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Sheltering Effects of Buildings from Biological Weapons

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Methods for modeling indoor air pollution are used to determine the degree of protection offered by buildings against airborne biological agents. The factors that determine the sheltering effectiveness of a particular building (air exchange rates, particle deposition rates, environmental decay of agents, and filter efficiencies) are considered. Representative values for each of these parameters are determined from available information. The protection offered by an average U.S. home is computed, and the effects of modest civil defense measures are quantified.

INTRODUCTION

In the past few years, terrorist attacks have become more daring and have produced greater numbers of casualties than ever before.[1] Many attribute this change to the emergence of a new kind of terrorist, one who believes strongly in extreme violence and who is subject to very different rational constraints than the political terrorists of the past. The 1989 bombing at the World Trade Center in New York and the 1995 sarin attack in Tokyo are often cited as examples of this new brand of terrorism.[2] In these attacks, the main goals were simply to inflict as many casualties as possible upon civilian targets. Fortunately, the attacks did not achieve the widespread damage planned by their perpetrators. However, a precedent may have been established for enormously destructive terrorist attacks, and the threat of a terrorist use of a weapon of mass destruction is now larger than ever.

Biological weapons (BW), in particular, have been singled out as weapons that could be extremely destructive and could potentially be acquired by a terrorist. The Office of Technology Assessment reports that under certain conditions, biological weapons have a destructive potential rivaled only by nuclear weapons.[3]

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Unlike nuclear weapons, though, the technologies involved in making biological weapons are not particularly difficult to acquire.

Several recent developments may have further eroded some of the constraints that previously existed for obtaining BW. First, the end of the Cold War loosened controls on biological weapons facilities and personnel in the former Soviet Union, providing a source of BW technology that may be relatively accessible. Second, the rapid growth of the biotechnology industry worldwide has hastened the diffusion of technologies that can be adapted for BW development and production.[4] The recent findings in Iraq have highlighted the ease with which states can acquire and develop biological agents. Because biological weapons are so destructive, and because proliferation constraints are eroding, there is a growing concern that they will be used against domestic U.S. targets.

This paper focuses on the question of how much protection a building provides its inhabitants from a BW attack. The reason for considering this problem is simple: most people spend the majority of their daily lives inside buildings. In fact, the U.S. EPA estimates that average Americans spend approximately 87% of their time indoors.[5] However, most previous technical assessments of BW incidents ignore the effects of buildings, computing casualties based only on integrated outdoor surface dosage. The protective effects of buildings have been considered for other toxic releases. Karlsson, for example, looks at the effects of indoor deposition upon toxic gas clouds,[6] and Engelmann[7] and others examine the sheltering effectiveness of buildings against respirable plutonium releases. In this paper we seek to extend these basic ideas to biological agents and to explore aspects of the problem that are unique to biological weapons.

The rest of this paper is organized as follows: A brief discussion of general aspects of biological weapons is first presented. Then, we introduce the method used to model the penetration of buildings by biological agents and discuss the factors that determine the sheltering effectiveness of a particular building. The paper concludes with a discussion of simple measures that individuals can enact to increase the sheltering effectiveness of a particular building.

Nature of Biological Weapons

Biological agents are defined as live organisms, or toxins that are derived from live organisms, that are disseminated with the intention of causing disease in the target population. A variety of agents and toxins have been considered for use as biological weapons, but in the interests of brevity, only two fairly typical agents are considered as examples in this paper. The first agent, anthrax, is used in most BW analyses and is often described as the ideal biological agent. It forms hardy spores that can survive in a variety of environments, and when an infective dose of 8,000 to 100,000 spores[8] is inhaled, it can develop into a virulent disease which is 90% fatal if left untreated.[9] To provide some evidence of the range of effects that arise solely from the choice of agent, we also consider Venezuelan equine encephalomyelitis virus (VEE virus). VEE virus is considerably more sensitive to the environment than anthrax spores, but its infective dose is only estimated to be 10-100 virions.[10] Also, in contrast to anthrax, naturally contracted VEE is rarely fatal, so it can be viewed as only an incapacitating agent.

