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# Leveraging Intelligent Building Infrastructure for Event Response

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## Leveraging Intelligent Building Infrastructure for Event Response

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### ABSTRACT

The frequency of attacks, including active shooters, kinetic devices, and hazardous (i.e., chemical or biological) agents, against occupied commercial buildings has seen a dramatic increase in the United States and around the world since 2001. Security professionals concur that the threat is ongoing and unlikely to diminish in the near future. Typical commercial buildings have no systems to actively mitigate these threats. Even iconic buildings rely primarily on restricted access to provide security. Video cameras are often present but are used primarily for forensics after an event has occurred. However, advanced systems that enable intelligent and connected buildings can be leveraged along with sensor technology to enable detection, notification and response to attacks. These same systems can also be used to enhance the response to other emergency events such as grid outages, extreme weather, and earthquakes. This paper will present current research showing how Intelligent Building Technology can be leveraged to provide an automated response to the release of a hazardous agent inside a building. Specifically, CONTAM model results validated with experimental data from a well-instrumented 40,000 sq. ft. testbed building will be presented to demonstrate the capability of using intelligent building infrastructure to affect dispersion of a chemical or biological agent inside a commercial office building.

### 1. INTRODUCTION

While the probability of a specific commercial building being targeted by an active shooter, kinetic device (use of vehicles), explosive device, or the release of chemical or biological agents remains low, the aggregate threat level to commercial buildings continues to increase. Building protection systems are typically limited to providing intrusion detection and, when required by code, detection and suppression of fire, and detection of carbon monoxide in areas with open or confined combustion. Building systems are not currently configured or capable of providing an active or passive response to active targeting of the building or its occupants by one of the means noted above. In addition, such systems could add significant cost to new construction or renovation that would be difficult to justify absent a specific code requirement.

UTRC is actively investigating how intelligent and integrated building systems can play an active role during these events to minimize the impact to occupants and property. This involves configuring building systems and their controls to implement an automatic and immediate response upon the detection of a threat to mitigate impact prior to the arrival of first responders. These intelligent buildings responses would be verified to minimize risk in all conditions ('do no harm') and have minimal inconvenience in the event of false alarms. Minimizing the cost of these systems through the use of existing components and technology is also a part of this research.

This intelligent building event response is enabled by three technology trends: ubiquitous and advanced sensing; integrated building systems; and the advancement of autonomous decision making for complex and uncertain systems. First, sensing platforms have become cheaper, connected, and multi-functional. Key advancements have been made in computer vision to enable object and activity recognition of video signals, as well as the advancement of optical-based detection of particulates (smoke, chemical and biological contaminants). Second, building systems are becoming more intelligent and integrated, driven by the desire for higher performing buildings in terms of both occupant experience as well as sustainability (Braun 2007, Manic 2016). Examples include the use of video signals by both elevators and heating, ventilating and air conditioning (HVAC) systems to improve occupant movement and comfort (Romano, 2015). Finally, the emergence of autonomous vehicles (both air-vehicles and automotive) has advanced the field of autonomy for complex and uncertain environments that need to make life-safety or other critical decisions. UTRC has played an active role in supporting the development of

autonomous solutions and the required model-based and formal methods to verify and guarantee their performance (Banaszuk, 2011; Clare, 2012; Mathew, 2011; Pinto, 2012).

This paper will present results related to one event response use-case: the active HVAC response to a chemical or biological agent release. While uncommon, the number of chemical and biological agent events has grown. These include the 1995 Sarin gas attacks in the Tokyo Metro that killed 12, the 2001 anthrax attacks in the United States that killed 5, and, more recently, state-sponsored nerve agent attacks at Kuala Lumpur International Airport in Malaysia and in Salisbury, England. Unless there are dedicated detection systems and protocols in place (which are prohibitively expensive for commercial buildings) such events are typically detected after exposed occupants become symptomatic, virtually eliminating the opportunity to minimize exposure to such agents during the initial release and endangering first-responders who arrive on-scene unaware of the nature of the threat. UTRC has been developing advanced sensing technology that would detect the release of biological agents in near real-time, enabling an automated building response. In this case the Building Automation System (BAS) would command the HVAC ventilation system to minimize the dispersion of the contaminant by increasing the amount of outdoor air being brought into the building. UTRC has demonstrated the effectiveness of such a response in both simulation as well as a fully operational commercial building. The remainder of this paper presents the modeling and testing methodology (Section 2) and the simulation results and full-scale building demonstration to verify their accuracy (Section 3). This is followed by a discussion on the estimated effectiveness of such a response (Section 4) and conclusions (Section 5).

