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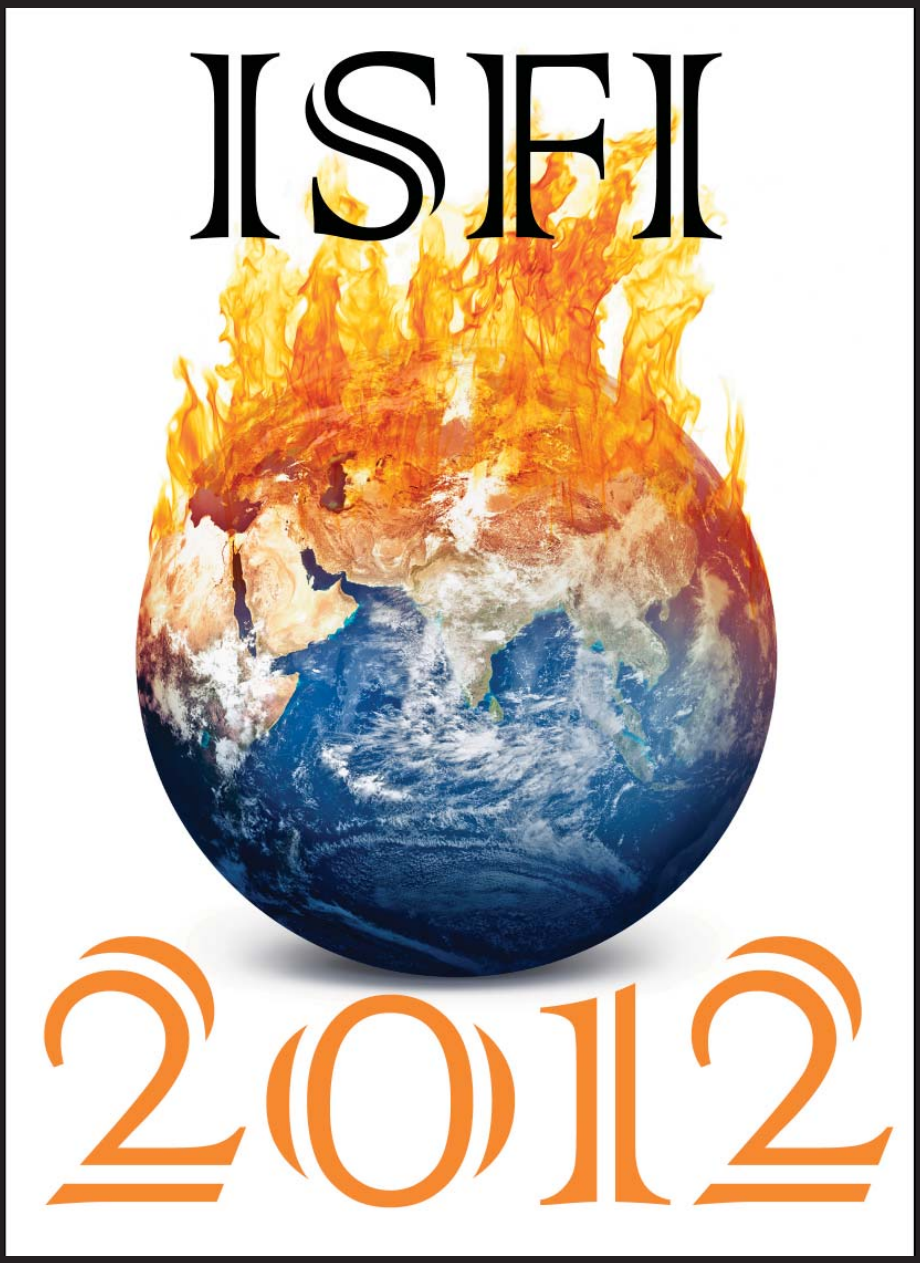

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OPTIMIZATION OF CARBON MONOXIDE DETECTOR LAYOUT IN RESIDENTIAL STRUCTURES

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ABSTRACT

The current NFPA 720 code requirement for carbon monoxide (CO) detectors in residential structures requires placement outside of each separate sleeping area and on each floor of the residence. There is however no further guidance to specific placement of the detector (high, low, near or within furnace closets, etc.), as well as no acknowledgement to different housing and HAVC styles (forced hot air, hot water, etc.). As the concentration of CO approaches several hundred parts per million, the time for detector alarm can be as little as a few minutes, much smaller than the characteristic mixing time of the residence. The general basis for detector placement requirements assumes that once the flue gases cool CO is generally neutrally buoyant in air, and becomes well mixed and distributed evenly throughout the residence. Previous investigations have concluded that the CO is well mixed for residences with forced hot air heating systems and the CO in hot flue gases stratifies due to buoyancy for systems without an air-handling device to cause mixing.

Using the CFD software FLACS, a study was performed to evaluate how CO would disperse and migrate in various residential structures and various HVAC designs. The goal would be to evaluate the migration of CO originating from hot flue gases, which are improperly vented into structures, and assess the validity of the well-mixed assumption as well as study the general dispersion patterns. In addition, the study will provide further guidance as to optimal places for detector placement to allow early detection, while minimizing nuisance alarms.

