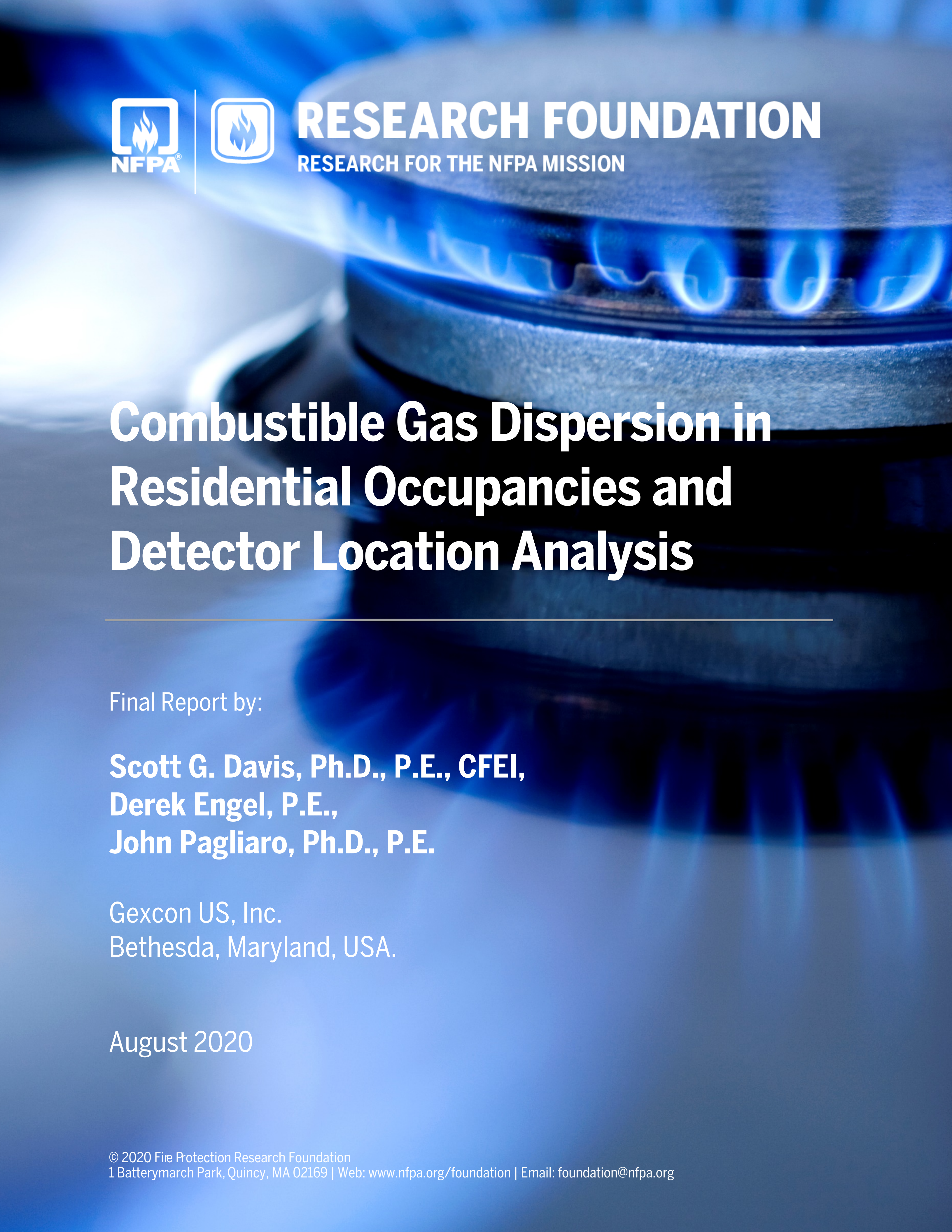

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Combustible Gas Dispersion in Residential Occupancies and Detector Location Analysis

Final Report by:

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Foreword

Recent experiences with combustible gas releases in residential buildings have led to a proposal for NFPA Standards Development for locating combustible gas detectors and consensus on installation location requirements. NFPA has initiated a project on detector location and installation, NFPA 715 "Standard for the Installation of Fuel Gases Detection and Warning Equipment", similar to the Standard NFPA 720, "Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment." To date, technical analysis for justifying combustible gas detector installation location is lacking to support standards development. This study is proposed to address the residential installation criteria for these devices and systems.

The present study uses computational fluid dynamics (CFD) to quantitatively evaluate gas detector performance as a function of placement in residential occupancies. Natural gas and liquefied petroleum gas releases are simulated in different residential structures and gas concentrations are tracked at numerous potential detector locations within these structures to evaluate which locations are most effective for reliable and early detection. Over 250 CFD simulations were performed with a wide range of plausible leak types and environments to produce robust technical bases upon which gas detector location recommendations can be made.

A hazard-based approach was applied to compare the performance of gas detector installation locations. More specifically, this study quantified detector location performance based on 1) the ability of a detector location to detect before certain hazardous conditions arise and 2) the ability to provide sufficient response time prior to the hazardous conditions arising.

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

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About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: gas detector, combustible gas, natural gas, propane, liquefied petroleum gas, residential, CFD.

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Executive Summary

The present study uses computational fluid dynamics (CFD) to quantitatively evaluate gas detector performance as a function of placement in residential occupancies. Natural gas and liquefied petroleum gas releases are simulated in different residential structures and gas concentrations are tracked at numerous potential detector locations within these structures to evaluate which locations are most effective for reliable and early detection. Over 250 CFD simulations were performed with a wide range of plausible leak types and environments to produce robust technical bases upon which gas detector location recommendations can be made.

A hazard-based approach was applied to compare the performance of gas detector installation locations. More specifically, this study quantified detector location performance based on 1) the ability of an installed detector at a specific location to detect before certain hazardous conditions arise and 2) the ability to provide sufficient response time prior to the hazardous conditions arising.

The results of this study highlight the importance of requiring a gas detector in the same room as permanently installed fuel-gas appliances. For these detectors, generally better performance was observed when: the detector was placed closer to the leak source, there was an unobstructed path between the detector and the leak source, and when the detector alarm threshold was lower (i.e., 10% LFL compared to 25% LFL). Generally poorer performance was observed when a detector was located: near HVAC supply registers; near passive openings such as doors and windows; and near openings to adjacent areas (e.g., door openings and stairwells).

For natural gas, the closer the detector was to the ceiling the more likely it was to detect a leak and the more time it provided for occupants to respond to an alarm before hazardous conditions occurred. Based on the applied threshold hazard conditions, detectors placed 6 inches or closer to the ceiling had significantly improved performance compared to those placed farther down in height when the detector alarm threshold was 10% LFL and 25% LFL. If a sensor cannot be placed this close to the ceiling, it should be placed at least above the highest doorway opening.

For liquefied petroleum gas, the closer the detector was to the floor the more likely it was to detect a leak and the more time it provided for occupants to respond to an alarm before hazardous conditions occurred. Based on the applied threshold hazard conditions, and provided certain installation locations are avoided (e.g., excluding locations with an obstructed path to the leak source, locations over registers, or at doorway openings), detectors placed closer than 8-10 feet from the leak and at no more than 6 inches above the floor had significantly improved performance for the alarm threshold of 10% LFL. When the alarm threshold was 25% LFL, improved performance occurred when sensors were placed closer than 8-10 feet from the leak and no more than 4 inches above the floor.

Additional gas detectors in rooms or areas remote from where a gas-fired appliance was located generally alarmed after a properly placed detector in the room where the gas-fired appliance was located. These additional or supplemental detectors mainly provide detection redundancy and the best places to put them include rooms or areas directly adjacent to the room containing the gas-fired appliance, and along pathways to upper and lower floors when the fuel is natural gas and liquefied petroleum gas, respectively.

1 Introduction

The National Fire Protection Association (NFPA) is developing a standard for combustible gas detector installation requirements, NFPA 715: Standard for the Installation of Fuel Gases Detection and Warning Equipment. It is envisioned that such requirements can be established as has been done for CO detection in NFPA 720, "Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment". The goal of the present study is to establish technical bases for combustible gas detector installation location recommendations in residences that use Natural gas (NG) or Liquefied Petroleum gas (LPG).

Residential gas leaks result in fires and explosions each year [1]. While fuel-gases are odorized to enable the detection of a leak (i.e., detectable odor at 1/5 lower flammability limit - LFL), fuel-gas users may benefit from using combustible gas detectors as an additional means of leak detection.

Reliable and early detection are the most critical aspects of effective gas detection/alarming. While general sensor placement recommendations exist, an NFPA Standard containing more specific prescriptive-based detector placement requirements supported by a robust technical basis would help to ensure more effective gas detection.

The present study uses computational fluid dynamics (CFD) to quantitatively evaluate gas detector performance as a function of placement in residential occupancies. Natural gas and LPG releases are simulated in different residential structures and gas concentrations are tracked at numerous potential detector locations to evaluate which locations are most effective for reliable and early detection. The main challenge to performing this type of study is considering all of the variables that affect how a released gas disperses in the environment where it is released and where it will begin to accumulate first. The variables that affect how a released gas disperses include certain leak characteristics and environmental characteristics. It is necessary that the broad range of plausible leak types and environments are considered for the results to be robust and for the sensor placement recommendations to be most effective. The following sections summarize the important background information that influenced our selection of fuel-gas release scenarios to model in this study.

1.1 Factors affecting the outcome of a release

There are several factors that affect the outcome of an NG or LPG release within a residence. As stated above, the important outcome of a release in terms of gas detector placement is how the gas disperses throughout the space where it is released (i.e., how it is distributed) and whether there are areas where it first accumulates at a higher concentration. The ideal detector placement for a given leak would be at the location where the concentration first reaches the detector threshold of the sensor. Placing a sensor in this location would provide the earliest detection possible and therefore the key to detector placement is knowing how the released gas disperses and where it tends to preferentially accumulate.

1.1.1 Leak characteristics

The resulting dispersion or distribution of fuel-gas from a leak depends on several factors, including the vapor density of the fuel gas, the leak momentum, and the leak height, as has been demonstrated both experimentally and theoretically in past studies [2-4]. The density of the released gas controls whether it will tend to accumulate at the ceiling or floor under certain release conditions. Natural gas is less dense than air and thus tends to migrate towards the ceiling. In contrast, LPG is more dense than air and tends to migrate towards the floor.

The leak momentum (i.e., the velocity of the leak source) is an important characteristic of a leak that influences mixing. Fuel-gas releases in residences typically occur from low-pressure systems (7" w.c. for NG and 11" w.c. for LP-gas), however there are some higher-pressure systems as well. When there is a release into open space (i.e., an un-impinged release) the source momentum causes the released gas to mix with air and become more uniformly distributed in the space where it is released. When a release impinges on a surface close to the release point, such as a wall or the back of an appliance, the velocity of the flow stagnates at the impingement. Hence, the amount of mixing is reduced, the gas becomes less uniformly mixed, and it preferentially migrates due to the effects of buoyancy within the space (e.g., along the ceiling for NG and along the floor for LPG).

The leak height is another characteristic of a leak that is particularly important to how the gas mixes and/or preferentially accumulates in the space where it is released. For NG, which is less dense than air, the closer the leak is to the floor the more it will mix with air as it buoyantly rises toward the ceiling and the more well-mixed the gas and air will be in the space as compared to a release near the ceiling. The opposite is true for LPG; the closer the leak is to the ceiling the more it will mix with air as it buoyantly cascades towards the floor as compared to release near floor level.

Certain releases are more likely to result in more uniform gas concentrations; for example, an un-impinged release of NG near the floor or LPG near the ceiling. For these releases, gas detector location is least critical because the gas concentration will be similar everywhere and thus a detector would go off at approximately the same time regardless of where it is placed. In contrast, certain releases are more likely to result in volumes or pockets of accumulated gas at higher concentrations compared to other areas; for example, an impinged release of NG near the ceiling or LPG near the floor. For these releases, gas detector location is most critical because there is the potential for gas concentrations to accumulate in one location while remaining below detection threshold levels in other locations, hence the importance of proper gas detector placement.

1.1.2 Environmental aspects

There are environmental aspects that influence the mixing and/or accumulation that occurs during a release. These include the size of the residence, the number of floors, whether mechanical ventilation is operating, the air tightness of the structure, and the general layout of the residence. In a multi-floor dwelling, gas could potentially accumulate on a different floor from where the leak occurs. Mechanical ventilation could cause additional mixing and more uniform concentrations and could also potentially transport the released gas to other areas of the dwelling. Air leakage through the exterior wall assemblies and openings could cause additional mixing and dilution in areas near passive leak paths through the building envelope. Layout plays a role in the amount of mixing and accumulation, for example whether the layout of a residence is more traditional with several partition walls and doorway headers or more open concept with less walls and no headers. As will be discussed further below, these various environmental aspects were considered in the CFD simulations so that the study produced robust results that were broadly applicable to various residential occupancies.

1.1.3 Residence building types

There are several different types of residential buildings, including single family homes, multi-family homes such as duplexes, townhouses, condominiums, high-rise apartments, and mixed-use residential / commercial occupancies. Detector placement recommendations need to be applicable for these different types of residences and therefore it is necessary to discuss the potential differences between these buildings that may lead to differences in how a gas leak disperses within each residence type.

The things that potentially vary most with residential buildings type are building envelope air leakage (i.e., outdoor air infiltration), ventilation requirements for acceptable air quality, and credible leak scenarios (i.e., larger leaks possible in mixed-use occupancies).

In addition to construction practices and local ambient environments, building envelope air leakage into a residence varies with factors such as the number of exterior walls (e.g., detached single-family house versus apartment) and the height above ground (i.e., high-rise apartments exposed to potentially higher winds than near ground level).