To be effective a biological agent must somehow be disseminated among the target population. In this paper, we focus on airborne dispersal, which is often cited as the dissemination method with the greatest potential for enormous numbers of casualties. To disperse BW through the air, one must first generate a cloud of very fine particles, which is then blown downwind and inhaled by the target population. However, the technical aspects of generating such a cloud are not trivial. First, the generated particles must be formed at a very specific size for inhalation and deposition within human lungs. Particles that are larger than $5\mu m$ tend to deposit in the upper tracts of the respiratory system, where they have a reduced probability of causing an infection. Particles smaller than $1\mu m$ are largely exhaled rather than remaining in the lungs.[11] (A μm is 10^{-6} meters.) Thus, the optimum size for particle is generally thought to be $1-5\mu m$, although this range can depend upon the specific organism. Second, because biological agents are living organisms, they must be dispersed gently enough to maintain viability. In this regard, anthrax spores are particularly well suited, as they are highly resistant to mechanical stresses and to changes in temperature and humidity.[12] Other agents are more delicate, and much greater care must be exercised when they are dispersed. The combination of these two factors provides a significant technical challenge to any biological weapons designer.

Once in the air, the behavior of particles depends heavily upon their density and size. Anthrax has a density approximately half that of water, and the densities of other bacterial and viral agents are of the same order of magnitude. At this density, $1-5\mu m$ particles are transported readily by atmospheric motions and follow all but the smallest fluid motions. Gravitational forces will act to settle them out of the air, but this process occurs quite slowly. (A $1\mu m$ particle requires approximately five months to settle 500m.)[13] Other natural processes remove the particles from the air much more efficiently. Raindrops, for example, collect particles as they fall to the ground and clean

Figure 1: Model schematic.

the air quite effectively. In the absence of precipitation, the main natural mechanism by which these particles are removed from the air occurs as the air motions bring the particles in contact with solid surfaces. When this occurs, the particles tend to adhere to the surface.[14]

Indoor Air Quality Model

To facilitate an understanding of how the indoor concentration of particles evolves in response to outdoor sources, we consider a simple model of airflow into and out of a building. Models of this type have been used for many years to examine indoor air pollution problems, and their effectiveness has been well documented. The particular variant we use draws heavily from work presented by Shair & Heitner.[15] We begin here by presenting an overview of the model and by discussing the associated governing equation. In subsequent sections, we discuss the individual components of the model in more detail.

As shown in Figure 1, several paths of airflow are included in the model. A generalized heating, ventilation and air conditioning system (HVAC) both recirculates interior air and draws in exterior air, while leakage into (infiltration) and leakage out of (exfiltration) the building are also represented. We discuss the various entry and exit pathways for air in detail in a later section, but for now, based on this model, we can write an expression for the concentration of particles inside the building as follows:

$$V\frac{dc_i}{dt} = q_0 c_0 + q_3 c_0(1-F) + q_2 c_i(1-F) - q_2 c_i - m c_i \qquad (1)$$

Here, V represents the total volume of the building. The variables c_o and c_i represent the outdoor and indoor concentrations, respectively, while t represents time. F represents the filter efficiency, while the volume flow rates along the various pathways are denoted by q_j $(j=0,1,2,3)$. Indoor loss processes are parameterized by the term mc_i.

The model idealizes the indoor air environment in several different respects. First, it represents the entire volume of the building as a single compartment. This simplification is appropriate primarily for single family, detached buildings, where the number of interior partitions is relatively small. Larger, multistory office and apartment buildings are better represented by multi-compartment models, as airflows can vary substantially between floors and between different rooms on the same floor.[16]

The spatial distribution of particles within the building is also idealized, as we have followed previous workers and assumed that the particle concentrations within the building are well mixed. The spatial distribution of particles inside the building is therefore always uniform. Of course, this assumption only approximates the actual distribution of particles, but the errors incurred are not excessive when weighed against the other uncertainties in the model.[17]

A third idealization inherent in the model formulation is that airflow rates are assumed to be constant. In reality, infiltration rates vary with the meteorological conditions outside the building, and the HVAC system is designed to only operate intermittently. Thus, all of the airflows vary with time. This simplification and the other assumptions listed above can affect the accuracy of the results, but for the nature of the analysis performed in this work, and the quality of data available, a simple model is most appropriate.

In formulating the model, we have also assumed that air entering the building through the infiltration pathway does not lose any particles along the way. Some researchers have hypothesized that a fraction of particles carried by infiltrated air is lost as the air passes through cracks in the wall. However, recent measurements by Thatcher & Layton[18] find no significant losses of particles in the $1-5\mu m$ size range that is of interest here.

Equation (1) can be re-expressed as follows:

$$\frac{dc_i}{dt} = (\alpha c_0 - \beta c_i)$$
$$\alpha = k_0 + k_3(1-F)$$
$$\beta = k_2 F + k_1 + m/V \tag{2}$$

In this form, in place of the volume flow rates, q_j, we have introduced air exchange rates, which are defined as $k_j = q_j/V$. Each air exchange rate therefore represents the percentage of the total volume of interior air that moves along each particular pathway. By rearranging in this way, we have reduced the governing equation to a fairly simple form, with two parameters, α and β, which depend upon combinations of air exchange rates, filter efficiency, and deposition rate.