INTRODUCTION

The current NFPA 720 code requirement for carbon monoxide (CO) detectors in residential structures requires placement outside of each separate sleeping area and on each floor of the residence. There is however no further guidance to specific placement of the detector (high, low, near or within furnace closets, etc.), as well as no acknowledgement to different housing and HAVC styles (forced hot air, hot water, etc.).

As the concentration of CO approaches several hundred parts per million, the time for detector alarm can be as little as a few minutes, much smaller than the characteristic mixing time of the residence. The general basis for detector placement requirements assumes that once the flue gases cool CO is generally neutrally buoyant in air, and becomes well mixed and distributed evenly throughout the residence. Previous investigations have concluded that the CO is well mixed for residences with forced hot air heating systems and the CO in hot flue gases stratifies due to buoyancy for systems without an air-handling device to cause mixing.

The migration of CO throughout a residential structure is dependent on many factors including: geometry of the residence or building, type of ventilation (natural, forced air), specifics of the HVAC system, temperature and source location of the flue gases with CO. Using CFD is an efficient way to systematically evaluate the various parameters affecting CO migration. These studies can then provide valuable performance based design parameters for CO detection systems (e.g., location of detectors and time to detection).

This study represents initial work on evaluating gas detector layouts in a representative residential structure using a performance based design approach. This preliminary study evaluates the location and time to detection based on the variation of certain parameters, which include: three geometric configurations of the flue gas source with CO, two flue gas temperatures, two flow rates of the flue gases, and three airflow rates within a two-story home with a basement.

FLACS CFD PACKAGE

FLACS is developed and maintained by GexCon in Norway. It is an advanced computation fluid dynamics (CFD) code for the modeling of ventilation, gas dispersion, gas/vapor cloud explosions and blasts in complex process areas. FLACS is not a general-purpose CFD model, but a model specifically designed to simulate gas dispersion and explosion scenarios for complex geometries.

FLACS solves the compressible Navier-Stokes equations on a 3-D Cartesian grid using a finite volume method. It takes account of the interaction between the flow (including the flame front) and complex geometries such as structure, equipment and pipework. In order to simulate the interactions for realistic geometries, with reasonable demands and limitations on computer resources, a distributed porosity concept is used for representing the geometry on a Cartesian grid. The model geometry is transferred to the computation grid by means of area and volume porosities, as well as an array of "wake-generating" sub—grid terms that contribute turbulence, drag and flame acceleration to each grid cell.

Development of FLACS started in 1980. Since then, FLACS has been used to simulate a large number of dispersion and explosion experiments in various geometries with a wide range of parameters [1-5]. The development of FLACS as a dispersion tool was initially focused on modeling the release of natural gas on offshore platforms. Since then, FLACS has been used and validated for a growing number of gas dispersion applications, ranging from toxic gas releases (e.g., chlorine, hydrogen sulfide) to liquefied gases (e.g., LNG and LPG).

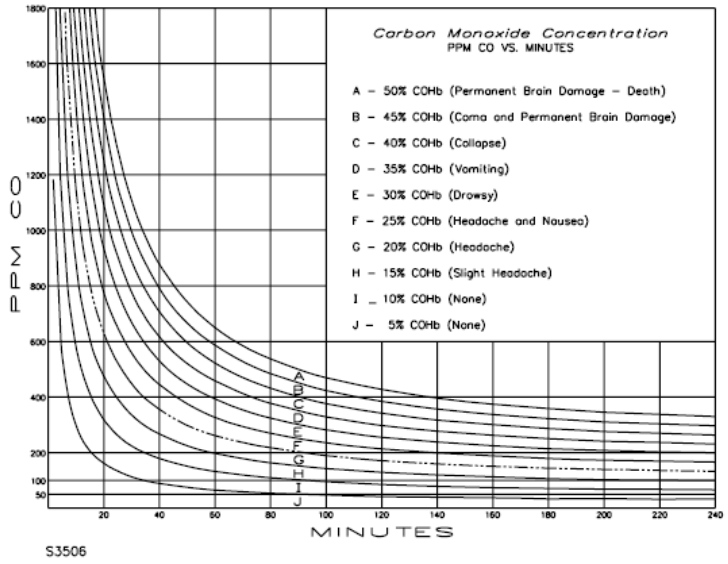
MATLAB CO ALARM MODEL

FLACS does not have functionality to directly access the potential for CO alarm activation. As such, a MATLAB script was developed to model the time to alarm that a potential CO detection device would take to activate. This time to alarm was based upon the standards set forth in UL 2034 – Single and Multiple Station Carbon Monoxide Alarms [6]. The test points that UL evaluates to are found in Table 1.

Table 1: Time to Detection Criteria Specified in UL 2034.

Carbon monoxide concentration versus time for alarm test points based on 10 percent Carboxyhemoglobin (COHb)	
Concentration (ppm)	**Response time (Minutes)**
70 ±5	60 - 240
150 ±5	10 - 50
400 ±10	4 - 15

Along with the above table, an equation and table is presented for the approximate time for various COHb levels based upon exposure concentration. These are replicated in Figure 1.



