
HEPA/Vaccine Plan for Indoor Anthrax Remediation

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We developed a mathematical model to compare 2 indoor remediation strategies in the aftermath of an outdoor release of 1.5 kg of anthrax spores in lower Manhattan. The 2 strategies are the fumigation approach used after the 2001 postal anthrax attack and a HEPA/vaccine plan, which relies on HEPA vacuuming, HEPA air cleaners, and vaccination of reoccupants. The HEPA/vaccine approach leads to few anthrax cases among reoccupants if applied to all but the most heavily contaminated buildings, and recovery is much faster than under the decades-long fumigation plan. Only modest environmental sampling is needed. A surge capacity of 10,000 to 20,000 Hazmat workers is required to perform remediation within 6 to 12 months and to avoid permanent mass relocation. Because of the possibility of a campaign of terrorist attacks, serious consideration should be given to allowing or encouraging voluntary self-service cleaning of lightly contaminated rooms by age-appropriate, vaccinated, partially protected (through masks or hoods) reoccupants or owners.

In addition to killing 5 of its 11 victims, the 2001 anthrax attack on the U.S. Postal Service and federal facilities also contaminated a number of buildings. The U.S. government spent several hundred million dollars recovering buildings with large-area contamination by using chlorine dioxide fumigation. The last of these federal facilities, the Hamilton, New Jersey Mail Sorting Facility, is not expected to reopen until early 2005, >3 years after the attack (1). A large-scale aerosol attack in a major metropolitan area could deny access to a portion of a city for years, with substantial economic and social consequences. While outdoor remediation would be challenging, the absence of sporocidal UV irradiation makes indoor remediation a particularly daunting task. Nonetheless, no federal agency has taken ownership of the wide-area remediation problem (2). A proactive plan to recover affected buildings quickly, safely, inexpensively, credibly, and with minimal collateral damage needs to be developed before such an event (2). To advance the analysis of these recovery options, we propose

and evaluate a very simple HEPA/vaccine plan, where HEPA air cleaners continuously clean the indoor air and Hazmat workers use HEPA vacuums to clean the floors, walls, ceilings, and room contents on a twice-a-day basis; HEPA filters are 99.97% effective for 0.3- μ m particles (3), which are 5–10 times smaller than a typical anthrax spore. In addition, residents are vaccinated before reoccupying the buildings. This strategy hypothesizes a nonzero standard for spore contamination and modest pre- and postremediation environmental sampling (in contrast, >5,000 negative environmental samples were taken after the fumigation of the Brentwood mail-processing facility [4]). The plan employs no sporicides, such as sodium hypochlorite (household bleach) or hydrogen peroxide, which can cause collateral damage to many hard surfaces, and does not discard carpets or furniture, which would generate profound solid waste problems. Using a hypothetical release in lower Manhattan, we compare the HEPA/vaccine and chlorine dioxide fumigation remedial options, in terms of anthrax cases among reoccupants, cost, and recovery time. No attempt is made to estimate the number of cases of cutaneous and gastrointestinal anthrax, which are less apt to be fatal. Although we focus on anthrax remediation, our framework may also be useful for indigenous agents of public health concern (e.g., tuberculosis, *Streptococcus*).

Materials and Methods

A mathematical model (see online mathematical model for details on model formulation and parameter estimation; www.cdc.gov/ncidod/eid/vol11no1/04-0635_mod.htm) was used to evaluate the HEPA/vaccine (Figure 1) and fumigation modalities. In the model, 1.5 kg of anthrax spores is released outdoors in lower Manhattan from a height of 2 m. We considered 92 different scenarios in total, depending upon the release location and the wind direction. A building inventory of lower Manhattan (5) and an atmospheric dispersion model (6) were used to calculate the concentration of spores in each building in the exposed region. We assumed that postattack environmental sampling and plume analysis allow at least some of the “exposed region” to be correctly diagnosed within 1 week

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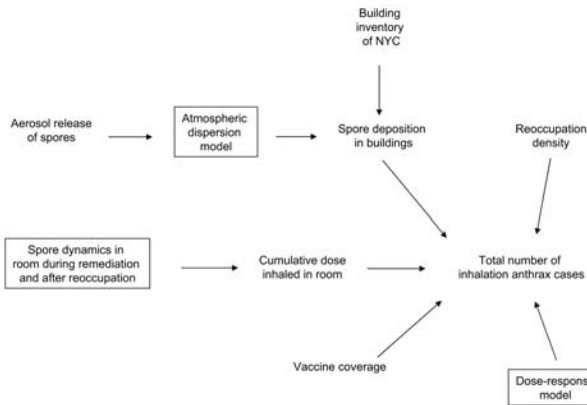


Figure 1. Graphic overview of the mathematical model. Mathematical submodels are in boxes. NYC, New York City.

after the attack, at which time remediation begins. We also assumed that by day 7, outdoor contamination would have subsided to the point where it did not affect indoor spore concentrations.

Since chlorine dioxide fumigation eliminated all detectable spores from the Hart Senate Office Building and several mail-sorting facilities, we assumed that it successfully eliminates all spores in the buildings of our model. In the 2001 attack, chlorine dioxide was used to decontaminate the 700-km² Brentwood postal facility, which took 1 year at a cost of \$130 million (4); further discussion of this cost estimate appears in the online mathematical model. Because the technology was new, we assumed that 50% of the cost was a 1-time investment in technology development. We further assumed a 90% learning curve in both cost and time (at this time, only a small number of companies possess chlorine dioxide expertise); i.e., each time the area of anthrax decontamination doubles, the marginal cost and time are reduced by 10%.

To assess the HEPA/vaccine plan, we developed a differential equation model (Figure 2) of the spore dynamics within a generic 12x12x8-ft room in a building in the exposed region. The model measures the evolution of spore concentration in the air, on the room surfaces, and in the HVAC (heating, ventilation, and air-conditioning) system. A small fraction of spores adhere to the HVAC ducts as they enter the building, and then become slowly disengaged and enter the room. Rather than build multizone models of each building (7), we assumed that each room received air from a duct that is 50-m long, contains 360° of curvature, and has an air velocity of 1,000 ft/min. We implicitly assumed that all rooms within a building are remediated simultaneously, so as to minimize the effect of inter-room contamination within a building. Airborne spores in the room deposit on the room surfaces at a certain rate, and spores on the room surfaces, particularly the

floor, re-aerosolize at a rate that depends on the amount of activity in the room; more re-aerosolization occurs during surface cleaning and re-occupation. The deposition rates and re-aerosolization rates were derived by using data from the Hart Senate Office Building (8). HEPA air cleaners (achieving 10 air changes per h, possibly with the aid of dilution ventilation from the HVAC system) are used continually during the remedial period, which involves successive rounds of testing and vacuuming until n_s postcleaning samples suggest that the floor spore concentration in the room is below the target level \bar{c}_f ; this approach is reminiscent of that taken during the asbestos remediation after the World Trade Center collapse (9). Rather than use a spatial model to capture spatial heterogeneity of spores within a room, we simply assume that the floor samples are log normally distributed, where 95% of within-room samples at a fixed point in time are within 1 order-of-magnitude (i.e., within $1/\sqrt{10}$ and $\sqrt{10}$ of the median), which is consistent with the sample variability in the Hart Senate Office Building (8). That is, in the initial testing of samples, we estimate the number of 2-h vacuumings of the room's surfaces and contents that are required to achieve the target concentration \bar{c}_f . After these vacuumings, a new set of n_s samples are taken. If the estimated concentration from these new samples is below \bar{c}_f then remediation ceases; otherwise, another round of vacuuming and testing is performed. Consecutive vacuumings are 48 h apart, and testing (if needed) occurs midway between these 2 vacuumings, both to allow re-aerosolized spores to resettle before testing and to permit the testing results to be received before the next scheduled vacuuming. We varied the 2 decision variables n_s and \bar{c}_f to explore the tradeoffs among our performance measures.

After the floor concentration is believed to have dropped below \bar{c}_f each generic room is re-occupied by 1 person for 12 h per day. After re-occupation, a portable HEPA air cleaner (at 3 air exchanges per h [10]) is used for 12 h every day, and 10 min of floor vacuuming occurs weekly at half the estimated efficiency of the remedial

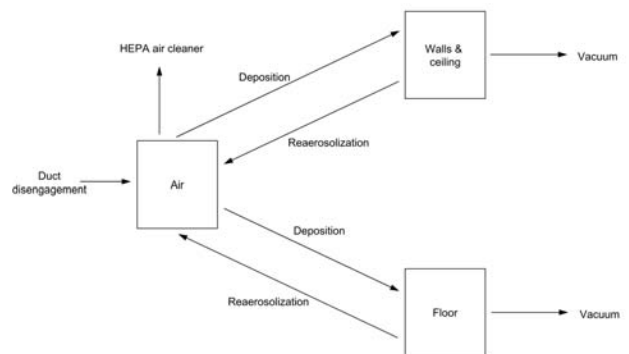


Figure 2. Graphic depiction of the compartments in the differential equation model and the spore movement among compartments.

vacuuming. We assumed that 85% of reoccupants are successfully vaccinated and will not become infected, regardless of the spore concentration in the room. The remaining 15% represent infants, the elderly, the immunocompromised, and persons for whom vaccination is contraindicated, who are assumed to have a dose-response curve that correspond to the lowest 30% of the probit dose-response model (11) with a 50% infectious dose (ID_{50}) of 8,000 spores (12) and a probit slope of 0.7 (13); e.g., the ID_{15} from the probit model in (11) (i.e., 253 spores) would infect half of the unvaccinated population. Here, ID_{50} denotes the dose that infects half of the population; because inhalational anthrax is nearly always lethal (in the absence of treatment), the ID_{50} coincides with the 50% lethal dose (LD_{50}). The differential equation model is used to measure the cumulative number of spores inhaled by each reoccupant in a 10-year period. Combining these cumulative doses, the dose-response model, the atmospheric dispersion model, and the population density of reoccupants allows us to compute the total number of inhalation anthrax cases.

