MODELING THE SPREAD OF ANTHRAX IN BUILDINGS

RG Sextro*, DM Lorenzetti, MD Sohn, and TL Thatcher

Indoor Environment Dept., Lawrence Berkeley National Lab, Berkeley, CA, USA

ABSTRACT
The recent contamination of several U.S. buildings by letters containing anthrax demonstrates the need to understand better the transport and fate of anthrax spores within buildings. We modeled the spread of anthrax for a hypothetical office suite and estimated the distribution of mass and resulting occupant exposures. Based on our modeling assumptions, more than 90% of the anthrax released remains in the building during the first 48 hours, with the largest fraction of the mass accumulating on floor surfaces where it is subject to tracking and resuspension. Although tracking and resuspension account for only a small amount of mass transfer, the model results suggests they can have an important effect on subsequent exposures. Additional research is necessary to understand and quantify these processes.

INDEX TERMS
Resuspension, tracking, deposition, multizone air flow, bio-aerosols

INTRODUCTION
The release and subsequent dispersion of anthrax spores within several U.S. buildings have illustrated the lack of detailed knowledge about the mechanisms by which building occupants can be exposed to anthrax or other bio-aerosols. In particular, the degree to which contamination spreads from one room to another – and by what mechanisms – is poorly understood quantitatively. The transport and fate of these bio-aerosols has implications not only for exposure assessment but for subsequent decontamination efforts as well.

The behavior of aerosols indoors has been studied both experimentally and theoretically (see, for example, Lai and Nazaroff, 2000; Thatcher et al., 2002; Wallace 1996) and many ofthe factors influencing aerosol transport and fate are reasonably well understood. These include: (1) air flow from room to room or between the building interior and outdoors driven by HVAC operation, by thermal stack effects, and by wind loads on the building shell; (2) deposition to interior surfaces; (3) filtration; and (4) coagulation. Occupant-related processes can also affect aerosol behavior. Some studies have observed differences between 'personal' and 'room' exposures, attributed – at least in part – to resuspension of deposited or tracked materials (Ozkaynak et al., 1996). However, these processes are not well quantified.

Our overall goal in this study is to examine the exposure potential from an anthrax release in a room using a broadly applicable mechanistic model. The objectives of this work are to gain a better understanding of the factors that influence potential exposures and to identify key features of this problem for which additional research is necessary.

*Contact author email: rgsextro@LBL.gov

METHODS

Model Description

The basic elements of the aerosol transport and fate model are illustrated in Figure 1. The simulation program represents the contaminant transport network as an assemblage of storage locations, which accumulate contaminant mass, and transport elements, which carry contaminant between locations. The resulting system of coupled ordinary differential equations describes mass conservation in the storage locations. This approach allows the addition of other storage locations or transport processes not captured in this initial effort.

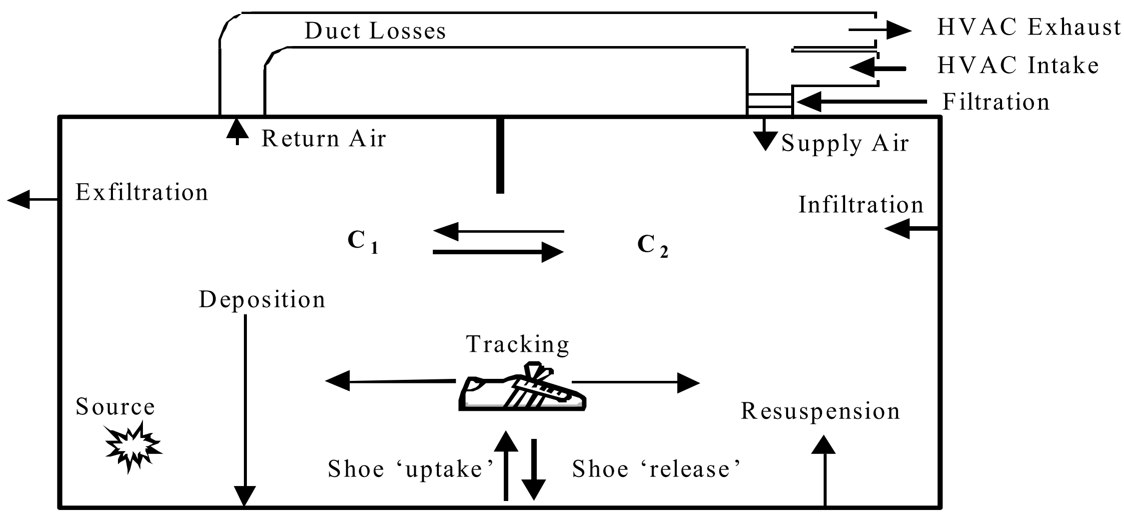

Figure 1. Schematic of the various anthrax transport and fate mechanisms. The floor surfaces are subdivided into tracked and untracked areas.