Equation For determining estimated percent COHb in blood[a]

$$\%COHb_t = \%COHb_0[e^{-(t/2398B)}] + 218[1-e^{-(t/2398B)}][0.0003 + (ppm\ CO/1316)]$$

in which:

$\%COHb_t$ is the percentage of COHb at time t,

$\%COHb_0$ is the percentage of COHb in the blood at time 0,

t is the time in minutes, and

B is 0.0404 (heavy work effort).

[a] A proposal for evaluating human exposure to carbon monoxide contamination in military vehicles, Steinberg, Nielson, March 1977, AMCMS Code 672716.H700011; Coburn, R.F., Forster, R.E., & Kane, P.G. Considerations for the physiological variables that determine the blood carboxyhemoglobin concentration in man. Journal of Clinical Investigation, 1965, 44 1899-1910.

Figure 1: UL Specified Equation for Estimation of COHb Levels [6].

Using this equation, an iterative approach was programed using the MATLAB software package. An evaluation was done as to the dependence upon sampling time. Both one second and one minute sampling times were evaluated. The results for each were compared against the exact solution or the UL provided 10% COHb concentration curve. The results are presented in Table 2 for the 70, 150 and 400 PPM concentrations. The results for the one second sampling rate were within 0.2% of the exact solution, while the results for the one minute sampling were greater than 5% for the 400 PPM concentrations. In addition, various time dependent CO profiles of known concentration were evaluated and compared to the exact solutions. The determination was made that the one-second sampling interval would provide the most accurate results and will be reported in the current study.

Table 2: Comparison of Script with Exact Solution.

	Exact Solution	**1 Sec Sampling**	**1 Min Sampling**
CO PPM	**Time (min)**	**Time (min)**	**Time (min)**
70	188.79	188.82	190
150	49.71	49.73	51
400	15.83	15.85	17

GEOMETRY MODEL AND FLACS SETUP

This study involved three different geometry configurations of the flue gas source release within a two-story home with a basement. For the current study all of the flue gas releases into the home originated near the gas fired water heater and boiler/furnace in the basement. The first configuration considered the gas fired equipment to be installed in an open basement, the second considered the equipment to be installed in a utility room where the flue gases could escape from the utility room only, and the last configuration include a utility room, but the flue gases were only allowed to escape via holes in the ceiling to the ground floor. Pictures of the geometry follow in Figure 2 through Figure 6.

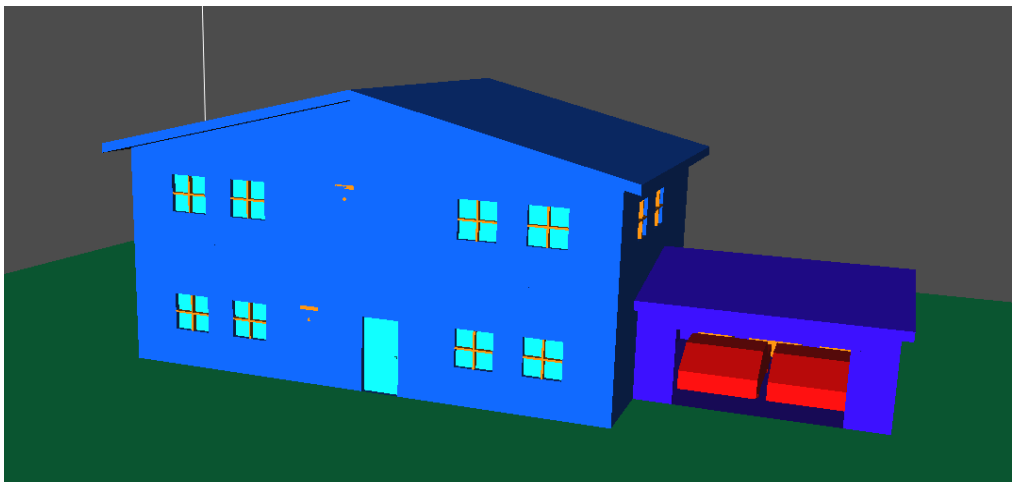


Figure 2: Exterior of Model House.

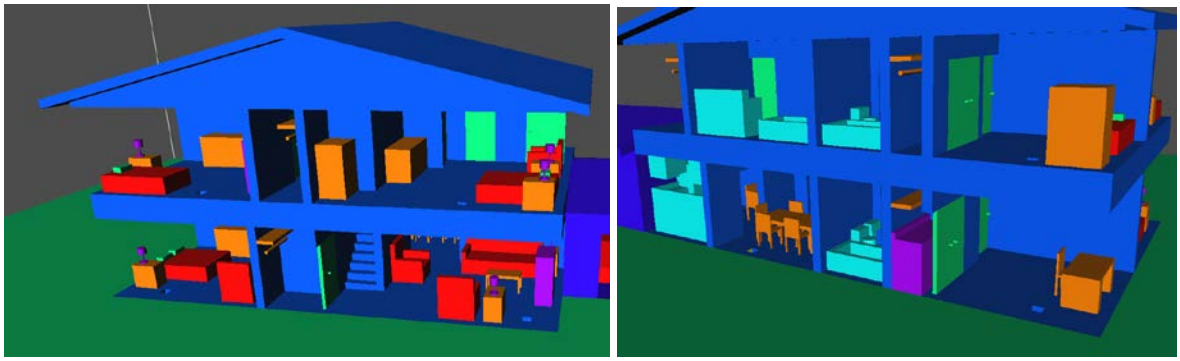


Figure 3: Exterior View with Walls Removed for Clarity. Front View (Left) and Rear View (Right).