The cost of the HEPA/vaccine plan includes \$75/h for each Hazmat worker, who spends 4 h per 10-h shift vacuuming and the remaining 6 h resting, rehydrating, and handling protective gear; a \$250 portable HEPA air cleaner for each 12x12x8-ft room; \$25 for each environmental sample, which includes the costs for sampling, shipping, and laboratory testing; and \$20 to vaccinate each person. If residents are vaccinated regardless of the remediation/reoccupation policy, the vaccination cost should be omitted from the comparison. The remediation time for the HEPA/vaccine plan was computed by assuming that 1,000 Hazmat workers (using level C protection) are available to perform remediation 10 h per day, which is ≈ 3 times larger than the labor force used at the Brentwood and Hart buildings, and that 200 samplers can each perform 24 samples in 4 h plus have 6 h for donning and removing protective gear, rest, and rehydration. The bottleneck for the total remediation time can be either sampling or vacuuming, depending upon the values of the concentration threshold (\bar{c}_f) and the number of samples per round (n_s).

Results

We averaged the 92 scenarios to obtain a base case. Figure 3A shows the depositional distribution averaged for the 92 scenarios, i.e., the number of square meters of indoor floor area that are contaminated at various levels. The particular forms of dips and peaks in Figures 3A and 3B are due to the irregular spatial distribution of tall buildings relative to the release location that caused the most indoor contamination. The total contaminated area in this average scenario is 5.73×10^7 m², which is >4 million 12x12x8-ft rooms. For this base-case scenario, the fumiga-

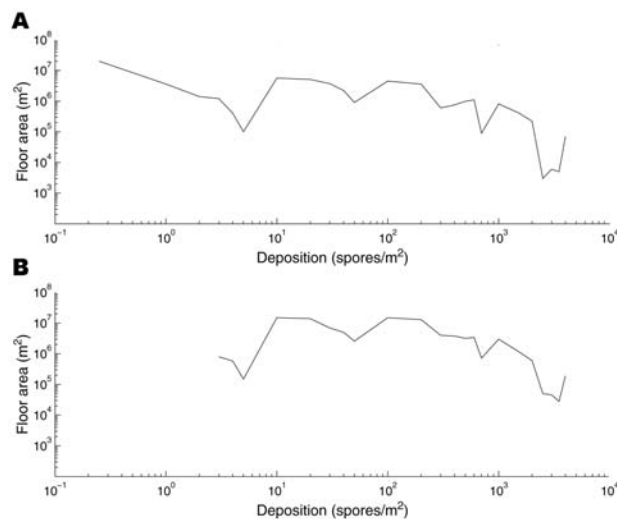


Figure 3. The amount of indoor floor area in lower Manhattan (vertical axes) that is contaminated at various anthrax concentration levels (horizontal axes) as a result of an outdoor release of 1.5 kg of anthrax spores. Plot A, an average of 92 scenarios (9 release locations in Manhattan times 8 wind directions, plus 20 release locations on the outskirts of Manhattan). Plot B, provides similar information for the scenario that generated the largest total area of contamination.

tion plan costs \$2.7 billion and takes 42 years. Figures 4A–C express the expected number of cases, cost, and time of the HEPA/vaccine plan for the base-case scenario in terms of the floor concentration threshold (\bar{c}_f) and the number of floor samples per round (n_s). Because of the random sample measurements, 50 simulations were performed to estimate each of the points in Figure 4, and the 95% half-confidence intervals are < 0.05 times the sample mean in all cases. Figure 4A shows that the mean number of anthrax cases is nearly independent of the number of samples per round, and drops from $\approx 3,000$ cases when the floor concentration threshold is 100 spores/m² to 28 cases when the floor concentration threshold is 0.1 spores/m². To put these numbers in perspective, we also found that 15,760 cases would occur if no cleaning was performed (i.e., $\bar{c}_f = \infty$). The total cost in Figure 4B varies from \$1.7 billion to \$6 billion and depends more on the spore concentration threshold than the number of samples per round. The mean remediation time ranges from 2.9 years to 39.3 years; since there are approximately 4 million rooms and vacuuming can be done at the total rate of 2,000 rooms/day, it would take 5.5 years to clean each room once. Vacuuming dictates the total remediation time in Figure 4C when $n_s = 1$ and $\bar{c}_f = 0.1$ or 1, and sampling is the bottleneck for the other values of tested. Because using $n_s > 1$ increases the cost and time without decreasing anthrax cases, we focus in Figure 4D on the cost versus time tradeoff by fixing $n_s = 1$.

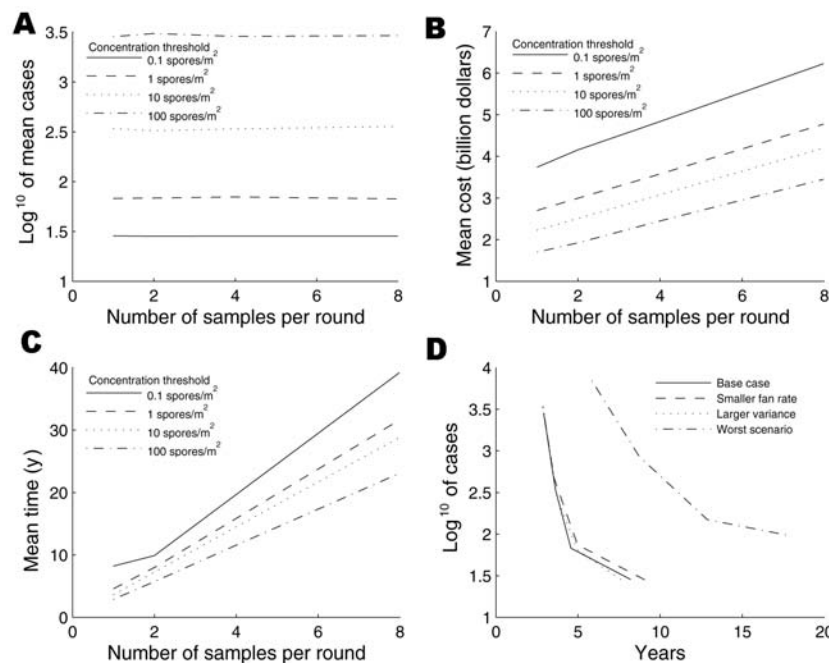


Figure 4. Performance of the HEPA/vaccine plan under the base-case scenario. The horizontal axes in plots A–C are the number of floor samples per round (n_s). Each of plots A–C have 4 curves, 1 for each value of the floor concentration threshold (\bar{c}_f). Cleaning stops after the estimated floor concentration from n_s samples per room is below the threshold \bar{c}_f . The vertical axes in plots A–C are A) the mean number of inhalation anthrax cases, B) the mean cost, and C) the mean recovery time. In plots A–C, the concentration threshold (\bar{c}_f) has a much bigger impact than the number of samples per room (n_s) on these 3 performance measures. Plot D shows the tradeoff of anthrax cases versus recovery time in the base case. The number of samples per room is assumed to be $n_s = 1$ in this plot, which is derived from plots A–C. Plot D also contains tradeoff curves for 3 sensitivity analyses: a lower air-cleaning rate, increased sampling variability of spore concentration, and the most severe of the 92 cases depicted in Figure 3B. This plot shows that the cases versus time tradeoff curve is very insensitive to changes in the air-cleaning rate and sampling variability.

Figure 5 depicts the mean cases and mean remediation time according to the amount of original spore deposition in the rooms. Figure 5A suggests a hybrid strategy that fumigates heavily contaminated rooms (>100 spores/ m^2) and uses the HEPA/vaccine approach for lightly contaminated rooms (<100 spores/ m^2). This hybrid approach results (on average) in only 2 anthrax cases, and the mean remediation time for the lightly contaminated rooms is 5.9 years. It takes 8.4 years to fumigate the highly contaminated rooms. Hence, the total remediation time ranges from 8.4 to 14.3 years, depending upon whether different workers are involved in the 2 decontamination modalities. For the 3 other threshold levels pictured in Figures 5B–5D, many of the anthrax cases occur right at the cutoff point, which is due to the tail behavior of the spore depositional distribution in Figure 3A. The hybrid strategy is not as helpful with these higher threshold levels; e.g., using a threshold of 1 spore/ m^2 to decide between fumigation and vacuuming in Figure 5A, the plan would vacuum for 2 years and fumigate for 28 years.

Sensitivity Analyses

A number of aspects of the model contain considerable uncertainty: the cost and time of the fumigation plan, the indoor spatial deposition after an attack, the reaerosolization and deposition rates inside a room, spore dynamics in a duct, air-cleaning efficacy, vacuum efficacy, Hazmat logistics, the spatial heterogeneity in sampling, vaccine coverage, and the low end of the dose-response curve. Before discussing each of these 10 variables in turn, we

note that our general approach to these uncertainties is to be conservative with respect to assessing the HEPA/vaccine option; i.e., we err on the side of overstating the mean number of anthrax cases that would result under this approach or understating the cost and time of the fumigation plan.

Although fumigation was successful during the cleanup after the 2001 postal attack, the fumigation of a skyscraper is a challenge that has yet to be tackled. Given the 42 years it would take to fumigate the exposed area, an alternative technology could be developed.

The estimated indoor spatial deposition contains orders-of-magnitude of uncertainty, depending upon the size of the release, the spore characteristics (e.g., dry versus wet, size, purity, viability, surface electrostatic properties), the weather conditions, building and canopy terrain in lower Manhattan, building HVAC infrastructure, and whether or not windows and vents were open. The goal of the atmospheric modeling is neither to accurately predict the probability distribution of indoor spatial concentrations for a possible future attack (such an attempt would be greatly limited by the irreducible uncertainty in the release size) nor to provide postattack situational awareness (which would require a much more detailed spatial model), but rather to generate a comparative set of plausible scenarios to evaluate remediation strategies before an attack. Hence, we focused on the average of 92 plausible scenarios. To give some sense of the upper range, we present in Figure 4D the results from the most severe of the 92 scenarios; the deposition distribution from this scenario appears in Figure 3B. This scenario contaminates

