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# Application of CFD to Predict and Control Chemical and Biological Agent Dispersion in Buildings

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## Abstract

Terrorist attack in buildings by chemical and biological agents (CBAs) is a reality in our lives. This study applies computational fluid dynamics (CFD) to predict CBA dispersion in an office building in order to find the best locations for CBA sensors and to develop effective ventilation systems to protect building occupants in case of indoor CBA releases. It is found that the CFD is a useful tool for such an application, while some challenges remain.

**Keywords:** computational fluid dynamics (CFD), chemical and biological agents, building protection, sensor, air distribution, indoor air quality

## Introduction

The terrorist attacks on New York City and Washington D.C. on September 11, 2001 and the following anthrax dispersion by mail have spawned concerns about various possible forms of terrorism, including airborne/aerosolized chemical and biological agent (CBA) attacks. The events have confirmed that the attacks are no longer a hypothesis but a reality. Current building environments are vulnerable to a CBA attack, since the conventional ventilation systems are not designed for such an attack. How to design ventilation systems that can protect buildings from such an attack is an urgent issue for the ventilation system designers.

Most CBAs are highly poisonous. A small amount of CBA can seriously affect one's health or even his/her life. For instance, one may suffer mild injury, serious injury, and death, respectively, while inhaling as little as 0.9, 10, and 15 milligrams of VX gas – a lethal nerve agent according to U.S. Army Chemical Biological Defense Command. Normally, the dispersion of airborne CBAs is surprisingly rapid and most of them are colorless and odorless so that people can hardly notice it. CBAs are especially hazardous when they are dispersed inside of a building, where traditional ventilation systems may actually help spreading the contaminants. On the other hand, each building has a unique layout and ventilation systems. To properly protect a building, it is important to place sufficient quantity of sensors and design proper ventilation and its control systems.

For design practice, CDC (2002) already issued common sense instructions on how to design a ventilation system for potential CBA attacks. However, these instructions are very general, while each building and each CBA release have specific characteristic that would greatly influence the actual spreading of CBAs. For example, not only the position of internal objects and partition, but also the outdoor wind conditions would influence the contaminant dispersion in a building, even if the CBA release location is the same. Therefore, detailed information about the CBA dispersion is needed to prepare responses to such a CBA attack.

Highly sensitive CBA sensors are the first-line of defense in a building. The sensors monitor the CBA level in the air in the building and send the information to building control system and personnel and further warn the building occupants under a CBA attack. The control system and personnel can make proper response, such as increase or shutdown ventilation and organize evacuation for the building occupants via a safe routine. Unfortunately, most of the sensors are expensive and may need a long time to response to CBAs. It is therefore crucial to determine the best locations for placing those expensive sensors in the building.

This paper reports how to use computational fluid dynamics (CFD) to calculate CBA dispersion in a building in order to find the best locations for the sensors and to activate appropriate emergency responses from the ventilation system.

## **Prediction of Contaminant Dispersion**

Prediction of CBA dispersion in a building can be done either experimentally or numerically. Unlike the numerical methods, the experimental methods do not use approximations so they are more reliable. However, the numerical simulation methods are becoming popular because many of them can produce detailed airflow pattern and CBA distribution in buildings with a fraction of the experimental costs. Many recent numerical studies for indoor and outdoor airflow and CBA dispersion have demonstrated the power of the numerical methods. The accuracy of the numerical methods is improving. The numerical method ranges from simple multi-zone flow model (Sextro 2002), database method (NRL 2003), to complicated CFD method (Chang and Meroney 2001).

Sextro (2002) found that the multi-zone model can help identify critical information or processes that contribute most to predicted outcomes or to uncertainties in a building with anthrax release. The database method (NRL 2003) pre-calculates the flow before the emergency ever occurs, and the flow data is then condensed into tables. The dispersion monographs can be recalled quickly if an airborne threat occurs to provide instant information on the source location and plume dispersion patterns. Chang and Meroney (2003) studied bluff body flow and transport of CBA in urban environments by both CFD computation and physical modeling. Their results show that CFD can accurately predict CBA dispersion. CFD solves the Reynolds averaged Navier-Stokes equations with turbulence models. The simulation results can be obtained with a few minutes computing time on a PC for a small room to a few days for a complex building. Although the computing time seems long since it is not a real time simulation, it is appropriate for studying sensor locations and comparing the performance of different ventilation systems. Therefore, CFD has been used in our study.

The principles of the CFD approach can be found in many textbooks, such as Versteeg and Malalasekera (1995). CFD solves the governing conservation equations of mass, momentum, energy, and CBA species in the following general form:

$$\frac{\partial \Phi}{\partial t} + (\mathbf{V} \cdot \nabla) \Phi - \Gamma_{\phi} \nabla^2 \Phi = S_{\phi} \quad (1)$$

where  $\Phi$  is  $V_j$  that stands for the air velocity component in the  $j$  direction, is 1 for mass continuity, is  $T$  for temperature, is  $C$  for different gas type of CBA contaminants. The  $t$  in Equation (1) is time,  $\mathbf{V}$  is velocity vector,  $\Gamma_{\phi}$  is diffusion coefficient, and  $S_{\phi}$  is source term. The  $\Phi$  could also stand for turbulence parameters.

Equation (1) can be solved by approximating turbulence quantities with turbulence model. This study has used a renormalized-group  $k$ - $\epsilon$  model (Yakhot et al. 1992), since the model has been found to generate reasonable accuracy for most indoor airflow.

Equation (1) and the turbulence model is highly non-linear and self-coupled, resulting in no analytical solutions for CBA dispersion in buildings. Therefore, Equation (1) and the turbulence model are solved numerically by dividing the spatial continuum into a finite number of discrete cells and by using an iterative procedure to achieve a converged solution.