Ventilation requirements for acceptable air quality are different for different residential buildings types and therefore could lead to different leak dispersion outcomes and different amounts of mixing when the mechanical ventilation is active.

Lastly, there may be the potential for larger leaks in mixed-use occupancies and residential building types that use centralized furnaces and boilers to provide heat and hot water to the entire building. These systems may include interior piping at higher pressure compared to a single-family home and may also have larger piping resulting in credible leak scenarios with larger leak rates.

1.2 Residential gas leak statistics and incident descriptions

Numerous leak locations were considered in the CFD modeling campaign and were chosen based on residential gas leak statistics summarized in ref. [5], “Fires Starting with Flammable Gas or Flammable or Combustible Liquid”. This NFPA-sponsored report summarizes the most common areas of origin and equipment involved in both NG and LPG residential incidents reported between 2007 and 2011. The data showed that NG incidents typically originated in the kitchen or heating equipment room and involved either a range, space heater, water heater, oven, or central heating unit. LPG incidents typically originated in outdoor areas (grilling / outdoor cooking) or in the kitchen and involved a grill or a range. As discussed in more detail below, NG and LPG leaks were simulated at gas ranges and water heaters in the present study.

Numerous leak rates (i.e., leak hole sizes) were modeled in this study. The focus was on releases large enough to potentially result in flammable concentrations, and thus ignition consequences, as these are the releases for which detection is most important. Small leaks such as those resulting from an unlit range burner or pilot are more likely to occur within residences, however they rarely if ever result in flammable hazards and therefore were not modeled in this study. The leak rates modeled are supported by 1) the incident descriptions outlined in ref. [1], "Natural Gas and Propane Fires, Explosions and Leak Estimates and Incident Descriptions"; and 2) the NG and LPG fire and explosion incidents investigated by Gexcon.

1.3 Existing guidance for residential gas detector placement

Recommendations currently exist for combustible gas detector placement in residential occupancies. Sources of these recommendations include: 1) gas detector Manufacturers' installation instructions; 2) European Standard, *EN 50244:2016 – Electrical apparatus for the detection of combustible gases in domestic premises – Guide on the selection, installation, use and maintenance*; and 3) the gas alarm installation manual issued by GKK, Japanese residential gas alarm organization [6]. These different sources are discussed, and tables are presented at the end of this section summarizing the recommendations from all sources.

Table 1.1 and Table 1.2 list the combustible gas detectors and combination combustible gas / carbon monoxide detectors for which we reviewed the manufacturers' installation instructions. Combination detectors were grouped separately because of differences in installation recommendations as discussed below.

Note: All the manufacturer installation instructions are available publicly from the respective websites. They are summarized here in tables to understand the existing guidance for gas detector placement locations.

Table 1.1: Currently available combustible gas detectors for which we reviewed the manufacturers' installation instructions.

Manufacturer	Model #	Intended gas	Notes
S-Tech	STCH-1000, STCP-1000	NG or LPG	UL Certified to UL1484
Visonic	GSD-441 PG2	NG	Meets requirements of EN 50194
Wizmart Technology Inc	Various models	NG or LPG	UL Certified to UL1484
Honeywell Analytics	Setpoint XCL	Various including NG	-
Technocontrol	Gamma 652-O	NG and LPG	-
LIFECO	NB-920	NG or LPG	Meets EN50291 & UL 1484 Standards
International Gas Detectors	TOC-10	NG or LPG	-
New Cosmos	ML-310	NG	UL1484 FCC certified
Fyrnetics Inc	FYNG-2N	NG	UL Certified to UL1484
Horing LIH Industrial Co Ltd	AH-0822	NG and LPG	UL Certified to UL1484
Canadian Tire Corp Ltd	46-0308-2	NG and LPG	UL Certified to UL1484

Table 1.2: Currently available combination combustible gas / carbon monoxide detectors for which we reviewed the manufacturers' installation instructions.

Manufacturer	Model #	Intended gas	Notes
Kidde Safety	KN-COEG-3	NG, LPG, and CO	UL 1484 Certified
First Alert	GC01	NG, LPG, and CO	Conforms to UL1484
Universal Security	MCND401	NG and CO	Intertek-ETL (UL2034 & UL1484)
MTI Industries	Various models	NG, LPG, and CO	UL Certified to UL1484

In general, manufacturers typically recommend that sensors be placed at a certain height in relation to the floor or ceiling and at a certain distance from gas-fired appliances. Additional recommendations often include where specifically not to place sensors (e.g., in an enclosed space) and where to place secondary sensors for additional protection. For combination combustible gas / carbon monoxide alarms, recommendations typically include not placing them in kitchens or too close to gas-fired appliances to reduce nuisance alarms and sensor damage.

EN 50244:2016 provides information on the selection, installation, use, and maintenance of combustible gas detectors designed for continuous operation in residential occupancies. In terms of installation, the Standard recommends that:

- Gas detectors should be installed in the room where a gas escape is most likely to occur.
- Natural gas detectors should be installed above the level of a possible gas escape and near the ceiling (typically < 30 cm (12 inches) from the ceiling), in a place where air movements are not impeded by furniture and furnishings.
- LP gas detectors should be mounted as low as possible (typically 10 cm (4 inches) above the floor) and in a place where air movements are not impeded by furniture.

EN 50244:2016 also provides the following recommendations for where combustible gas detectors should not be installed: in an enclosed space, directly above a sink, next to a door or window, next to an exterior fan, in an area where the temperature may drop below -10 °C (14 °F) or exceed 40 °C (104 °F), where dirt and dust may block the sensor, in a damp or humid location, too close to openings or ventilation ducts, immediately above or next to gas appliances since small gas releases may occur before appliance ignition that may result in unwanted alarms.

The GKK gas alarm installation manual recommends sensor heights and maximum distances from gas-fired appliances. It also recommends not placing sensors near doors, windows, exterior fans, and ventilation registers.

Table 1.3 and Table 1.4 summarize the various sensor height recommendations for NG and LPG sensors respectively.

Table 1.3: NG detector height recommendations.

Source	Distance from ceiling
BS EN 50244:2016	< 12 inches
GKK, Japanese residential gas alarm organization	-
S-Tech	6-12 inches
Visonic	12 inches below ceiling and above the highest window or door opening
Wizmart	< 12 inches
Technocontrol	< 12 inches
Kiddie (Combo CO)	High on the wall (no closer than 6 inches from ceiling)
First Alert (Combo CO)	6-12 inches
Universal (Combo CO)	-
MTI Industries (Combo CO)	6-12 inches

Table 1.4: LPG detector height recommendations.

LPG	
Source	**Distance from floor**
BS EN 50244:2016	4 inches
GKK, Japanese residential gas alarm organization	< 12 inches
S-Tech	24 inches
Visonic	-
Wizmart	< 12 inches
Technocontrol	< 12 inches
Kiddie (Combo CO)	Near floor
First Alert (Combo CO)	Near floor
Universal (Combo CO)	-
MTI Industries (Combo CO)	< 20 inches

Table 1.5 summarizes the various recommendations for minimum and maximum sensor placement distance from gas-fired appliances for both NG and LPG detectors.

Table 1.5: Recommendations for minimum and maximum sensor place distance from a gas-fire appliance.

Source	Minimum distance from appliance	Maximum distance from appliance
BS EN 50244:2016	-	-
GKK, Japanese residential gas alarm organization	-	13 feet from farthest edge
S-Tech	-	-
Visonic	3 feet	20 feet
Wizmart	-	12 feet for LPG and 24 feet for NG
Technocontrol	3 feet	12 feet
Kiddie (Combo CO)	5 feet (recommends 15 feet)	-
First Alert (Combo CO)	5 feet (recommends 20 feet)	-
Universal (Combo CO)	5 feet (recommends 20 feet)	-
MTI Industries (Combo CO)	-	-

Table 1.6 summarizes the recommendations on where to avoid placing combustible gas detectors.

Table 1.6: Recommendations for where to avoid placing combustible gas detectors.

Where not to install detecors	Source
Near ceiling/wall corners or wall/wall corners	First Alert, S-Tech
In an enclosed space	BS EN 50244
Next to a door or window	BS EN 50244, GKK, Kiddie, MTI Industries
Next to an exterior fan	BS EN 50244, GKK, Kiddie, First Alert, Universal, Visonic
Too close to openings or ventilation registers	BS EN 50244, GKK, Kiddie, Universal, S-Tech, MTI Industries
In dead air spaces	Kiddie, First Alert
Directly above sink (nuisance alarms)	BS EN 50244, Visonic, Technocontrol
Immediately above or next to a gas appliance (nuisance alarms)	BS EN 50244, S-Tech, Visonic, Technocontrol

Note that EN 50244:2016 recommends installing a gas detector in the room where a gas escape is most likely to occur. Furthermore, statistics specific to the United States show that incidents most often result from leaks in the kitchen indicating that gas detectors should be installed in kitchens. This conflicts with manufacturer recommendations for combination combustible gas / carbon monoxide detectors; whereby they state to not install these devices in kitchens.

2 CFD Modeling

The CFD modeling in this study was done with FLACS. FLACS is a commercially available software developed by Gexcon that can model gas dispersion events and has been extensively validated for predicting dispersion processes in many applications. For example, FLACS was been extensively validated for NG releases and more recently validated for indoor releases of LPG near ground level and at elevated heights [7, 8]. Validation of a CFD software such as FLACS at both large-scale and room-scale confirms the suitability of FLACS for predicting the dispersion of NG and LPG in residential and mixed-use structures, thus why we chose to use it for this study. FLACS can also model both premixed and non-premixed ignition events such as gas explosions and jet/pool fires.

As discussed in the Section 1, it is necessary that a broad range of environments and leak types are considered for the results to be robust and for the sensor placement recommendations to be most effective. The following sections summarize the various environments and leaks that were considered.

2.1 Leak parameters

Leak Locations

Based on the statistics outlined in Section 1.2, NG and LPG leaks were simulated at gas ranges in kitchens and water heaters in either utility rooms/closets or basements.

Leak Rates

Three different NG and LPG leak rates were considered: 30 SCFH, 70 SCFH, and 110 SCFH. Based on our experience and review of available literature, these leak rates are large enough to potentially result in flammable concentrations and they approximately bound the range of leak rates which we have seen result in incidents (~25-170 SCFH). As stated previously, we focused on leaks that could result in a hazardous condition as these leaks are more important to detect compared to those that do not create a hazardous condition. For reference, a 30 SCFH leak and a 110 SCFH leak of either NG or LPG occurs through approximately a 0.1 in (2.5 mm) and 0.2 in (5 mm) diameter hole respectively.

Leak Types

As summarized in Section 1.1.1, the resulting dispersion from a leak is affected by the degree of leak impingement. Therefore, we modeled two types of releases: “free-jet”, or un-impinged releases that do not hit any surfaces near the leak origin, and severely impinged releases that have little to no release-induced momentum (i.e., low-momentum releases).

2.2 Geometries

Gas leaks were modeled in three different geometries, which we built for past projects and were all based on actual buildings: a single-family colonial style house, a single-family split-level house, and a two-story townhouse (see Figure 2.1). These three geometries provided a range of overall square-footage and general layout. In addition, we also varied certain characteristics in each geometry. In all geometries, we varied the height of the headers above doorways and openings in interior walls separating rooms. This was done specifically when modeling NG leaks as these headers potentially influence the dispersion and spread of the gas within a residence. Furthermore, in some simulations we closed off the second floor and/or basement to effectively model dispersions in residences with different numbers of floors or when certain doors separating floors were closed. In other simulations we included active mechanical ventilation and in others we simulated exterior winds to create different passive air leakage rates through the building envelope. All of this was done to ensure that we were simulating gas leaks in a wide variety of residential environments so that the results would be generally applicable to all residential occupancy types (single-family, condominiums, high-rise apartments) and serve as preliminary estimates for mixed-use residential/commercial occupancies. The results from a reduced set of CFD simulations with a mixed-use occupancy are provided in Section 4.4.3. The following sections further describe the three geometries and the variations implemented in each geometry.

