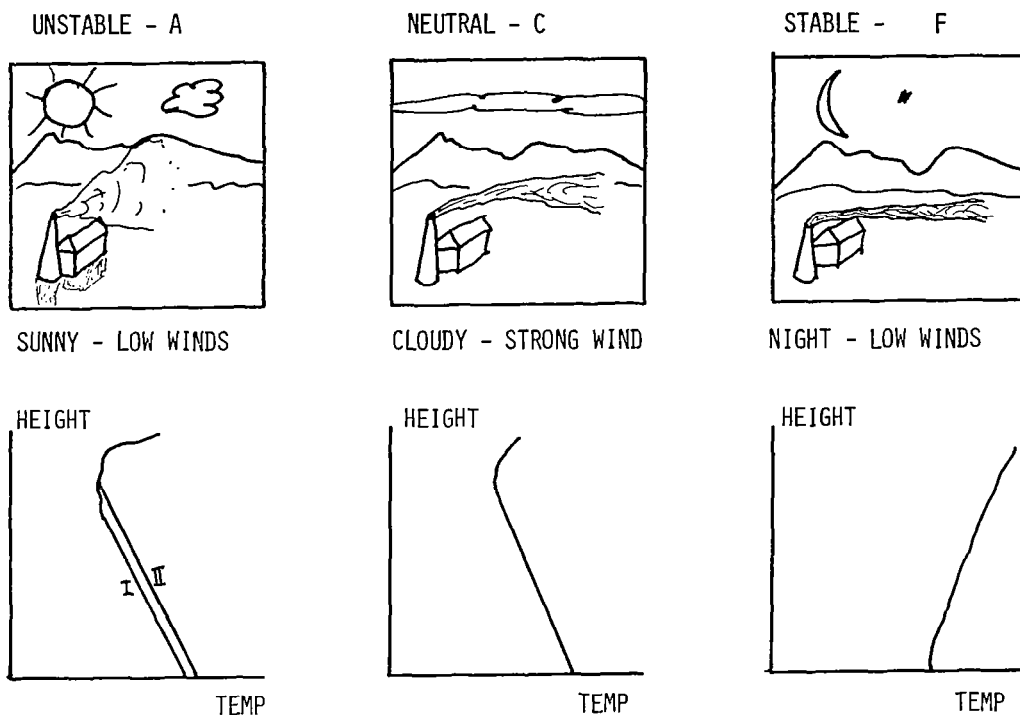
UNSTABLE - A

NEUTRAL - C

STABLE -   F

SUNNY - LOW WINDS

CLOUDY - STRONG WIND

NIGHT - LOW WINDS

HEIGHT

HEIGHT

HEIGHT

TEMP

TEMP

TEMP

Figure 1.- Dissemination meteorology with Pasquill-Gifford stability classes A, C, and F.

D

H_p (FROM BRIGGS EQUATIONS)

40°

Figure 2.- Characteristic smoke plume development.