## Case Setup

This investigation employs an office building as an example to demonstrate how to use CFD to predict CBA dispersion under a terrorist attack and to develop building-protection strategies. The office building used for this study has offices in both sides and a corridor in between. Assuming all the offices are identical, this study only uses a section as shown in Figure 1. Each office has two occupants and two tables, two computers, several lamps and one of them has a copy machine as summarized in Table 1. This study further assumes that the two offices shown in Figure 1 are in the middle of the building. Hence, the walls, ceiling and floor can be considered to be adiabatic. The sole thermal sources are the internal heat gains. This office complex is air-conditioned with a displacement ventilation system, which supplies fresh air from the lower part of the offices and exhausts contaminated air from the ceiling level. The supply air mass flow rate to each office is 0.0595 kg/s at 17°C. Because the office building is generally air-conditioned, the higher indoor air pressure than that outdoors limits the outdoor CBA's penetration into the indoor space by infiltration. The space is then assumed under three different types of indoor airborne CBA attacks from three locations – under a desk in office 1 (C1), in the corridor (C2), and from the supply air in office 1 (C3). Table 2 provides the locations and the release rates of these CBAs.

This study used a commercial CFD program, PHOENICS, that has been validated in numerous occasions for indoor airflow studies. The authors (Zhai 2003) have further validated the CFD program by detailed experimental data for an office similar to the one under the present investigation (Yuan et al. 1999). The agreement between the computed results and the measured

data is good. The validation results have shown that we can CFD to predict contaminant dispersion under different air distribution systems.

The CFD simulation divided the two offices and the corridor into  $80$  (length)  $\times$   $30$  (width)  $\times$   $20$  (height) =  $48,000$  discrete computational cells. In order to investigate the CBA dispersion, it is necessary to perform an unsteady calculation although the airflow pattern is assumed to be steady. The ventilation system and heat gains remain unchanged all the time in this case. The entire time length simulated is 20 minutes, which is divided equally into 300 time steps (four seconds per time step). The contaminants are released at the 50<sup>th</sup> time step after the steady indoor airflow is obtained.

The CFD first models attack scenarios without any emergency responses, and attempts to predict the distribution of the three contaminants and to optimize the chemical and biological sensor locations. Thereafter, three different emergency response strategies from the ventilation system are proposed by using emergency air supply/exhaust (EASE).

## **Analysis on CBA Dispersion, Sensor Locations, and Control Strategies for Ventilation Systems**

In the attack scenarios without emergency responses, this study assumes that the indoor airflow pattern in the offices is steady and independent of the gas-phase contaminant distributions. The driving force for the airflow and CBA dispersion is the ventilation and buoyancy from the heated objects. Figures 2, 3, and 4 illustrate the dispersion processes of three CBAs, respectively. Due to different source locations, the high concentration area for C1, C2, C3 are the lower-left corner of office 1, the upper corners of the corridor and the lower-left corner of office 1, respectively. Figure 2 shows that occupant O1 is mostly affected in the first five minutes because the source C1 is located underneath his/her desk. Nevertheless, the concentration level becomes very high for all the other occupants after ten minutes. In case of CBA released in the corridor, the C2 concentration is much higher in office 2 than that in office 1. This is because office 2 has a copy machine, which entrains contaminated air from the corridor due to its strong buoyancy force from the high heat source. Figure 4 also illustrates that the dispersion is the fastest when the CBA is released from the diffuser of the ventilation system. C3 is transported rapidly and is dispersed quite evenly in both of the offices, which agrees with our common sense. In any of the three simulated cases, the spreading rate of contaminants is very fast causing the CBAs to affect the occupants within only five to ten minutes. C2 has a relatively weaker and slower adverse effect on the occupants than C1 and C3. Note that the CBA concentration distribution approaches to a near constant pattern in ten minutes due to the steady airflow, but the concentration levels are still increasing because of the assumption of a constant release of the CBAs from their sources.

The CFD results can be useful for the determination of the best locations for CBA sensors in the building. Figure 5 shows the accumulated CBA concentration perceived by the sensors at different locations in office 1 as detailed in Figure 1 and Table 3. O1 and O2 are the occupants' nose locations (0.9 m above the floor) in office 1. For comparison, this study assumes that the alarm threshold of the accumulated CBA concentration is  $50 \text{ mg} \cdot \text{min} / \text{m}^3$  for Mustard. For release at C1 location, occupant 1 is more vulnerable than occupant 2 because O1 reaches the

threshold in four minutes while it takes 16 minutes for O2 to reach the same level. Sensor 8 has a faster response than the others, since it has the highest accumulated concentration. Only Sensor 8 can give early warning to O1 so that this occupant's life may be saved. Sensors 9 and 10 are placed in good locations, since they can give O2 early warning and O2 has sufficient time to evacuate.

The CBA release at C2 location in the corridor obviously has less effect on office 1 than the C1 and C3. At least four sensors in office 1 can give early warnings. However, it is important to note that those sensors are not the same as those that gave early warning for C1. The CBA concentration level would not reach to lethal level for the two occupants in 30 minutes.

The release of CBA at C3 location (from the diffuser) seems most devastating, The results seem agree well with our common sense. The CBA reaches O1 and O2 almost at the same time and with the same concentration level. It takes around 5 minutes for O1 and O2 to reach the alarm threshold. Again, Sensors 8, 9, and 10 provide earlier warning for C3.

For C1 and C3, the sensors placed near the floor can reach the alarm threshold before either of occupants was severely affected. In other words, those sensors can provide an effective CBA attack warning for the building occupants. However, the early warning sensors for C2 are completely different from those for C1 and C3. The best sensor locations depend on CBA source locations. However, this does not mean that we could not identify the best sensor locations. One can assume more release scenarios and the best sensor locations would be those often giving early warning. For example, in this particular case, the best locations are S8, S9, and S10 since C2 is not as dangerous as C1 and C3.

With the information obtained from Sensors 8, 9, and 10, the next step is to develop strategies that can be used to protect occupants from the CBA attacks or at least to minimize casualties. This investigation proposes an emergency response ventilation system that can be triggered after CBA release is detected. The response system consists of three ceiling-mounted emergency air supply/exhaust (EASE) diffusers in the two offices (EASE1 and EASE3) and the corridor (EASE2). Figure 1 and Table 1 give the locations and sizes of these EASE diffusers. An EASE diffuser can be a supply or an exhaust by reversing the fan rotation direction that can be easily controlled by a power supply switch.