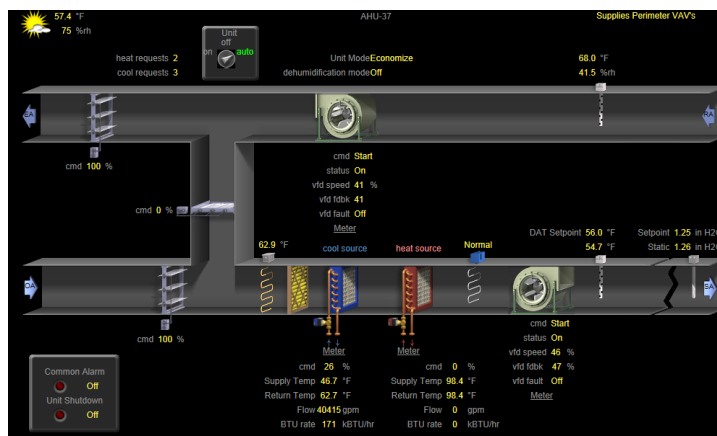
## 2. MODELING AND EXPERIMENTAL VERIFICATION OF CONTAMINANT DISPERSION AND RESPONSE

This Section describes the modeling and testing campaign used to evaluate the effectiveness of a building HVAC system's response to a contaminant release.

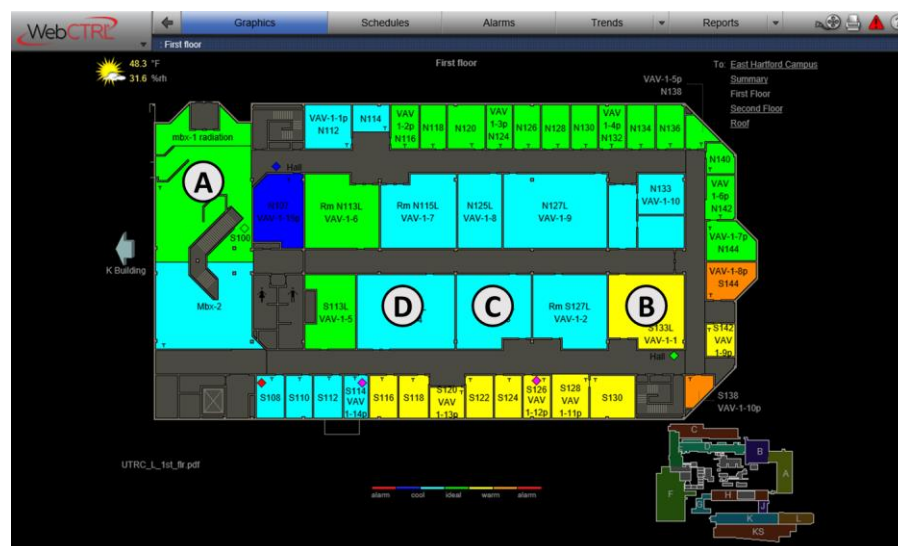
## 2.1 Demonstration Facility

The contaminant dispersion and response demonstration was performed at UTRC's High Performance Building Test Bed (HPBT) located in East Hartford, Connecticut. The 2-story, 40,000 sf, office building consists of offices, conference rooms and an atrium. The building is served by two rooftop Air Handling Units (AHUs), one of which supplies the atrium and perimeter offices, while the other serves the core spaces (which are primarily conference rooms). HVAC return air is ducted above the drop ceilings on both floors. The corridors have direct overhead HVAC supply from the perimeter HVAC system and return is through the atrium and individual room return ducts. The stairwells have no direct supply or return to either HVAC system; neither do the bathrooms, which only have exhaust fans.

The HVAC system controls and operating data are accessible from the Building Automation System (BAS). Figure 21 shows a representation of one of the AHU systems. Figure 2 shows the building floor plan identifying zones of interest. The BAS allows the building HVAC system operation to be set up to match simulated release and response scenarios. In addition, the BAS provides the zone by zone supply and return flow data used in modeling the dispersal of contaminants inside the building.



**Figure 1: Schematic of the Air Handling Unit.**



**Figure 2:** Schematic HPBT floor plan showing zones of interest.

## 2.2 Experimental Methodology

Since the testing site is an operational building that is typically occupied during normal weekday working hours, a contaminant simulant was required that would not leave a lasting presence in the building and could be easily measured with off-the-shelf sensing systems. It also had to be relatively safe to handle since setting up and operating the tests would require people to be in the building during and after each release.

The only reasonable choice of contaminant simulant was determined to be carbon dioxide, CO<sub>2</sub>. This is an odorless, colorless gas that is typically present in the atmospheric background at a level of ~411 ppm and can be released into the building atmosphere at significantly higher levels without hazard to those operating the test. In addition, the HPTB has sensors for CO<sub>2</sub> as part of its demand controlled ventilation system and the output of these sensors could be accessed through the BAS providing sensor coverage of the majority of the building core spaces and the core HVAC system return duct.