Storage locations include: (1) zones, which contain airborne contaminant (e.g. C_1 and C_2 in Figure 1); (2) zone and duct surfaces, such as walls and floors, where contaminant may settle; and (3) filters, which trap contaminants in the HVAC flow path. Transport elements include: (1) flow paths, which move air between zones; (2) deposition to zone and flow path surfaces; (3) a source rate term; and (4) an activity model, described below. For this study, the steady airflow rates were calculated using the multizone airflow program COMIS (Feustel 1999). .

The activity model accounts for three effects associated with human activity: (1) exchanges of contaminant between a person and building surfaces, for example between shoes and floor surfaces; (2) resuspension of contaminant from building surfaces to zone air, as a result of a person touching the surface (in this case, a person walking); and (3) tracking from room to room, for example when shoes load with pollutant from a heavily-contaminated floor, then lose mass after moving to a different, relatively clean floor. The exchange and resuspension processes vary directly with the activity level, defined as the rate at which a person touches building surfaces. The activity rate, the building surface for exchange, and the zone for resuspension, all may be scheduled within the model to vary over time. In this study, we partitioned floor surfaces into tracked and untracked areas. Deposition of airborne particles occurs uniformly on surfaces in both categories, however, tracking and resuspension occur only on the tracked surfaces.

Scenarios

We established a set of scenarios, built around a specific arrangement of rooms in a hypothetical office building, to explore the model assumptions and the various input parameters. Figure 2 shows the floor plan of the office suite and the location of the anthrax source. The scenarios consist of different HVAC system configurations, building operating conditions and sets of occupant activity patterns. For the present paper we describe the results obtained from one scenario. In this case, the HVAC supply and return flows in each room are balanced, with a total HVAC system flow equal to 6 volume changes per hour and with the outdoor air supply making up 25 percent of this flow.

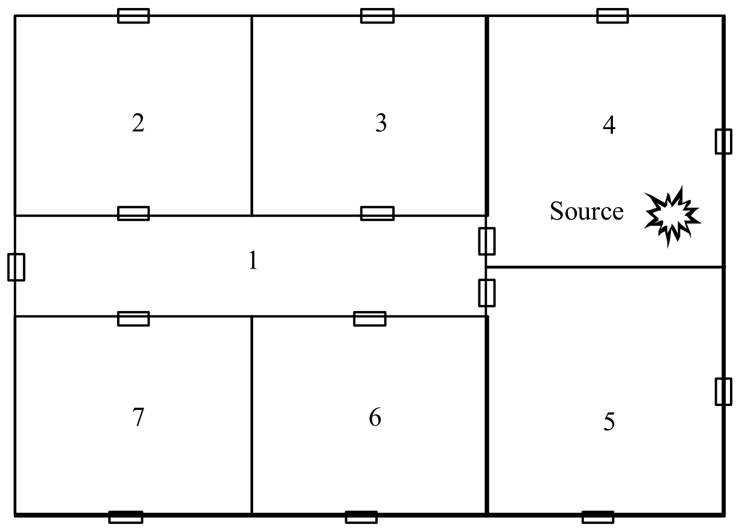

Figure 2. Floor plan of the hypothetical office suite. Room 1 is a hallway, room 2 is a common room, and rooms 3 to 7 are each assigned an occupant. The small open rectangles represent closed exterior windows and open doors between the offices and the hallway. The volume of each room is ~80 m^3.

We established activity patterns for six people in the space – each following a different movement pattern. For this scenario we assigned one person to each of the five offices and assumed they are all in their own offices at the time of the anthrax release in Room 4 (each person is labeled with their respective office number in Figure 2). A sixth individual (referred to as person 8) walks into the office suite two hours after the initial release, when airborne concentrations have been substantially reduced. Thus the exposure experienced by this person is dominated by resuspension. We simulated a 48 hour time period following the anthrax release, assuming that all six people followed the same activity pattern on day 2 as on day 1, but without a second anthrax release.