To study the performance of different combinations of emergency air supplies and exhausts, Table 4 compare three EASE strategies. For all the three strategies, EASE diffusers are simultaneously activated as an air supply inlet or an air exhaust outlet at the 80<sup>th</sup> simulation time step, which is two minutes after the CBA release.

Figures 6, 7 and 8 show the computed C1, C2 and C3 distributions with the active EASEs. The CBA concentration levels with the EASEs are much lower than those without them. Also, the CBAs can be successfully confined within the space where they are released. Nevertheless, some strategies provide better protection than the others.

For example, Figure 6 shows that the level of contaminant C1 in office 1 decreases with all EASE strategies, but Strategy 2 has obviously better performance than Strategies 1 and 3. The

advantage of Strategy 2 for removal of C1 contaminant is even more evident as shown in Figure 9 due to the high C1 peak values at O1 for Strategies 1 and 3. Furthermore, Figure 9 shows that even after 17 minutes, the C1 concentration level for Strategy 3 (about 10 ppm) is ten times higher than for Strategies 1 and 2 (about 1 ppm). Therefore, Strategy 2 is the best for removal of contaminant C1 because the space where CBA is released (office 1) should be vacuumed and other spaces should be pressurized.

For CBA release at C2 location that is in the corridor, both Strategies 1 and 2 are poor because they force the contaminated air to flow from the corridor into the offices (Figures 7 and 9). Figure 9 shows that Strategy 3 can safely and quickly remove the “dirty” air because EASE2 works as an exhaust in the corridor. In fact, four sensors will trigger the alarm system before any occupants would be affected by the contaminant released in the corridor. This result is very encouraging because the evacuation under C2 attack is difficult. Finally, in case of C3 release, all of the EASE strategies seem effective as shown in Figures 8 and 9. Since Strategy 2 uses EASE1 as an exhaust, it is the best as anticipated.

The conclusions obtained in this section are obvious because this example involves only two offices and one corridor that present only a portion of a building. This investigation uses the simple example to demonstrate basic principle how to use CFD to develop effective strategies for building protection. Since the results are the same as we would expected, it is not necessary to validate the results. Without this exercise, one can apply the approach to study a much more complicated problem in a complex building and expect to obtain results with confidence. The only difference would be that an EASE system for a large building would require simulation of airflow and CBA dispersion for the entire building and much more complex control strategies should be developed.

## **Discussion**

Although the study is limited to indoor CBA releases, an outdoor release can be handled in the similar way. The C3 can be considered as a CBA from an outdoor release through the air intake. If the outdoor release is not through the ventilation system, the entire building can be pressurized to prevent the infiltration of the CBA attacks from outdoors. The simulation of CBA dispersion by CFD around the building would be necessary to ensure the emergency air used is clean.

The above-example shows that CFD can be used to locate the best sensor positions and to develop the best control strategies to protect occupants from CBA releases. However, using CFD for such a problem is still not an easy job. This section will discuss four major challenges: physical models, computing time, user expertise, and collaboration, when using CFD for protecting buildings from CBA attacks.

### **(1) Physical models**

Accurate prediction of airflow and CBA distribution requires deep understanding of physics of airflow and contaminant dispersion in the atmosphere and confined spaces. For building indoor simulations, since the airflow ranges from laminar to turbulent flow, a comprehensive airflow model considering both laminar and turbulence effect is desired. Although there are a number of turbulence models available nowadays, a universal model that is able to describe diversity of

flow regimes in and around buildings is still not available. The distribution of air-phase contaminant concentration, although mainly determined by the airflow patterns, needs special models to handle the correlation between the fluctuation of concentration and airflow. Different contaminant sources may have different behaviors and need different models. If the contaminants are in liquid or solid particle phase, the problem is then becoming the two-phase or multi-phase flow. Additional models should be used/developed to represent interactions between the particles and air motions. Moreover, rigid surfaces may need particle absorption and reflection models, and they could be material dependent. In general, further development of physical models is needed.

## **(2) Computing time**

The capacity and speed of computer have tremendously grown in the last decades. However, the time consumed by CFD simulation is still high as an analysis tool. It is far from practical to develop real time defense strategies. The CFD calculation for the two offices and a corridor for 20 minutes real time took about 60 hours computing time in a modern PC with the modest grid number. A high-performance parallel supercomputer is necessary to have a simulation faster than real time. The study from Boris (2002) indicated a CFD computation by a 128-node Intel iPSC-860 parallel computer can be performed faster than real time and the graphical results then can be communicated over the Internet to the command site. Since the high-performance supercomputer is extremely expensive, NRL (2003) has developed a new, high-fidelity zero-latency approach called dispersion nomographs for exterior contaminant threats. The method pre-computes possible threat scenarios and forms a database, which can provide the basis for informed operational decisions in real-time crisis management, even when the precise parameters of a release are unknown. The similar bin-approach can be developed for building indoor environment protection, particularly for those buildings that are the most attractive targets. Indoor environment is generally more stable than outdoor environment because indoor airflow pattern does not change as much as outdoors. The database would not be too large and difficult to establish. The zero-latency information extracted from bins then can orient line-of-sight sensors, activate building air supply defenses, plan escape routes, and backtrack to possible source locations for cleaning purposes.

## **(3) User expertise**

Although many commercial CFD programs now come along with a powerful user-friendly graphic interface and detailed user manuals, correct and efficient usage of these programs still requires high expertise on fluid mechanics and its numerical procedure. The first crucial part in the CFD simulation is a method of abstracting, simplifying and reconstructing real world into computer models, which directly affects the accuracy of final solutions. The knowledge and experience on the similar problems can expedite this process. Meanwhile, because CFD solves the non-linear partial differential equations for fluid flows, the performance of CFD programs heavily depends on the case characteristics. No general and simple rules can guarantee the convergence and stability of the solution. A professional with adequate knowledge of fluid physics and numerical techniques is always desired to solve the complex flow problems. Finally, the judgment and analysis of the results provided by computer simulation are also not an easy job for people without sufficient expertise on fluid mechanics. Recently, ASHRAE has developed a standard procedure to simulate indoor environment by CFD (Chen and Srebric 2002). The procedure should be used for studying CBA dispersion in buildings.