The existing wall mounted CO<sub>2</sub> sensors in the HPTB connected to the BAS were supplemented by two types of sensors to provide additional coverage in spaces where there were no building sensors, verify the accuracy of the existing sensors, and to measure contaminant dispersion at multiple points within the release zone. The BAS-connected sensors were supplemented by 15 HOBO sensors. These sensors measure CO<sub>2</sub> levels up to 5000 ppm, in addition to temperature and humidity, and could store several days' worth of data collected at sub-minute intervals. During testing the HOBO sensors were mounted on stands at approximately 5.5 ft from the floor. Small fans were placed in front of the sensing unit on the HOBOs to ensure adequate airflow across the sensor to achieve minimum response time to changes in concentration levels. Finally, since the peak concentration of CO<sub>2</sub> near the release point would substantially exceed the 5000 ppm range of the HOBO sensors, an INNOVA gas analyzer was acquired that could measure CO<sub>2</sub> levels in excess of 100,000 ppm. The sampling point was located as close to the release point as possible and this sensor provided an additional level of safety for ensuring that safe levels of contaminant were present before entering the release room between tests.

During testing, CO<sub>2</sub> was released in a core conference room (zone 'B'), which is in the lower right corner of the floor plan shown in Figure 2. This location matches the release location in the modeling effort. A simple CO<sub>2</sub> release mechanism was designed to accurately meter the quantity of gas released in each test. This ensured repeatability between tests. The method selected was a weather balloon that was burst on command with a heated nichrome wire taped to its surface as seen in Figure 3. The quantity of gas inside the balloon was determined from the balloon's volume (the pressure inside the balloon being essentially the same as the external pressure), which could be computed by measuring the circumference with a wire of known length. It was then a straightforward process to inflate all subsequent balloons to the same size using the 'calibrated' wire loop to inflate the balloon to the correct size. The gas was supplied from a tank containing pure liquid CO<sub>2</sub> at 800 psi and regulated down to near

atmospheric pressure. During tests, the nichrome wire bursting mechanism consistently burst the balloon within 2-3 seconds of the electrical current being switched on.



**Figure 3:** Inflated weather balloon showing wiring for heated wire bursting mechanism.

### 2.3 CONTAM Modeling Methodology

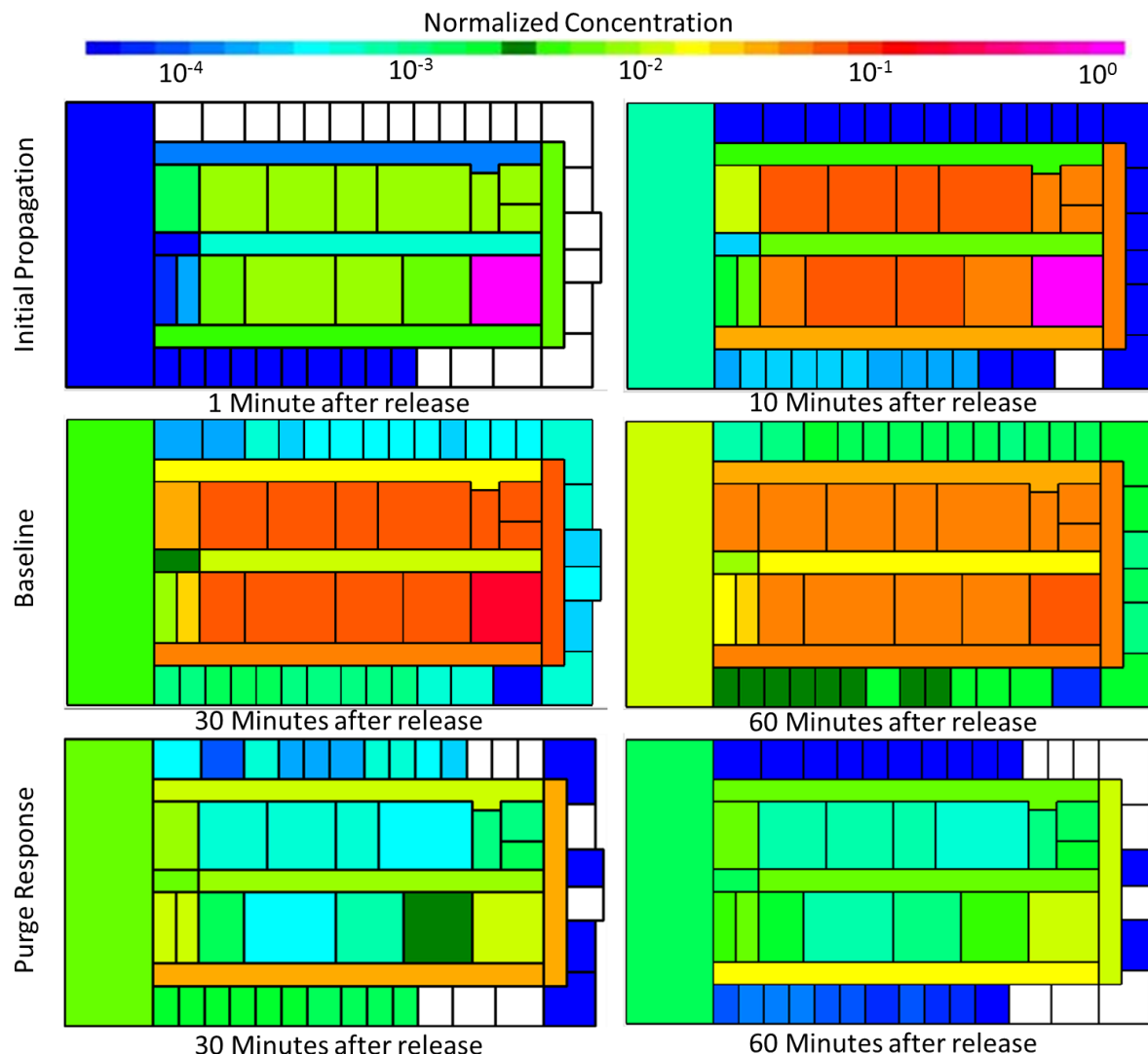
UTRC constructed a CONTAM model of the HPTB to investigate propagation of contaminant in a medium size office building. CONTAM is a software tool developed by NIST for modeling airflows and contaminant concentrations within buildings. The goal of the simulation was to understand how quickly and widely a localized release spreads through the building, and what will be the effectiveness of HVAC responses designed to limit the spread of contaminant.