The general solution to Equation (2) can be written as follows:

$$c_i(t) = \alpha e^{-\beta t} \int_0^t e^{\beta\tau} c_0(\tau)\, d\tau \tag{3}$$

For the purposes of evaluating the effects of a biological weapons attack, the quantity of interest is the total integrated exposure. This quantity corresponds to the exposure to the agent received by a person who remains in the building for the duration of the attack and for a relatively long period of time afterwards. We can compute the total exposure by integrating the indoor concentration over all time, as follows:

$$E_i = \int_0^\infty c_i(t)\,dt \tag{4}$$

Then, by combining equations (3) and (4), an expression for the total indoor exposure in terms of the outdoor concentration can be derived:

$$E_i = \int_0^\infty a e^{-\beta t} \int_0^t e^{\beta\tau} c_0(\tau)\,d\tau\,dt \tag{5}$$

Equation (5) can be integrated by parts and yields the following result:

$$E_i = \frac{a}{\beta}\int_0^\infty c_0(t)\,dt \tag{6}$$

Thus, the integrated exposure experienced by building occupants is equal to the integrated outdoor exposure multiplied by the factor α/β. We follow precedent and refer to α/β as the dose reduction factor, R, although technically, it represents only the reduction in exposure to the agent, rather than a reduction in the actual dosage experienced by the inhabitants. Other factors, such as minute volume and retention rate in the lungs, must be considered to convert exposure values to dosages.

We can write the dose reduction factor as follows,

$$R = \frac{\alpha}{\beta} = \frac{k_0 + k_3(1-F)}{k_2 F + k_1 + m/V} \tag{7}$$

The value of the dose reduction factor depends upon the various elements that have been included in the model. We consider each of these elements, air exchange rates, indoor removal processes, and filtration efficiencies, in the next sections.

Air Exchange Rate

The net air exchange rate is simply the rate at which air inside a particular building is replaced by outside air. Outside air enters a building through a variety of pathways that can be grouped into three general categories.[19] The first category, natural infiltration, occurs as air seeps through cracks in the walls, under doors, and through poorly sealed vents. The rate at which this seepage occurs is heavily dependent upon external, environmental factors. For example, higher wind speeds lead to greater infiltration rates into the building. Similarly, a large temperature difference between the building and the outside environment can increase infiltration rates. That is, when indoor air is warmer than outdoor air, it will rise and escape through the top of the building, while cool air is drawn into the bottom of the building. The second source of outside air, forced ventilation, is a factor primarily in tightly sealed commercial buildings where the ventilation systems actively mix outside air into the return flow to improve the air quality. The rates at which this mixing occurs are usually determined automatically by a preprogrammed ventilation system. The final way that outside air enters a building is through human activity, as the inhabitants of the building open and close windows and doors. Because of these many factors, the variability in net air exchange rates between different buildings is enormous.

Experimental measurements of net air exchange rates confirm that large differences do exist between individual buildings. In general, most studies of air exchange rates have been conducted on single family detached buildings, rather than large office buildings. Consequently, statistical analyses for the smaller buildings are much more readily available. Several groups have examined the available data for single family detached buildings and have attempted to develop approximations for predicting exchange rates for a typical U.S. home. For example, researchers at the U.S. EPA fit experimental measurements to an empirical relationship in which the net exchange rate varies with wind speed and temperature difference.[20] Engelmann[21] conducts an extensive survey of previous air exchange measurements and also develops an empirical relationship between wind speed, temperature difference and exchange rate. Other data compilations seek only to provide concise statistics of air exchange rates in U.S. homes. Sherman & Dickerhoff[22] compile a vast amount of air leakage data collected by blower door techniques. Because this method of measuring leakage requires one to pressurize the home above normal levels, converting these measurements to natural air exchange rates is not straightforward. In a different study, Murray & Burmaster[23] compile net air exchange rate data from over 2800 households in the United States. The exchange rates they use were directly measured by tracking the time evolution of inert tracer gases that were injected into each home. They find that the average exchange rate is 0.76 hr^{-1} for all U.S. residences averaged over all seasons. That is, in a typical home, 76% of indoor air will be exchanged for outdoor air every hour. The exchange rates used in this study vary substantially according to the region of U.S. and with changes in season, so the variability of the entire data set is quite high.

Air exchange rates for larger buildings can vary even more than single family detached buildings, because of the wide variety of HVAC systems one finds in these buildings. As such, to the author's knowledge no statistics are available for air exchange rates in these buildings.