#### **(4) Collaboration**

Protecting occupants in a building from CBA injury is system engineering that involves the efforts from many parties, such as, building design and construction, ventilation system design, CBA sensor systems, emergency rescue, crisis management, law enforcement responses, and medical and health service. A large team is needed to provide adequate expertise to protect building occupants from CBA attacks. The method presented in this paper can provide building and system designers guidelines and can help rescue and incident-response teams by providing them critical information. However, it is important to develop the method further to provide faster than real time control strategies.

#### **Conclusions**

This investigation uses an office building to demonstrate how CFD can be used to predict the contaminant dispersion under indoor CBA releases. The CFD results are useful for the determination of the best locations for CBA sensors and for development of effective emergency response strategies. The results show that the CBA dispersion is very fast (usually less than five minutes to reach the lethal threshold). Early warning from the sensors is possible if they are placed properly, although the sensor locations depend on CBA release location. By supplying or exhausting emergency air through three ceiling-mounted air devices, it is possible to protect building occupants from the assumed CBA attacks. The results show that CBA dispersion can be effectively controlled by pressurizing/vacuuming the offices.

The paper also discussed the challenges in applying CFD for protecting building from CBA attacks and proposed possible approaches to the challenges.

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Table 1 The office configurations

Objects	Length	Width	Height	Location			Heat*
	$\Delta x$ [m]	$\Delta y$ [m]	$\Delta z$ [m]	x [m]	y [m]	z [m]	Q [W]
<b>Office 1</b>	5.16	3.65	2.43	0.0	0.0	0.0	
Window 1	0.0	3.65	1.43	12.32	0.0	1.0	
Diffuser 1	0.0	0.65	1.0	5.16	1.5	0.0	
Exhaust 1	0.35	0.35	0.0	0.4	1.65	2.43	
Door Opening 1	0.0	0.75	2.43	5.16	0.0	0.0	
Occupant 11	0.40	0.35	1.1	1.1	0.95	0.0	75
Occupant 12	0.40	0.35	1.1	3.89	2.35	0.0	75
Computer 11	0.40	0.35	0.35	1.1	0.1	0.75	108.5
Computer 12	0.40	0.35	0.35	3.89	3.2	0.75	173.4
Table 11	1.47	0.75	0.05	0.58	0.0	0.7	
Table 12	1.47	0.75	0.05	3.69	2.9	0.7	
Lamp 11	0.2	1.2	0.1	1.1	0.1	2.23	68
Lamp 12	0.2	1.2	0.1	1.1	2.35	2.23	68
Lamp 13	0.2	1.2	0.1	3.49	0.1	2.23	68
Lamp 14	0.2	1.2	0.1	3.49	2.35	2.23	68
<b>Office 2</b>	5.16	3.65	2.43	7.16	0.0	0.0	
Window 2	0.0	3.65	1.43	12.32	0.0	1.0	
Diffuser 2	0.0	0.65	1.0	7.16	1.5	0.0	
Exhaust 2	0.35	0.35	0.0	11.57	1.65	2.43	
Door Opening 2	0.0	0.75	2.43	7.16	0.0	0.0	
Occupant 21	0.40	0.35	1.1	8.26	0.95	0.0	75
Occupant 22	0.40	0.35	1.1	11.05	2.35	0.0	75
Computer 21	0.40	0.35	0.35	8.26	0.1	0.75	108.5
Computer 22	0.40	0.35	0.35	11.05	3.2	0.75	173.4
Table 21	1.47	0.75	0.05	7.74	0.0	0.7	
Table 22	1.47	0.75	0.05	10.85	2.9	0.7	
Lamp 21	0.2	1.2	0.1	8.26	0.1	2.23	68
Lamp 22	0.2	1.2	0.1	8.26	2.35	2.23	68
Lamp 23	0.2	1.2	0.1	10.65	0.1	2.23	68
Lamp 24	0.2	1.2	0.1	10.65	2.35	2.23	68
Xerox machine	0.8	0.8	1.0	11.32	0.2	0.0	1600
<b>Corridor</b>	2.0	3.65	2.43	5.16	0.0	0.0	
<b>EASE 1</b>	0.35	0.35	0.0	2.20	1.65	2.43	
<b>EASE 2</b>	0.35	0.35	0.0	5.985	1.65	2.43	
<b>EASE 3</b>	0.35	0.35	0.0	9.38	1.65	2.43	

\*Note: The heat generated includes radiation and convection.

Table 2 CBA location and source strength

Contaminant Sources	Length	Width	Height	Location			Generation Rate or Concentration
	$\Delta x$ [m]	$\Delta y$ [m]	$\Delta z$ [m]	x [m]	y [m]	z [m]	
C1 (in office 1)	0.2	0.1	0.1	1.3	0.1	0.0	2.5 mg/s
C2 (in the corridor)	0.1	0.2	0.1	7.06	2.7	0.0	2.5 mg/s
C3 (from diffuser 1)	0.0	0.65	1.0	5.16	1.5	0.0	2.5 mg/s or 42 ppm

Table 3 Locations of sensors and occupant noses in office 1 (x, y, z)

<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>
(0.2, 0.15, 2.28)	(0.2, 1.83, 2.28)	(0.2, 3.46, 2.28)	(4.9, 0.15, 2.28)	(4.9, 1.83, 2.28)	(4.9, 3.46, 2.28)
<b>S7</b>	<b>S8</b>	<b>S9</b>	<b>S10</b>	<b>O1</b>	<b>O2</b>
(2.64, 0.15, 2.28)	(0.2, 0.15, 0.16)	(2.64, 0.15, 0.16)	(4.9, 0.15, 0.16)	(1.35, 0.9, 0.9)	(4.09, 2.75, 0.9)

Table 4 Three strategies for emergency air supply and exhaust (EASE)