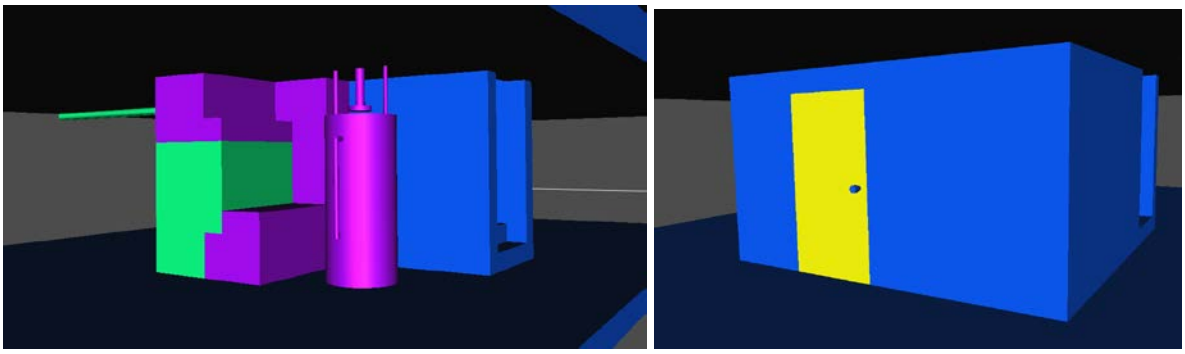


Figure 4: Basement View, Close up view of HVAC and Water Heating Equipment With (Right) and Without (Left) Utility Room Enclosure.

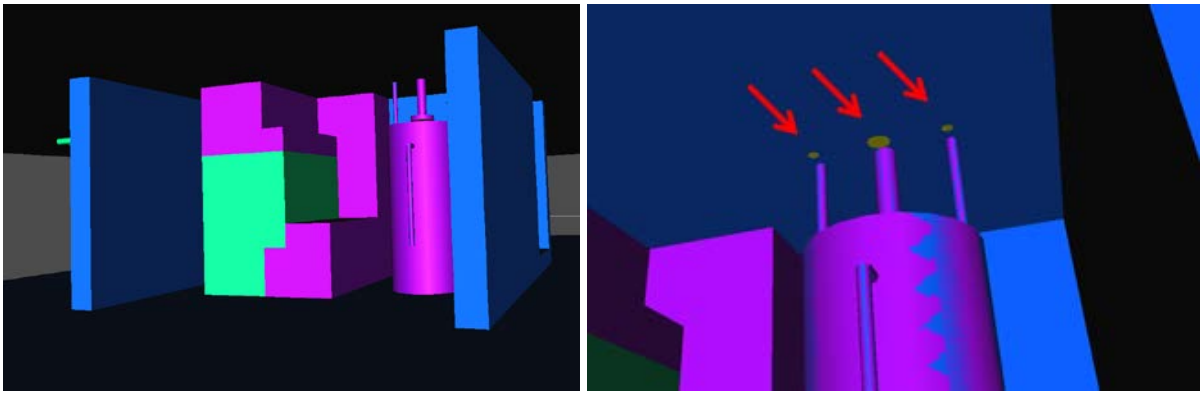


Figure 5: Basement View, Close up View of HVAC and Water Heating Equipment for Geometry with Hole Around the Pipes in the Ceiling (Right). The Front Wall Has Been Removed For Clarity.

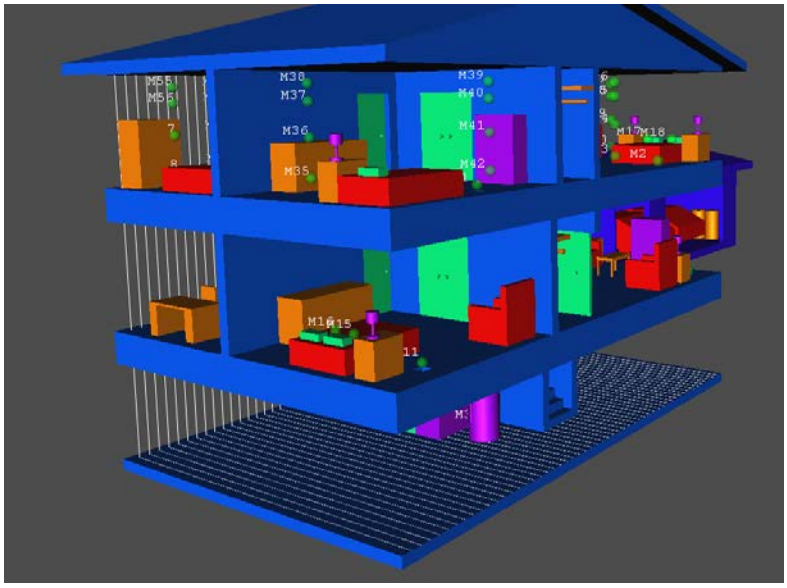


Figure 6: Walls and Ground Plane Removed. Illustration of Grid and Monitor Point (Detector) Locations.