In our model we have combined human activities with natural infiltration as a single entry pathway (k_0), and retained a second entry pathway through the HVAC system (k_3). This distinction provides a simple means to examine differences between small residential and large commercial buildings. Exfiltration (k_1) is the only exit pathway that is represented.

To isolate the effects of air exchange rate upon the indoor concentration, we simplify the model to its most basic form by neglecting indoor loss processes (setting $m = 0$) and assuming no forced ventilation (setting $k_2 = k_3 = 0$). By conservation of mass, the remaining two air exchange rates (k_0 and k_1) must be the same, and the coefficients in equation (2) can be written as $\alpha = \beta = k$. We further idealize the situation by assuming that the outdoor concentration is constant for a finite amount of time, and then changes instantaneously to zero. This simple model simulates the passage of a single cloud of toxins or biological agents, but ignores the concentration fluctuations inside the cloud itself. For an outdoor concentration evolution of this form, Equation 2 can be solved quite easily. The results are plotted in Figure 2 for two sample air exchange rates.

The evolution of the indoor concentration levels follows a relatively simple pattern. While the cloud is present, the indoor concentration rises and approaches the outdoor value asymptotically. As soon as the cloud passes, the indoor concentration begins an exponential decay back to zero. The time constant for both of these processes is the air exchange rate, k. From the plot, it is evident that the maximum concentration attained inside is dependent on the magnitude of the air exchange rate relative to the extent of the toxic cloud. For cases in which the cloud is small and air exchange rate slow, the concentration inside the building will not have sufficient time to increase to a maximum magnitude comparable to outdoor levels. However, if we consider total integrated dose (Equation 6), we see that the dosage experienced inside a building is identical to that experienced outside ($\alpha = \beta$ and $R = 1$). Intuitively, this result seems reasonable. A slow air exchange rate would keep maximum concentrations inside the building low, but after the toxic cloud passes outside, the slow exchange rate hinders the prompt replacement of the

Figure 2: Time evolution of indoor concentration levels.

contaminated air inside the building with clean outside air.

Now, the utility of a sensor for biological agents becomes clear. If the inhabitants of a building know precisely when the cloud has passed, they can evacuate the building at the appropriate moment and greatly reduce their total dosage. In such cases, the total dosage would depend strongly upon the air exchange rate, as a low air exchange rate could greatly reduce the maximum concentrations observed inside the building. Many calculations for the sheltering effectiveness of buildings against nuclear accidents are based upon this premise, as planners assume that they will know the location of the radioactive cloud.[24] In the case of biological weapons, building inhabitants will not generally know the location of the cloud. In fact, in many scenarios, the BW attack occurs without notification, and identification of the attack only occurs later as people begin to contract the disease. Therefore, in this paper we assume that building inhabitants will remain indoors throughout the attack and for a substantial period afterwards, and use Equation (6) to compute total dose.

Indoor Removal Processes

We now consider the effects of processes inside the building that reduce particle concentrations. Two possibilities are relevant in this study: deposition and decay. Each contributes to the term mc_i in Equation (1), and in the following section we discuss appropriate values for the coefficient m.

Deposition occurs as particles that are carried by the local field collide with solid surfaces. Once they come into contact with a surface, the particles tend to stick quite firmly. The physical processes by which this adhesion occurs are not well understood, but it is generally thought that a combination of Van der Waals, electrostatic, and surface tension forces is responsible for keeping the particles attached to the surface.[25] Because particles do stick firmly to virtually any surface, in most cases the limiting factor in the deposition process is the rate at which particles are transported from the air to the solid surface.

The transport process is highly complex and depends upon the particle size and the nature of the local flow field. To develop an expression that can be used in practical situations, most researchers assume that the deposition rate is proportional to the local particle concentration and the total surface area available. The proportionality constant in this expression is then a deposition velocity, v_d, so we can represent deposition as follows:

$$m = \nu_d A \tag{8}$$

In this expression, A represents the total surface area within the building. Of course, v_d also depends upon the orientation of the surface in question. For example, for upward facing surfaces v_d must include the effects of gravitational settling in addition to deposition by the flow field. To simplify the representation, most models consider an average deposition velocity for all surfaces, but specify different values for different particle size ranges.

The deposition velocity for particles has proven to be extremely difficult to quantify theoretically or experimentally. The most recent theoretical approach relies upon several simplifying assumptions and computes deposition velocity for three different ideal cases of air flow in a room: a homogeneously turbulent flow, a forced laminar flow, and a buoyancy driven flow.[26] These theoretical arguments provide a basis for predicting qualitative trends for the deposition velocities of particles of different sizes and in different flow conditions. In comparisons with experimental measurements, reasonable agreement is achieved, but this agreement depends upon adjusting the numerical parameters that characterize the airflow in the room. Accurately specifying these parameters a priori is difficult, which limits the applicability of the theory.