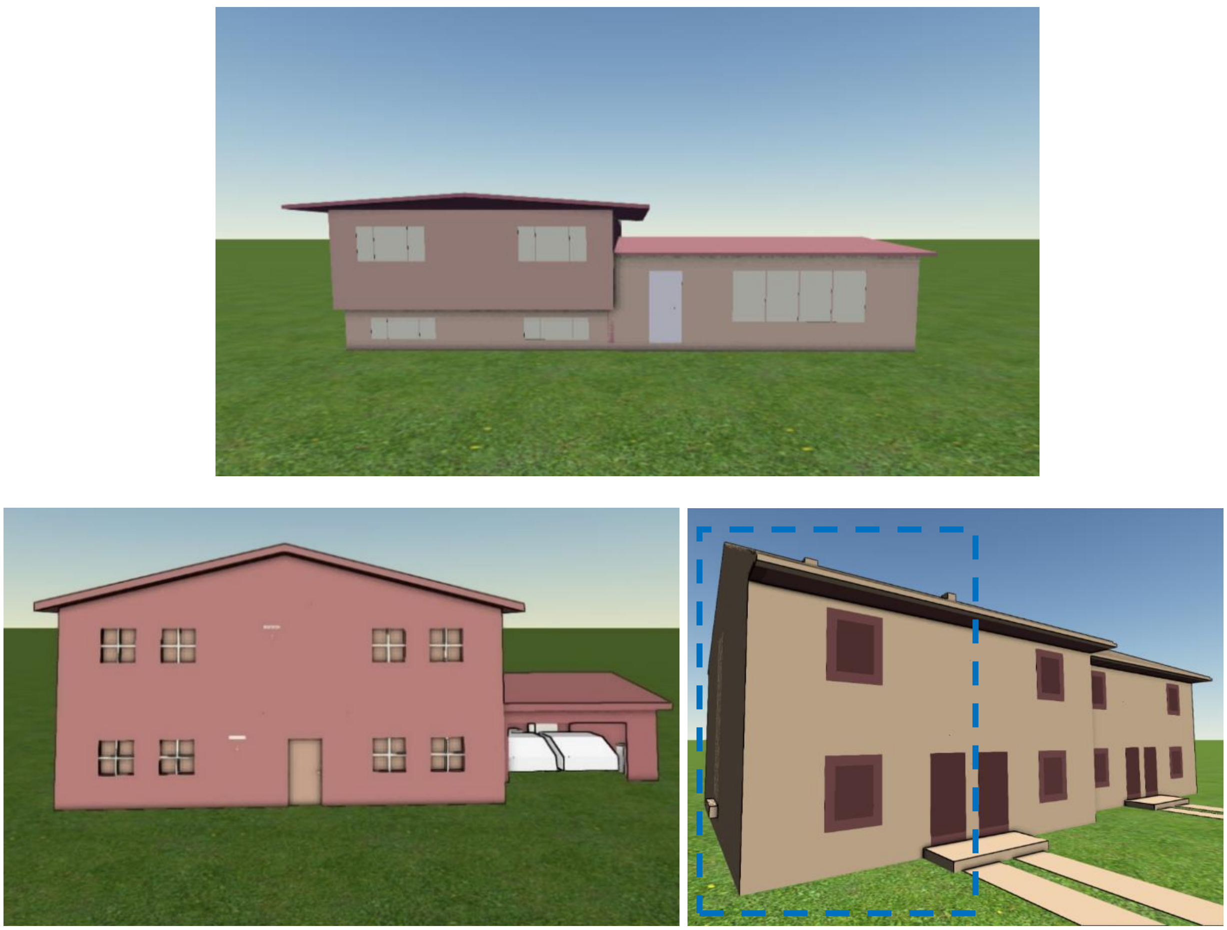

Figure 2.1: Split Level Residence (top), Colonial style house (bottom left) and Townhouse (bottom right)

2.2.1 Townhouse

The townhouse geometry is a single-family residence with two floors. The dimensions of the residence are approximately 15 ft (4.6 m) wide and 30 ft (9.4 m) long with an approximate area of 450 ft^2 (43 m^2) per floor, for a total approximate area of 900 ft^2 (86 m^2). The residence shares a wall with a neighboring townhouse on one side. The main living floor has a dining room in the front with a passageway to a living room in the rear. The kitchen is located centrally on the first floor and contains a gas-fired range. The kitchen has walls on three sides and is open to the dining room toward the front of the house.

The passageway from the front of the residence to the rear is through a central hallway. This hallway has a utility closet located about halfway down. The utility closet has a fully louvered door and contains a water heater and HVAC unit. This residence also has a stairwell located near the front of the house that leads to the second floor which has two bedrooms and a bathroom. Figure 2.2 shows a top-down view of the first floor and Figure 2.3 shows a view looking into the kitchen from the front dining room.

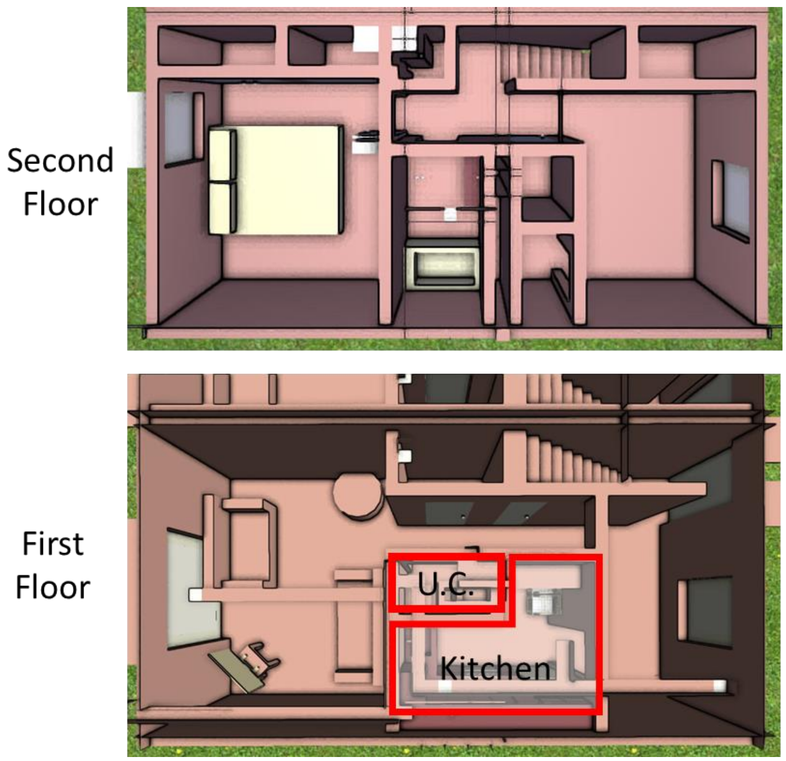

Figure 2.2: Top-down view of the first and second floors of the townhouse.

Figure 2.3: Kitchen and hallway looking from the room at the front of the house.

The townhouse contains accurate representations of air leakage pathways into the residence. This CFD geometry was modeled after an actual townhouse for which we performed a blower door test to identify air leakage paths and quantify air leak rates through the major paths contributing to air infiltration. This level of detail allows for modeling of passive ventilation conditions and evaluation of any air infiltration affects that may impact the dispersion. External winds can be simulated in FLACS thus we can evaluate actual air infiltration for any given wind condition.

Doorway Header Height Variations

There was one header between the room at the front of the house and the kitchen that was varied in the townhouse geometry. We ran simulations without a header and with an 8-inch (20 cm) and 16-inch (40 cm) header.

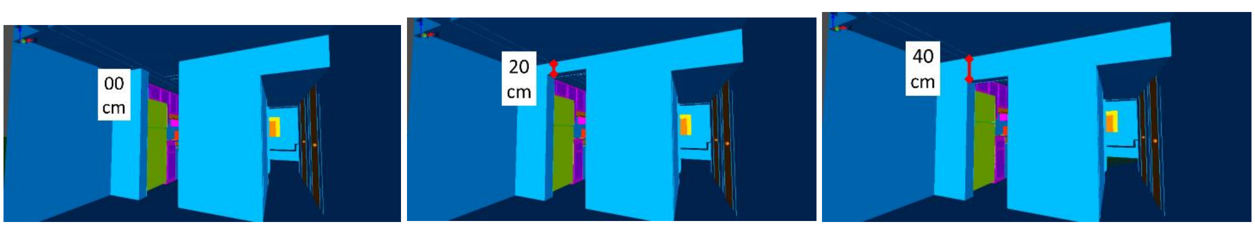

Figure 2.4: Doorway header variation in the townhouse.

While there appears to be a header along the hallway from the front to the rear of the residence, this is actually the HVAC ductwork. Thus, this height was not varied.

Number of Floors

Simulations were performed with and without the staircase to the second floor blocked off. In some simulations, the staircase was blocked off so that the geometry was representative of a single-story apartment-style residence with less available volume and pathways for gas migration.

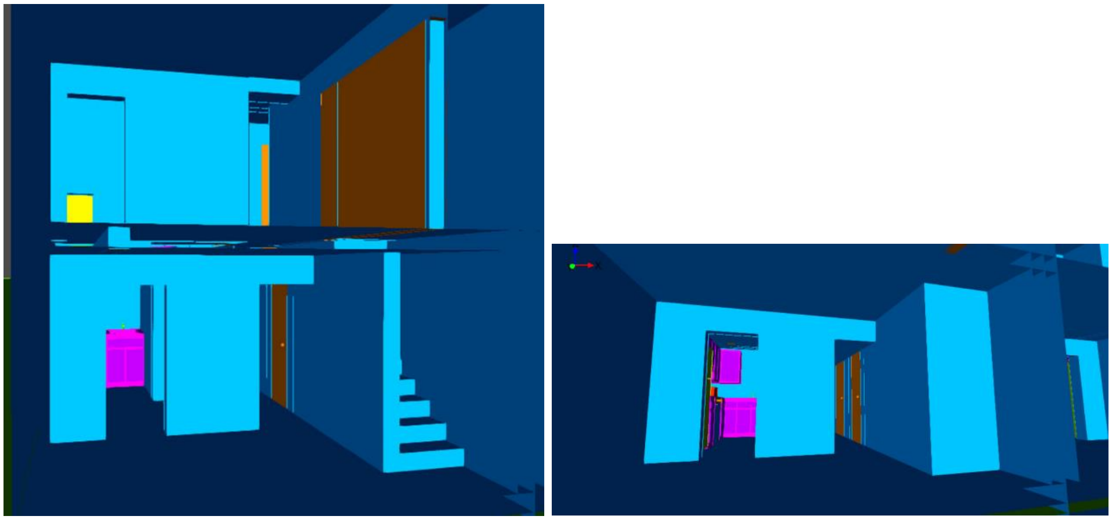

Figure 2.5: Two story configuration (left image) and single story configuration with stairs blocked off (right image).

Leak Locations

In the townhouse, NG and LPG leaks were modeled at near the floor at the range in the kitchen and above the water heater in the utility closet (see Figure 2.6 and Figure 2.7). In each location, free-jet leaks and impinged low-momentum leaks were modeled. Note the direction of the jet leaks are shown and diffuse leaks have no direction and thus are shown without a direction.

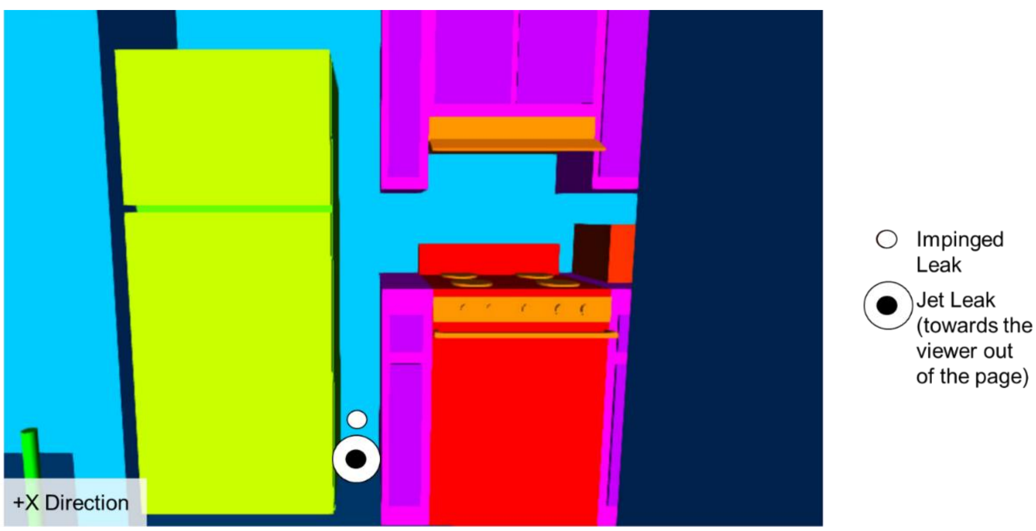

Figure 2.6: Range leak location.

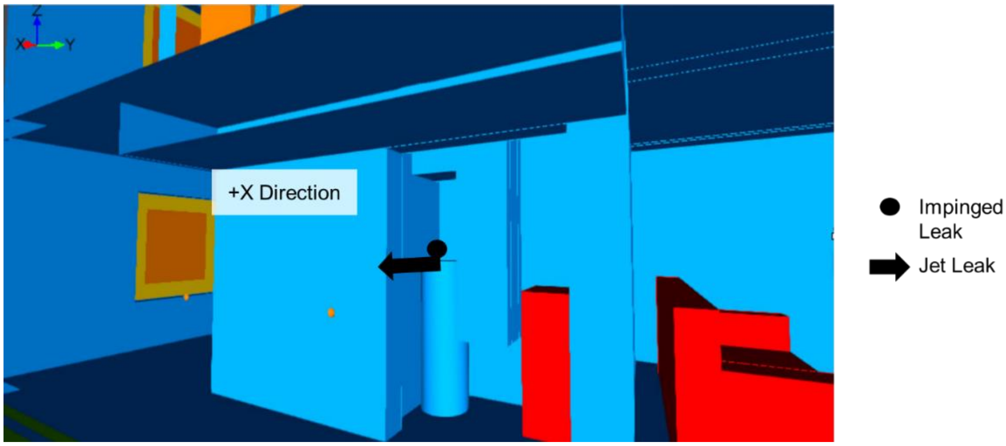

Figure 2.7: Water heater leak location.

Given the size of the utility closest, air for combustion and ventilation per NFPA 54 require: (1) communication with the indoor volumes with two openings, one within 12 inches from the ceiling and one within 12 inches from the bottom; (2) communication with the outdoors with either two permanent openings, one within 12 inches from the ceiling and one within 12 inches from the bottom, or one permanent opening within 12 inches from the ceiling. The room was modeled without a door, which would conservatively let either lighter-than-air or heavier-than-air gas leave the source room of the leak. Had the room been modeled with openings on the door to indoor spaces, the gas would have been more easily retained in the utility closet and gas detectors would have more easily activated than in the geometry modeled in the present study. In addition, had permanent openings been provided to the outdoors and a closed door, gas that remained within the closet would have preferentially built up in the utility closet, and gas detectors would have more easily activated than in the geometry modeled in the present study.