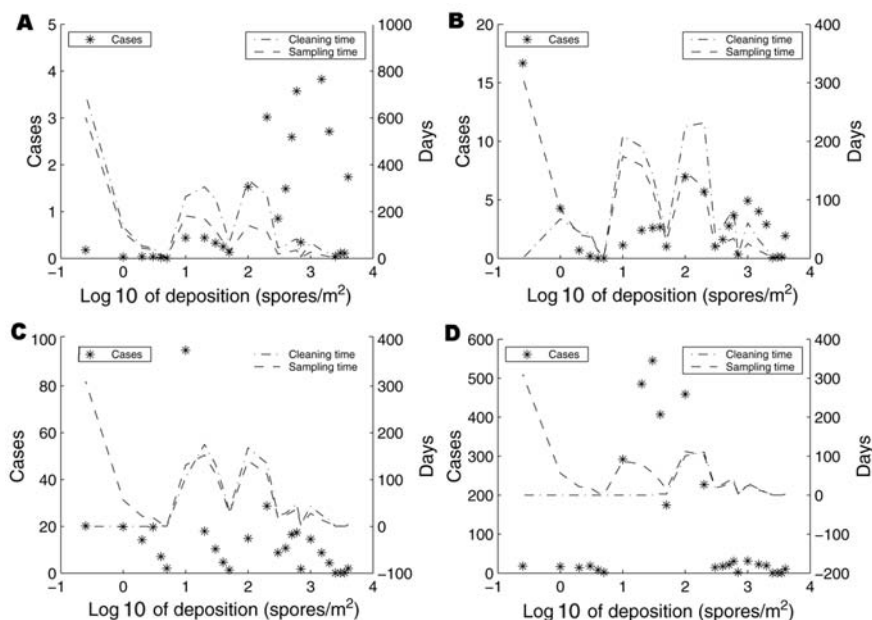


Figure 5. The horizontal axes in these 4 plots give the original room deposition level before remediation begins. These plots show how the total number of anthrax cases (the stars and the left vertical axes) are distributed across room deposition levels, e.g., in plot A, most of the anthrax cases occur in rooms with original deposition levels >100 spores/m². Similarly, the 2 curves and the right vertical axis of each plot show how much time is spent cleaning and sampling in rooms of various deposition levels. These 4 plots are identical except that the spore concentration threshold in spores/m² (\bar{c}_f), which dictates when remediation is stopped, is A) $\bar{c}_f = 0.1$; B) $\bar{c}_f = 1$; C) $\bar{c}_f = 10$; D) $\bar{c}_f = 100$. These plots motivate the hybrid policy, which fumigates heavily contaminated rooms and uses the HEPA/vaccine approach in lightly contaminated rooms.

≈ 7 million rooms and requires 17.7 years to reduce the number of cases to 98.

Because air and surfaces are concomitantly remediated, the number of anthrax cases is rather insensitive to the reaerosolization and deposition rates in the room.

The large uncertainty with respect to duct modeling led us to adopt a worst-case approach and use the spore disengagement rate that maximizes the number of anthrax cases. Many new buildings and some retrofitted older buildings have HEPA filters built into the HVAC system (14), which would largely eliminate the risk for spore disengagement.

We have focused on portable air cleaners, whereas dilution ventilation, in which 15%–25% of the total airflow rate consists of outside airflow (15), may also play a key role in remediation. Figure 4D also presents results when we reduce the air-cleaning rate during remediation from 10/h to 3/h. The latter quantity, which can be achieved with an off-the-shelf air cleaner and an open window (10), generates only a minor change in the cases versus time trade-off curve.

To the extent that reaerosolized spores resettled before or during postvacuum testing in the referenced study (16), we may have underestimated the vacuum efficacy. We conservatively assumed that all floors are carpeted and that sporicides such as sodium hypochlorite, hydrogen peroxide, or foams (17,18), which are much more effective than vacuuming for hard surfaces, are not deployed.

Our assumption that each Hazmat worker has 4 productive hours of work per day underestimates the rate that could be achieved over a several-week time frame but is prudent over a longer period of time and would help avoid worker fatigue and burnout.

Because the amount of spatial heterogeneity of spores in a room is difficult to assess, we considered the case where 95% of samples within a room fall within 2 orders of magnitude rather than 1. Figure 4D shows that the effect of this increased sampling variability is negligible and that the optimal amount of sampling did not change relative to the base case.

As noted in section 3.8 of the online mathematical model, our 85% vaccine coverage of reoccupants may be a considerable underestimate. No age groups are being left behind in the plans for the next-generation anthrax vaccine, and persons with weak immune systems may achieve partial protection.

We considered a cumulative dose during a 10-year period, whereas infection may be a result of a challenge over a shorter time horizon; our overestimate of cases is very modest because of the exponential decreases in spore concentration during the reoccupation period, and changing the horizon from 10 years to 6 months led to a negligible ($<1\%$) reduction in cases. Our dose-response model assumed that the 15% unvaccinated population comes from the most vulnerable 30% of a widely used probit model, which itself has been criticized for greatly overestimating the number of cases at the lower end of the curve (19). If we used 95% vaccine coverage with the remaining 5% sampled from the lower 50% of the probit model, then the number of anthrax cases with $\bar{c}_f = 10$ spores/m² and $n_s = 1$ sample per round would be reduced from 341 to 72. Even within the class of probit models, others have used a probit slope twice as steep, which results in many fewer cases (20). If we use a probit slope of 1.4 rather than 0.7, then the mean number of cases with $\bar{c}_f = 10$ spores/m²

and $n_s=1$ sample per round decreases from 341 to 3×10^{-5} , which highlights the value of further research into the low end of the dose-response relationship. However, in the online mathematical model we note that the slope of 0.7 is more consistent with data from the 2001 anthrax attack. Dahlgren et al. (21) estimated that goat-hair mill workers routinely inhaled about 500 ($\leq 5 \mu\text{m}$) anthrax spores per shift without accompanying illness or death, raising the possibility (although no subsequent work on this topic has been published) that chronic low-level exposure might induce adaptive or innate immunity. In any case, adaptive or innate immunity is unlikely to occur in the 15% of people in our model who are not successfully vaccinated. One assumption that is not conservative is that people reoccupy these rooms for 12 h per day. A small fraction of people may work at home, stay at home most of the day, or work and live in different buildings within the exposed region. We are underestimating the inhaled doses for these people by a factor of 2. Nonetheless, taken together, the numerical results reported here may overstate the actual number of anthrax cases by at least 1 order of magnitude, and perhaps many.

Discussion

The base-case release, which is an average of 92 different scenarios under various weather conditions and locations in lower Manhattan, contaminates the equivalent of 4 million 12x12x8-ft rooms. Our analysis suggests that an outdoor release would generate a more diffuse depositional distribution of spores than an indoor attack: we estimate that $\approx 10,000$ spores/m² were deposited in parts of the Hart Senate Office Building (section 3.2 of the online mathematical model), which is considerably higher than the concentrations in Figure 3. As an alternative to a multidecade fumigation effort, the HEPA/vaccine plan appears capable of substantially reducing the number of anthrax cases but would require ≈ 8 years with the current estimated Hazmat labor pool. Both plans would require several billion dollars in direct costs. The HEPA/vaccine plan eventually experiences diminishing returns: from a base of 341 expected cases after 3.6 years of remediation, another year is required to reduce the mean number of cases to 67, but then an additional 3.6 years and \$1 billion are needed to reduce the mean number of cases to 28. A hybrid HEPA/vaccine/fumigation plan, in which lightly contaminated buildings receive the HEPA/vaccine approach and heavily contaminated buildings are fumigated, could eliminate almost all of the anthrax cases. The required remediation time would be 8.4–14.3 years, depending upon whether the same Hazmat personnel carried out both operations.

A key finding of our study is that only a moderate amount of sampling appears to be required. In theory, additional sampling reduces type I and type II errors, thereby

avoiding anthrax cases in rooms that were inadvertently thought to be sufficiently safe, and reducing unnecessary remediation of rooms that were mistakenly perceived as overly contaminated. However, the number of anthrax cases was essentially independent of the number of room samples per round, as long as at least 1 sample was taken. Indeed, with current vacuuming and sampling capacity, the only impact from taking >1 sample per 12x12x8-ft room is prolonged remediation and increased cost. However, in the absence of exhaustive environmental testing, on-site coordinators need to validate that work is performed according to the required standards (i.e., vacuuming is actually being done for the specified number of minutes/m²).

Our results have several implications. First and foremost, field tests with simulants are required to accurately assess the real-world spore reduction that can be achieved—and the number of vacuumings required—by this HEPA/vaccine approach. If field tests confirm the model predictions, then the concentration threshold \bar{c}_f , the number of samples per round n_s , and the level of concentration that requires fumigation versus vacuuming should be determined with greater precision. These threshold values should be chosen so that the reoccupant risk level (in terms of quality-adjusted life years) is consistent with those for other hazards (e.g., asbestos, radiation).

Large-area urban remediation strategies must confront a number of difficult issues, the most important of which is surge Hazmat capacity. We have assumed that remediation and vaccination are initiated simultaneously 1 week after the attack. The initial vaccination of reoccupants would require ≈ 1 week; protective immunity is believed to develop at 35 days after initial vaccination (22). Hence, residents will be able to reoccupy buildings by 42 days after remediation is initiated. Presumably, most reoccupants would receive prophylactic antimicrobial agents because they would have been in these building during or soon after their exposure. Consequently, some of these residents may be interested in moving back in even earlier. Considering that 8.2 years is required to carry out the HEPA/vaccine plan in the base-case scenario, this reoccupancy delay may be viewed by the major stakeholders as unacceptable. Our analysis assumes the availability of 1,000 Hazmat personnel, compared to the 300 Hazmat workers (after attrition) used to perform the Brentwood cleanup and the roughly 3,000 licensed asbestos workers in New York State. To reduce the recovery delay from 8.2 years to 5 months requires a 20-fold increase in Hazmat labor, i.e., 20,000 personnel. To reduce the delay another 4-fold so as to allow reoccupation within 42 days is probably not realistic for this large-area scenario. Nonetheless, U.S. government coordination with the Hazmat, fumigation, and building protection industries—not just locally, but nationwide and perhaps including the U.S. military and

key allies—would be necessary to guarantee available capacity and resources. In addition, scheduling theory (23) implies that aggregate waiting time for reoccupants can be minimized by remediating the least-contaminated buildings first (i.e., use the shortest expected processing time priority rule).

There are other aspects to optimizing surge remediation and recovery capacity. Just as the worried well caused a surge in ciproflaxin sales in 2001, many people outside of the exposed region will attempt to buy HEPA air cleaners and vacuums. Hence, demand will come not only from the exposed area but also from surrounding regions. In the same way that the U.S. government is working with pharmaceutical companies to provide surge capacity of medical countermeasures (including anthrax vaccine) in the event of a biologic attack, it needs to develop cooperative agreements with building protection service companies so that equipment shortages do not block the critical path to recovering the exposed area.