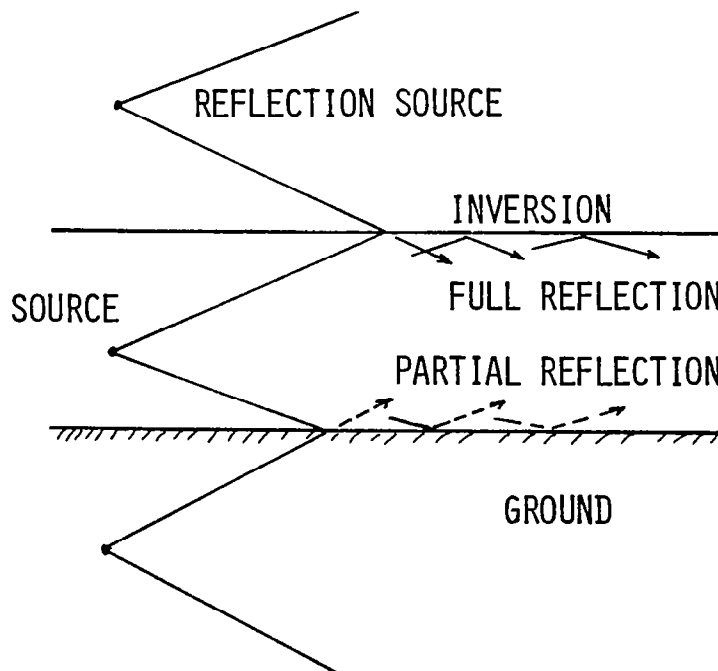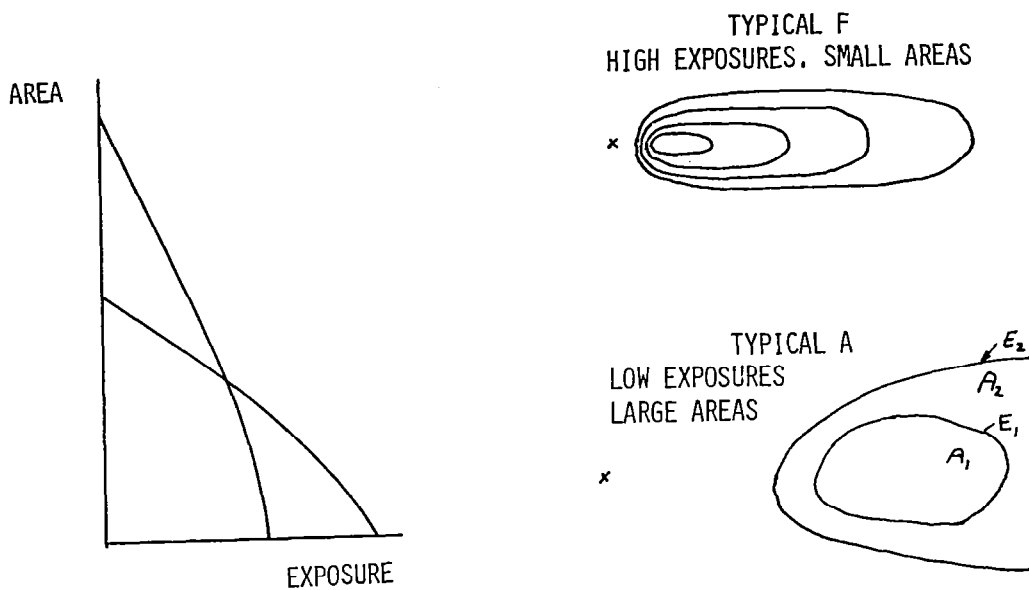Figure 3.- Gaussian distribution of pollutant
in a drifting cloud.

Figure 4.- Pollutant cloud growth with reflection from
inversion and ground.

TOTAL DEPOSITION EQUATION: $\sum E_i A_i = N/v_s$

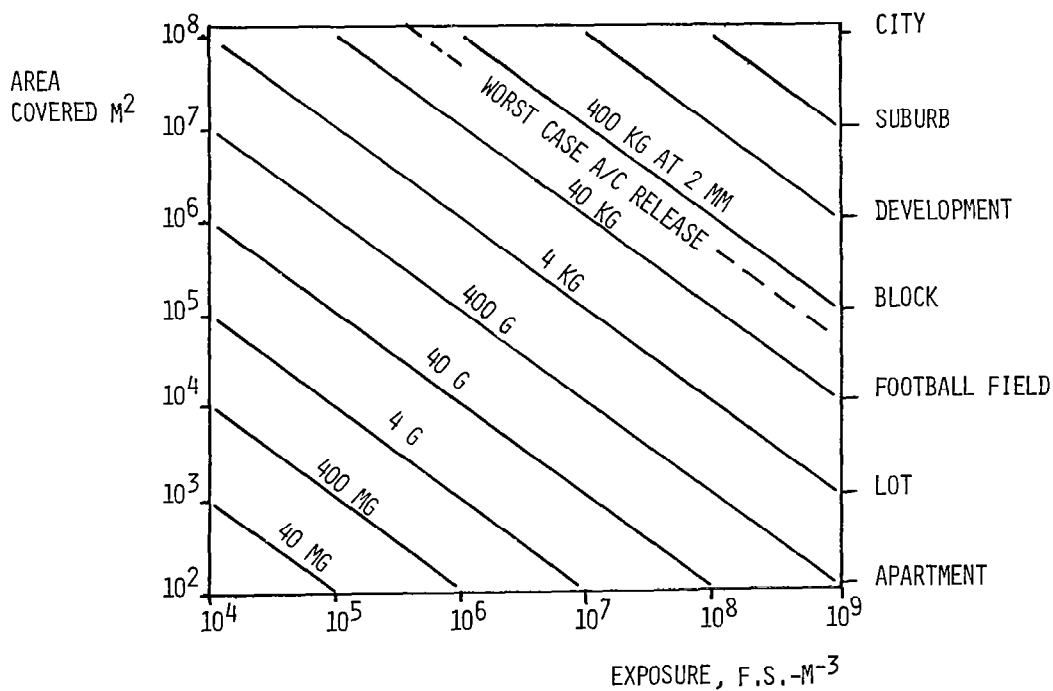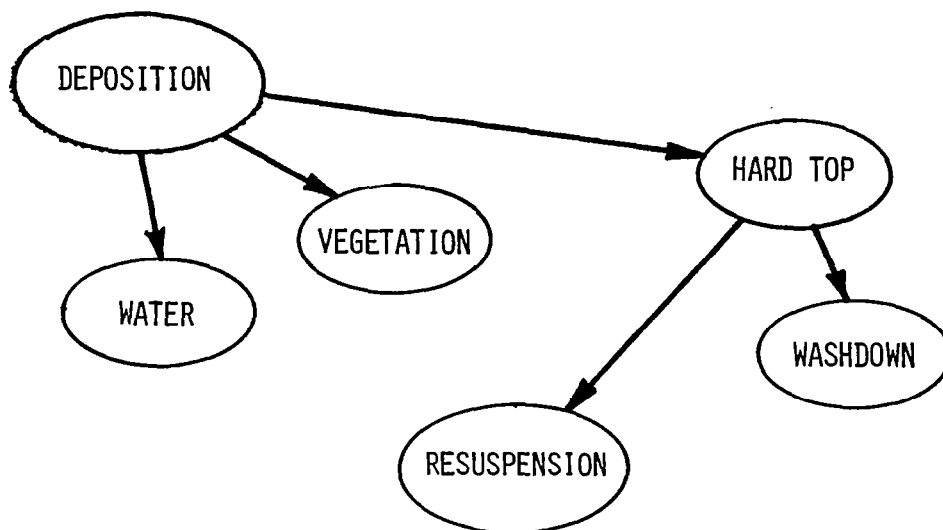Figure 5.- Typical exposure patterns and area coverage definition.