		<b>Strategy 1</b>	<b>Strategy 2</b>	<b>Strategy 3</b>
<b>EASE1</b>	Mass flow rate [kg/s]	↓ (supply) +0.437	↑ (exhaust) -0.437 kg/s	↓ (supply) +0.437
	Velocity [m/s]	-2.97	2.97	-2.97
	Temperature [°C]	23	23	23
<b>EASE2</b>	Mass flow rate [kg/s]	↓ (supply) +0.437	↓ (supply) +0.437	↑ (exhaust) -0.437 kg/s
	Velocity [m/s]	-2.97	-2.97	2.97
	Temperature [°C]	23	23	23
<b>EASE3</b>	Mass flow rate [kg/s]	↓ (supply) +0.437	↓ (supply) +0.437	↓ (supply) +0.437
	Velocity [m/s]	-2.97	-2.97	-2.97
	Temperature [°C]	23	23	23

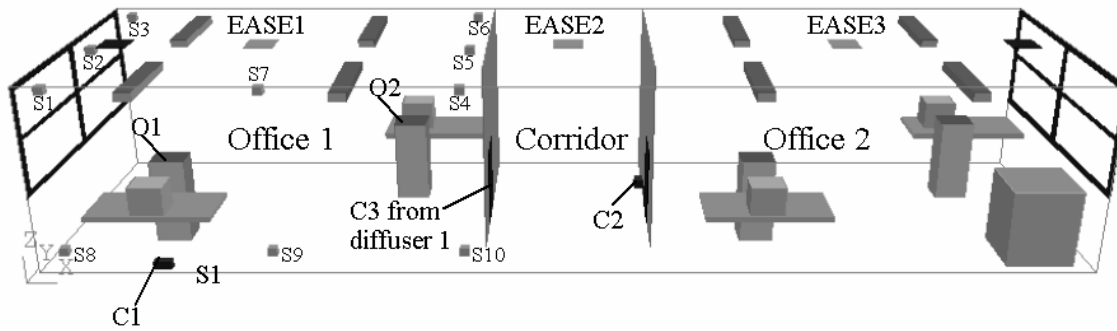
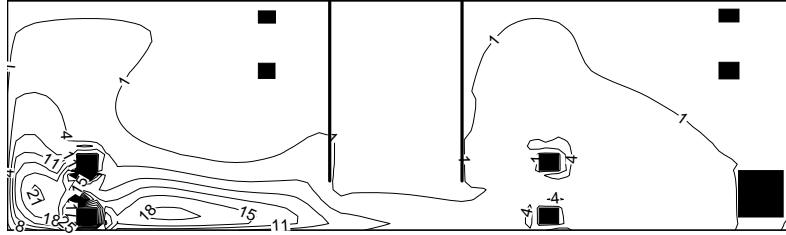
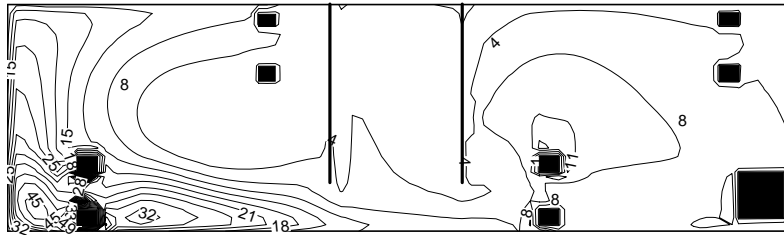


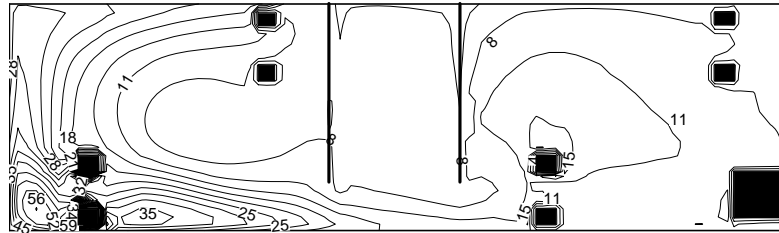
Figure 1 Schematic of a section of the office building



**C1 concentration contour at occupant head section at t = 5 mins**

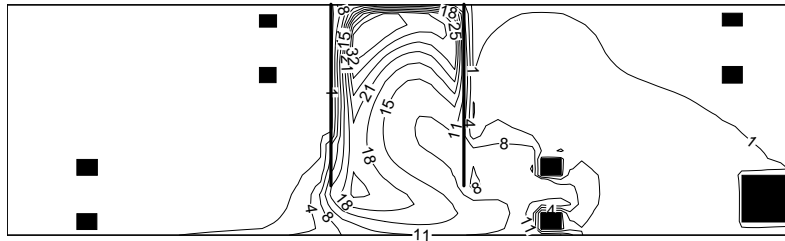


**C1 concentration contour at occupant head section at t = 10 mins**

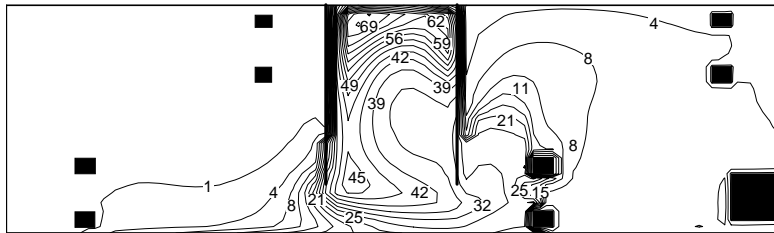


**C1 concentration contour at occupant head section at t = 15 mins**

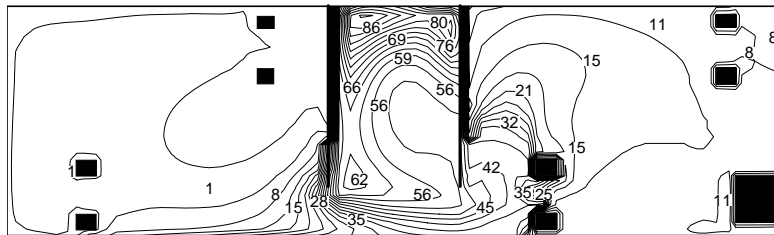
Figure 2 C1 distribution at different time steps (ppm) (plane view)