Air Leakage and Passive Ventilation

Simulations were performed with and without external wind. In simulations with wind, a 4.5 mph (2 m/s) wind was directed at either the front of the house or at the rear of the house. For illustration, Figure 2.8 shows a side-on view of the flow pattern through the length of the house for both the first and second floors when the wind was blowing on the front of the house.

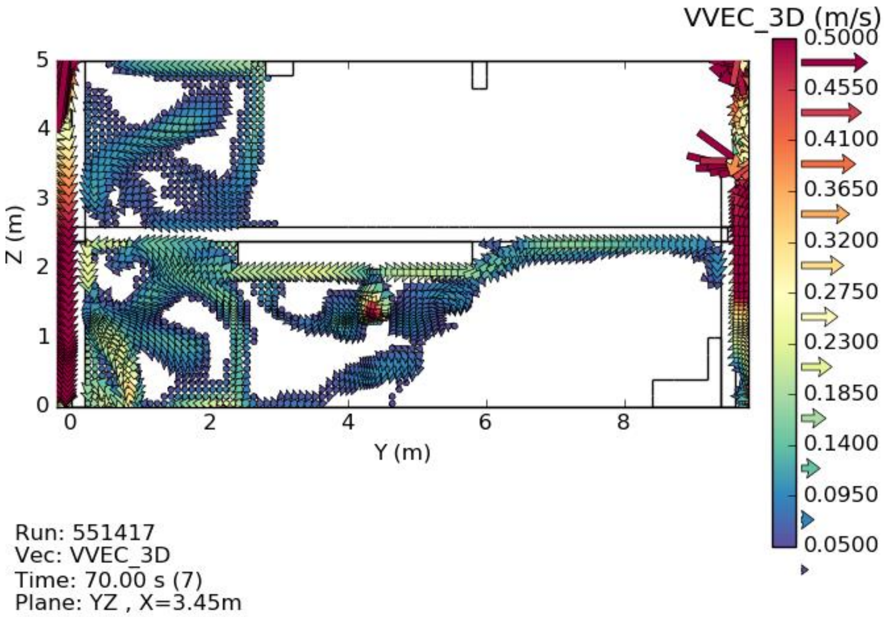

Figure 2.8: Example flow pattern resulting from external wind infiltration.

While the external wind velocity was held constant, the geometry variations resulted in a range of ventilation rates inside the building. Depending upon the wind direction and the number of floors, the measured air changes per hour (ACH) of the residence interior varied from 0.6 to 1.8, which are consistent with values presented in ASHRAE Fundamentals Handbook [9].

Townhouse Simulation Matrix

The following graphics outline the matrix of simulations performed for the simulations conducted in the townhouse geometry. For each branch of the matrix, all variable permutations were simulated.

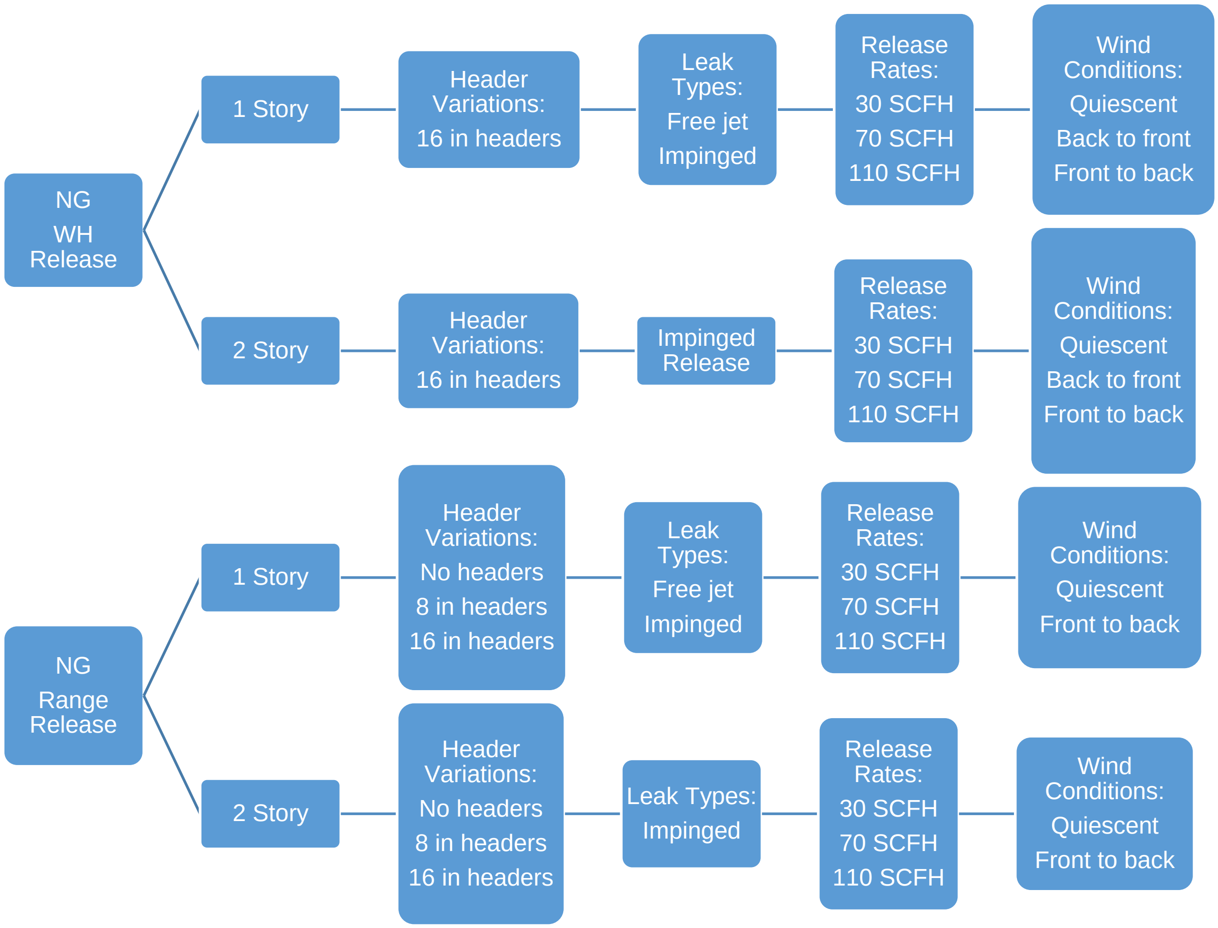

Figure 2.9: Simulation matrix for natural gas releases conducted in the townhouse geometry.

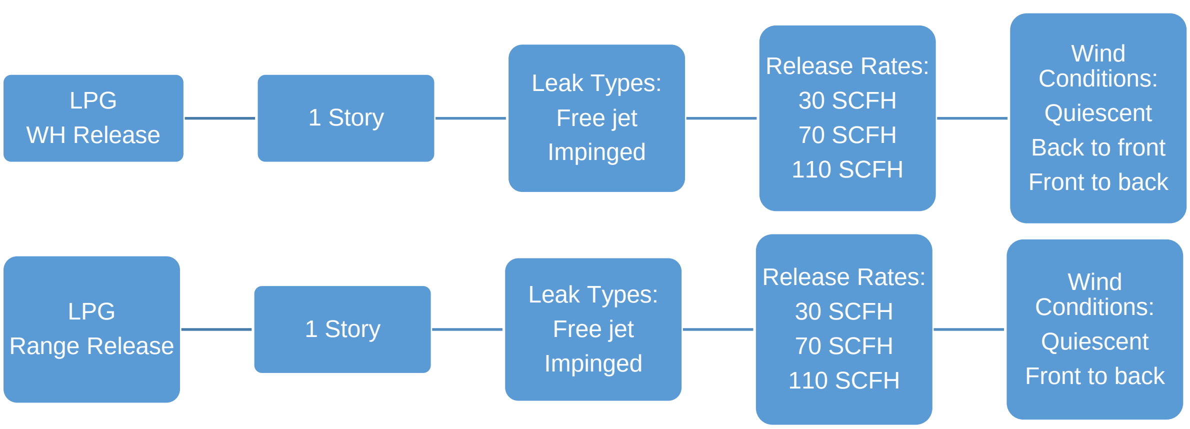

Figure 2.10: Simulation matrix for LPG releases conducted in the townhouse geometry.

2.2.2 Colonial House

The colonial house is a detached, single-family residence with two floors and a basement. The interior dimensions of the house are approximately 42 ft (12.75 m) wide and 26 ft (8 m) deep resulting in an area of 1,092 ft^2 (102 m^2) per floor. Hence, the total area of the basement, first and second floors is approximately 3,276 ft^2 (306 m^2). The first floor contains a kitchen, dining room, living room, study/den and a bedroom. There is a staircase from the dining room area down to the basement and an open staircase from near the front door to the second floor. The second floor contains three bedrooms and the basement is completely open and contains a water heater and HVAC unit.

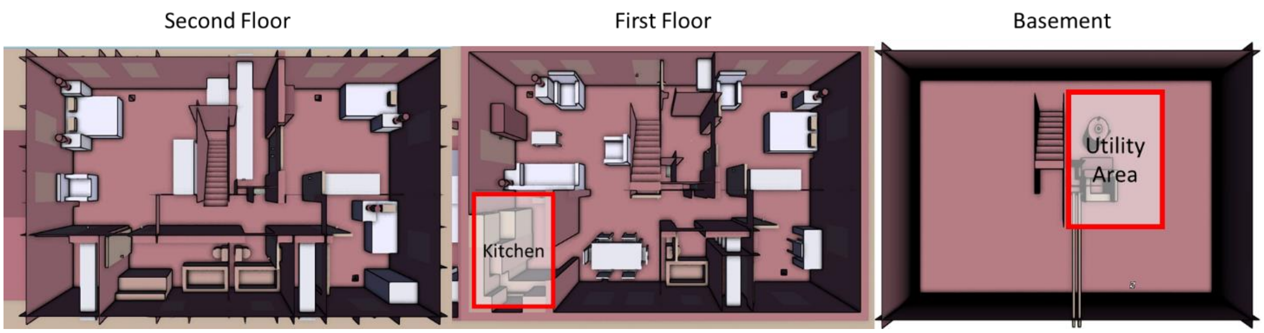

Figure 2.11: Top-down view of each floor: second floor (upper left), first floor (upper right) and basement (bottom).

The colonial house geometry has a balanced mechanical ventilation system. The geometry includes supply and return ducts to various rooms in the house and flow can be created in the CFD simulations via several fan sources. This allows for modeling of gas leaks when the mechanical ventilation system is on or off.

Doorway Header Height Variations

Two headers were varied in the colonial house. We ran simulations without headers and with 16-inch (40 cm) headers above the doorway from the kitchen to the dining room and above the doorway from the dining room to the living room (see Figure 2.12).

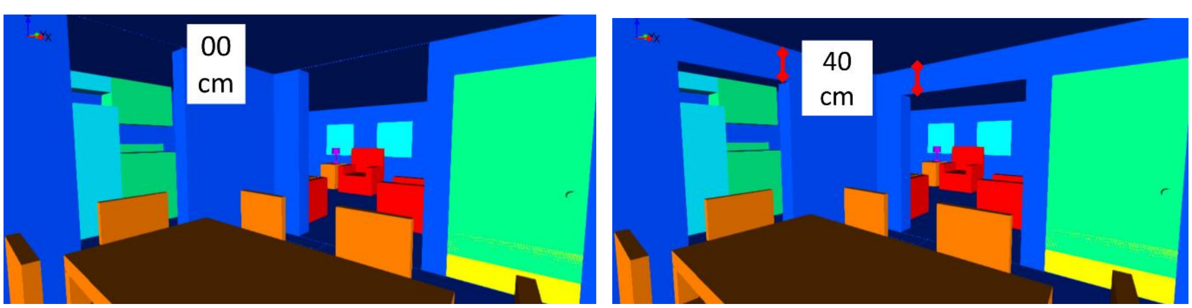

Figure 2.12: Header variations. The kitchen is located through the doorway on the left.

Number of Floors

Like the townhouse geometry, this geometry can be converted into a single-story rancher-style house by blocking off the stairs and reducing the available volume and pathways for gas migration, providing further geometrical diversity in the simulation set. Thus, the staircase to the second floor was blocked off in some simulations.

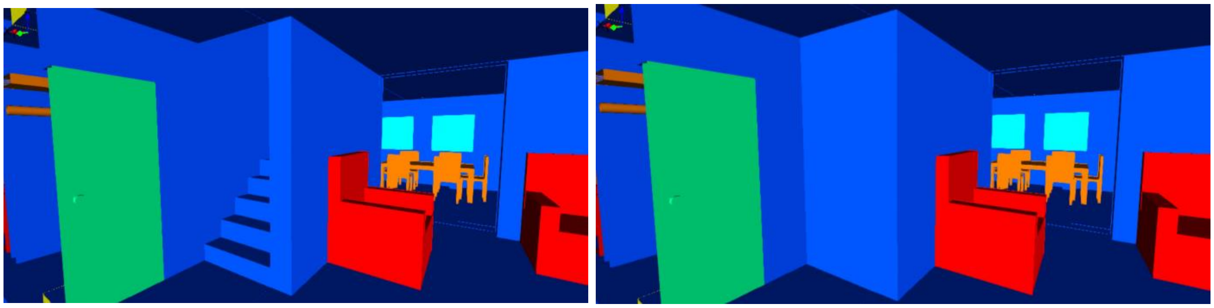

Figure 2.13: Open (left image) and closed (right image) stairwell to the second floor.

Basement Door Open and Closed

For LPG leaks at the range in the kitchen and NG leaks at the water heater in the basement, simulations were performed with the basement door open and closed, thus either preventing or allowing gas to migrate to/from the basement.