Figure 6.- Parametric plot of carbon fiber area coverage limit.

● RESUSPENSION POSSIBLE FROM FEW AREAS.
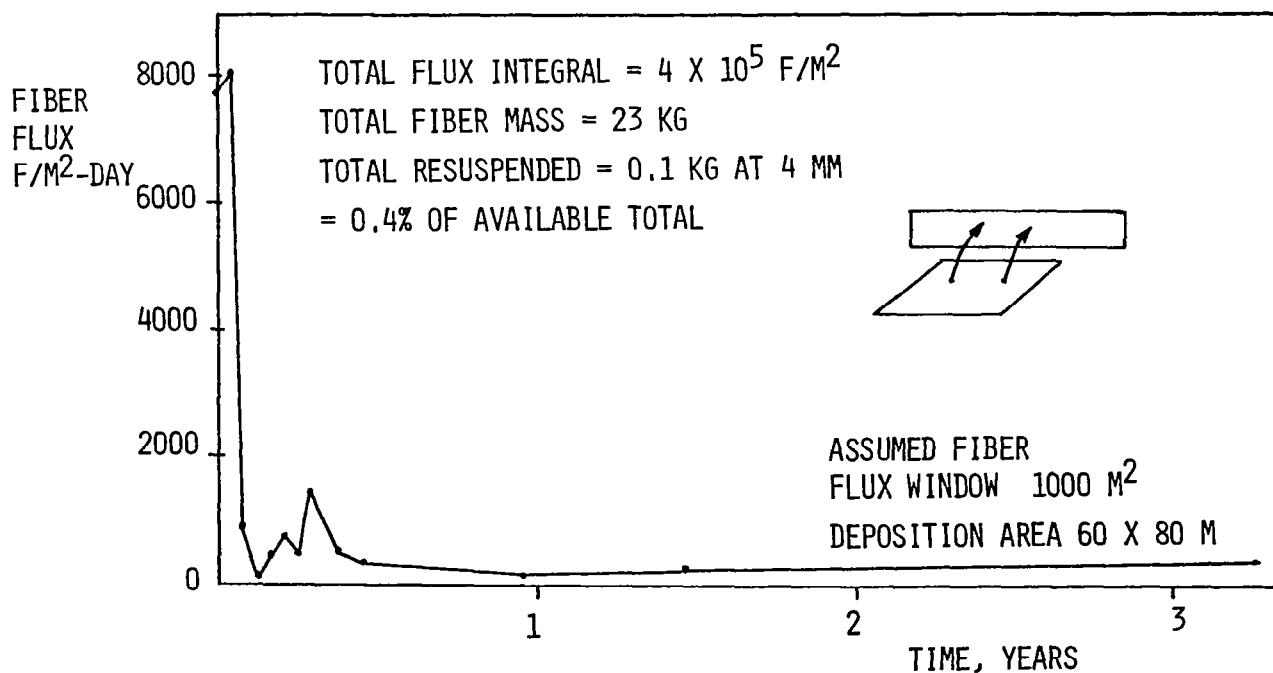
Figure 7.- Resuspension logic chart.