Another key aspect of a detailed plan is exception management: the HEPA/vaccine plan will not work for 100% of the buildings in the exposed area. More aggressive remediation of critical assets (hospitals; nursing homes; daycare centers; emergency response facilities; electrical, water and sanitation facilities; transportation facilities) will be desirable. Some nonresidential buildings (such as the buildings contaminated in the 2001 attack) have extremely high ceilings, and achieving a high air-exchange rate in these spaces may be not be feasible with portable air cleaners. Another confounding issue is visitors to the impacted region. In the aftermath of a catastrophic anthrax attack, the public would expect nationwide voluntary mass vaccination. Visitors to the exposed areas should be offered an anthrax vaccine, and guidelines for unvaccinated visitors should be developed. Also, because the spore concentration continues to decrease exponentially during reoccupation (but not during semiquiescent periods), more vulnerable residents might delay their reoccupation until several months after the other residents. A significant logistical issue is the disposal of contaminated carpets, furniture, and other household goods. Some reoccupants will insist on discarding these items, even after they have been heavily cleaned. Reoccupant education and outreach measures, including perhaps temporal or financial disincentives for disposal, need to be taken to avoid overwhelming solid waste disposal capacity. Emergency plans (e.g., medical incinerator capacity) should be developed for the HEPA vacuum bags and other items that need to be discarded during remediation. Another difficult issue is postevent building maintenance, particularly of HVAC systems, which must minimize spore reaerosolization during maintenance and disposal of old ducts. Safe procedures to rid ducts of asbestos (asbestos fibers are roughly the same size as

anthrax spores, but the U.S. Environmental Protection Agency limit for asbestos is 900 fibers/m³ [9], which is larger than the postremediation spore concentrations considered here) and other materials have been developed (24); the important point is that HVAC cleaning should not block the critical path to reoccupation but rather should be performed asynchronously in a low-intensity manner over many years.

In summary, this study suggests that a HEPA/vaccine approach is viable for most buildings after a large-scale anthrax attack. This outcome is dependent on a qualitative increase in surge Hazmat remediation capacity to reduce the recovery delay to a level that would not invite permanent mass relocation. Detailed mass remediation plans need to be developed now; as noted by Danzig (2), without such a plan we are inviting economic and social disruption. Ultimately, the extent of restoration and sampling will be dictated by the reoccupants and building owners, and hence risk communication will be of the utmost importance. Inconvenience and cost may force relaxation of standards, and some thought should be given to whether voluntary “self-service” cleaning of minimally contaminated rooms by age-appropriate, vaccinated, partially protected (e.g., with N95 masks) reoccupants or owners would be allowed or encouraged. Indeed, in the face of a campaign of terrorist attacks (2), this self-service approach, with more effective masks or hoods, may be the only feasible response. Finally, a safe, effective, single-dose vaccine would have a profound impact on mitigating the undesirable consequences of this scenario.

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HEPA/vaccine Plan for Indoor Anthrax Remediation

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November 8, 2004

Mathematical Model

This document describes the mathematical model that generated the results reported in the article (see www.cdc.gov/eid/vol11no1/04-0635.htm). The calculation of the post-attack indoor contamination levels is described in Section 1, the chlorine dioxide parameters are given in Section 2, and the various aspects of the HEPA/vaccine proposal are formulated in Section 3. Values of the model parameters are given in Tables 1 and 2.

1 Indoor Contamination Levels

The calculations in this section were performed by David Miller at Risk Management Solutions. The results in Fig. 3a of the main text are an average over 92 scenarios, where each scenario corresponds to a location of the point release and a wind direction. Each scenario consists of 1.5 kg of anthrax spores (assuming 2.5×10^{14} spores/kg, which corresponds to a 25% purity preparation where a pure preparation contains 10^{15} spores/kg) released from

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a height of 2 m. For each of nine release locations in lower Manhattan, eight different wind directions were simulated. In addition, we included 20 other scenarios corresponding to releases on the outskirts of Manhattan, for a total of 92 scenarios. For each scenario, the SCIPUFF atmospheric dispersion model [1], which uses a Gaussian puff model with a boundary layer using default values in [1], a wind speed of 2 m/s and a decay rate of 1/s in the daytime and 0.1/s at night, computed the outside deposition in spores/m².

The building inventories in this analysis consist of all structures south of Central Park in New York City, using a database that contains accurate location, plan dimensions and number of floors for all buildings in this locale [2]. Indoor deposition levels were calculated by assuming that only a fraction of spores enters a structure. Because taller buildings are better sealed, we assume that the fraction of spores that entered the building and deposited in the rooms decrease with the number of floors in the building, and range between 0.05 and 0.4. We further assume that once inside a structure, spores are evenly distributed across the rooms of the structure. While this is an oversimplification, it appears that anthrax spores have the potential to quickly disperse throughout a large building [3]. As explained in §3.5, we also assume an additional small fraction of spores are deposited in the ducts.

We let $n(D)$ be the total number of square meters of indoor floor space that has a deposition of D spores/m² (see Figure 1a of the main text). We also define $A = \int_0^\infty n(D) dD = 5.73 \times 10^7$ to be the total number of square meters of contaminated indoor floor space.

2 Chlorine Dioxide Fumigation

Since chlorine dioxide fumigation eliminated all spores from the Hart Senate Office Building and several mail sorting facilities, we assume that it successfully eliminates all spores in these 92 scenarios. In the 2001 attack, chlorine dioxide was used to decontaminate the 700k m² Brentwood postal facility, which took one year at the estimated cost of \$130M [4]. The

final cost, including indirect costs, may be considerably larger than this estimate, and the USPS claims that the future cost of such an endeavor would be \$10-15M [5], even though earlier remediation estimates from the 2001 attack were far too optimistic [5, 6]. Because the technology was new, we assume that 50% of the cost was a one-time investment in technology development. We further assume a 90% learning curve in both cost and time (at this point in time, there are only two companies that possess the chlorine dioxide technology); i.e., each time the amount of square area of anthrax decontamination doubles, the marginal cost goes down by 10%. Hence, the total cost to fumigate A m² is $c_c \int_0^A x^{-0.152} dx$, where $0.152 = \ln 0.9 / \ln 2$ and c_c is the cost to fumigate the first square meter. Solving $\$65\text{M} = c_c \int_0^{700,000} x^{-0.152} dx$ yields $c_c = \$609$. Similarly, the time required to fumigate A m² is $\tau_c \int_0^A x^{-0.152} dx$, where $\tau_c = 0.082$ hr is the time to fumigate the first square meter, and satisfies $\tau_c \int_0^{700,000} x^{-0.152} dx = 1$ yr. Substituting the parameters A , c_c and τ_c into these integrals reveals that the total fumigation cost is \$2.7B and the total fumigation time is 41.9 years.

3 HEPA/vaccine Approach

This section describes the modeling elements of the HEPA/vaccine approach. A dynamic compartmental model is formulated in §3.1, the surface deposition and reaerosolization parameters are derived in §3.2, the cleaning of surfaces and the air are described in §3.3 and §3.4, a duct analysis is performed in §3.5, the sampling and cleaning strategies are prescribed in §3.6, the post-reoccupation cleaning and cumulative dose are described in §3.7, vaccine coverage, efficacy and cost are stated in §3.8, the dose-response model is specified in §3.9, and the computation of cases, costs and total time is described in §3.10.

3.1 Dynamic Compartmental Model

We consider a well-mixed three-compartment model to assess the spore dynamics in a generic room of size $12 \times 12 \times 8$ ft, consisting of the spore concentrations in the air ($c_a(t)$ spores/m³), on the walls and ceiling ($c_w(t)$, spores/m²) and on the floor ($c_f(t)$ spores/m²) at time t . The aggregation of the walls and ceiling into a single compartment is justified in §3.2. We denote the room volume by $V = 32.62$ m³, the floor surface area by $A_f = 1.2(13.38) = 16.05$ m² and the surface area of the walls and ceiling by $A_w = 1.2(49.05) = 58.86$ m², where the 20% inflation factor of the surface areas accounts for the furniture and other contents in the room. The model captures the inflow of spores from contaminated ducts at rate $d(t)$, the adsorption of spores to the room surfaces at rate l_a , where a fraction $f_w(t)$ adheres to the walls and ceiling and the remaining fraction is deposited on the floor, and the reaerosilization from the surfaces at rate $r_f(t)$ from the floor and $r_w(t)$ from the walls and ceiling. The deposition fraction $f_w(t)$ and the reaerosilization rates are expressed as functions of time because they will vary depending on the activity conditions in the room, as explained in §3.2. Cleaning occurs via two first-order mechanisms: a portable HEPA filter with a fan reduces the airborne spore concentration at rate $k_a(t)$, and HEPA vacuuming of the ceiling, walls and floor (and, implicitly, all room contents, although there will be areas – e.g., individual pages of books – that are difficult to access by Hazmat workers) decreases the spore concentration of the walls and floor at rates $k_w(t)$ and $k_f(t)$, respectively. The cleaning parameters are function of time because some cleaning also occurs after reoccupation. We assume that all of the outdoor spores have been inactivated by the time that indoor remediation of the generic room begins, which is $\tau_d = 7$ days after the attack and taken to be time $t = 0$. Remediation lasts for T hours, during which time the fan and HEPA filter are in continuous use. For $t \in [0, T]$, let the indicator function $I_w(t) = 1$ if the wall is being vacuumed at time t and $I_w(t) = 0$ otherwise, and define $I_f(t)$ for the floor in an analogous fashion. The system dynamics are

given by

$$\underbrace{\dot{c}_a(t)}_{\text{air}} = \underbrace{d(t)}_{\text{duct}} + \underbrace{\frac{A_w r_w(t)}{V} c_w(t)}_{\text{reaerosolization}} + \underbrace{\frac{A_f r_f(t)}{V} c_f(t)}_{\text{reaerosolization}} - \underbrace{l_a c_a(t)}_{\text{deposition}} - \underbrace{k_a(t) c_a(t)}_{\text{cleaning}}, \quad (1)$$

$$\underbrace{\dot{c}_w(t)}_{\text{walls}} = \underbrace{\frac{V f_w(t) l_a}{A_w} c_a(t)}_{\text{deposition}} - \underbrace{r_w(t) c_w(t)}_{\text{reaerosolization}} - \underbrace{k_w(t) I_w(t) c_w(t)}_{\text{cleaning}}, \quad (2)$$

$$\underbrace{\dot{c}_f(t)}_{\text{floor}} = \underbrace{\frac{V(1-f_w(t))l_a}{A_f} c_a(t)}_{\text{deposition}} - \underbrace{r_f(t) c_f(t)}_{\text{reaerosolization}} - \underbrace{k_f(t) I_f(t) c_f(t)}_{\text{cleaning}}. \quad (3)$$

We determine the values of the parameters in (1)-(3), including the initial system state, in the next five subsections.