Within the geometry, there is a mixing air distribution system built into the walls and floors. The ductwork pathways (not pictured) run to each room in the structure, and depending upon the area of the room, have either one or two Group B supply outlets (discharge air vertically in a non-spreading jet). Each of the vents is located on the floor near the exterior of the structure. The air distribution system was designed with flow resistance elements (porous plates) in the geometry to equalize the flow through each of the segments. The door to the garage on the side of the house was designed to be partially porous and allow some outflow to avoid over-pressurization in the house due to the flue gas source term.

For this study a uniform grid of 0.25m was used. The uniform grid is not a requirement of FLACS, however, with the ducts of the air distribution system having a uniform cross section of 0.5m wide by 0.25m high throughout the house, the resolution was maintained to ensure accuracy in the ductwork.
This study also utilized the incompressible solver to be issued in the next release of FLACS and simulations were allowed to run to a maximum of 10,000s (166.66min).

DESCRIPTION OF SCENARIOS

For this study several different conditions were evaluated. The varying factors included: three geometric configurations of the flue gas source with CO, two flue gas temperatures (representative of high or lower efficiency systems heating systems), three airflow rates within the home (representative of no forced air, low airflow and higher flow) and two flow rates of the flue gases (e.g., 100,000 and 150,000 BTU/hr rating of the heating appliance).

For the purposes of this study, all the flue gases were assumed to contain 20,000 PPM of CO. Other factors that were not evaluated were ambient conditions of the house, weather outside the house (wind and temperature) and different heating fuel types. These variables would all contribute to variations in the CO generation rate and dispersion characteristics, however were outside the scope of this study and will be evaluated in future work.

A total of 36 scenarios have been investigated for this study. All combinations of the conditions in Table 3 have been analyzed.

Table 3: Variables Considered for the Present Study

Geometry	Airflow	Temperature	BTU Rating
Open Basement	0 cfm	100 °C	100,000 BTU/hr
Porous Closet Door	60 cfm	300 °C	150,000 BTU/hr
Pipe Pathway Leak	100 cfm		

According to ASHRAE 62.2, for a house of 1120 ft^2, with 4-5 bedrooms, the minimum ventilation rate is 60cfm. This value corresponds to approximately 5 ACH in this dwelling. This value along with zero airflow (e.g. a home heated by a boiler) and 100 cfm were evaluated.

RESULTS

A preliminary look at the results show that there is a great dependence upon the location of the detector with respect to the time to alarm. Out of all the simulations, the shortest time to detection is 55 seconds (1 min), while the longest time is nearly 100 times longer and on the order of 5000 seconds (~1.4 hrs). With these two data points, it is clear that there is a direct relationship between detector placement and specific release scenarios and structure layouts.

In all cases, as expected, the first monitor point location to alarm was located near the heating appliances, either in the room or just above the water heater. However, there were differences in time to detection

based upon the details of the geometry in the vicinity of the flue gas source. Figure 7 shows the average time to detection for each geometry using the two monitor points located closest to the source, within the room (if applicable). As expected the open geometry takes longer time to activation as the flue gases can migrate to all areas of the basement, while the case with the small holes in the ceiling allows the CO level to build up in the vicinity of these detectors and results in faster detection times.

Time to detection was very sensitive to detector location and the source scenario. An example of this can be seen in Figure 8, which shows the time to detection (as a function of height) for the CO alarm tree on the first floor just above the source room. For the open basement and leaks past the utility room door, the CO migration to the main floor was predominately driven by the buoyancy of the hot flue gases filling the upper layer of the basement and moving up the basement stairs. The leaks scenarios passing through the holes in the ceiling provided a direct path to the main floor. Not surprisingly, the times to detection for the releases through the holes in the ceiling to the main floor were the fastest, followed by the releases into the open basement. The longest detection times on the main floor were the cases where the flue gases were somewhat retained in the utility room at ceiling level, and could ultimately escape through the door. The trends also show that for releases in the basement, the time to detection was very sensitive to the height of the detector (e.g., placement near the ceiling resulting in detection times twice as fast as the lower lying detectors).