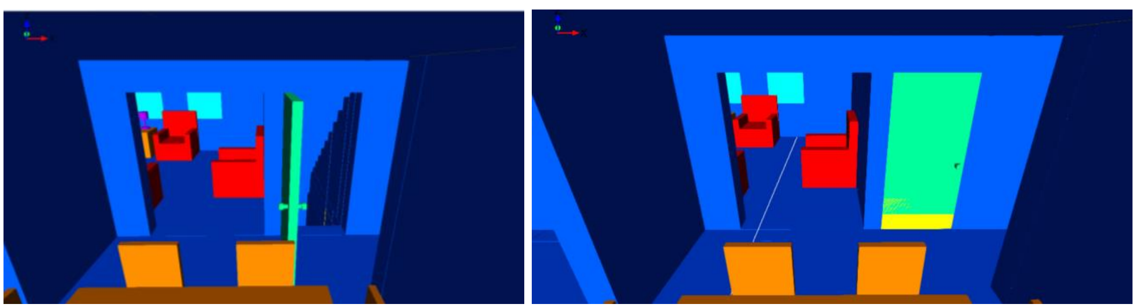

Figure 2.14: Open (left image) and closed (right image) door to basement.

Leak Locations

In the colonial house, NG and LPG leaks were modeled near the floor at the range in the kitchen and above the water heater in the basement (see Figure 2.15 and Figure 2.16). In each location, free-jet leaks and impinged low-momentum leaks were modeled.

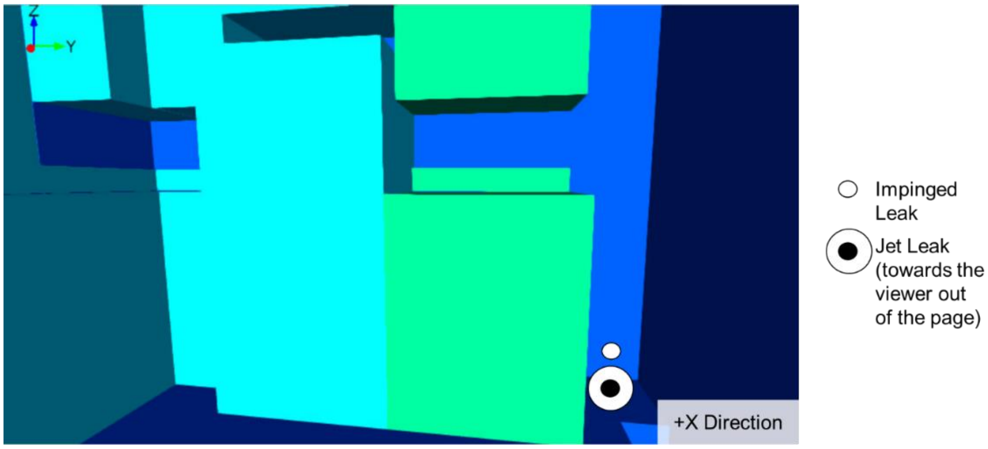

Figure 2.15: Leak location at the range.

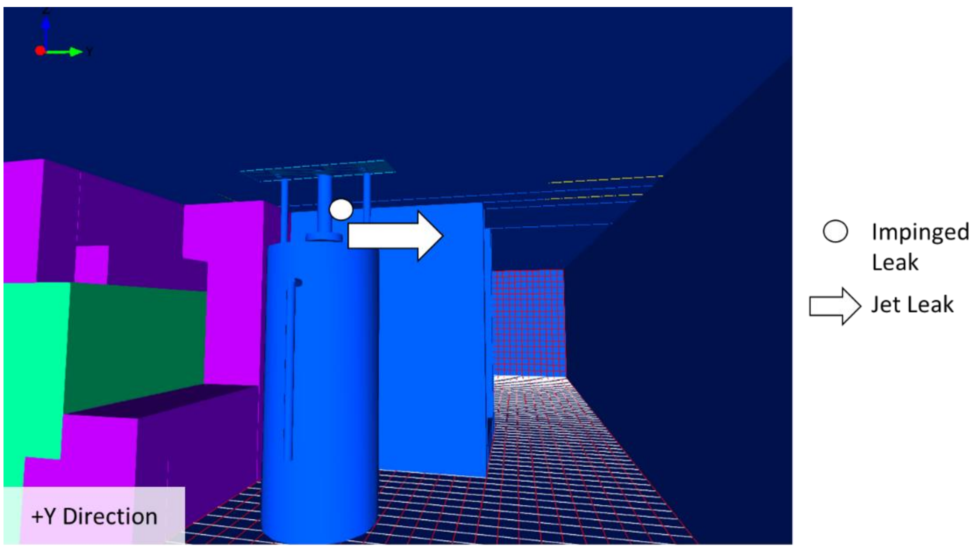

Figure 2.16: Leak location at the water heater.

Mechanical Ventilation

Simulations were performed with and without mechanical ventilation active. When active, the system provides an ACH of 5 air changes per hour. There are six supply registers on the first floor and five supply registers on the second floor generally located around the perimeter of the structure. There is one return register on each floor located near the staircase (see Figure 2.17). Figure 2.18 provides an example of the airflow paths with the mechanical ventilation system active.

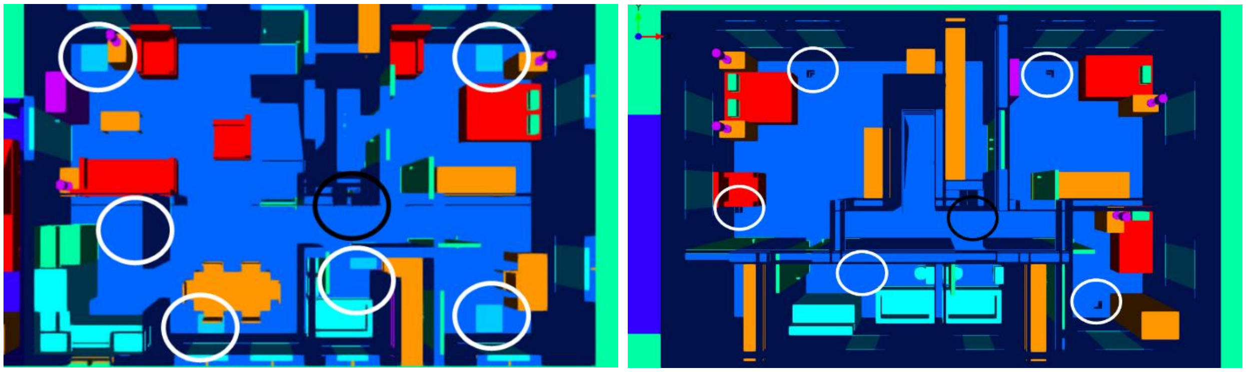

Figure 2.17: Mechanical ventilation supply (white) and return (black) registers on the first floor (top image) and second floor (bottom image).

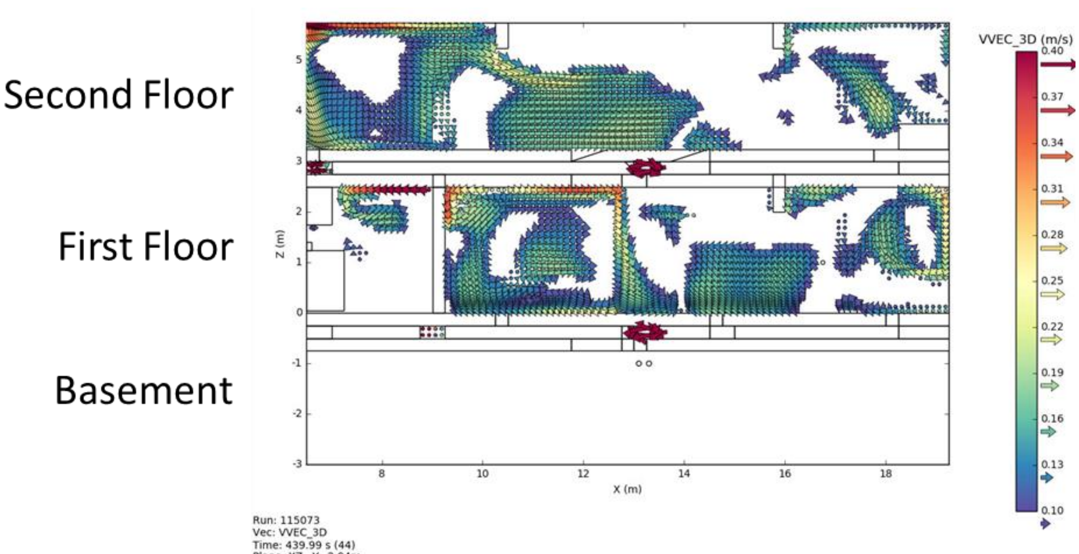

Figure 2.18: Side-on view of airflow paths with the mechanical ventilation system active.

Colonial House Simulation Matrix

The following graphics outline the matrix of simulations performed for the simulations conducted in the colonial house geometry. For each branch of the matrix, all variable permutations were simulated.

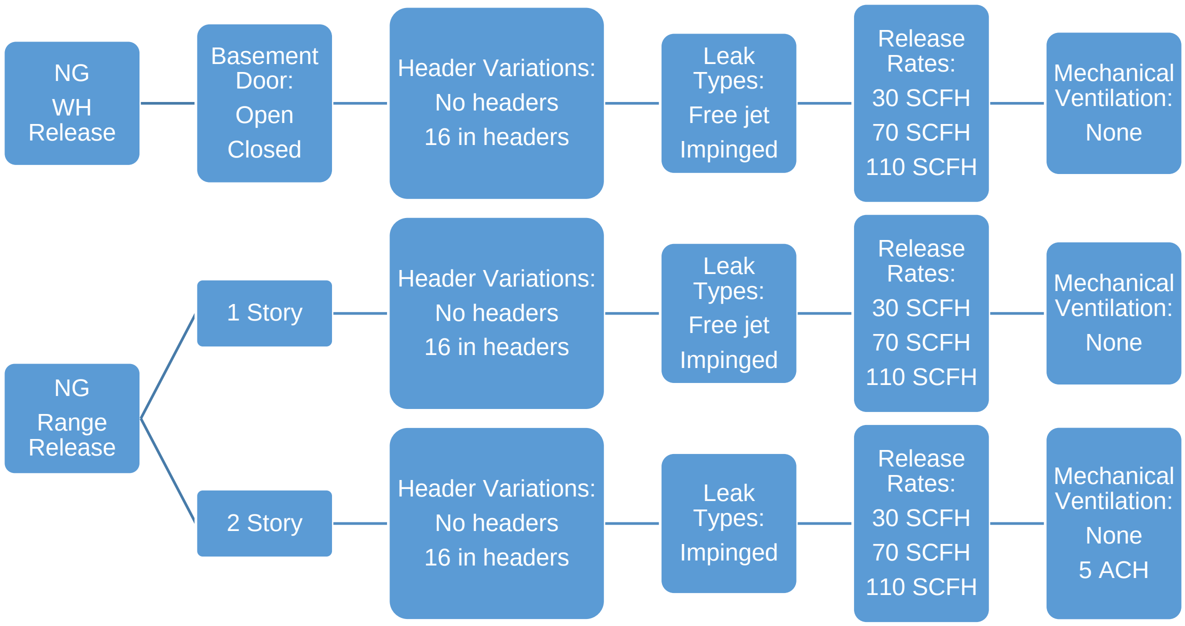

Figure 2.19: Simulation matrix for natural gas releases conducted in the colonial house geometry.

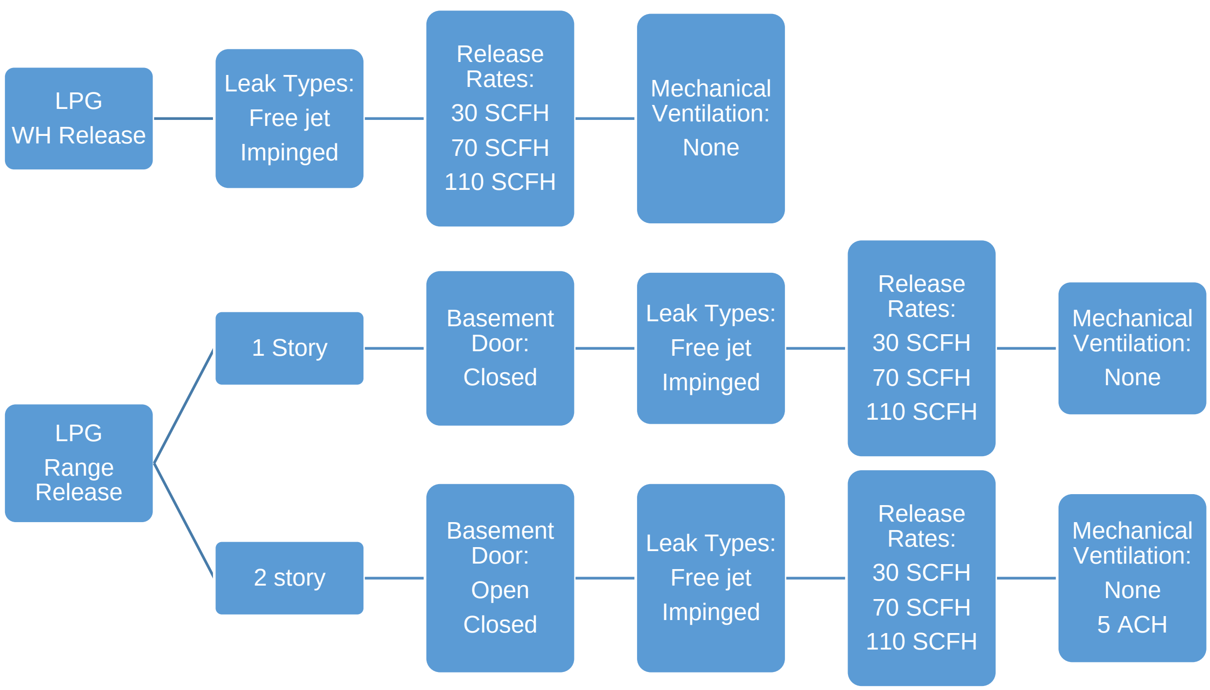

Figure 2.20: Simulation matrix for LPG releases conducted in the colonial house geometry.