One dynamic aspect we fail to capture in (1)-(3) is that all rooms are assumed to start cleaning seven days after the attack, whereas some rooms will be cleaned later than that if there are not enough Hazmat laborers to clean all buildings simultaneously (see §3.10). However, the only term in our model that depends on the exact starting time of cleaning is the duct source term $d(t)$ in (1), and the relative magnitude of this term is too small (see §3.5) to have this simplifying assumption affect our qualitative conclusions.

3.2 Surface Deposition and Reaerosolization

In this subsection, we estimate the initial system state, the deposition parameters l_a and $f_w(t)$, and the reaerosolization parameters $r_w(t)$ and $r_f(t)$. We use data from Tables 2 and 4 in Weis *et al.* [7], who measured air and floor concentrations in the Hart Senate Office Building during simulated semi-quiescent and active conditions. During active conditions, they found 2800 spores/m² deposited on the floor and other horizontal surfaces, 11,000 spores/m³ in the air near the floor, 707 spores/m³ in the air near the breathing zone, and 75 spores/m² on the office dividers (i.e., walls). During semi-quiescent conditions, they

measured 171 spores/m³ in the air near the floor. They also found very little change in vertical surface concentrations as a result of increased activity.

We first use these data to estimate the initial conditions, assuming that active conditions prevailed as the spores deposited during the hours after the silent attack. The ratio of wall-to-floor concentration is 75/2800=0.026. To estimate the ceiling concentration, we ignore the walls and use a simple one-dimensional reaerosolization model, where during active conditions a fraction $1 - f_a^a$ of the spores in the room stay on the floor, and the remaining fraction of spores are distributed in the air at height h according to the exponential function ae^{-ah} , and stick to the ceiling (at height $H = 8$ ft) according to $\int_H^\infty ae^{-ah} dh = e^{-aH}$. Using the data in [7], we solve $D(1 - f_a^a) = 2800$, $Df_a^a e^{-0.1a} = 11,000$, and $Df_a^a e^{-1.6a} = 707$, and get $D = 10,018.8$ spores/m² (the deposition in [7]), $f_a^a = 0.72$ and $a = 1.83/\text{m}$. Hence, the ceiling-to-floor concentration is $\frac{f_a^a e^{-aH}}{1 - f_a^a} = 0.030$. Since the ceiling and wall depositions are very similar, we aggregate the ceiling and walls into a single compartment in (1)-(3). Using the average of 0.030 and 0.026, we derive the conditions soon after the attack to be $c_a(t) = 0$, $c_w(t) = 0.027D$, and $c_f(t) = 0.973D$, where D is the total deposition (spores/m²) computed in §1. As explained in §3.5, the floor and wall concentrations when cleaning begins (at time 0) will include not only $0.027D$ and $0.973D$, respectively, but also some spores that originally adhered to the duct but disengaged from the duct and deposited on the walls and floor before time 0.

The surface absorption parameter l_a is equal to the surface area of the room, $A_s = 1.2[2(12^2) + 4(8)(12)] \text{ ft}^2 = 806.4 \text{ ft}^2 = 74.96 \text{ m}^2$, times the adsorption coefficient (in m/s), divided by the room volume, V . For particles of diameter larger than 2 or 3 μm – we assume the spores are $D_p = 3 \mu\text{m}$ in diameter – the adsorption is dominated by gravimetric settling and the adsorption coefficient is taken to be the gravimetric settling velocity [8], which is

$$v_y = \frac{Cg(\rho_p - \rho)D_p^2}{18v_d}. \quad (4)$$

In (4), $C = 1.05$ is the Cunningham slip factor, $g = 9.81 \text{ m/s}^2$ is the acceleration of gravity, $\rho = 1.184 \text{ kg/m}^3$ is the density of air, $v_d = 1.83 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$ is the dynamic velocity under standard temperature and pressure, and $\rho_p = 283 \text{ kg/m}^3$ is the density of anthrax spores, assuming 2.5×10^{14} spores/kg. These substitutions lead to $v_y = 7.93 \times 10^{-5} \text{ m/s}$. Taking the room surface area to be $A_s = 74.96 \text{ m}^2$ and the room volume to be $V = 32.62 \text{ m}^3$, we find that the surface absorption parameter is $l_a = 1.82 \times 10^{-4}/\text{s}$, which is in close agreement with experiments [9, 10].

The remaining three parameters, $f_w(t)$, $r_w(t)$ and $r_f(t)$, can take on one of two values, depending on whether active or semi-quiescent conditions prevail at time t . In particular, we assume conditions are active during surface cleaning, which is consistent with the observation that vacuuming may increase the rate of re-aerosolization [11], and are semi-quiescent throughout the remainder of the remediation period:

$$f_w(t) = \begin{cases} f_w^a & \text{if } I_w(t) = 1, \quad t \in [0, T]; \\ f_w^s & \text{if } I_w(t) = 0, \quad t \in [0, T]; \end{cases} \quad (5)$$

$$r_w(t) = \begin{cases} r_w^a & \text{if } I_w(t) = 1, \quad t \in [0, T]; \\ r_w^s & \text{if } I_w(t) = 0, \quad t \in [0, T]; \end{cases} \quad (6)$$

$$r_f(t) = \begin{cases} r_f^a & \text{if } I_f(t) = 1, \quad t \in [0, T]; \\ r_f^s & \text{if } I_f(t) = 0, \quad t \in [0, T]. \end{cases} \quad (7)$$

We simultaneously solve for these parameter values by assuming that the data in Weis *et al.* [7] represent an equilibrium state in either active or semi-quiescent conditions. That is, we set the left sides of (1)-(3) to 0, ignore the duct term and the cleaning terms in these equations, set $c_a(t)$, $c_w(t)$ and $c_f(t)$ to their equilibrium values, and then solve for $f_w(t)$, $r_w(t)$ and $r_f(t)$. We let $c_a(t)$ be the average air concentration, which is $\frac{Df_a^a}{H} \int_0^H a e^{-ah} dh = Df_a^a(1 - e^{-aH})/H$, and as before let $c_w(t) = Df_a^a e^{-aH}$ and $c_f(t) = D(1 - f_a^a)$. Substituting these expressions into (1)-(3) gives (the deposition level D cancels out)

$$0 = \frac{A_w f_a^a e^{-aH}}{V} r_w(t) + \frac{A_f(1 - f_a^a)}{V} r_f(t) - \frac{l_a f_a^a(1 - e^{-aH})}{H}, \quad (8)$$

$$0 = \frac{Vl_a f_a^a (1 - e^{-aH})}{A_w H} f_w(t) - f_a^a e^{-aH} r_w(t), \quad (9)$$

$$0 = \frac{Vl_a f_a^a (1 - e^{-aH})}{A_f H} (1 - f_w(t)) - (1 - f_a^a) r_f(t). \quad (10)$$

We define the three parameter values by (f_w^a, r_w^a, r_f^a) under active conditions and by (f_w^s, r_w^s, r_f^s) under semi-quiescent conditions. Under active conditions, we substitute the values derived earlier in this subsection, $f_a^a = 0.72$ and $a = 1.83/\text{m}$, into (8)-(10). Under semi-quiescent conditions, we maintain $a = 1.83/\text{m}$ but use $f_a^s = 0.02$, which solves $Df_a^s e^{-0.1a} = 171$ with $D = 10,018.8$ spores. However, the systems of equations (8)-(10) is singular and has rank two, and hence we need another independent equation to solve for the three parameter values. Under active conditions, we impose the extra condition

$$r_w^a = r_f^a \quad (11)$$

because all the surfaces are being vacuumed. Under semi-quiescent conditions, we add the equation

$$r_w^s = r_f^s \quad (12)$$

because none of the surfaces experience much activity. The three parameter values that solve (8)-(11) and (8)-(10), (12), respectively, are given in Table 1.

3.3 Surface Cleaning

Sodium hypochloride (household bleach), diluted with water to reduce the pH from 12 to 7, can achieve a 4-log decrease of *Bacillus* spores in 30 minutes [12], which gives a first-order killing rate of 0.307/min. Hydrogen peroxide (25.8%), which should result in less mucosal irritation than sodium hypochloride, can achieve a 5-log reduction in 15 minutes at room temperature (first-order killing rate is 0.768/min) [13]. The sporicidal efficiency of both agents may be reduced by the presence of organic matter [14]. Newer sporicidal foams

[15, 16] and emulsion surfactants [17] also appear to be effective, and may cause less damage to the environment and/or the treated surfaces than the two traditional agents.

We have chosen to use a simpler, if less effective, surface cleaner – a HEPA vacuum – because sodium hypochloride and hydrogen peroxide may cause undesirable collateral damage to room contents and sporicidal foams are difficult to remove from hard surfaces. Unfortunately, there is no data on the efficiency of HEPA vacuuming for anthrax spores. Because anthrax spores are roughly the same size as asbestos fibers, we use asbestos data to estimate the vacuuming efficiency. HEPA-filtered hot water extraction achieved a 69% reduction of asbestos fibers in carpets after vacuuming 46.5 m^2 for 65 min [18]. We assume that walls and ceilings would achieve about a 90% reduction for the same amount of vacuuming. A 90% spore reduction on the floor of our generic room requires $\frac{-\ln 0.1}{-\ln 0.31} \frac{65 \text{ min}}{46.5 \text{ m}^2} A_f = 44.2 \text{ min}$, and a 90% reduction on the walls and ceiling requires $\frac{65 \text{ min}}{46.5 \text{ m}^2} A_w = 82.4 \text{ min}$, for a total of 126.6 min. For simplicity, we round this cleaning time down to two hours (see §3.6), and assume that a 1-log reduction can be achieved on the surfaces in two hours, so that $k_f(t) = k_w(t) = \frac{\ln 10}{2 \text{ hr}} = 1.15/\text{hr}$ for $t \in [0, T)$.