**C2 concentration contour at occupant head section at t = 5 mins**

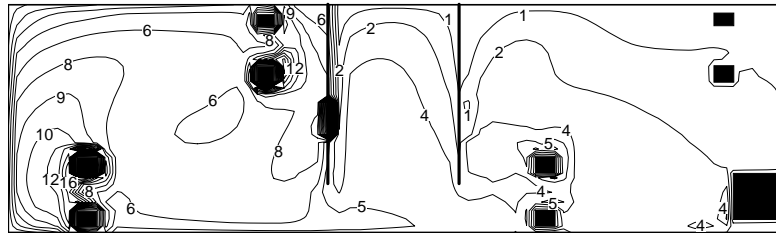


**C2 concentration contour at occupant head section at t = 10 mins**

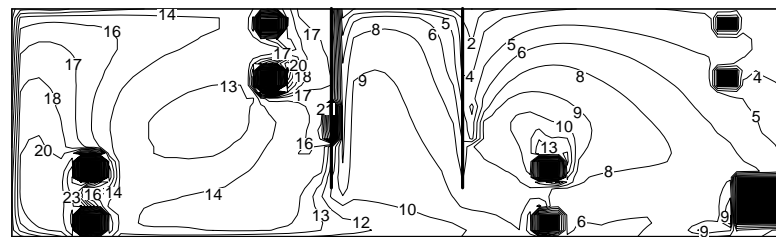


**C2 concentration contour at occupant head section at t = 15 mins**

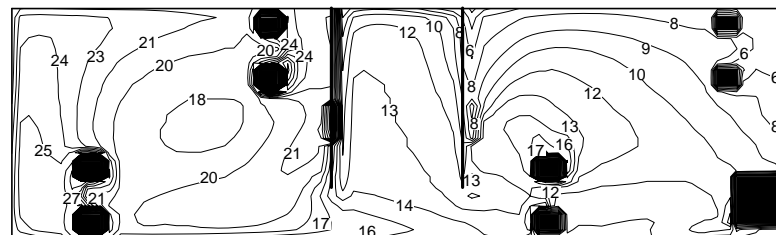
Figure 3 C2 distributions at different time steps (ppm) (plan view)



**C3 concentration contour at occupant head section at t = 5 mins**



**C3 concentration contour at occupant head section at t = 10 mins**



**C3 concentration contour at occupant head section at t = 15 mins**

Figure 4 C3 distributions at different time steps (ppm) (plan view)

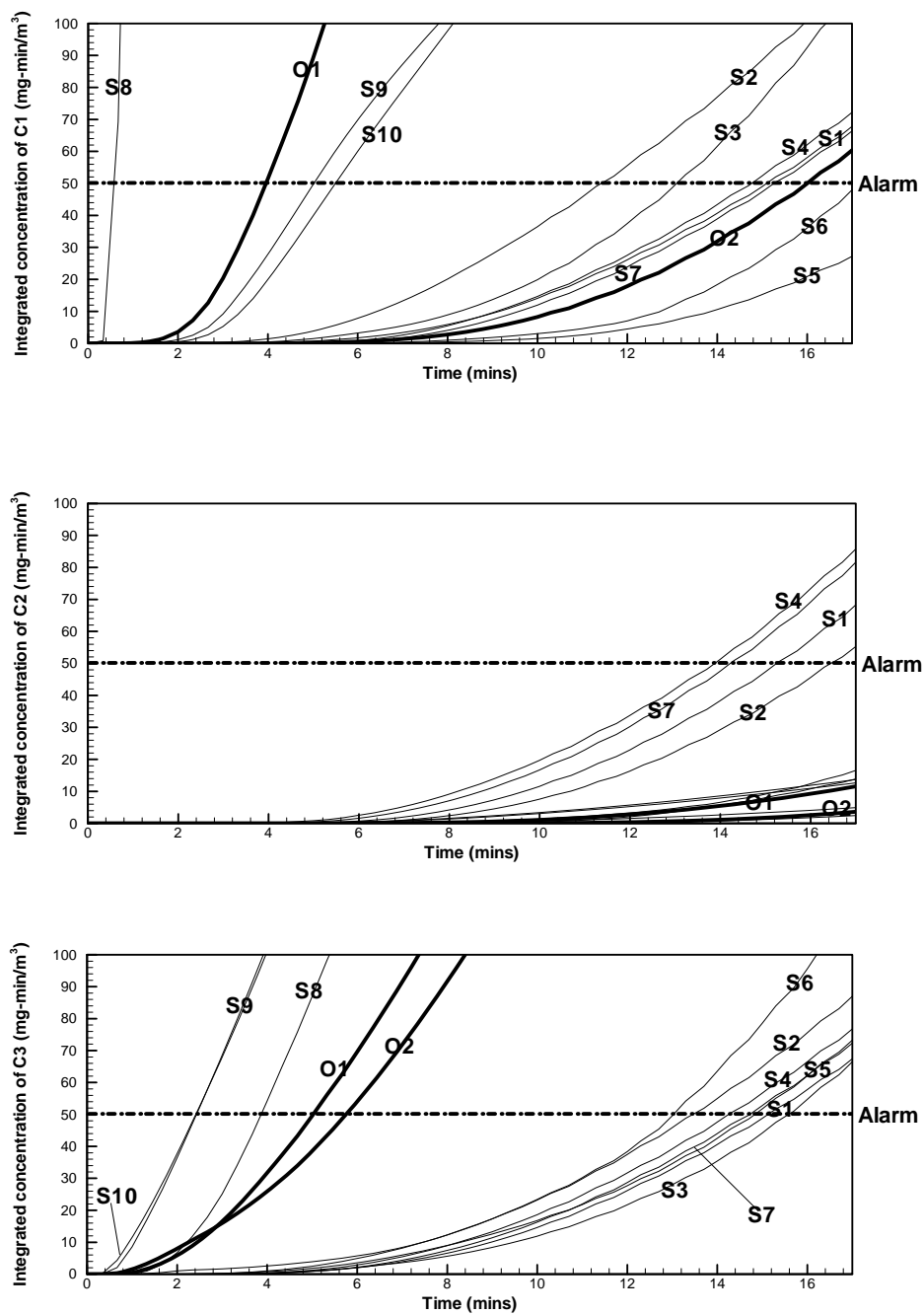
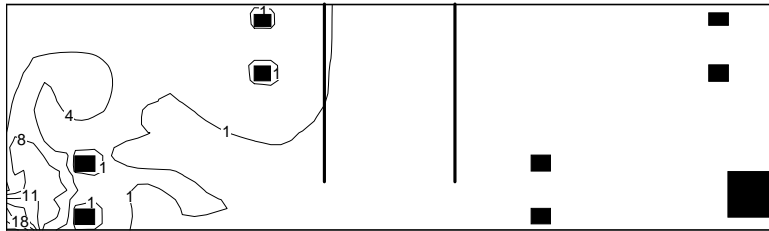
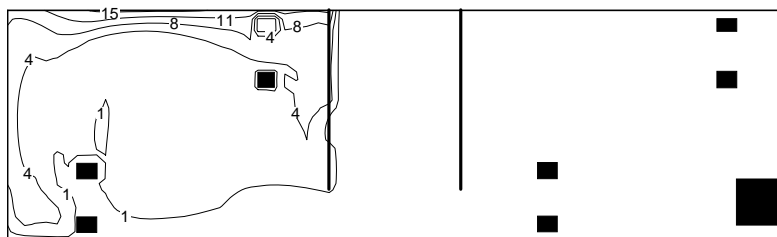