The CONTAM model was setup using default leakage areas for leakage paths between zones. These include doors and windows, as well as cracks and other penetrations in walls and ceilings. The zone supply and return flows were defined using typical flow data extracted from the BAS. The baseline inter-zone flows result in a building that is positively pressurized compared to the ambient air and the core has a higher pressure than the perimeter so that there is net outward flow in the building other than in the restrooms. The exhaust flows from the restrooms put them at significant negative pressure compared to the rest of the building.

## 3. CONTAMINANT DISPERSION AND RESPONSE VALIDATION RESULTS

### 3.1 Modeling Results of Dispersion during Baseline and Response Scenarios

This section discusses the CONTAM simulation of contaminant dispersion for both the baseline case and when the system is purged (HVAC switches to 100% out-door air) starting at 10 minutes after release. Figure 4 shows the contaminant levels in the building for these two scenarios when the contaminant is released in Zone B. In the initial propagation (top row of Figure 4) the contaminant is dispersed to the other core zones with minor amounts of contaminant reaching the perimeter offices via the corridors after 10 minutes. For the baseline case (middle row, Figure 4) the contamination levels of the core zones and perimeter offices continue to increase at 30 minutes, but have started to decrease from their peak values by 60 minutes. The purge response case results in the Air Handling Unit's outdoor air damper going from a nominal 20% fresh air to 100% fresh air 10 minutes after the contaminant release. This has a substantial effect on the contaminant levels (bottom row, Figure 4). After 30 minutes the contaminant levels have already started to decrease in the core zones. After 60 minutes there has been a substantial decrease in the contaminant levels in both the core zones and perimeter offices. Later sections will show detailed time histories for various zones compared to experimental results. Section 4 will also discuss the predicted impact on life safety.



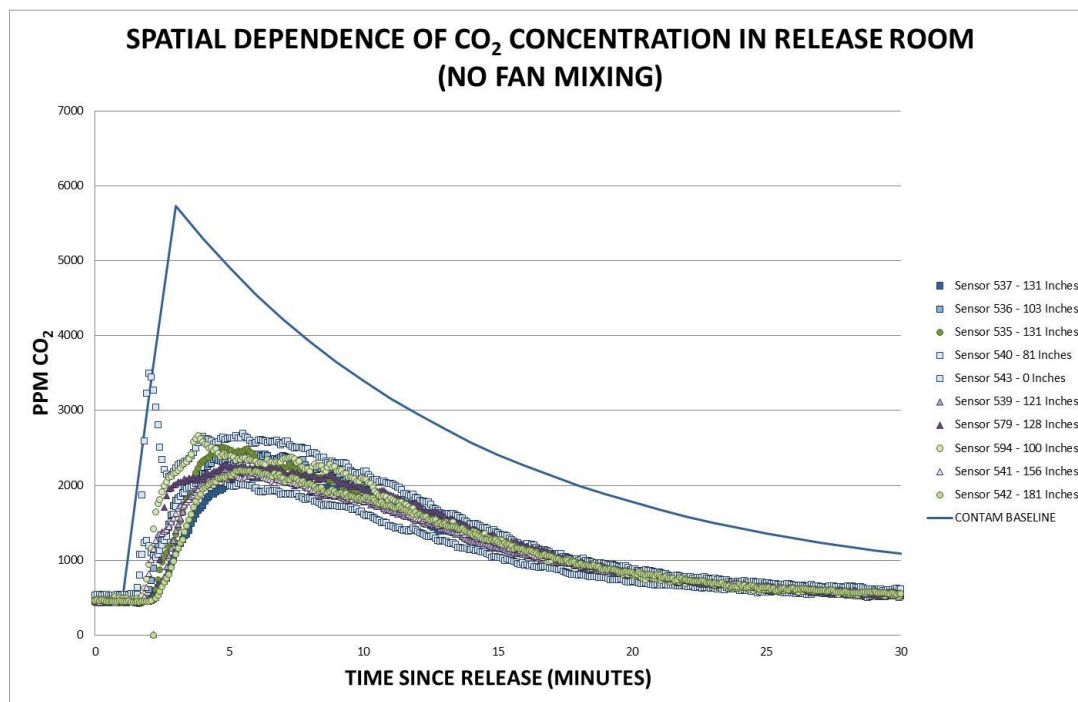
**Figure 4:** CONTAM modeling results for a contaminant release in Zone B. Dispersion is substantially reduced when a purge response is enacted after 10 minutes.