TOTAL FLUX INTEGRAL = 4×10^5 F/M^2
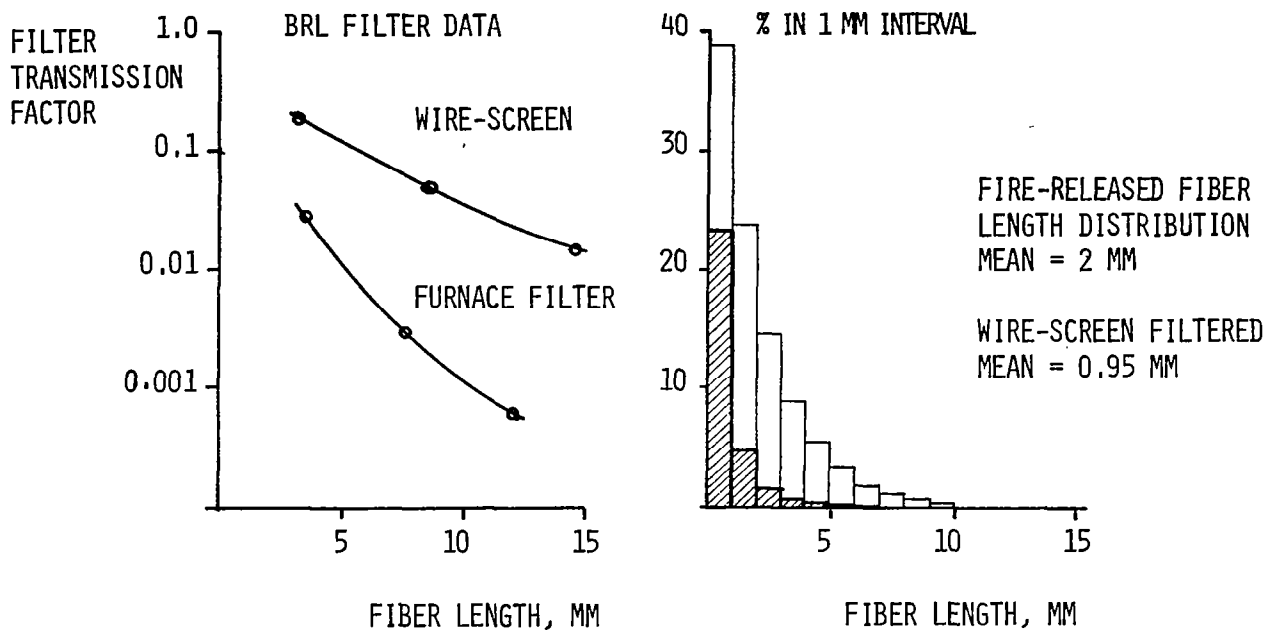
TOTAL FIBER MASS = 23 KG

TOTAL RESUSPENDED = 0.1 KG AT 4 MM

= 0.4% OF AVAILABLE TOTAL

ASSUMED FIBER
FLUX WINDOW 1000 M^2

DEPOSITION AREA 60 X 80 M

Figure 8.- Resuspension data.

FILTER
TRANSMISSION
FACTOR

1.0

BRL FILTER DATA

WIRE-SCREEN

0.1

0.01

FURNACE FILTER

0.001

5   10   15

FIBER LENGTH, MM

40

% IN 1 MM INTERVAL

30

20

10

FIRE-RELEASED FIBER
LENGTH DISTRIBUTION
MEAN = 2 MM

WIRE-SCREEN FILTERED
MEAN = 0.95 MM

5   10   15

FIBER LENGTH, MM

Figure 9.- Filter data.