For our simulations we postulated that the source is an envelope containing 1 gram of anthrax opened in Room 4. We assumed that 50% of the initial mass stays in the envelope (and thus warrants no further consideration here), 75% of the mass of anthrax released from the envelope deposits uniformly on the floor surface in Room 4 and the remaining 25% disperses immediately and uniformly into the room air. This represents the initial state for the modeling. Note that exposures described below will scale with alternative mass distributions.

Other key assumptions are: (1) anthrax spores deposited on 'untracked' surfaces, in the ducts or on the HVAC filter remain in those locations; (2) spores deposited on the floor do not change physically, that is, spores deposited with a given aerodynamic diameter maintain that diameter for purposes of resuspension; and (3) the rates for anthrax 'uptake' and 'release' by shoes are strictly estimates and have been set equal. The key aerosol parameters are shown in Table 1; for the baseline case, we used the parameter values for five-micrometer-diameter aerosols. Anthrax aerosols, consisting of spore aggregates, range in diameter from ~2 to ~10 micrometers (Thatcher et al., 2000).

Table 1. Values for aerosol parameters used in simulations

Transport values (units)	Aerosol diameter (micrometers) 1	3	5	10	Reference
Shoe uptake (h^{-1})	0.1	0.1	0.1 (a)	0.1	Current estimate
Shoe release (h^{-1})	0.1	0.1	0.1 (a)	0.1	Current estimate
Resuspension (h^{-1})	$1.2x10^{-4}$	$1.9x10^{-3}$	$3.8x10^{-3}$	$3.4x10^{-2}$	Thatcher & Layton 1995
Deposition-floors (h^{-1})	0.1	0.6	2.0	8.1	Composite experimental
Dep'n - walls/ceiling (h^{-1})	0.1	0.4	0.8	0.9	Composite experimental
Duct loss fraction (m^{-1})	$4x10^{-5}$	$6.0x10^{-4}$	$1.9x10^{-3}$	$6.1x10^{-3}$	Sippola 2001
Filter efficiency (-)	0.098	0.49	0.74 (b)	0.88	Delp 2001

Note a: parameters ranged from 0.01 to 0.5 in sensitivity analysis
Note b: filtration efficiency ranged from 0 to 1.0 in sensitivity analysis

RESULTS AND DISCUSSION

Figure 3 shows, for the first four hours after the release, the fraction of anthrax in several representative storage locations. The airborne concentration in Room 4 rapidly declines within the first hour due largely to removal by deposition, by ventilation to outdoors, and by air exchange with other rooms. The response of Room 7 shown in Figure 3, typical of the response in the other five rooms, shows an initial increase in concentrations as air movement within the office suite transports contaminant from the source room. The moderate filtration efficiency used for the baseline case in this scenario limits, but does not prevent, the spread of anthrax via the HVAC system.