### 3.2 Release Zone Model Validation

A key assumption of CONTAM is that the individual zones being modeled can be treated as well mixed: i.e., any contaminant is uniformly distributed spatially throughout each zone. While it is reasonable that the well-mixed assumption would hold for zones where the contaminant was not released directly, it was not clear that this would be true for the release zones. A series of tests were conducted in which HOBO sensors were distributed spatially around the point of release in zone 'B' to determine how rapidly the CO<sub>2</sub> contaminant approached a well-mixed state in the release zone. This demonstrated that the bursting of the balloon, on its own, did not provide sufficient energy to the CO<sub>2</sub> to spread it throughout the release zone. Instead, the contaminant tended to sink to the floor and then spread out at floor level due to CO<sub>2</sub>'s negative buoyancy compared to the surrounding air. This was overcome by providing a high velocity fan near the release point to stir the zone air and enhance mixing after the release occurred.

In Figure 5, results are shown for the zone 'B' release test. CO<sub>2</sub> concentrations are shown for multiple sensor locations (all approximately 5.5 ft above the floor), the legend identifies the sensor and its radial distance from the release point. Except for sensor 543 directly adjacent to the release point, the sensors' responses track similarly from the moment of release. Sensor 543 saw an initial spike in CO<sub>2</sub> concentration at release. There is a spread in sensor concentration readings of approximately 700 ppm at the peak concentration, which occurs about ten

minutes after the release. This spread in concentration decreases to about 250 ppm after a further ten minutes and then continues to decrease so that the room is essentially well-mixed after 30 minutes. The solid line on the graph is the concentration curve predicted by CONTAM for this case. This curve is qualitatively similar to the tests in the duration of the initial concentration rise and the shape of the decay curve, but shows significantly higher concentrations throughout the event than is indicated by the test data. The experiment suggests that contaminant sinks to the floor and is initially exhausted from the release room through the undercuts in the doors in significantly higher quantities than predicted. However, the simulation predicts the timing of peak concentration and the characteristics of the decay curve with acceptable accuracy.



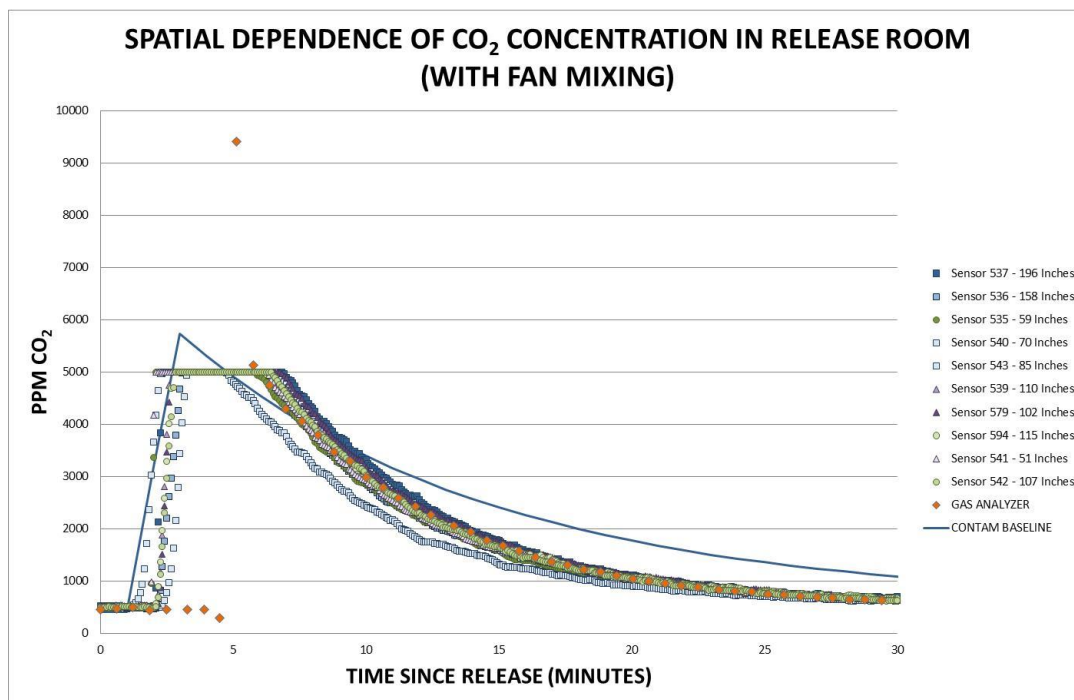
**Figure 5:** Spatial variation of CO<sub>2</sub> levels in release zone 'B' for the first 30 minutes post-release (no fan mixing).