3.4 Air Cleaning

The parameter $k_a(t)$, sometimes called the air exchange rate, is typically calculated by dividing the volumetric flow rate Q by the room volume V , and then multiplying this ratio by a mixing factor, which can range from about 0.1 to 0.5, depending upon the ventilation characteristics of the room [8]. We assume that an air exchange rate of $k_a(t) = 10/\text{hr}$, which is typical during an asbestos cleanup, is achieved for $t < T$.

3.5 Duct Modeling

To assess the source rate from the duct, we first need to estimate how many spores are initially deposited in the duct. Consider a straight duct of height and width $W = 0.4$ m [8], and length L , through which air is flowing horizontally at rate v_x . The duct efficiency, η , which is the fraction of spores entering the duct that are deposited there, is given by $1 - \exp\left(-\frac{v_y L}{v_x W}\right)$ under well-mixed conditions and by $\frac{v_y L}{v_x W}$ under laminar conditions [8]. If we assume that all spores entering the building do so through the ducts (many will enter through windows, doors and other gaps) then the number of spores deposited in the duct is $\frac{\eta}{1-\eta}$ times the number of spores in the room. We assume the horizontal duct velocity is $v_x = 1000$ ft/min = 5.08 m/s, which is at the low end of values reported for industrial applications (Table 6.6 in [8]). With any reasonable value of L , the duct efficiencies under well-mixed and laminar conditions nearly coincide and are very small, and for concreteness we use the laminar efficiency, $\frac{v_y L}{v_x W}$. To be conservative, we set $L = 50$ m, which is considerably longer than most ducts, and obtain an efficiency of 1.95×10^{-3} .

However, many ducts are curved. Consider a curved duct of width $W = 0.4$ m, inner radius $r_1 = 0.3$ m and outer radius $r_2 = 0.7$ m [8]. Under the well-mixed, irrotational flow model [8], the efficiency of this curved duct (due solely to the curvature, ignoring gravitational settling) that traverses the angle θ is $1 - e^{-CKS\theta}$, where $C = 1.05$ is the Cunningham slip factor, $K = \frac{r_2 - r_1}{r_2 \ln(r_2/r_1)} = 0.796$, and the average Stokes number $S = \frac{\rho_p D_p^2 v_x}{18 \nu_d r_2} = 5.61 \times 10^{-5}$. The amount of total curvature in ducts varies widely, and we assume 360 degrees in total (i.e., $\theta = 2\pi$), which has efficiency 2.95×10^{-4} . To be conservative, we add these two efficiencies (which overstates the efficiency, due to the possibility of double counting deposited particles) and set $\eta = 2.24 \times 10^{-3}$ and $\frac{\eta}{1-\eta} = 2.25 \times 10^{-3}$.

A room that has a deposition of D spores/m² in §1 has $0.027DA_w + 0.973DA_f$ spores in the room just after the attack. Hence, the number of spores deposited in the duct just

after the attack is

$$\tilde{D} = \frac{\eta}{1 - \eta} [0.027DA_w + 0.973DA_f]. \quad (13)$$

We assume that these spores disengage from the duct and enter the room at a rate α per unit time. If remediation begins $\tau_d = 7$ days after the attack, then the room concentrations at the time cleaning begins are $c_a(0) = 0$,

$$c_w(0) = 0.027D + \frac{0.027\tilde{D}}{A_w} \int_0^{\tau_d} \alpha e^{-\alpha s} ds = 0.027D + \frac{0.027\tilde{D}(1 - e^{-\alpha\tau_d})}{A_w}, \quad (14)$$

$$c_f(0) = 0.973D + \frac{0.973\tilde{D}(1 - e^{-\alpha\tau_d})}{A_f}, \quad (15)$$

and the duct term in equation (1) is given by

$$d(t) = \frac{\tilde{D}\alpha e^{-\alpha(\tau_d+t)}}{V}. \quad (16)$$

The parameter α is largely unknown and depends upon the age and composition of the duct. Hence, to be conservative, we attempt (via the following simplified model) to choose the value of α that maximizes the number of anthrax cases. Let $x(t)$ denote the number of spores from the duct that are in the room at time t . Then at the time cleaning begins, we have $x(0) = \tilde{D}(1 - e^{-\alpha\tau_d})$. For simplicity, we ignore the surface cleaning and assume that these spores die at rate $k_a(t)$, which is 10/hr for $t < T$ and 1.8/hr for $t \geq T$ (this is the average during the post-reoccupation period; see §3.7). Hence, the quantity $x(t)$ evolves according to

$$\dot{x}(t) = \tilde{D}\alpha e^{-\alpha(\tau_d+t)} - k_a(t)x(t). \quad (17)$$

Assuming a reoccupation period of 10 years, we analytically solve the linear ODE (17) and integrate its solution from time $T = 21$ days (which represents a typical value, given our goal of full reoccupation by 42 days) to 10 years, and then computationally maximize $\int_T^{10 \text{ yr}} x(t) dt$ to get $\alpha = 1.34 \times 10^{-3}$ /hr.

3.6 Sampling and Cleaning Strategies

Our strategy employs an initial pre-cleaning sample followed by successive rounds of cleaning and sampling, and contains two decision variables, one dictating how much sampling to do and one specifying how clean the room should be. Each sampling includes n_s floor samples per room; n_s is a decision variable that allows us to assess the appropriate amount of sampling. A room's microenvironment will lead to unpredictable spatial heterogeneity of spore concentrations within the room. Rather than use a spatial model to capture this statistical uncertainty [19], we assume that samples are log-normally distributed with median e^μ equal to the true spore concentration on the floor, which is given by $c_f(0)$ in (15) if sampling occurs before cleaning is initiated and by $c_f(t)$ in (3) if sampling occurs at time $t > 0$. The dispersion is $e^\sigma = 10^{1/4}$ (i.e., the ln of the samples are normal with mean μ and standard deviation σ), so that 95% of the samples fall within one order of magnitude (i.e., between $1/\sqrt{10}$ of the median and $\sqrt{10}$ of the median). The samples from the Hart Senate Office Building appear to have somewhat more variability than this, although they were taken from an area larger than the size of our generic room. The initial pre-cleaning samples are denoted by $(Y_{01}, \dots, Y_{0n_s})$, and our point estimate of $c_f(0)$ is

$$\hat{D}_0 = \exp\left(\frac{\ln(Y_{01} \cdots Y_{0n_s})}{n_s}\right). \quad (18)$$

We assume that vacuuming the room surfaces and contents takes $\tau_v = 2$ hr per room, and each worker cleans two rooms per day; as explained in the main text, six hours per ten-hour shift are required for rest, rehydration, and dealing with protective gear. Cleaning and testing are on the following 48-hour cycle. The initial testing takes place at time 0, the first cleaning takes place during the interval [24,26] hours and, if need be, every 48 hours thereafter. Additionally, any desired testing takes place at multiples of 48 hours (i.e., $t = 48, 96, \dots$). The 24-hour delay between the initiation of cleaning and subsequent testing (if need be) allows most of the spores to resettle after cleaning, while the 24-hour

delay between testing and subsequent cleaning (if need be) permits test results, which are typically known within about 18 hours, to be received before deciding whether subsequent cleaning is required. We implicitly assume that each cleaner works on two sets of two rooms on alternate days so as to avoid idleness while waiting for test results from the first set of rooms. Let $\tau_a = 24$ hr, which represents the time between a test and the next cleaning (if need be) and between a cleaning and the next test (if need be). Let n_r be the number of days until reoccupation, i.e., reoccupation occurs at time

$$T = n_r \tau_a. \quad (19)$$

Because reoccupation occurs after a final test result (see below), n_r must be an odd number. Hence, the number of vacuumings will be $(n_r - 1)/2$, and the indicator function for cleaning is given by

$$I_f(t) = I_w(t) = \begin{cases} 1 & \text{if } t \in \{[\tau_a, \tau_a + \tau_v), [3\tau_a, 3\tau_a + \tau_v), \dots, [(n_r - 2)\tau_a, (n_r - 2)\tau_a + \tau_v)\}; \\ 0 & \text{if } t \in \{[0, \tau_a), [\tau_a + \tau_v, 3\tau_a), \dots, [(n_r - 3)\tau_a + \tau_v, (n_r - 2)\tau_a)\}. \end{cases} \quad (20)$$

To allow more highly contaminated rooms to receive more intensive cleaning, we let n_r vary according to the estimated deposition. In fact, n_r (and hence T) will be a random variable because of the statistical uncertainty in the measurement samples. More specifically, in each round of cleaning and sampling, we vacuum the room on alternate days (i.e., once every 48 hours) until it is believed that the floor concentration is below the threshold parameter \bar{c}_f , which is the second decision variable in our strategy. Then we take n_s samples in an attempt to confirm that the floor concentration is indeed below the threshold. If our new estimate is below the threshold, then vacuuming ceases. Otherwise, we use the new estimate to determine how many more vacuumings are needed to get below the threshold; in the latter case, we then perform these vacuumings and retest. This process of cleaning and sampling is repeated until a post-cleaning sample produces an estimate that is below the threshold. Hence, we assume that the decision maker has access to the compartmental model

in (1)-(3) and the current point estimate, but not the exact current state. This implicitly assumes that the managers have a reasonably good estimate of the number of air exchanges per hour ($k_a(t)$) and the vacuuming efficiencies ($k_f(t)$, $k_w(t)$), which is likely the case for an experienced asbestos cleanup crew, for example. To describe this process mathematically, we note that in round l , we perform $n_l/2$ vacuumings until our estimated floor concentration next drops below the threshold parameter \bar{c}_f ; by definition, n_l is an even number. Then we take our l^{th} set of post-cleaning samples, $(Y_{l1}, \dots, Y_{ln_s})$, which are log-normally distributed with median $e^\mu = c_f(\sum_{k=1}^l n_k \tau_a)$, thereby generating the estimated post-cleaning floor concentration of

$$\hat{D}_l = \exp\left(\frac{\ln(Y_{l1} \cdots Y_{ln_s})}{n_s}\right). \quad (21)$$