2.2.3 Split-Level House

The split-level geometry is a single-family detached residence. There is a kitchen on the main floor with a gas-fueled range and a utility room on the lower floor with a gas-fueled water heater. The lower and upper floors have approximate dimensions of 23 ft (7.1 m) wide by 25.5 ft (7.8 m) deep. The main floor has approximate dimensions of 27 ft (8.2 m) wide by 25.5 ft (7.8 m) deep. The residence has a total area of approximately 1,860 ft^2 (175 m^2). The main floor is open to both the upper and lower floors via short staircases near the center of the house.

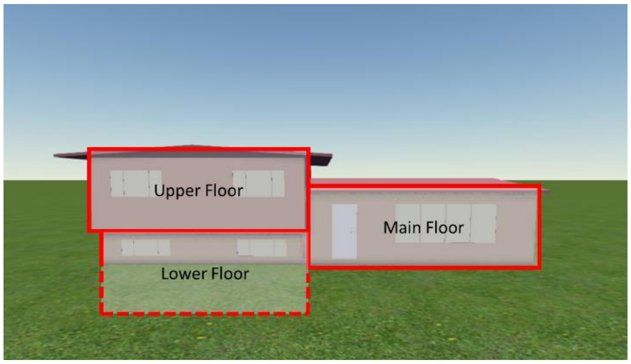

Figure 2.21: Split-level house layout and floor-naming convention.

Figure 2.22: Top-down view of main floor with kitchen area (left image) and lower floor with the utility room (right image).

Doorway Header Height Variations

Four headers were varied in this geometry. The kitchen on the main floor has three passageways where headers could be present: from the kitchen to dining room, kitchen to living room, and a kitchen to lower level (Figure 2.23). There was also one header location above the doorway from the utility room to the neighboring laundry room. Simulations were performed without a header and with an 8-inch (20 cm) and 16-inch (40 cm) header at these four potential header locations (Figure 2.23 through Figure 2.27).

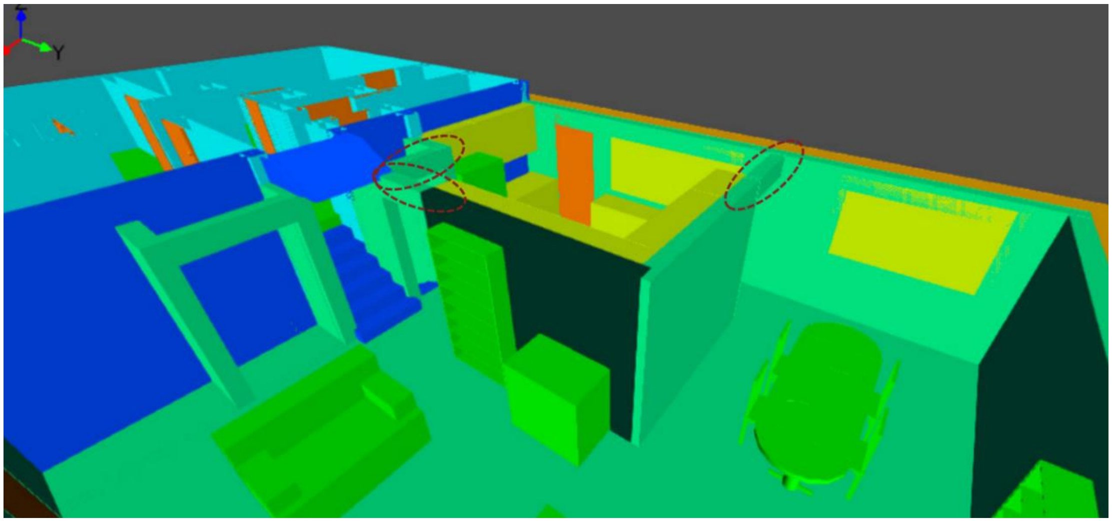

Figure 2.23: Header locations near the kitchen.

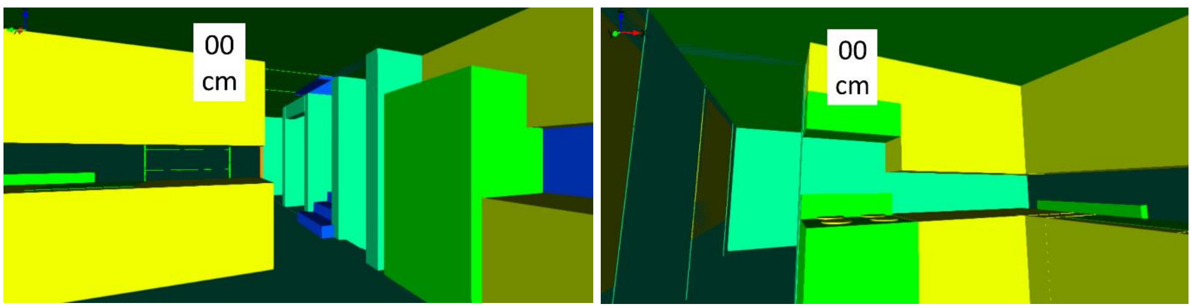

Figure 2.24: No headers at locations near the kitchen.

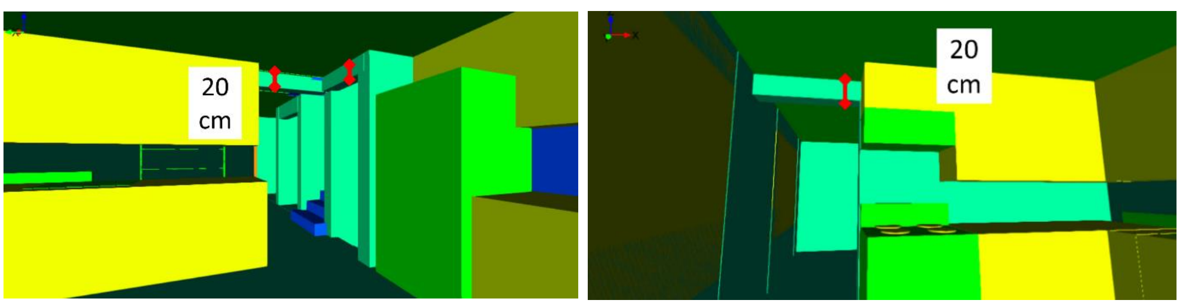

Figure 2.25: 8-inch (20 cm) headers at locations near the kitchen.

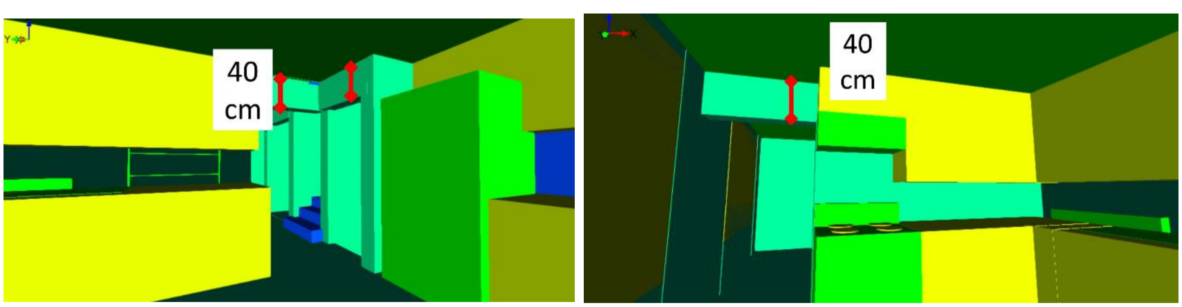

Figure 2.26: 16-inch (40 cm) headers at locations near the kitchen.

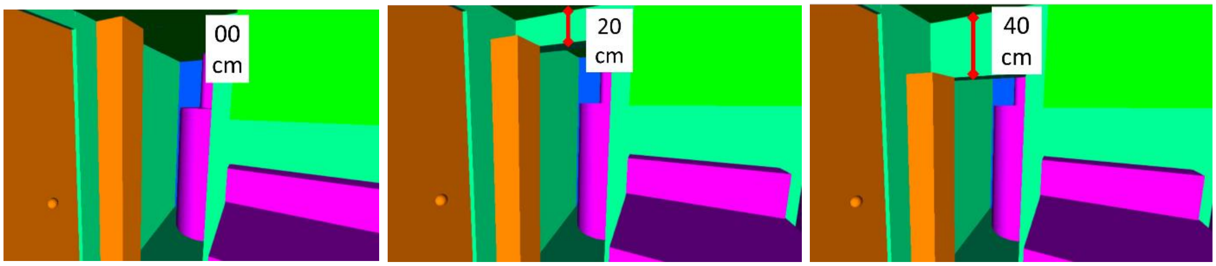

Figure 2.27: No header, 8-inch (20 cm) header, and 16-inch (40 cm) header between utility room and laundry room.

Leak Locations

In the split-level house, NG and LPG leaks were modeled near the floor at the range in the kitchen and above the water heater in the utility room (see Figure 2.28 and Figure 2.29). In each location, free-jet leaks and impinged low-momentum leaks were modeled.

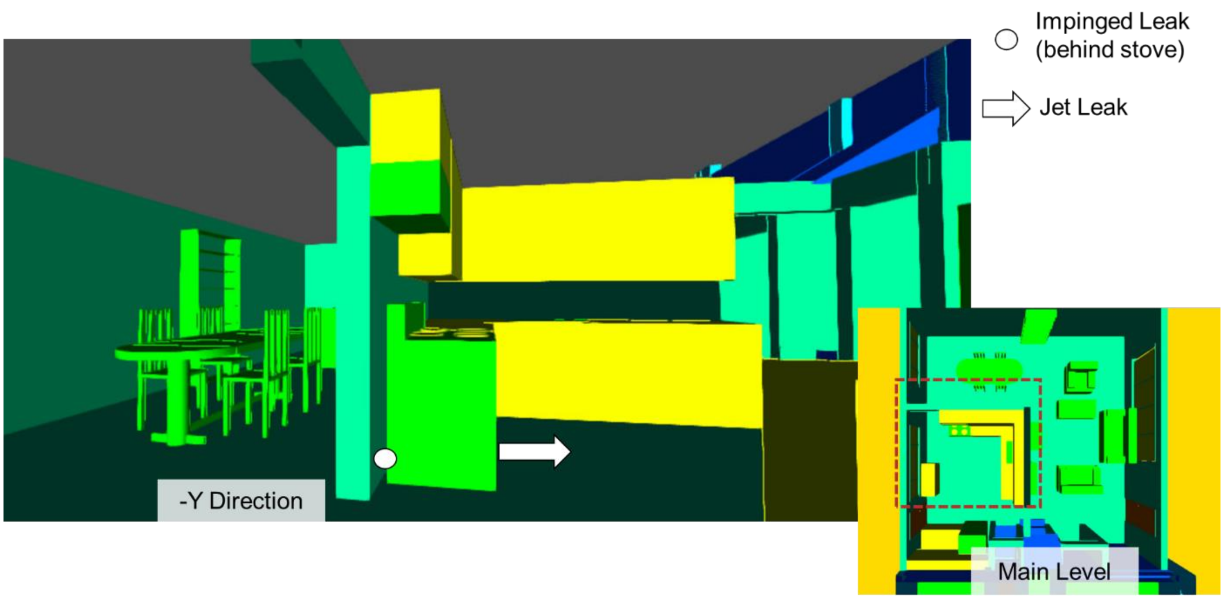

Figure 2.28: Leak location at the range.

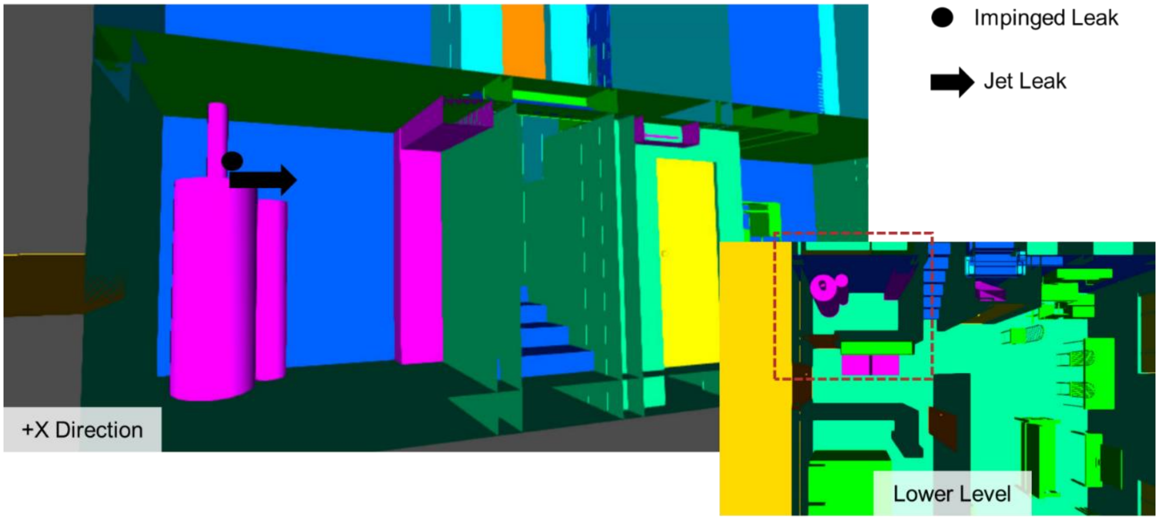

Figure 2.29: Leak location at the water heater.