Further investigation with the INNOVA gas analyzer showed that the balloon burst was not effectively dispersing the CO<sub>2</sub> as expected. In fact, after the balloon envelope fell away, the data suggest that the sphere of CO<sub>2</sub> contained within it quickly fell to the floor and then spread out with very little mixing with the room air at all. This was the reason for the high concentrations of CO<sub>2</sub> observed flowing out of the room through the door undercut.

The CONTAM model assumes the contaminant is immediately well-mixed with the air in the release location. To improve mixing in the release room, a high volume fan was acquired and positioned so that the fan discharge would impinge on the CO<sub>2</sub> as it fell to the floor after the release. Data from a test with fan mixing is shown in Figure 6. In this test, the HOBO sensors were placed so as to form a vertical plane roughly through the center of the room, with lines of sensors at heights of 33, 64, and 94 inches from the floor. The INNOVA gas analyzer was placed directly under the release point at floor level, one HOBO was placed in a corner of the room at ceiling level near the return air grille, and one sensor was placed in the opposite corner, also at ceiling height.

There are some differences in the evolution of CO<sub>2</sub> concentration with the fan operating compared to the case without the fan that are immediately apparent. First, in Figure 6 all the HOBO's are observed to saturate at 5000 ppm less than 3 minutes after release, whereas the peak concentration in the case with no fan was around 2700 ppm. Second there is much less spread in concentration between different sensor locations with the fan operating, as might be expected. Third, agreement with the CONTAM baseline result is much better with the fan operating, consistent with the CONTAM well-mixed assumption. Therefore, the fan was used to enhance mixing in all subsequent tests.





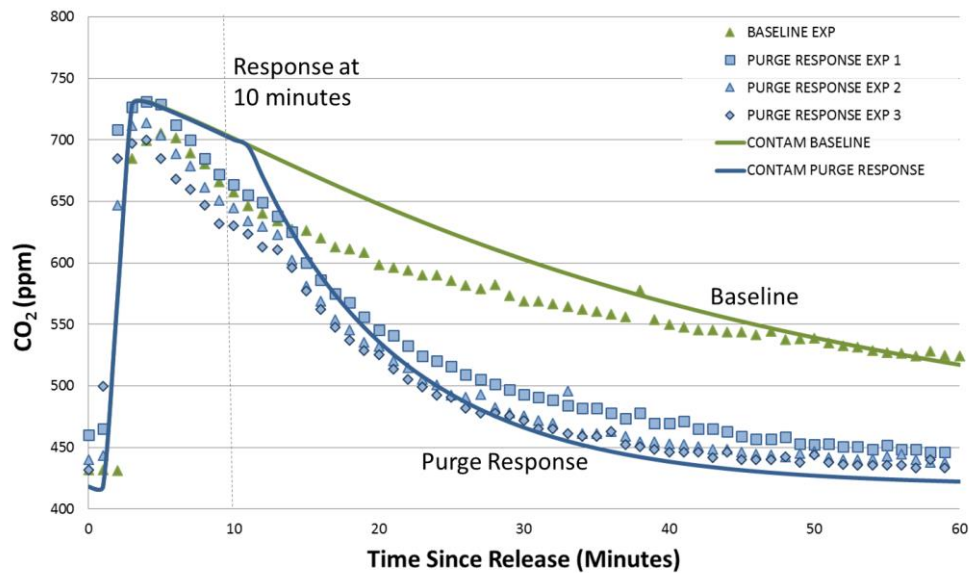
**Figure 6:** Spatial variation of CO<sub>2</sub> levels in release zone 'B' for the first 30 minutes post-release (with fan mixing)

### 3.3 Building-wide Model Validation

The previous section shows comparisons between model and experimental results for the release zones. This section of the report looks at other selected locations of the building and compares the model results with the test data for baseline and purge response scenarios to determine how well the CONTAM models agree with the test data assuming minimal tuning of the models to the experiment. This last point is important because, in practice, tuning a simulation is time consuming and expensive, which would limit the utility and applicability of CONTAM in the future.