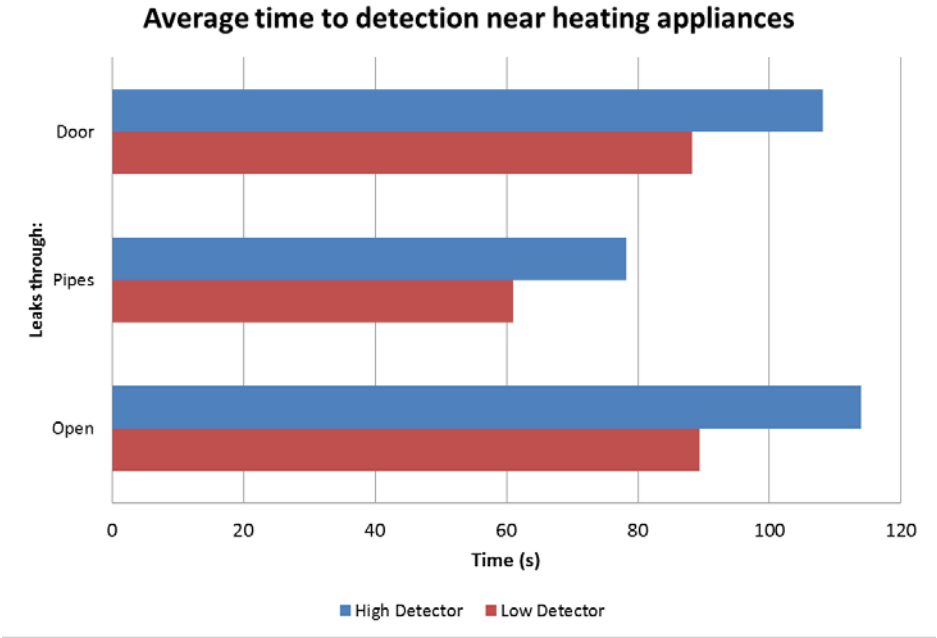


Figure 7: Average Time to Detection for Each Geometry Layout.

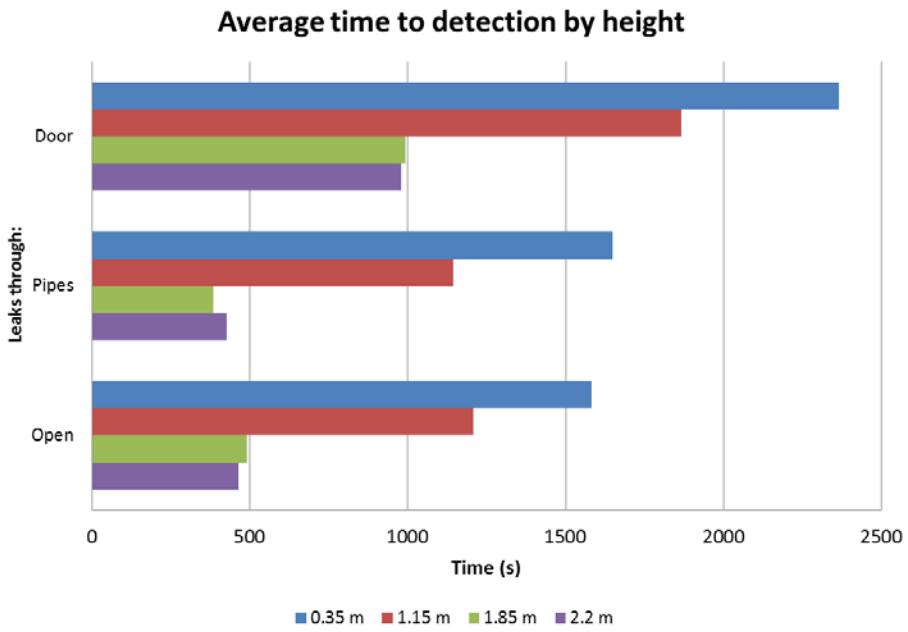


Figure 8: Average Time to Detection in Main Floor Hallway for Each Geometry, Sorted by Height of Detector.

Figure 9 and Figure 10 are plots of the average time to detection for all monitoring points in each scenario, sorted by source temperature (Figure 9) and airflow (Figure 10). These results further illustrate a dependence upon the specific scenario and conditions in which CO is released.

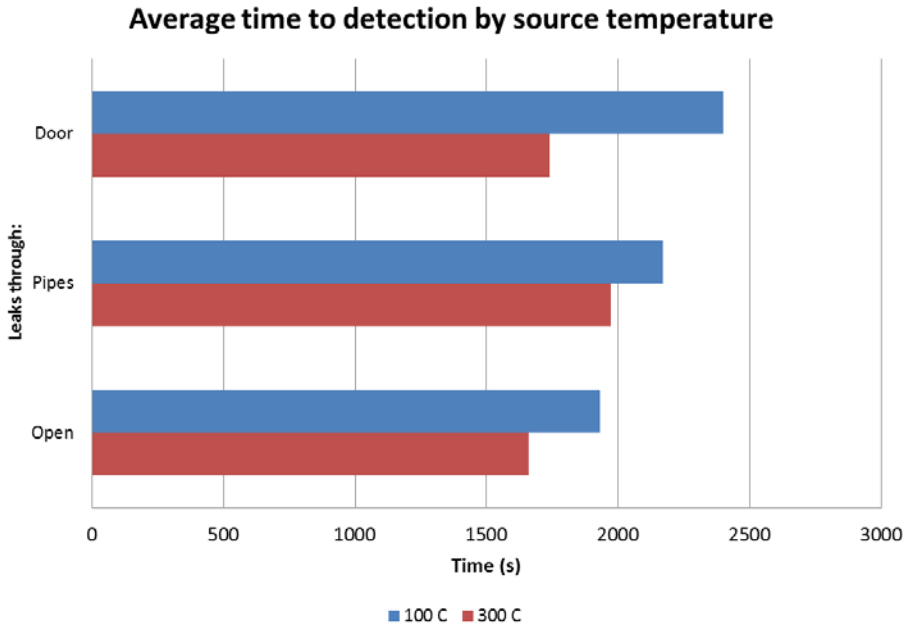


Figure 9: Average Time to Detection for Each Geometry Layout, Sorted by Temperature of Source.