Given the size of the utility closest, air for combustion and ventilation per NFPA 54 require: (1) communication with the indoor volumes with two openings, one within 12 inches from the ceiling and one within 12 inches from the bottom; (2) communication with the outdoor with either two permanent openings, one within 12 inches from the ceiling and one within 12 inches from the bottom, or one permanent opening within 12 inches from the ceiling. The room modeled without a door, which would conservatively let either lighter-than-air or heavier-than-air gas leave the source room of leak. Had the room been modeled with openings on the door to indoor spaces, the gas would have been more easily retained in the utility closet and gas detectors would have more easily activated than in the geometry modeled in the present study. In addition, had permanent openings been provided to the outdoors and a closed door, gas that remained within the closet would have preferentially built up in the utility closet, and gas detectors would have more easily activated than in the geometry modeled in the present study.

Split Level House Simulation Matrix

The following graphics outline the matrix of simulations performed for the simulations conducted in the colonial house geometry. For each branch of the matrix, all variable permutations were simulated.

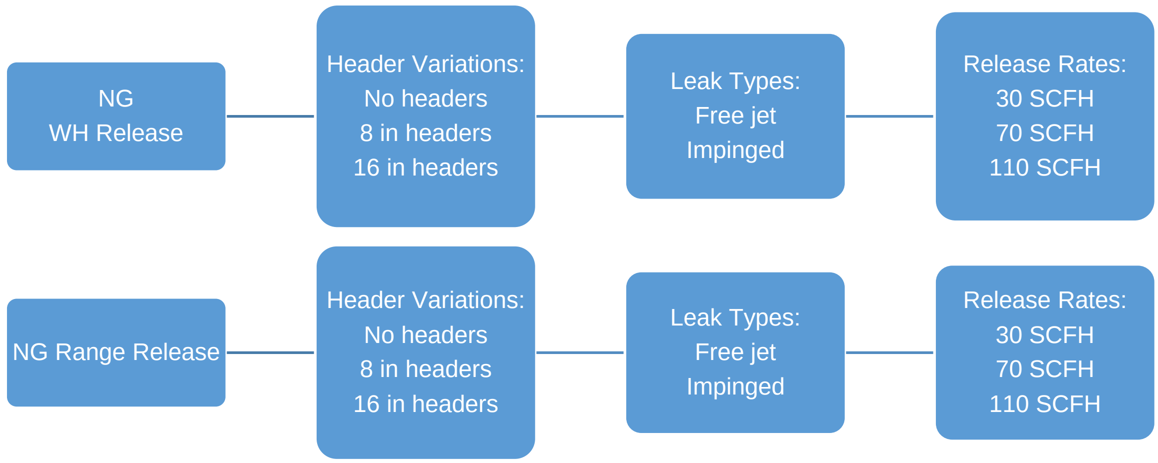

Figure 2.30: Simulation matrix for natural gas releases conducted in the split-level house geometry.

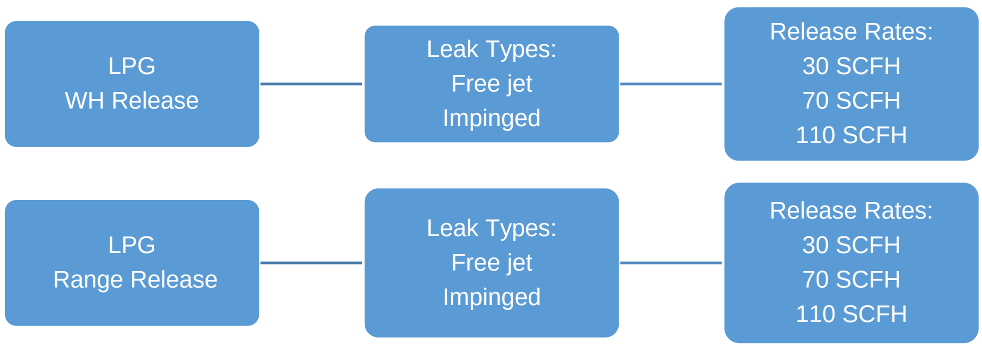

Figure 2.31: Simulation matrix for LPG releases conducted in the split-level house geometry.

2.3 Gas detector placements in the CFD geometries

Hundreds of gas detectors (i.e., monitor points) were placed in each CFD geometry to facilitate a thorough evaluation of detector performance as a function of detector placement. Detectors were placed at locations in accordance with manufacturers' instructions, EN50244:2016, and the GKK guidance. Special care was taken to ensure that the necessary locations were included to evaluate the various recommendations outlined in Section 1.3. More specifically, we wanted to evaluate: 1) the best place to put a sensor in rooms where gas-fired appliances are located; 2) performance of sensors close to doors, windows, ventilation registers, exterior fans; 3) effective locations for additional detectors in rooms or areas adjacent to rooms where gas-fired appliances are located.

No sensors were placed on cabinets, windows, doors or other locations were placement would be impractical. Potential for nuisance alarms was not considered when deciding where to place the sensors.

In general, for NG releases, detector placements in the CFD geometries were as follows:

- In the region of origin, placed:
    - In 12 in (30 cm) arrays at or on the ceiling level in the region of the leak source
    - At 12 in (30 cm) spacing along the walls at 6 in, 12 in and 18 in (15, 30 and 45 cm) below ceiling
- In adjacent areas, placed:
    - In 39 in (1 m) arrays at or on the ceiling level in the rooms adjacent to the leak source
    - At 39 in (1 m) spacing along the walls at 6 in, 12 in and 18 in (15, 30 and 45 cm) below ceiling
- In passageways or along probable flow paths
    - Line arrays of 39 in (1 m) spacing at or on the ceiling level
    - Line arrays of 39 in (1 m) spacing along the walls at 6 in, 12 in and 18 in (15, 30 and 45 cm) below ceiling
- Near stairways to floors above

For LPG releases, detector placements in the CFD geometries were as follows:

- In the region of origin, placed:
    - At 12 in (30 cm) spacing along the walls at 4 in, 6 in, 8 in, 10 in, 12 in, 14 in, 16 in, and 18 in (10, 15, 20, 25, 30, 35, 40, 45 cm) above floor
- In adjacent areas, placed:
    - At 1 m (39 in) spacing along the walls at 4 in, 6 in, 8 in, 10 in, 12 in, 14 in, 16 in, and 18 in (10, 15, 20, 25, 30, 35, 40, 45 cm) above floor
- In passageways or along probable flow paths
    - Line arrays of 1 m (39 in) spacing along the walls at 4 in, 6 in, 8 in, 10 in, 12 in, 14 in, 16 in, and 18 in (10, 15, 20, 25, 30, 35, 40, 45 cm) above floor
- Near stairways to floors below

Examples of detector layouts can be found in the following figures. Additional images of the sensor arrays in other rooms and other geometries are provided in Appendix A – Detector Location Placement.

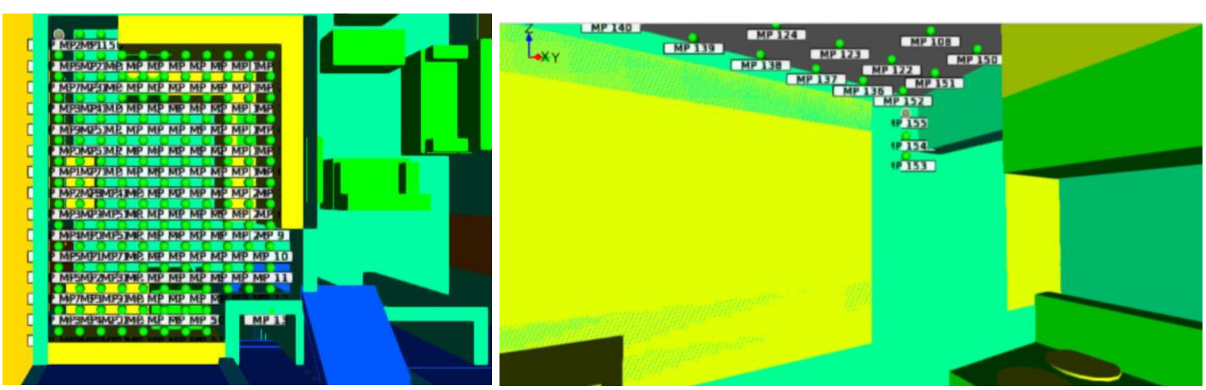

Figure 2.32: Detectors on the ceiling and wall in the split level kitchen for NG releases.

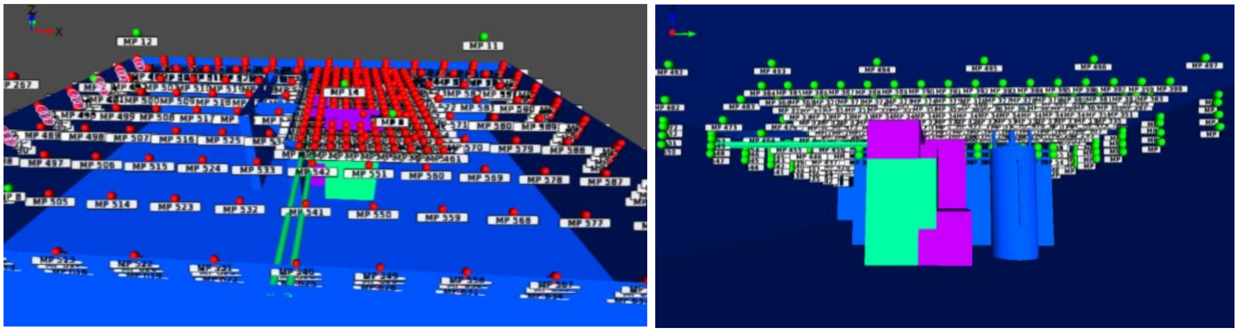

Figure 2.33: Detectors on the ceiling and walls in the open basement of the colonial house for NG releases.

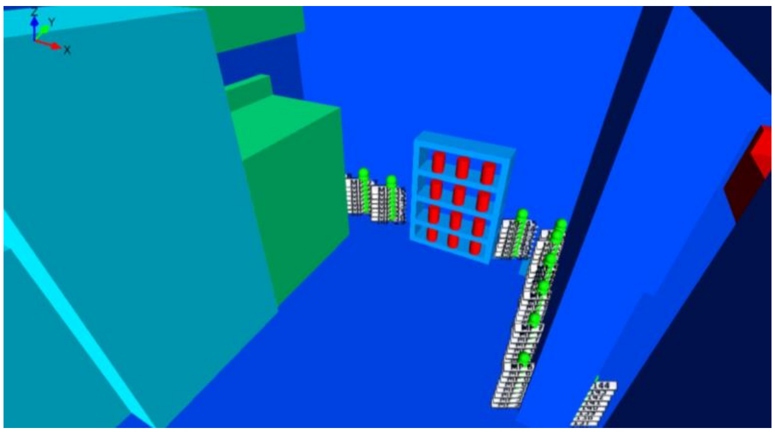

Figure 2.34: Detectors in the colonial house kitchen for LPG releases.

3 Quantitative Evaluation Approach

Reliable and early detection are the most critical aspects of effective gas detection. Hence the best detector installation locations are those that will most likely detect a leak, especially before a hazardous condition arises, as well as detect it as soon as possible to give occupants enough time to respond.

This study applies a hazard-based approach to compare the performance of gas detector installation locations. More specifically, the study quantifies detector location performance based on 1) the ability to detect before certain hazardous conditions arise and 2) the ability to provide sufficient response time prior to the hazardous conditions arising. This approach was applied because it facilitates comparisons of detector location performance across the wide variety of leak/geometry scenarios that were modeled.

3.1 Threshold hazard conditions

The first step in applying the hazard-based approach is to define the threshold hazard conditions. For example, a seemingly obvious threshold hazard condition would be when the lower flammability limit (LFL) is reached or exceeded anywhere in the residences as this would be the first instance when an ignition event could occur. Detector location performance could then be evaluated based on whether detectors placed at specific locations would detect prior to, and if so, how long prior to, this threshold hazard condition occurring.

In the present study, we define two threshold hazard conditions to evaluate the performance of gas detector locations. The first threshold hazard condition is the presence of a 10 ft^3 (0.3 m^3) volume with a fuel gas concentration above the LFL (i.e., 2% by volume for LPG and 5% by volume for NG). This threshold hazard condition has a non-negligible combustion consequence if ignited, however it is unlikely to result in significant damage. Choosing a threshold hazard condition with volumes of flammable gas above the LFL is necessary because certain leak scenarios will always result in the formation of flammable levels above the LFL prior to any practically placed gas detector activating. Figure 3.1 provides two examples of a 10 ft^3 (0.3 m^3) volume above LFL (note that the figure only shows where the concentration is above the LFL and does not imply that the concentration is zero everywhere else). The left image shows the volume resulting from a low-momentum NG release above a water heater and the right image shows the volume resulting from a low-momentum LPG release at the base of a range.