Figure 5 Accumulated CBA concentration at different sensor locations for C1, C2, and C3, respectively.

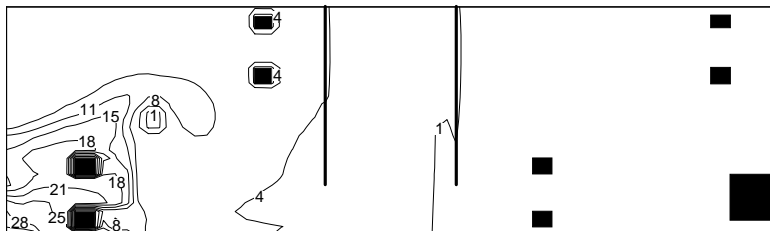




**C1 concentration contour at occupant head section at t = 5 mins with EASE Strategy1**

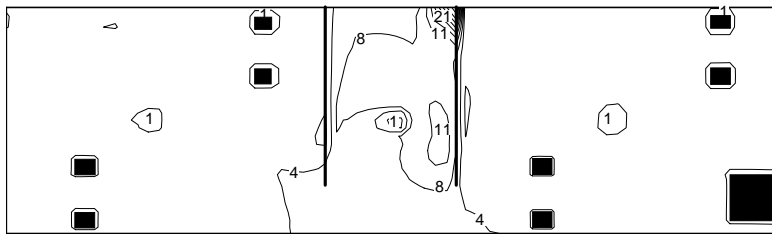


**C1 concentration contour at occupant head section at t = 5 mins with EASE Strategy2**

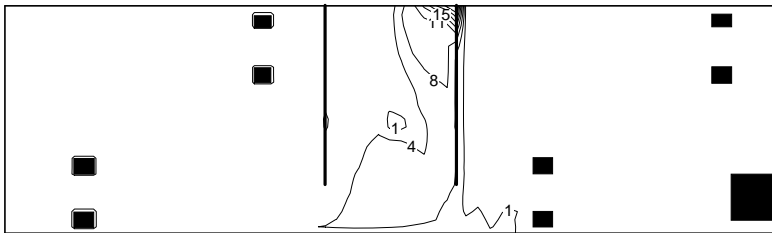


**C1 concentration contour at occupant head section at t = 5 mins with EASE Strategy3**

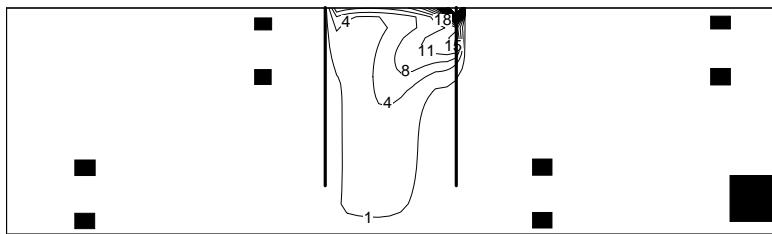
**Figure 6 C1 distributions at t=5 minutes with different EASEs**