Let $c_a(t; \hat{D}_l)$, $c_w(t; \hat{D}_l)$ and $c_f(t; \hat{D}_l)$ be the estimated room concentrations at time $t \in [\sum_{k=1}^l n_k \tau_a, \sum_{k=1}^{l+1} n_k \tau_a)$, which is the time interval between the l^{th} and $l+1^{\text{st}}$ post-cleaning samples. These quantities are computed as follows. The true state of the system at the time of the l^{th} post-cleaning sample is $c_a(\sum_{k=1}^l n_k \tau_a)$, $c_w(\sum_{k=1}^l n_k \tau_a)$ and $c_f(\sum_{k=1}^l n_k \tau_a)$, as computed by (1)-(3). After taking the measurements leading to \hat{D}_l in (21) at time $\sum_{k=1}^l n_k \tau_a$, the estimated floor concentration at time $\sum_{k=1}^l n_k \tau_a$ is by definition

$$c_f\left(\sum_{k=1}^l n_k \tau_a; \hat{D}_l\right) = \hat{D}_l. \quad (22)$$

We assume that air and wall concentrations at time $\sum_{k=1}^l n_k \tau_a$ are also misestimated by the factor $\frac{\hat{D}_l}{c_f(\sum_{k=1}^l n_k \tau_a)}$, which gives

$$c_a\left(\sum_{k=1}^l n_k \tau_a; \hat{D}_l\right) = \frac{\hat{D}_l}{c_f(\sum_{k=1}^l n_k \tau_a)} c_a\left(\sum_{k=1}^l n_k \tau_a\right), \quad (23)$$

$$c_w\left(\sum_{k=1}^l n_k \tau_a; \hat{D}_l\right) = \frac{\hat{D}_l}{c_f(\sum_{k=1}^l n_k \tau_a)} c_w\left(\sum_{k=1}^l n_k \tau_a\right). \quad (24)$$

The quantities $c_a(t; \hat{D}_l)$, $c_w(t; \hat{D}_l)$ and $c_f(t; \hat{D}_l)$ for $t \in [\sum_{k=1}^l n_k \tau_a, \sum_{k=1}^{l+1} n_k \tau_a)$ are computed by solving (1)-(3) starting at time $\sum_{k=1}^l n_k \tau_a$ with initial conditions given by the estimated concentrations in (22)-(24) rather than the true concentrations.

We can now define the number of days until reoccupation, n_r , which is a random variable given by

$$n_r = \begin{cases} 1 & \text{if } \hat{D}_0 < \bar{c}_f; \\ 2(\sum_{l=1}^j n_l) + 1 & \text{if } \begin{cases} \text{for } l = 1, \dots, j \begin{cases} \hat{D}_{l-1} \geq \bar{c}_f; \\ c_f(i\tau_a; \hat{D}_{l-1}) \geq \bar{c}_f, i = 0, 2, 4, \dots, n_l - 2; \\ c_f(n_l\tau_a; \hat{D}_{l-1}) < \bar{c}_f; \end{cases} \\ \hat{D}_j < \bar{c}_f. \end{cases} \end{cases} \quad (25)$$

3.7 Post-reoccupation Cleaning and Cumulative Dose

We assume that the contaminated zone is reoccupied at the density of $\gamma = 0.075$ people/m² of floor space [2], which is one person per generic room. These reoccupants reside in these buildings for 12 hours per day, breathing at rate $b = 138$ m³/hr [20] from a (sitting or sleeping) height of 1 m. To be conservative, we assume that these rooms experience active conditions during these 12 hours and experience semi-quiescent conditions during the other 12 hours. That is, we assume that for $t > T$ measured in hours,

$$f_w(t) = \begin{cases} \tilde{f}_w^a & \text{if } t \in [T + 24n, T + 24n + 12), n = 0, 1, \dots; \\ \tilde{f}_w^s & \text{if } t \in [T + 24n + 12, T + 24(n + 1)), n = 0, 1, \dots; \end{cases} \quad (26)$$

$$r_w(t) = \begin{cases} \tilde{r}_w^a & \text{if } t \in [T + 24n, T + 24n + 12), n = 0, 1, \dots; \\ \tilde{r}_w^s & \text{if } t \in [T + 24n + 12, T + 24(n + 1)), n = 0, 1, \dots; \end{cases} \quad (27)$$

$$r_f(t) = \begin{cases} \tilde{r}_f^a & \text{if } t \in [T + 24n, T + 24n + 12), n = 0, 1, \dots; \\ \tilde{r}_f^s & \text{if } t \in [T + 24n + 12, T + 24(n + 1)), n = 0, 1, \dots. \end{cases} \quad (28)$$

The deposition and reaerosolization parameter values during the semi-quiescent post-reoccupation periods are assumed to be identical to the semi-quiescent parameter values during the cleanup period, i.e., $\tilde{f}_w^s = f_w^s$, $\tilde{r}_w^s = r_w^s$ and $\tilde{r}_f^s = r_f^s$. However, the walls are not cleaned during the active post-reoccupation periods (see below), and are likely to experience much less reaerosolization than in the active cleaning period. On the other hand, spores are more apt to deposit on the walls during active conditions than semi-quiescent conditions. Hence, we

assume that $\frac{\tilde{r}_w^a}{\tilde{r}_f^a} = \frac{\tilde{r}_w^s}{\tilde{r}_f^s} = 8.79 \times 10^{-3}$, i.e., the ratio of wall-to-floor reaerosolization during the active reoccupation period is the same as the wall reaerosolization during the semi-quiescent cleanup period divided by the floor reaerosolization during the active cleanup period. We solve this equation simultaneously with (8)-(10) and obtain the values of \tilde{r}_w^a , \tilde{r}_f^a and \tilde{f}_w^a that appear in Table 1.

We assume that post-reoccupation cleaning (performed or paid by the reoccupants, without protective gear) occurs at lower levels than during the remediation period. A portable HEPA filter with a fan operated at a flow rate of 404 m³/hr, which is representative of commercial air cleaners, achieved an air exchange rate of 3.0/hr in a room the size of our generic room [9]. We assume that the HEPA filters and fans achieve an air exchange rate of $\tilde{k}_a^a = 3.0$ /hr during the 12 hours of active conditions (i.e., the fans are left running while people are present), and achieves an air exchange rate of $\tilde{k}_a^s = 0.5$ /hr during the other 12 hours in a day. That is,

$$k_a(t) = \begin{cases} \tilde{k}_a^a & \text{if } t \in [T + 24n, T + 24n + 12), n = 0, 1, \dots; \\ \tilde{k}_a^s & \text{if } t \in [T + 24n + 12, T + 24(n + 1)), n = 0, 1, \dots \end{cases} \quad (29)$$

We assume that the floor, which has area $A_f = 16.05$ m², is HEPA vacuumed (dry rather than wet) once per $\tilde{\tau}_a = 7$ days for $\tau_f = 10$ minutes. To derive the cleaning rate $k_f(t)$, we assume that the post-reoccupation vacuum is half as efficient as the wet vacuum used during the cleanup, so that $\frac{65\text{min}}{46.5\text{m}^2}$ achieves only a 35% reduction in spores. Therefore, for $t \geq T$, we have $k_f(t) = \frac{-\ln(0.65)46.5\text{m}^2}{A_f 65\text{min}} = 1.15$ /hr, which coincidentally is the same as $k_f(t)$ during cleanup. Because $e^{-k_f(t)\tau_f} = 0.825$, each round of post-reoccupation vacuuming only removes 17.5% of the remaining spores. No vacuuming of the walls or ceilings occurs during the reoccupation period. That is, for $t > T$, we set $I_w(t) = 0$ in (2) and change $I_f(t)$ in (3) to

$$I_f(t) = \begin{cases} 1 & \text{if } t \in \{[T + n\tilde{\tau}_a, T + n\tilde{\tau}_a + \tau_f), n = 1, 2, \dots\}; \\ 0 & \text{if } t \in \{[T, T + \tilde{\tau}_a), [T + n\tilde{\tau}_a + \tau_f, T + (n + 1)\tilde{\tau}_a), n = 0, 1, \dots\}. \end{cases} \quad (30)$$

We calculate the number of spores inhaled by each reoccupant over a 10-year horizon by solving the ODE system (1)-(3) for $t > T$ and converting the average air concentration $c_a(t)$ into the air concentration at the height of 1 m by multiplying $c_a(t)$ by the factor

$$\frac{ae^{-a}}{\frac{\int_0^H ae^{-aH}}{H}} = \frac{Hae^{-a}}{1 - e^{-aH}} = 0.716. \quad (31)$$

Hence, if we let s denote the number of spores inhaled by a reoccupant over a post-reoccupation period of ten years, and define the indicator residential function

$$I_r(t) = \begin{cases} 1 & \text{if } t \in [T + 24n, T + 24n + 12), n = 0, 1, \dots; \\ 0 & \text{if } t \in [T + 24n + 12, T + 24(n + 1)), n = 0, 1, \dots, \end{cases} \quad (32)$$

then

$$s = \frac{Hae^{-ab}}{1 - e^{-aH}} \int_T^{T+10 \text{ yr}} c_a(t) I_r(t) dt. \quad (33)$$

Note that s is a random variable because the lower integration limit T and the air concentration $c_a(t)$ depend on the sampling results.

3.8 Vaccine Coverage, Efficacy and Cost

The current vaccine is only licensed for, and has only been tested on, people from 18 to 65 years of age [21]. The vaccine is contraindicated for people with prior hypersensitivity or other severe reaction to any anthrax vaccine or those who have recovered from a prior clinical exposure. Precautions would apply to immunocompromised patients and those on immunosuppressant therapy, and those with a history of hypersensitivity to other medication. In addition, people who are pregnant or breastfeeding, have an infection/febrile illness or are on a short course of steroids should delay taking the vaccine [22]. To be conservative, we assume that a fraction $f_v = 0.85$ of the reoccupants are vaccinated, leaving 15% of the population, including young children, people over 65, and the immunocompromised, unvaccinated. The Working Group on Civilian Biodefense suggests that the US vaccine is likely

to be safe and effective in children [21]; hence, it is more likely that all noncontraindicated people would be offered the vaccine, and that the vaccine would be effective for more than 15% of the population. For the 85% vaccinated population, we assume the vaccine is fully protective, and causes no inhalational anthrax cases for the reoccupants, regardless of the spore levels. Because it is not practical to keep people on prophylactic antibiotics indefinitely, we assume that the 15% unvaccinated reoccupants receive no medical protection. The vaccine, which requires a series of six shots over 18 months plus an annual booster [21], is assumed to cost $c_v = \$20$ per person.