Directly measuring deposition velocity is also difficult. The results from several recent investigations are summarized in Table 1 for $1\mu m$ particles. As can be readily observed from the listed data, the values of measured deposition velocity are surprisingly comparable between different experiments. The deviations that do exist can be attributed to differences in the experimental configurations. Deposition velocities from Xu et al., for example, are substantially lower than the other experiments. This difference can probably be explained by two factors. First, Xu et al. used environmental tobacco smoke for their particle source, and the majority of these particles fall below $1\mu m$ in diameter. The data listed above represents only the largest particles in their study. Second, and probably more importantly, the Xu study was performed in a model room constructed of plywood and left unfurnished. Thus, the surfaces in their room were less rough than those one would expect in an ordinary, furnished room.

Table 1: Experimental particle deposition velocities

	Location	Vd (cm/s)
Fogh et al.[27]	Furnished house	0.011
Thatcher and Layton[28]	Furnished house	0.017
Xu et al.[29]	Model room	0.001 - 0.004
Offerman et al.[30]	Furnished house	0.01
Okuyama et al.[31]	Laboratory vessel	0.01 - 0.05

The same caveats used in interpreting the Xu et al. measurements also apply to assessing the reliability of the other studies. The types of particles used are quite different for each study. Offerman examined environmental tobacco smoke, Thatcher & Layton used ambient dust, and Fogh et al. and Okuyama et al. used silica and polystyrene particles. Differences also exist in the configurations of the experimental chambers. The Okuyama et al. study was performed in a small, smooth, laboratory vessel that was stirred with a propeller, while the remaining studies were conducted in furnished rooms with air movements generated only by the inhabitants and the existing HVAC system. Because of the many differences between the experiments, one should not attach excessive significance to the apparent agreement in deposition velocities, and understand that a considerable amount of uncertainty exists with these numbers. Nonetheless, based on this survey of deposition velocities, we use a deposition velocity of 0.01 cm/s for $1\mu m$ particles. This value is also comparable to that used by Weschler & Shields [32] in their model.

The values presented in Table 1 all correspond to particles that are $1\mu m$ in diameter. Unfortunately, deposition rate data for larger particles are not as plentiful. Nazaroff & Cass[33] present a complete analysis of the particle deposition mechanisms, and in general, find that deposition rates increase for particles larger than $1\mu m$, as gravitational settling increases in importance for larger particle sizes. The measurements of Fogh et al. and of Thatcher & Layton support this hypothesis. Based on these theories and limited experimental data, we use a value of 0.05 cm/s for $5\mu m$ particles.

To explore the effects of deposition velocity, we return again to the model equation (2). We continue to neglect the effects of HVAC, but now can include the effects of indoor removal processes as follows,

$$\beta = k_1 + m/V \tag{9}$$

The dose reduction factor now becomes less than one:

$$R = \frac{k_0}{k_1 + \nu_d A/V} \tag{10}$$

It is now possible to examine the sheltering effects of a building, taking into account the deposition of agents on the indoor surfaces. In Figure 3 the dose reduction factor, R, is plotted as a function of air exchange rate for $1\mu m$ and $5\mu m$ particles, using the deposition velocities noted above. A typical value

Figure 3: Dose reduction factor as a function of air exchange rate.

of 2.0 m^{-1} is used for the ratio of surface area to volume.[34]

Before, when deposition was neglected, the dose reduction factor was fixed at one, regardless of the choice of air exchange rate. Now, with deposition, we find that the dose reduction factor decreases with reductions in air exchange rate. This trend makes physical sense: Since the rate of deposition does not vary, the slower air exchange rates provide additional time for deposition processes to remove particles from the air. As noted earlier, the average air exchange rate for all U.S. homes is 0.76 hr^{-1}; and thus, with the assumed deposition velocity these homes provide a protection factor of approximately 0.51

against $1\mu m$ particles. That is, people who remain indoors for the duration of the attack only receive 51% of the dose of those who are outdoors. An air exchange rate for a more tightly sealed, energy efficient home is probably closer to 0.2, which drops the dose reduction factor to about 0.19. Because $5\mu m$ particles deposit more quickly than $1\mu m$ particles, the protection effects of the building are more pronounced. At an air exchange rate of 0.76 hr^{-1}, the indoor dose of $5\mu m$ particles is only 17% of that observed outside. Clearly, when one includes the effects of deposition, reductions in air exchange rate have a positive effect on the sheltering properties of buildings.