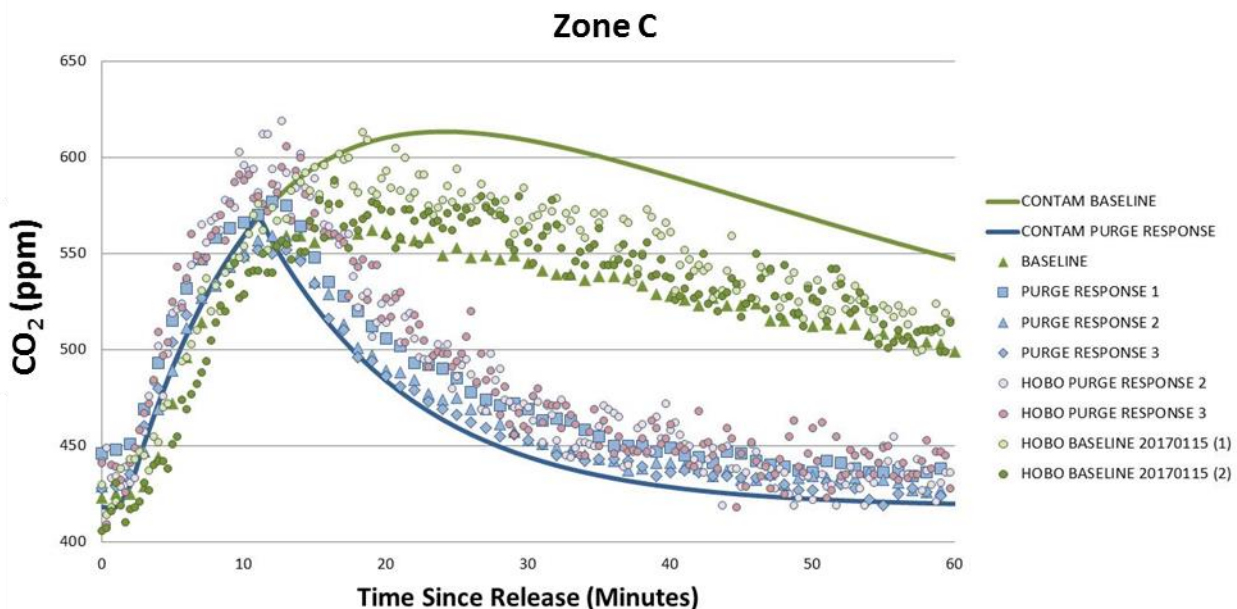
The first result, shown in Figure 7, is for the CO<sub>2</sub> concentration in the return duct of the HVAC system serving the core of the HPTB for the baseline and purge response cases. The solid lines show the CONTAM model results while the test data is shown by the individual data points. A single baseline test is shown along with the results of three purge response tests, which show good agreement thereby validating the repeatability of the experiment. The CONTAM model result for the purge response case shows particularly good agreement with the corresponding test results in both peak concentration and shape of the response curve after the peak. The agreement with the baseline decay is not as good but still considered acceptable due to the uncertainty in the actual outdoor air fraction of the experimental data. This uncertainty exists because only the fresh air damper position is known, not the fresh air flow rate.





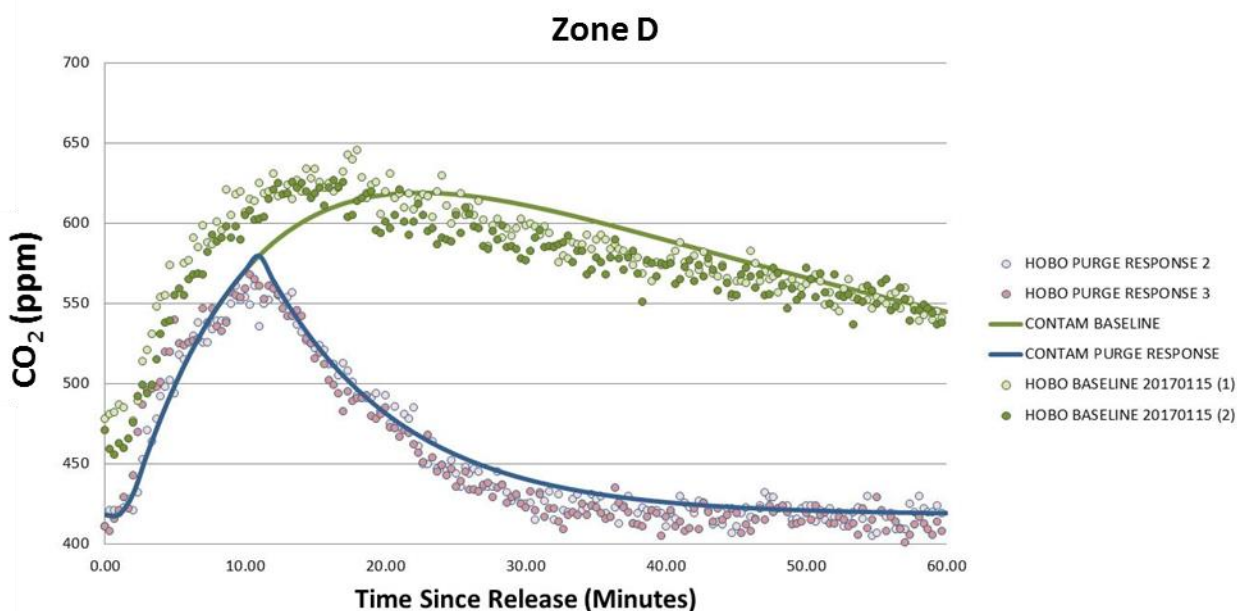
**Figure 7:** Comparison of CONTAM model and test data in the core HVAC system return duct for baseline and HVAC purge response cases during core zone release tests.