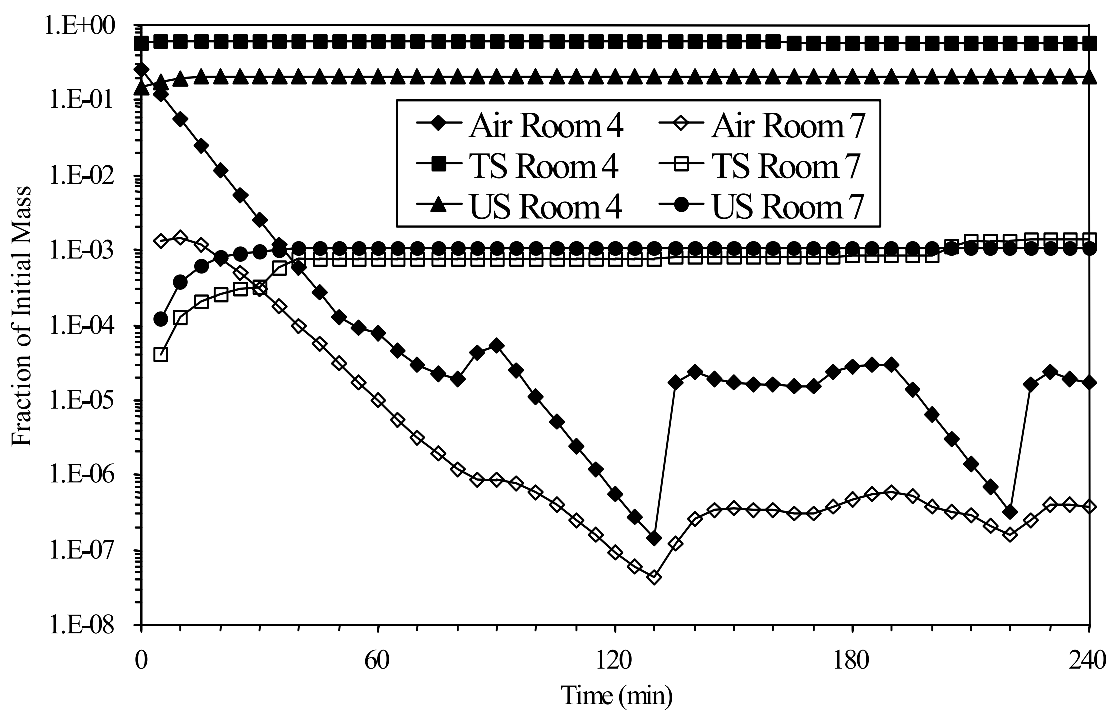

Figure 3. Mass fraction of anthrax in several representative storage locations as a function of time after release, where TS and US refer to tracked and untracked surfaces, respectively.

Although there is activity in both rooms, it is not until the airborne spore concentrations decline significantly that the effects of occupant activity can be discerned. For example, the concentration peaks seen at ~80 min result from resuspension. Furthermore, Figure 3 shows that occupant-related tracking increases the concentration on the tracked portion of the floor, relative to the untracked surface (the greater mass contained on the untracked surfaces reflects the fact that they take up a greater area than the tracked part of the floor).

These effects are also illustrated by the data in Table 2, which show a slight decrease in the mass fraction for all tracked surfaces over time, but an increase in the fraction of mass accumulating on the tracked surfaces when Room 4 is excluded. Simulations over greater time periods, or with more activity, would show even greater transport of spores due to human activity. The amount of mass collected on the HVAC filter, ~10%, reflects our choice of filtration efficiency. Note that under the simulation conditions we assumed, only ~ 6% of the anthrax is transported outdoors over the 48 hour time period.

Table 2. Fraction of released anthrax in various storage locations as a function of time

	Time (hr)					
Location	0.5	1	4	8	24	48
All tracked surfaces (TS)	0.62	0.61	0.61	0.61	0.61	0.61
All untracked surfaces (US)	0.21	0.22	0.22	0.22	0.22	0.22
All TS w/o Room 4	0.0066	0.0075	0.02	0.031	0.036	0.066
All US w/o Room 4	0.0082	0.0089	0.0089	0.0089	0.0089	0.009
Outside	0.059	0.060	0.060	0.060	0.060	0.061
HVAC filter	0.1	0.1	0.1	0.1	0.1	0.1
HVAC ductwork	0.0034	0.0035	0.0035	0.0035	0.0035	0.0035

The model calculates the integrated exposures for each of the six persons included in this scenario, based on the air concentrations in the rooms as functions of time and the activity pattern for each person. To convert the exposures to dose (in spores), we assume a constant breathing rate of 20 L/min and a bulk concentration for anthrax of $3x10^{10}$ spores per gram (Thatcher et al., 2000).

Table 3. Cumulative Doses (in spores) for selected time intervals for each day. The dose on day 2 is the incremental dose for that day.