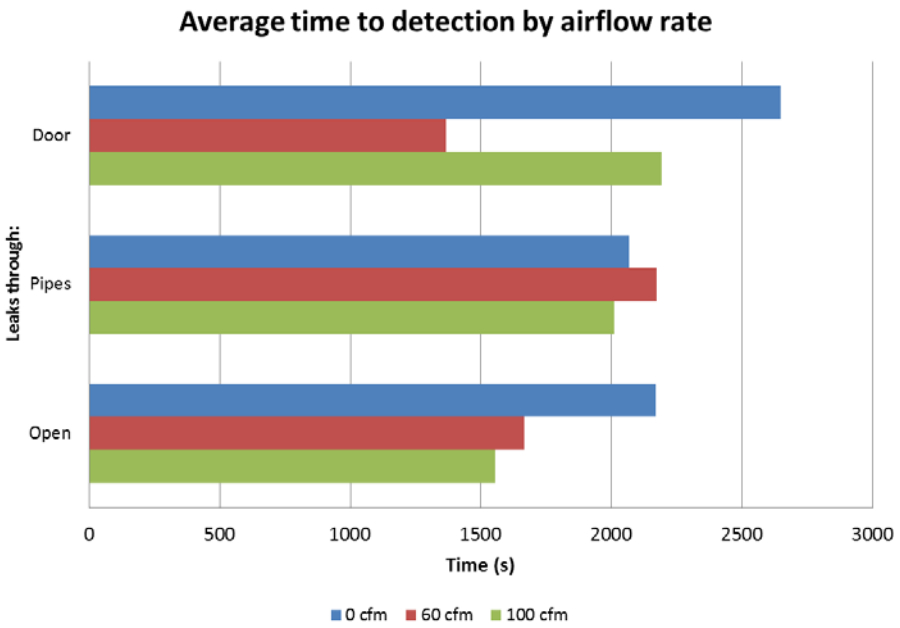


Figure 10: Average Time to Detection for Each Geometry Layout, Sorted by Ventilation Rate in the Structure.

Figure 11 shows various CO releases at 1000s seconds. The blue region has a concentration of 50 ppm or higher. From the pictures it is evident that there is a large dependence upon the factors investigated. In the upper left corner, the CO was released from the basement and allowed to flow through the holes in the ceiling, as such there is no concentration in the basement or adjacent to the combustion appliances. With this scenario the air distribution within the structure has diluted the CO concentration below the alarm threshold levels. The scenario is the upper right, has a porous door with the emissions from 150,000 BTU/hr system and no mechanical air movement. The CO remains mostly in the basement. The scenario in the lower left is in the open basement with 60 cfm airflow and release temperature of 300 °C. The CO is very buoyant and spread throughout the bottom two floors of the house. For the case in the lower right, the CO was allowed to escape freely into the basement and has filled the basement and begun to fill the main floor, with no active air distribution in place the hot CO remains buoyant and near ceiling level.