Figure 8 shows data from the same set of tests for zone ‘C’, a conference room/office on the first floor. In this case, the room CO<sub>2</sub> data includes points from the HOBO sensors and the wall mounted CO<sub>2</sub> sensors that are part of the building monitoring system. Again, good agreement is seen between the CONTAM models and the experiments and between the three purge tests. It can also be seen that the HOBO data and the wall mounted sensor data agree within the measurement uncertainty of the instruments. This meant that the wall mounted sensors could be used to provide additional CO<sub>2</sub> concentration data for tests where there were insufficient HOBO sensors to provide the desired coverage of the building.



**Figure 8:** Comparison of CONTAM model and test data in zone ‘C’ for baseline and HVAC purge response cases during core zone release tests.

A final result for this test series is shown in Figure 9 for a zone where only the HOBO data was deemed reliable. This shows similarly good agreement between test and model prediction as seen in the previous cases.



**Figure 9:** Comparison of CONTAM model and test data in zone ‘D’ for baseline and HVAC purge response cases during core zone release tests.

#### 4. DISCUSSION

In general there was good agreement between model predictions and experimental data of contaminant levels when fan mixing was used at the point of release. The agreement for the Response tests (purge the building after 10 minutes by commanding the outdoor air dampers to full open, e.g. 100% fresh air) was better than for the Baseline tests (do nothing). The discrepancy during the Baseline test may be due to uncertainty in the damper position. During Baseline operation, the damper was only open 10%, so a small error in position sensing would create a significant error in the amount of outside air flow. However, for the Response case, the damper was fully opened so a small error in the damper position has a less significant impact (relative to 100% open).

While the Response scenario had minimal impact in the room where the release occurred, the increased ventilation introduced by the Response resulted in a significant (70%) reduction in excess CO<sub>2</sub> level in rooms adjacent to the release room (measured 30 minutes after release). Similar results from additional tests were scaled to estimate the lethality of the release of a known biological agent. These results showed that for the Baseline scenario, the fraction of rooms in which the cumulative dosage exceeds the lethal level approaches 90% of the building after one hour. In contrast, the Response scenario keeps the fraction of rooms with lethal dosage from exceeding 40% through the one hour mark. This is a clear demonstration of the effectiveness of the response strategy in minimizing total dose and potential loss of life.

The results of these tests, while generally validating the ability of CONTAM to predict the building response accurately, suggested three additional learnings for consideration in future work:

- The baseline model results are sensitive to the assumed outdoor air percentage, which may be difficult to compute from the experimental data, either due to non-linear damper performance or damper position uncertainty having a proportionally larger impact at low openings
- Pretest predictions were not calibrated to test flow levels so some room performance discrepancies were due to different flow rates being encountered in the test
- Some individual room responses differed due to internal layout (e.g., cubicle dividers) creating spatial sensitivity to sensor location (as witnessed by differences in BAS and HOBO CO<sub>2</sub> sensor results).

## 5. CONCLUSIONS

Analysis and full-scale experimental results were presented showing that intelligent building infrastructure can be used to reduce dispersion of an airborne chemical or biological agent inside a commercial office building. Specifically, an automated HVAC response was demonstrated to provide a 70% reduction in simulated contaminant versus a “no response” scenario in rooms adjacent to the release room (measured 30 minutes after release). The experimental measurements of simulant versus time after release in a full-scale office building demonstrated good agreement with predictions generated using CONTAM. While this investigation focused only on HVAC responses to hazardous agents, the sensing, connectivity, and security systems of intelligent buildings could also be used to reduce the lethality/impact of other types of attacks/events.

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