The second indoor removal process we consider is biological decay. Live organisms have a finite lifetime when dispersed as an aerosol in the environment. Ultraviolet light, excessive moisture, and extreme temperatures all combine to kill biological agents before they can be inhaled. While the spores formed by anthrax are hardier than unprotected bacteria or viruses, they can still decay at a rate of 2% per minute under bright sunlight.[35] Consequently, most models of biological weapon dispersion include an exponential decay term to represent the loss of viable organisms due to environmental factors. In the case of biological agents that have penetrated into the indoor environment, significant levels of ultraviolet radiation no longer are present, and the decay of anthrax spores is negligible. Other agents would still decay, though. VEE, for example, decays at a rate of 2% per minute indoors when the humidity is high, and at a rate of 0.5% per minute at lower humidities.[36] To model the effects of biological decay in the indoor environment, we add another term to our expression for the coefficient m, using the parameter k_e to represent the rate of biological decay:

$$m = \nu_d A + k_e V \tag{11}$$

As before, a dose reduction factor can then be computed, taking into account both deposition and biological decay.

$$R = \frac{k_0}{k_1 + \nu_d A / V + k_e} \tag{12}$$

In figure 4, we compare the predicted dose reduction factors for anthrax and for VEE, for 1mm particles. The decay rate used for VEE is 2% per minute; however, this relatively slow environmental decay rate still produces a substantial reduction in indoor exposure when coupled into the air exchange problem. Recall, however, that the infective dose of VEE is approximately two

Figure 4: Effects of environmental decay.

orders of magnitude less that anthrax. So, low exposures may still lead to a significant infection rate.

Filtering

Most buildings in the U.S. use some form of forced ventilation system that recirculates interior air after heating or cooling. In the more complex HVAC systems found in larger buildings, a certain fraction of outdoor air is also mixed into the return flow. In all of these systems, air is passed through filters before returning to the building interior, a process that can reduce the indoor particle concentrations.

HVAC filters used in the U.S. are rated with efficiencies that have been defined by ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers). One filter rating system currently in use measures the opacity of a dust spot formed in the air downstream of a particular filter relative to one formed upstream, providing a "dust spot efficiency."[37] Unfortunately, the dust spot efficiency and other ASHRAE filter standards only provide information for the total mass of particulate material collected by the filter and do not provide any information for the effectiveness of the filter for different particle sizes. An effort is currently underway to revise the rating system and to provide particle-size dependent efficiencies, and we use some of these preliminary studies to provide some data for estimating filter efficiencies for the particle sizes of interest in BW.[38]

The type of filters most commonly found in residential HVAC systems are low efficiency filters, rated with dust spot efficiencies of 25%. These filters are designed to remove very large particles with diameters greater than $50\mu m$, so the $1-5\mu m$ particles characteristic of BW would pass through unimpeded. Because commercial buildings are more tightly sealed than residential buildings, they generally need more efficient particle filters in their HVAC systems to maintain acceptable indoor air quality. A typical, modern office building will pass all recirculated and outdoor air through a bank of medium efficiency filters (60% to 65% dust spot efficiency). These filters remove approximately 55% of $1\mu m$ particles, approximately 88% of $2\mu m$ particles, and continue to increase in efficiency for still larger particles.[39]

Special HEPA (high efficiency particle air) filters, which are specifically designed to remove small particles, are available for use in hospitals and portable air filters, and can remove nearly 100% of $1-5\mu m$ particles. However, these high filter efficiencies also produce a substantial resistance to the flow of air, so they require ventilation systems that are specifically designed to overcome this resistance.

A new type of filter, known as an electret filter, has recently been commercially introduced in which the fiber strands are formed from an electrically non-conductive material, allowing the filter to hold a static electrical charge. This static charge has the added effect of attracting small particles, so the electret filter removes a substantial fraction of fine particulates while using a fairly coarse fiber spacing that maintains high airflow rates. Research versions of this filter have removed as much as 95% of $1\mu m$ particles,[40] while commercial filters that are currently available claim to remove approximately 60% of $1\mu m$ particles. The efficiency of this commercial filter improves at larger particle sizes, reaching 92% for $3\mu m$ particles, and 97% for $5\mu m$ particles.[41]

To examine the effects of filtration on building protection, we first assume that the HVAC system only recirculates interior air and that outside air is introduced only by infiltration. That is, no additional air is forcibly drawn into the ventilation system $k_3 = 0$, as is the case for most single family residential buildings.