**C2 concentration contour at occupant head section at t = 5 mins with EASE Strategy1**

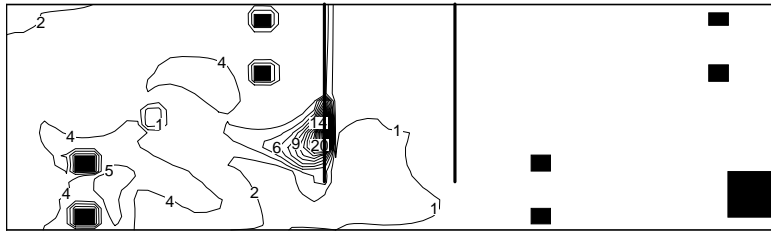


**C2 concentration contour at occupant head section at t = 5 mins with EASE Strategy2**

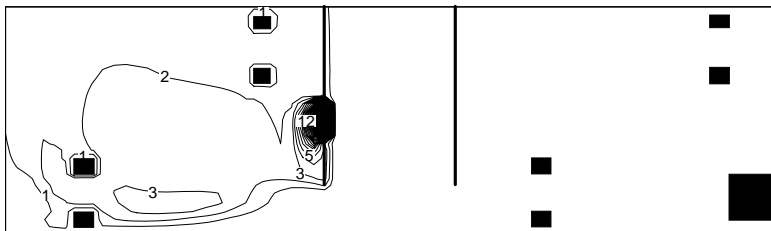


**C2 concentration contour at occupant head section at t = 5 mins with EASE Strategy3**

Figure 7 C2 distributions at t=5 minutes with different EASEs



**C3 concentration contour at occupant head section at t = 5 mins with EASE Strategy1**

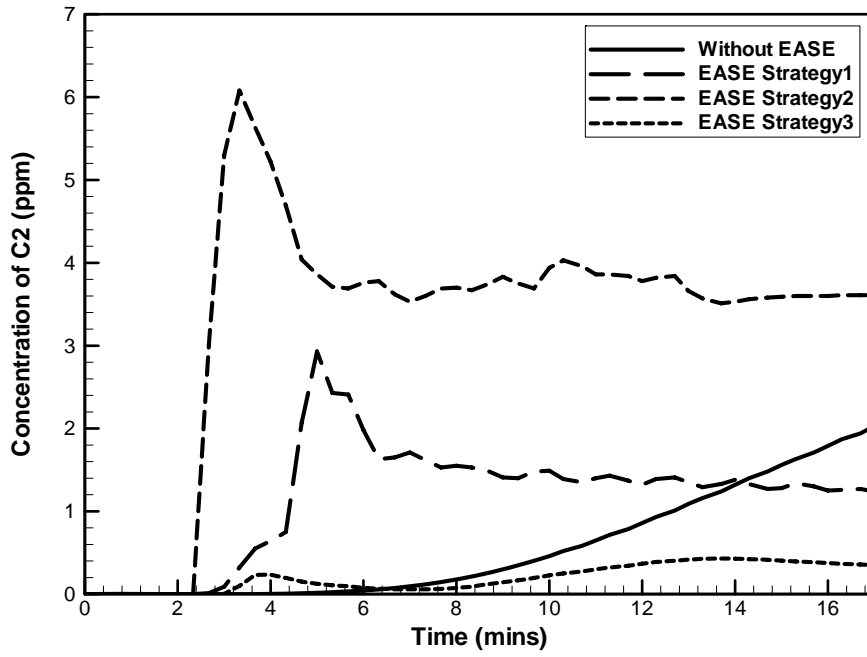
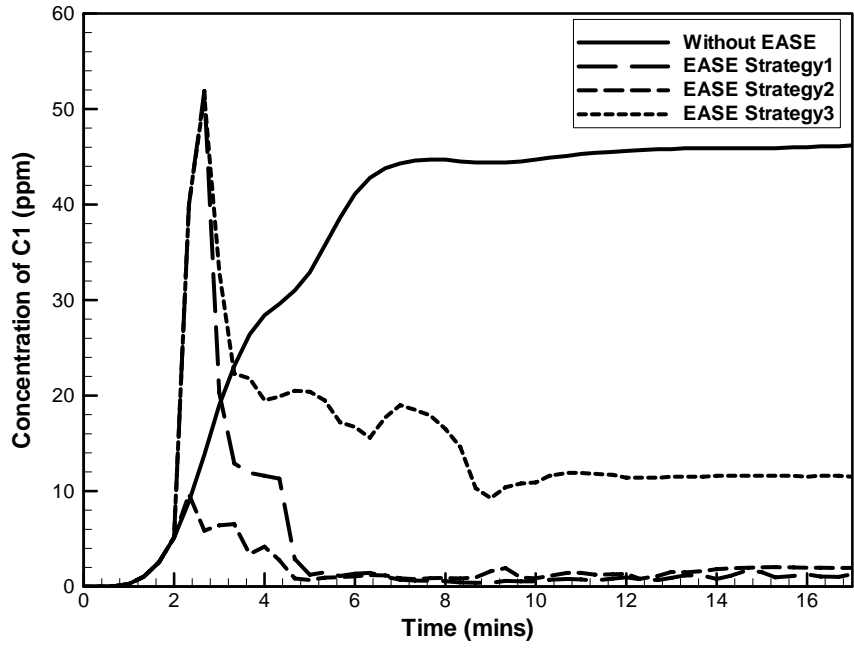


**C3 concentration contour at occupant head section at t = 5 mins with EASE Strategy2**



**C3 concentration contour at occupant head section at t = 5 mins with EASE Strategy3**

**Figure 8 C3 distributions at t=5 minutes with different EASEs**



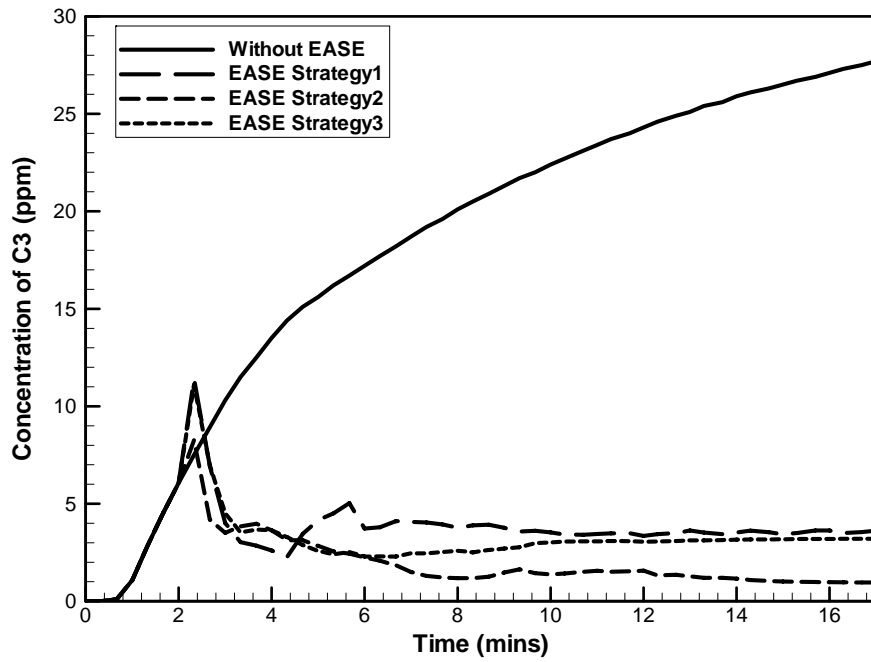


Figure 9 CBA concentrations at occupant 1 over time with different EASEs for C1, C2, and C3, respectively