		Time (hr)				
Person		0.5	1	4	8	10
3	day 1	$1.0x10^5$	$1.1x10^5$	$1.1x10^5$	$1.1x10^5$	$1.1x10^5$
	day 2	51	76	710	1900	2100
4	day 1	$5.1x10^6$	$5.1x10^6$	$5.2x10^6$	$5.2x10^6$	$5.2x10^6$
	day 2	2300	3300	$1.1x10^4$	$1.7x10^4$	$2.0x10^4$
5	day 1	$2.2x10^5$	$2.4x10^5$	$2.4x10^5$	$2.4x10^5$	$2.4x10^5$
	day 2	130	1200	2200	4500	5000
6	day 1	$1.1x10^5$	$1.2x10^5$	$1.2x10^5$	$1.2x10^5$	$1.2x10^5$
	day 2	53	80	330	530	790
7	day 1	$1.1x10^5$	$1.2x10^5$	$1.2x10^5$	$1.2x10^5$	$1.2x10^5$
	day 2	60	110	2300	3600	3900
8	day 1	0.0	0.0	190	420	420
	day 2	0.0	0.0	360	840	840

The resulting doses based on our scenario assumptions are shown in Table 3 accumulated for each 24-hour period. In this way, the additional doses obtained the second day can be seen more easily. The dose estimates in Table 3 can be compared with the dose at which 50 percent of an exposed population suffers lethal effects (the LD_{50}). For anthrax the LD_{50} is ~8,000 spores (Thatcher et al., 2000). Thus even very small fractions of the initial anthrax mass can pose a significant health risk - in some cases long after the initial release. Many of the second-day doses alone are close to the LD_{50}, while on the first day, the individual doses (excepting person 8) exceed the lethal dose by one to three orders of magnitude. On the other hand, for person 8, the cumulative dose on the second day is larger than for the first, due to the increased amount of anthrax accumulated on tracked surfaces, as shown in Table 2.

We examined the effects of two parameters, filtration efficiency and tracking, on exposures; parameter ranges are shown as footnotes to Table 1. Changing filtration efficiency illustrates the dispersion of anthrax within the office suite via the HVAC system. For some occupants, increased filtration reduces exposures dramatically in the first 24 hour period; however, this effect is not uniform, due to room-to-room airflow and tracking. For the second period, the changes in exposure are less significant, typically a 20 to 30% reduction. Changing the tracking parameter by a factor of 50 has a more modest effect on exposures. The largest effects, ~ 50% reduction in exposure, occur on the second day, when exposures are due to resuspension. Again this effect isn't uniform and depends upon the occupant activity pattern used in the scenario.

CONCLUSIONS

We developed a model to examine various scenarios for anthrax release and transport within buildings. These simulations help identify critical information or processes that contribute most to predicted outcomes or to uncertainties. This paper describes results from one of several scenarios and – based on this scenario – our simulations show the importance of airflow as a means of transporting aerosols through the building, with tracking having a more modest effect. However, activity-related resuspension is an important potential source of human exposure. Although advection and deposition are well understood, additional studies are necessary to understand better the effects of tracking and resuspension.

ACKNOWLEDGEMENTS

This work was carried out at the Lawrence Berkeley National Laboratory (LBNL) through U.S. Department of Energy under Contract Grant No. DE-AC03-76SF00098.

REFERENCES

Delp WW. 2001. Private communication, Lawrence Berkeley National Laboratory.

Feustel H. 1999. COMIS- an international multizone air-flow and contaminant transport model. *Energy and Buildings* Vol. 30, pp. 3-18.

Lai ACK, and Nazaroff WW. 2000. Modeling indoor particle deposition from turbulent flow onto smooth surfaces. *Journal of Aerosol Science* Vol 31, pp. 463-476.

Ozkaynak H, Xue J, Spengler J, *et al.* 1996. Personal exposure to airborne particles and metals: Results from the Particle Team study in Riverside, California. *Journal of Exposure Analysis and Environmental Epidemiology.* Vol 6, pp. 57-78.

Sippola M. 2001. Private Communication, University of California, Berkeley.

Thatcher TL, Lai ACK, Moreno-Jackson R, et al. 2002. Effects of Room Furnishings and Air Speed on Particle Deposition Rates Indoors. *Atmospheric Environment* (in press).

Thatcher TL, and Layton DW. 1995. Deposition, resuspension, and penetration of particles within a residence. *Atmospheric Environment*, Vol. 29, pp. 1487-1497.

Thatcher TL, Sextro R, and Ermak D. 2000. Database of Physical, Chemical and Toxicological Properties of CB Warfare Agents for Modeling Airborne Dispersion In and Around Buildings, Lawrence Berkeley National Lab report LBNL-45475 (Appendix B).

Wallace L. 1996. Indoor particles: A review. *Journal of the Air & Waste Management Association*, Vol. 46, pp. 98-126.