If recirculation through a filter is taken into account, the dose reduction factor, R, becomes,

$$R = \frac{K_0}{k_2 F + k_1 + \nu_d A / V} \tag{13}$$

For now, we neglect environmental decay. As shown in Figure 1, the exchange rate, k_2, represents the rate at which interior air is recirculated through the filters. The filter efficiency is denoted by F, such that a perfectly efficient filter, which removes all of the contaminants in the air, would have $F = 1.0$. The additional factor that has now appeared in the denominator, k_2F, reflects the effects of filtering. High values of F would have an obvious effect upon the total inhaled dose, as more efficient filters would remove more contaminants from the air. The presence of the factor k_2 demonstrates the importance of recirculation. That is, the faster one recirculates the air in the building through the filters, the more effect the filters have upon the final integrated dose.

As discussed before, most existing filters in residential HVAC systems do not remove the small particles one observes in biological weapons. Consequently, $F = 0$, and filtration has no effect. However, if one were to replace the standard air filters with an electret filter, the HVAC system becomes an effective means of removing particles from the air. Dose reduction curves are plotted for $1\mu m$ particles for the original unfiltered case and the filtered case in Figure 5. For these calculations, we have assumed that the filter is 60% efficient and that the rate of recirculation, k_2, is 1.5 hr^{-1}. Deposition velocities are the same as those used in previous examples. At the average air exchange rate of 0.76 hr^{-1}, the dosage for people sheltering inside is now only 34% of the dosage received outside.

In Figure 6, the effects of the electret air filter for $5\mu m$ particles are plotted. The decrease in dose reduction factor observed with the addition of the filter is somewhat smaller than that observed for the smaller particles, despite

Figure 5: Effects of electret air filter (1 μm particles).

the increase in filter efficiency. For these large particles, deposition is such an efficient means of reducing concentrations that additional filtering does not have as strong of an effect.

A typical commercial building is more tightly sealed than residential buildings, so the main source of outside air is through the HVAC system. As noted before, the single compartment model we use does not capture the complexities of airflow in a multistory, multi-office building. Furthermore, average air exchange rate data for such buildings is not readily available. We can therefore only provide an example of the numbers one might observe by pre-

Figure 6: Effect of electret air filter (5 μm particles).

senting a set of sample calculations that use air exchange rates for one particular building on which extensive measurements has been conducted.[42] As is typical with new office buildings, infiltration is negligibly small, and recirculation is the dominant source of air change. From the ventilation data provided, we compute the recirculation rate, k_2 = 5 hr^{-1}, and the rate at which outdoor air is introduced, k_3 = 0.5 hr^{-1}. We also neglect infiltration (setting k_0 = 0), and assume that the HVAC intake flow is the same as the exfiltration flow ($k_3 = k_1$). The dose reduction factor can then be written as,

$$R = \frac{k_3(1-F)}{k_2 F + k_1 + \nu_d A/V} \tag{14}$$

Using the same deposition velocities as before, we can compute dose reduction curves for two different particle sizes (Figure 7). Because all outside air must first pass through the filter, we observe greater dose reduction across the range of air exchange rates. At an outdoor exchange rate of 0.5 hr^{-1}, dose reduction factors range from 0.02 for the $2\mu m$ particles to 0.07 for the $1\mu m$ particles. Of course, the numbers presented here apply only to the particular building we have chosen, and extension to a more general statement for all office buildings requires much more complete data.

Civil Defense Measures

Based on the previous discussions, it is clear that very simple measures can significantly improve the sheltering effectiveness of buildings. To examine the effects of such measures, we compute dose reduction factors for a series of cases in which a building is gradually modified to optimize its protective capacity against BW. Here, we focus on single family residences that only have recirculating HVAC systems. To establish a basis of comparison, we compute the dose reduction factor for an unmodified house. As before, we use an average air exchange rate of 0.76 hr^{-1} and an average deposition velocity of 0.01 cm/s. These values produce a dose reduction factor of 0.5 for the unmodified house.

The easiest defense measure an individual homeowner can implement is to change the air filter in the ventilation system. Switching to an electret air filter can be accomplished with minimal financial outlay,[43] and can substantially improve the protective capacity of a building by providing another mechanism for removing particles from the air. For the purposes of illustration, we assume that the installed filter has an efficiency of 0.6 for $1\mu m$ particles, and the ventilation exchange rate is 1.5 hr^{-1}, giving a new dose reduction factor of 0.30. Thus, changing the air filter produces a 36% drop in the dose reduction factor.