FIBER
SOURCE
3 MM

12 MM TUBE

FIBER
SAMPLING
SCREEN

RANGE OF
PREDICTIONS

1.0

FRACTION
<1 MM

0.5

A/C COMPRESSOR
CONDITIONS

0

0   200   400

FIBER IMPACT SPEED (FPS)
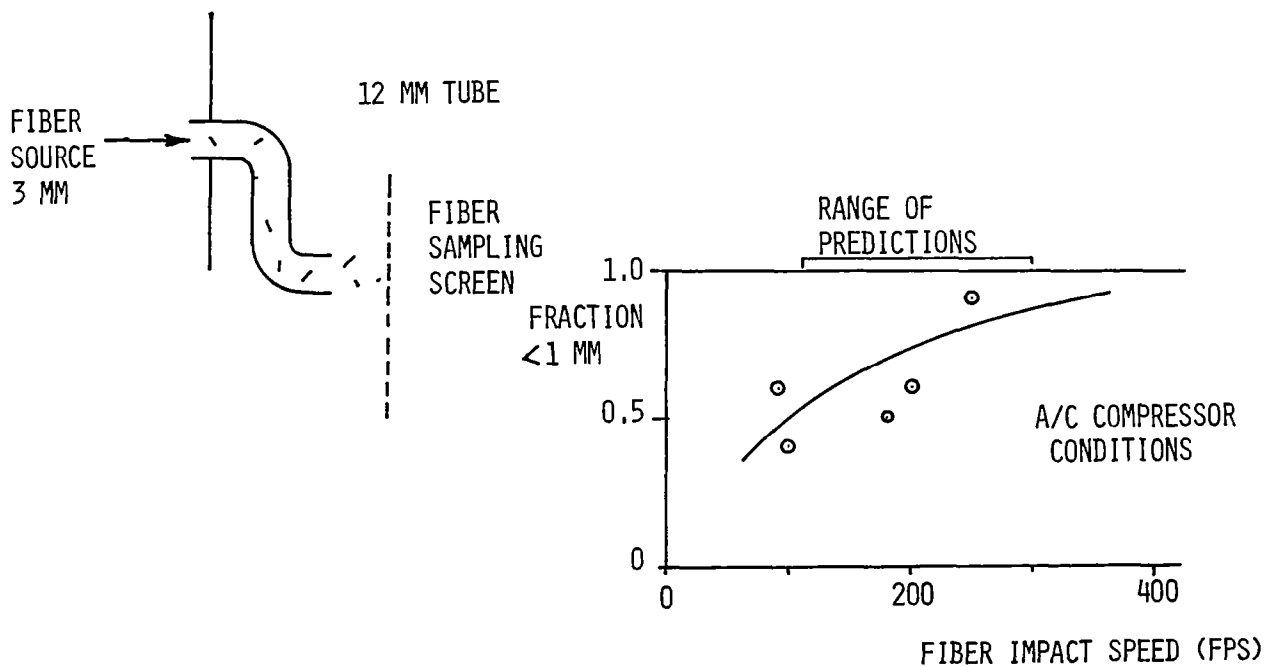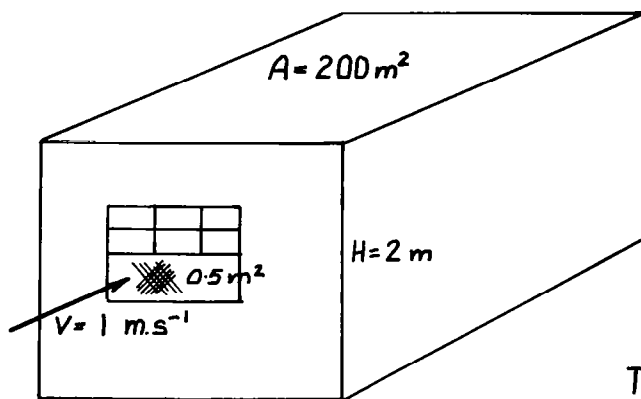
Figure 10.- Fragmentation data.

$$T.F. = \frac{\text{FILTER FACTOR} \times \dfrac{Q_i}{V}}{\left(\dfrac{Q_i}{V} + \dfrac{Q_R(1-\mu_F)}{V} + \dfrac{V_s}{H}\right)}$$

$A = 200\,m^2$

$H = 2\,m$

$0.5\,m^2$

$V = 1\,m.s^{-1}$

$$T.F. = \frac{0.2 \times 1.2 \times 10^{-3}}{(1.2 \times 10^{-3} + 7.5 \times 10^{-4} + 1.25 \times 10^{-2})}$$

$$= 0.01$$

$0.5\,m^3s^{-1} = 1000\,cfm$

$\equiv$ ONE WINDOW FAN

Figure 11.- Transfer of carbon fibers into buildings.