3.9 The Dose-Response Model

We need a dose-response curve that maps the cumulative dose in (33) into a response. The most widely accepted model is a probit model with a slope of 0.7 probits per log dose and an ID_{50} of 8000 spores [23]; i.e., the probability that someone who inhales s spores becomes infected is $\Phi(0.3 \ln s - 2.7)$, where $\Phi(\cdot)$ is the standard normal cumulative distribution function. This probit slope is from Glassman's primate study [24] and the ID_{50} is an estimate from the US Department of Defense [25]. There is considerable uncertainty on the low end of the dose-reponse curve. Haas [26] considers three data sources: Glassman's unpublished data (1236 animals, lowest dose considered is about ID_{20}) [24], Druett's monkey study (72 animals, range from 70,000 to 400,000 spores) [27], and Brachman's study (120 monkeys, range from 1000 to 25,000 spores) [28]. He argues that an exponential model is a better fit to the latter two studies than the probit model, and also that the probit model overestimates the fraction infected. However, Glassman's study is probably the most reliable, since it uses a large sample size and controlled conditions. In addition, Dahlgren [29] claims that goat-hair mill workers routinely inhaled about 500 (sub 5 micron) anthrax spores per shift without getting infected. Hence, people may develop immunity if exposed at low levels for

long periods. More recently, the 94-year old CT woman who died from inhalation anthrax without any evidence of anthrax in her house suggests that an elderly person can get infected from several spores [30]. This case is more consistent with a slope of 0.7 than of 1.4: the probability of someone getting infected from 5 spores is 0.013 if the slope is 0.7 (note that hundreds of people probably received cross-contaminated letters in 2001), but is only 4×10^{-6} if the slope is 1.4.

Because the dose-response curve for our model is for those who are not vaccinated, the probit model discussed above may underestimate the fraction of cases from these subpopulations. Consequently, we assume that the 15% unvaccinated are sampled randomly from the bottom 30% of the probit dose-response curve described above, so that the probability $p(s)$ that an unvaccinated reoccupant is infected by inhaling s spores is

$$p(s) = \min \left\{ \frac{\Phi(0.3 \ln s - 2.7)}{0.3}, 1 \right\}. \quad (34)$$

3.10 Computation of Cases, Cost and Total Cleaning Time

From §1, we have $n(D)$ square meters of indoor space that have a deposition of D spores/m². For a deposition of D spores/m², equations (19), (25) and (33) give the random number of spores inhaled over a 10-year reoccupancy, equation (34) gives the dose-response curve for the 15% of reoccupants that are unvaccinated, and γ is the population density of reoccupants. Taken together, if we define $f(s; D)$ to be the probability density function of the number of inhaled spores s in (33) for a fixed value of D , then the expected number of inhalation anthrax cases is

$$(1 - f_v)\gamma \int \left(\int p(s) f(s; D) ds \right) n(D) dD, \quad (35)$$

where the inner integral represents the likelihood of infection given the dose D , and the outer integration is over the entire dose range in the exposed region. Because the function $f(s; D)$ does not have an explicit analytical form, we resort to Monte Carlo simulation to

compute (35). More specifically, we simulate (35) 50 times, which results in the 95% half-confidence interval for the number of anthrax cases to be less than 0.1 times the sample mean of the number of cases.

We assume that each Hazmat person is paid $c_l = \$75/\text{hr}$, which includes the use of the vacuums. According to §3.6, the labor cost to clean four generic rooms is $c_l(2\tau_v + \tau_p)(n_r - 1)$, where $\tau_p = 6$ hr accounts for getting in and out of, and decontaminating, protective gear, and rest and rehydration. In addition, each environmental sample costs $c_s = \$25$, which includes a $\$30/\text{hr}$ sampler obtaining 2.4 samples/hr (see the next paragraph), plus $\$1$ for shipping, plus $\$11.50/\text{sample}$ for the laboratory cost. We assume that each portable HEPA cleaner costs $c_h = \$250$; everyone is assumed to already own a vacuum. Let us define $h(n_r; D)$ to be the probability density function of n_r as given in (25), and $g(j; D)$ to be the probability density function of the quantity j in (25) for fixed D , which is the total number of rounds of post-cleaning sampling. Then the total expected cost, which includes labor, sampling, HEPA cleaners and vaccines, to remediate the entire exposed region of A m² of floor surface area is

$$\begin{aligned} & \frac{(2\tau_v + \tau_p)c_l}{4(13.38)} \int \left(\int (n_r - 1)h(n_r; D) dn_r \right) n(D) dD + \frac{A}{13.38} c_h + f_v \gamma A c_v \\ & + \frac{c_s n_s}{13.38} \int \left(\int (j + 1)g(j; D) dj \right) n(D) dD. \end{aligned} \quad (36)$$

The Brentwood cleanup used about 300 Hazmat people (after attrition) and there are about 3000 licensed asbestos cleanup workers in New York State, many of whom could be recruited. We assume that $l_h = 1000$ Hazmat people are available to perform cleanup for $2\tau_v + \tau_p = 10$ hours per day. Hence, $4l_h$ rooms can be cleaned every $n_r - 1$ days. In addition, $l_s = 200$ samplers require 10 min per sample over four hours plus six hours to rest, rehydrate, and put on and remove protective gear, leading to a throughput rate per sampler of $\mu_s = 24$ samples per day. We assume the bottleneck for the cleanup time can be either vacuuming or sampling. Hence, the expected number of days required to remediate the entire exposed

region is

$$\max \left\{ \frac{1}{4(13.38)l_h} \int \left(\int (n_r - 1)h(n_r; D) dn_r \right) n(D) dD, \frac{n_s}{\mu_s(13.38)l_s} \int \left(\int jg(j; D) dj(D) \right) n(D) dD \right\}. \quad (37)$$

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Parameter	Description	Value	Reference
A	Total exposed indoor floor area	$5.73 \times 10^7 \text{ m}^2$	§1
	Size of generic room	$12 \times 12 \times 8 \text{ ft}$	§3.1
V	Room volume	32.62 m^3	§3.1
A_f	Floor surface area in room	16.05 m^2	§3.1
A_w	Walls surface area in room	58.86 m^2	§3.1
D_p	Spore diameter	$3 \text{ }\mu\text{m}$	[21]
C	Cunningham slip factor	1.05	[8]
g	Acceleration of gravity	9.81 m/s^2	§3.2
ρ	Density of air	1.184 kg/m^3	§3.2
v_d	Dynamic velocity	$1.83 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$	§3.2
ρ_p	Density of anthrax spores	283 kg/m^3	§3.2
	Inverse spore mass	$2.5 \times 10^{14} \text{ spores/kg}$	[21]
v_y	Gravimetric settling velocity	$7.93 \times 10^{-5} \text{ m/s}$	(4)
l_a	Surface adsorption parameter	$1.82 \times 10^{-4}/\text{s}$	§3.2
f_w^a, \tilde{f}_w^a	Fraction deposited on walls (active)	0.098, 9.55×10^{-4}	(8)-(11)
f_w^s, \tilde{f}_w^s	Fraction deposited on walls (semi-quiescent)	8.63×10^{-4}	(8)-(10),(12)
r_w^a, \tilde{r}_w^a	Reaerosolization from walls (active)	1.252/hr, 0.012/hr	(8)-(11)
r_w^s, \tilde{r}_w^s	Reaerosolization from walls (semi-quiescent)	0.011/hr	(8)-(10),(12)
r_f^a, \tilde{r}_f^a	Reaerosolization from floor (active)	1.252/hr, 1.387/hr	(8)-(11)
r_f^s, \tilde{r}_f^s	Reaerosolization from floor (semi-quiescent)	0.011/hr	(8)-(10),(12)
a	Exponential settling parameter	1.83/m	§3.2
f_a^a	Fraction reaerosolized (active)	0.72	§3.2
f_a^s	Fraction reaerosolized (semi-quiescent)	0.02	§3.2
W	Duct width	0.4 m	[8]
L	Duct length	50 m	§3.5
v_x	Duct air flow rate	5.08 m/s	[8]
r_1	Inner radius of curved duct	0.3 m	[8]
r_2	Outer radius of curved duct	0.7 m	[8]
S	Average Stokes number of spores	5.61×10^{-5}	§3.5
θ	Total curvature in ducts	2π	§3.5
η	Duct efficiency	2.24×10^{-3}	§3.5
α	Spore disengagement rate from duct	$1.34 \times 10^{-3}/\text{hr}$	(17)
γ	Population density	0.075 people/m^2	3.7
b	Breathing rate	$1.38 \text{ m}^3/\text{hr}$	[20]
	Breathing height	1 m	§3.7
	Dose-response model		(34)

Table 1: Values for non-remediation parameters.

Parameter	Description	Value	Reference
c_c	Cost to fumigate first square meter	\$609	§2
τ_c	Time to fumigate first square meter	0.082 hr	§2
	Chlorine dioxide learning rate	90%	§2
τ_d	Remediation delay	7 days	§3.1
$k_a(t), t < T$	HEPA air exchange rate during cleanup	10/hr	§3.7
e^σ	Dispersion of random floor samples	$10^{1/4}$	§3.6
τ_v	Vacuuming time per room	2 hr	§3.6
$k_w(t), t < T$	Wall cleaning rate during cleanup	1.15/hr	§3.6
$k_f(t), t < T$	Floor cleaning rate during cleanup	1.15/hr	[18], §3.6
n_s	Number of floor samples	Decision	§3.6
\bar{c}_f	Floor threshold level for vacuuming	Decision	§3.6
τ_a	Time interval between vacuuming and testing	24 hr	§3.6
\tilde{k}_a^a	Post-reoccupation air exchange rate (active)	3/hr	§3.7
\tilde{k}_a^s	Post-reoccupation air exchange rate (semi-quiescent)	0.5/hr	§3.7
$\tilde{\tau}_a$	Post-reoccupation time interval between vacuummings	7 days	§3.7
$k_f(t), t \geq T$	Post-reoccupation floor cleaning rate	1.15/hr	§3.6
τ_f	Post-reoccupation floor vacuuming time	10 min	§3.7
f_v	Fraction vaccinated	0.85	§3.8
c_v	Vaccination cost	\$20/person	§3.8
c_l	Hazmat salary	\$75/hr	§3.10
τ_p	Time for protective gear	6 hr	§3.10
c_h	Cost of portable HEPA air cleaner	\$250	§3.10
l_h	Number of Hazmat personnel	1000	§3.10
c_s	Sampling cost	\$25	§3.10
μ_s	Sampling rate per sampler	48/day	§3.10
l_s	Number of human samplers	200	§3.10

Table 2: Values for remediation parameters.