The other method of enhancing the sheltering effectiveness of a building is to reduce its air exchange rate. As noted earlier, reducing the air exchange rate relative to the speed of the particle removal mechanisms results in an improvement in the dose reduction factor. Because the air exchange rate depends on such a variety of factors, it is difficult to predict the effectiveness of

Figure 7: Dose reduction factors for commercial buildings.

various measures in different houses. However, numerous studies on the effects of retrofitting existing houses have been conducted. For example, Nagda et al.[44] find that modest efforts such as additional caulking and taping lead to reductions of up to 25% in air exchange rate, while Goldschmidt[45] reviews a series of house-tightening experiments and also finds that modest efforts reduce exchange rates by about 25%. More involved efforts can decrease air exchange rates even more. For example, installation of semi-permeable membrane beneath the siding of a home can reduce exchange rates by up to 60%.[46] If a building has been constructed with the goal of minimizing leakage, air exchange rates are even lower. (Average exchange rates for Scandinavian houses are approximately 0.15 hr^{-1}.) To illustrate the effects of resealing, we compute the dose reduction factor for two cases: k = 0.54 hr^{-1}, which represents the 25% gain one might expect from modest retrofitting, and k = 0.15 hr^{-1}, which represents a more extensive sealing effort. The results for these cases are summarized in Table 2, along with the unmodified and filtered cases.

Table 2: Effects of civil defense measures

	R
Unmodified	0.51
Change to electret air filter	0.32
Modest sealing effort	0.43
Tighter construction	0.17
Cumulative (all defense measures)	0.08

The modest effort case, which consists of taping and caulking obvious holes and cracks, produces a 19% improvement in the dose reduction factor, while the low air exchange rate of a tightly constructed home results in a 67% improvement in dose reduction factor. Buildings with air exchange rates comparable to the values used in this last case are becoming increasingly common for energy conservation reasons, as tightly sealed homes require less energy to heat and cool. Thus, the cumulative 8% dose reduction factor, which includes installation of a new air filter, is not unlikely.

These numbers are presented only to demonstrate the types of results one might observe in attempting to improve a building's sheltering effectiveness. Of course, all of the parameters can vary quite significantly in value. In one retrofit study, the researchers note that the changes in air exchange rates between summer and fall were twice the magnitudes of any changes produced by retrofit. Indeed, the standard deviations of the air exchange rate and deposition velocities are both approximately the same magnitude as the mean values. Despite this variability, the qualitative results remain unchanged. That is, installing electret filters and plugging air leaks in the building will lead to lower dose-reduction factors. Furthermore, it seems reasonable to infer that buildings with higher air exchange rates will benefit more from enacting modest defense measures. Such buildings would tend to have leakage sources that can be substantially reduced by simple caulking, whereas improving on buildings that already have low air exchange rates would probably be much more difficult.

Since biological weapons would typically take the form of a cloud of particles distributed across a variety of sizes, we also should consider the effects of these defense measures for different particle sizes. In general, one would expect that the effectiveness of these measures would increase for larger particles, primarily because the filter efficiencies improve. Instead of the 60% efficiency observed for 1μ*m* particles, one can expect a 97% efficiency for 5μ*m* particles. However, the protection offered by an unmodified home against 5μ*m* particles is already quite good. Using a deposition velocity of 0.05 cm/s for 5μ*m* particles results in a protection factor of 0.17 for the unmodified home. Homeowners installing electret air filters would reduce protection factors by about 24% to 0.13 for 5μ*m* particles. Further efforts to reduce air exchange rates would produce reductions similar to those observed for the smaller particles. In any case, the protection factors presented for 1mm particles can be viewed as a lower bound for the protection offered against typical BW particle sizes.

CONCLUSIONS

We have demonstrated that a small building offers its inhabitants a modest degree of protection from BW attacks, even in cases in which the building inhabitants are unaware of the location of the cloud of biological agents. This protection arises because the process of introducing biological agents into the building occurs at a finite speed and provides the opportunity for removal mechanisms inside the building to reduce total concentrations. We have computed that the average dose reduction factor for U.S. single family residence is approximately 0.5, and can be as low as 0.2 for larger particles. While this factor can vary greatly depending upon the configuration of each particular building and depending upon the current meteorological conditions, it is a representative value, and could be used to improve analyses of BW incidents.

In this study we have also briefly considered the protection offered by large commercial buildings. Because such buildings tend to be more tightly sealed and because they have more sophisticated HVAC systems, large buildings can offer substantially more protection against BW attacks.

Two suggestions for increasing the sheltering effectiveness of residential buildings have arisen from this study: installing electret air filters and reducing air exchange rates. Both of these measures have numerous benefits outside of civil defense applications. Manufacturers of electret filters tout reduced maintenance of the HVAC systems and relief for allergy sufferers as its primary benefits, while reducing air exchange rates has the added benefit of energy conservation. These measures are fairly inexpensive and simple to implement, and can substantially increase the sheltering effectiveness of small houses.

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