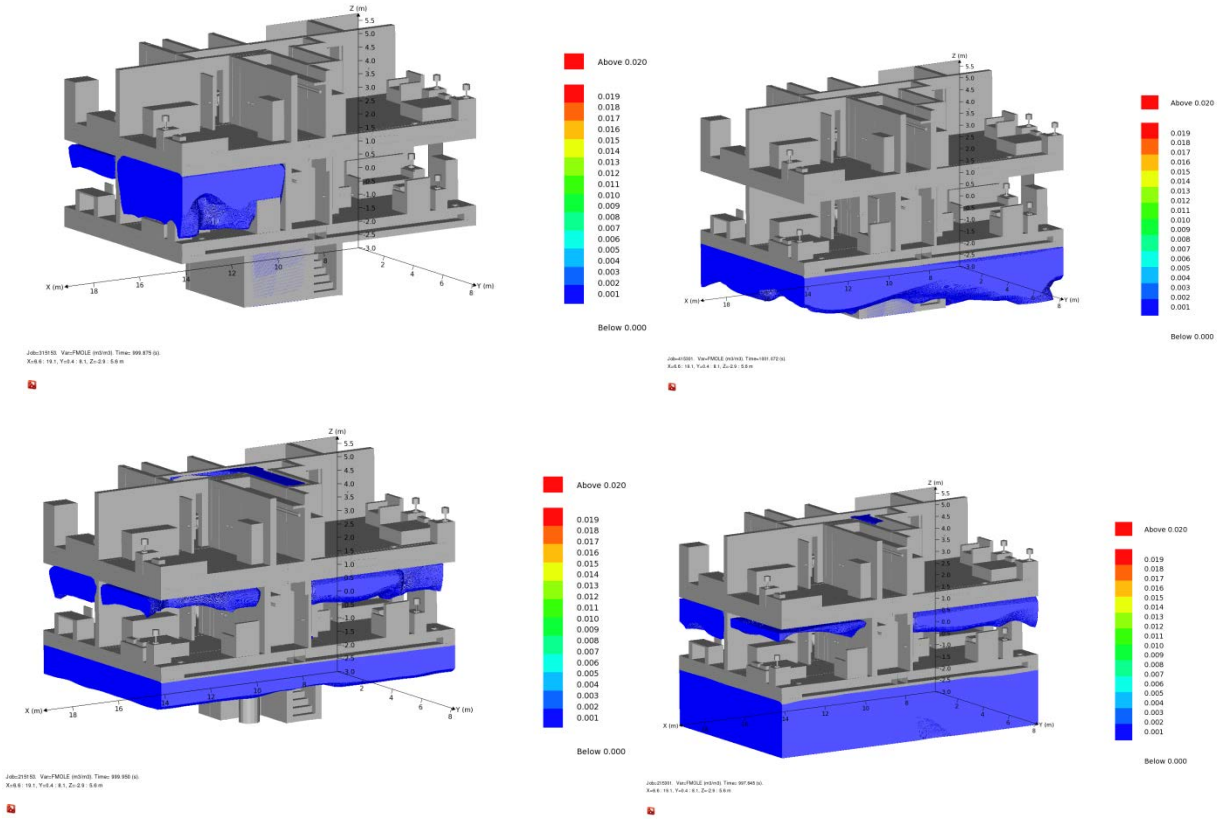


Figure 11: Various release scenarios at 1000s.



Figure 12: No Ventilation Release of CO at 100C. Pipe permeation (left) versus door (right).

Figure 12 shows identical releases, with different geometric conditions surrounding the source term. It can be seen that the highest concentration of CO for the release allowed to flow through the floor is near ceiling level above the CO source, when the CO is allowed to migrate out of the door of the appliance room, the highest concentrations are at ceiling level in the basement.

Some of the scenarios were generally well mixed, however a majority were not. For the cases in which the CO was stratified and an air movement system was present, a CFD based approach would be the most appropriate methodology. A zone type model, in which the rooms were assumed to be well mixed would likely over predict detection times as the concentration of the entire room would be generally lower and not provide the optimal solution.

CONCLUSIONS

From the results presented, it has been shown that there is a high dependence upon the time for a CO detector to alarm depending upon the various conditions that can contribute to the dispersion of the gas. There were correlations between the temperature of the release, the airflow characteristics within the structure, flow rate of the flue gases and the geometry layout. This study was preliminary in nature and will be expanded in future work.

The analysis of the two different temperature releases showed that, for this study, the average time to alarm was noticeably shorter for the higher temperature release. The shortest time to detection was always within the vicinity of the CO source. Nuisance alarms were not evaluated in the present study; however, they should be considered when placing detectors in close proximity to the gas-fired appliance. Depending on the leak scenario, fastest detection times may occur on lower or upper floors. The study substantiates the guidance to place a detector on each level of a residential structure.

This study was not meant to be a comprehensive analysis of all possible conditions and scenarios. It was meant to consider the implications of a performance based design system for CO detector layout. This study has shown that there is a large dependence upon the factors of the release and other ambient and geometric considerations to warrant further investigation. After multiple conditions and combination of events are evaluated, a final layout will be proposed based on the performance of the CO detection system. The results of this preliminary study have shown that a performance based design approach for CO detection siting is feasible and a worthwhile pursuit.

FUTURE WORK

As discussed previously, several additional factors that were not included in this study that could reasonable affect the time to detection and placement for CO alarms. These include, fuel type, external weather conditions, house geometry and layout changes, temperature of release and CO generation rates. In addition the air distribution system was sealed within the appliance room. Infiltration of CO into the HVAC system would also be an interesting consequence to analyze. These scenarios will be developed in the future and published when available.

ABOUT THE AUTHORS

Derek Engel is an engineer within the Explosion and Fire Safety group at GexCon US Inc. Mr. Engel is responsible for fire and explosion related activities as well as safety studies for various industries. He specializes in mechanical, thermal and fluid engineering. Derek uses GexCon's world leading FLACS to aid in cause and origin investigations as well as explosion risk analysis and toxic gas distribution studies.
Dr. Scott Davis is the President at GexCon US and specializes in the engineering analysis and testing of combustion, thermal, and fluid processes. Dr. Davis is responsible for fire and explosion related activities, which include post-incident investigative work, worldwide training and experimentation, as well as performing risk assessments and safety studies for offshore and floating oil & gas installations, petrochemical facilities, and various other industries. These studies include explosion risk assessment, blast and venting analyses, assessment of combustible dust explosions, toxic/flammable gas releases and dispersion, hydrogen safety, ventilation, detector placement, and carbon monoxide dispersion. He is a member of the NFPA 720 technical committee.

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