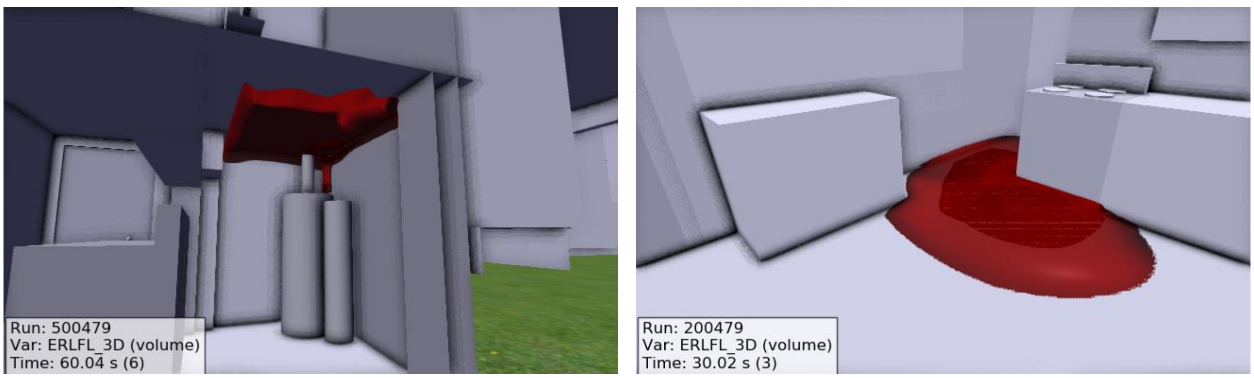

Figure 3.1: Two examples of threshold hazard condition #1 - 10 ft^3 (0.3 m^3) above LFL.

The second threshold hazard condition is the presence of a 350 ft^3 (10 m^3) volume with a fuel-gas concentration above 40% the LFL (i.e., 0.8% by volume for LPG and 2% by volume for NG). This threshold hazard condition does not represent an actual ignition hazard as the concentration is below the LFL, however it does represent a condition that if left undetected or unmitigated, could result in a large premixed flammable volume with significant consequences if ignited. Thus, it is of value to detect this condition prior to an ignitable volume of gas forming. Figure 3.2 provides two examples of a 350 ft^3 (10 m^3) volume above 40% LFL (note that the figure only shows where the concentration is above 40% LFL and does not imply that the concentration is zero everywhere else). The left image shows the volume resulting from an impinged LPG release above a water heater and the right image shows the volume resulting from an impinged NG release at the base of a range.

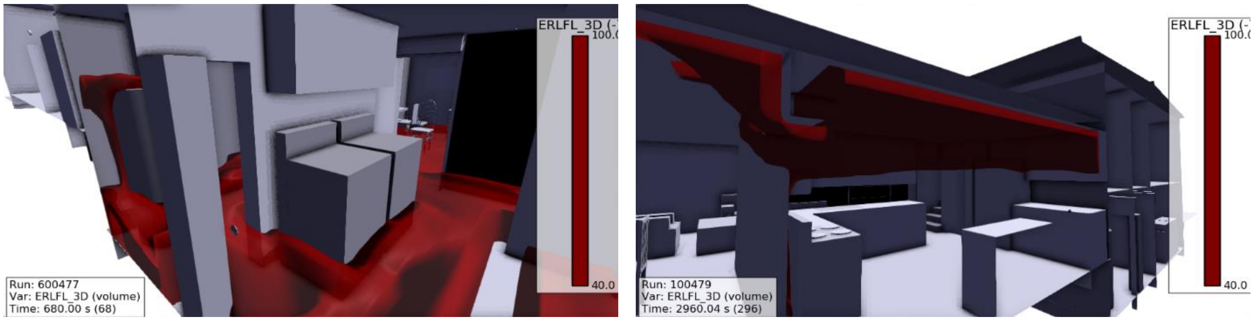

Figure 3.2: Two examples of threshold hazard condition #2 - 350 ft^3 (10 m^3) above 40% LFL.

The two different threshold hazard conditions are needed to evaluate detector location performance because of the vastly different outcomes possible for free-jet and impinged leaks. Certain leaks result in less mixing and therefore tend to more quickly produce small pockets or rich layers above the LFL. These volumes above LFL then grow in size as the leak progresses and therefore the first threshold hazard condition of 10 ft^3 (0.3 m^3) above LFL is considered a desirable and reasonable hazard condition to detect prior to when little mixing occurs during a leak (e.g., an impinged low-momentum leak). Conversely, other releases result in more mixing and therefore tend to more readily produce larger volumes initially containing lower concentrations of fuel-gas. The concentration of fuel gas gradually increases in these large volumes as the leak progresses and therefore the second threshold hazard condition of 350 ft^3 (10 m^3) at 40% LFL is considered a desirable and reasonable hazard condition to detect prior to when more mixing occurs during a leak (e.g., free-jet releases). 40% LFL is also adequately above the upper limit of gas detector alarm thresholds (25% LFL), thus there is some margin for these detectors.

It is important to note that the results of this study are somewhat dependent on the chosen threshold hazard conditions. As will be discussed in more detail, this study provides relative quantitative comparisons of the performance of various detector locations. Thus, adjusting the threshold hazard conditions will shift the "values", however the relative comparisons between detector locations and overall trends will remain consistent.

3.2 Performance criteria

Gas detector location performance is evaluated using two criteria:

Criteria # 1 - the ability to detect before the above-defined threshold hazard conditions arise

Criteria # 2 - the ability to provide sufficient response time prior to the above-defined threshold hazard conditions arising

In other words, does a sensor placement detect prior to the threshold hazardous conditions (Criteria #1)? If so, how much time does it provide for occupants to respond before either of these conditions exist (Criteria #2)?

Criteria #1 is a binary performance indicator: a detector at a location either does or does not alarm prior to the threshold hazard conditions. Criteria #2 is an additional analog performance indicator for those sensors that did detect prior to the threshold hazard conditions. It is best assessed as the normalized time to detection as illustrated below in Figure 3.3. The normalized time to detection is the time from the start of the leak to detection, divided by the time from the start of the leak to when either of the threshold hazard conditions forms. Thus, normalized time to detection is a percentage between 0% and 100% with lower values indicating earlier detection in reference to when the hazard forms, and thus longer time to respond to an alarm before the hazard forms. This is an effective and convenient way to make comparisons of detector location performance across the wide variety of leak/geometry scenarios that were modeled.

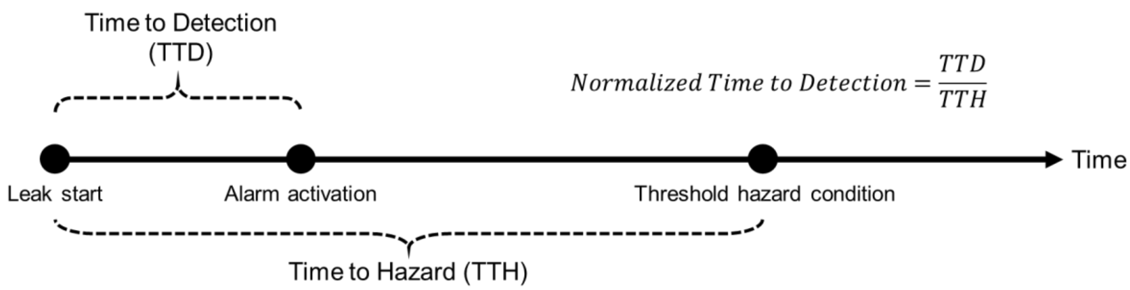

Figure 3.3: Illustration of performance criteria #2 – normalized time to detection.

4 Results and Discussion

4.1 Introduction

The results and discussion are presented as follows. First, we compare the performance of detector locations limited to the room in which the permanently installed fuel-gas appliance is located (i.e., in the room where the leak occurs). Most of the current guidance outlined in Section 1.3 mandates a detector be placed in the room where a gas-fire appliance is located and thus we specifically evaluate the performance of detector locations meeting this requirement. More specifically, we evaluate detector performance based on distance from the leak source and height relative to the ceiling and floor for NG and LPG respectively. Next, we compare the performance of supplemental gas detector locations in rooms or areas near the room where the gas-fired appliance is located. Some of the current guidance outlined in Section 1.3 recommends where to put additional detectors when installing more than one detector and thus we present the results for best places to put these additional detectors. Throughout these two separate discussions we point out instances and results that provide technical bases for recommendations related to detector placement in relation to ventilation registers, doorways, exterior fans, etc.

As frequently discussed throughout this report, the resulting fuel gas dispersion when a leak occurs can vary widely depending on the leak characteristics. Some releases are more likely to result in uniform gas concentrations within a residence and other releases are more likely to result in volumes or layers of accumulated gas at higher concentrations compared to other areas of the residence. We have therefore grouped the leaks modeled in this study into four categories based on certain leak characteristics and the amount of mixing that is anticipated to occur.[1] These categories are labeled A through D and the results are presented by category so that they are more easily interpreted. The categories are described below and summarized in Table 4.1.

Category A includes releases that result in the most mixing. These are free jet releases of NG at lower leak heights and LPG at higher leak heights. These releases have comparatively high release momentum (compared to impinged releases) and additional buoyancy-induced flow/mixing.

Category B includes releases that result in moderately high level of mixing. These are free jet releases of NG at higher leak heights and LPG at lower leak heights. These releases have high release momentum, but less buoyancy-induced mixing.

Category C includes releases that result in moderately low level of mixing. These are impinged releases of NG at lower leak heights and LPG at higher leak heights. These releases have low release momentum, but comparatively higher amount of buoyancy-induced mixing (compared to high NG releases and low LPG releases).

Category D includes releases that result in the least amount of mixing. These are impinged releases of NG at higher leak heights and LPG at lower leak heights. These releases have low release momentum and less buoyancy-induced mixing.

Table 4.1: Leak type categorization summary.

Category	Amount of mixing	Release type	Fuel and leak height
A	High	Free jet	NG low and LPG high
B	Moderately high	Free jet	NG high and LPG low
C	Moderately low	Impinged	NG low and LPG high
D	Low	Impinged	NG high and LPG low

This report presents the results of over 250 CFD simulations each containing hundreds of gas detector locations. Because of the large amount of data, results are consistently presented in two matrix tables, with an example of each shown below. These matrix tables typically include two different sensor location variables such as distance from the leak source and height in relation to the ceiling (for NG). This creates “bins” for which the sensors are grouped according to both variables.

The first table provides the performance of the sensors in each “bin” as the percentage of sensors in that bin that did not alarm prior to either threshold hazard condition. Thus, low percentages show location “bins” where few sensors failed to activate before the threshold hazard conditions and higher percentages show the opposite. In these tables, a color scale is applied such that low percentages are colored green and high percentages colored red to reinforce the notion that lower percentages indicate better performance.

[1] It is very important to note that we have not attempted to assign frequencies or likelihoods of the different leak categories occurring. Furthermore, it should not be interpreted that each of the four leak categories are equally likely to occur (i.e., a uniformly distributed likelihood of 25%).

The second table provides the average normalized time to detection for the sensors in each "bin" that did detect prior to the threshold hazard conditions. Lower percentage values indicate earlier detection in relation to when the threshold hazard condition forms. In these tables, the area of each cell is colored grey in proportion to the percentage value it contains, again, to help facilitate quick interpretation of the data.[2]

Using these tables, we can present together the results from multiple simulations in different geometries and with different leak rates, thus showing the overall trends for a wide variety of leak scenarios.

Table 4.2: Example matrix table showing the percentage of detectors in each bin that *did not* detect prior either of the threshold hazard conditions forming.

Detector Alarm Threshold - 10%					
Distance from	Distance from leak (ft)				
floor (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%
8	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.0%	0.0%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%
14	0.0%	0.0%	0.0%	0.0%	0.0%
16	0.0%	0.0%	0.0%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4.3: Example matrix table showing the average normalized time to detection for the sensors in each "bin" that did detect prior to the threshold hazard conditions.

Detector Alarm Threshold - 10%					
Distance from	Distance from leak (ft)				
floor (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	1.1%	3.0%	2.2%	3.8%	18.2%
6	1.0%	3.1%	2.2%	3.8%	18.3%
8	1.0%	3.1%	2.2%	3.8%	18.5%
10	1.0%	3.3%	2.2%	3.8%	18.7%
12	1.0%	3.3%	2.2%	3.9%	18.9%
14	1.0%	3.5%	2.2%	4.3%	19.1%
16	0.9%	3.8%	2.4%	4.4%	19.2%
18	0.9%	3.9%	2.5%	4.9%	19.7%

[2] Note that to make accurate performance comparisons using average normalized time to detection, it must be evaluated in tandem with the percentage of non-activations in each bin, as lower average normalized times to detection alone are not an indicator of better performance since bins containing lower values for this parameter could have higher percentages of non-activation. Nonetheless, average normalized time to detection does provide additional insight, for instance when the percentage of non-activation in two bins is the same or very similar. As seen below, there are instances where average normalized time to detection is lower in one bin compared to another because of a higher number of non-activations in the former. This occurs when a certain detector fails to activate in time and a nearby detector, in a different bin, but say a few inches closer to the ground (for LPG), activates just before the threshold hazard condition. This results in a higher non-activation percentage and lower average normalized time to detection in the bin containing the one detector and vice versa in the bin containing the other detector.

Existing residential gas detectors have a range of detector alarm thresholds generally between 10% LFL and 25% LFL. Sensor performance may be improved by reducing the concentration at which a sensor activates, thus the results are presented below for detector alarm thresholds of 10% LFL and 25% LFL. This study does not evaluate the potential for nuisance alarms. Detector activation is considered to occur instantaneously when the gas concentration at the detector reaches the alarm threshold.

4.2 Detector placement locations in room with gas-fired appliance

This section presents the results for detector locations in rooms where a gas-fired appliance is located. Results for detector alarm thresholds of 10% LFL and 25% LFL are presented concurrently. Results for the different category leaks are presented successively.

4.2.1 Category A Results

Category A releases result in the most mixing and include free jet releases of NG at lower leak heights (Figure 4.1) and LPG at higher leak heights (Figure 4.2).

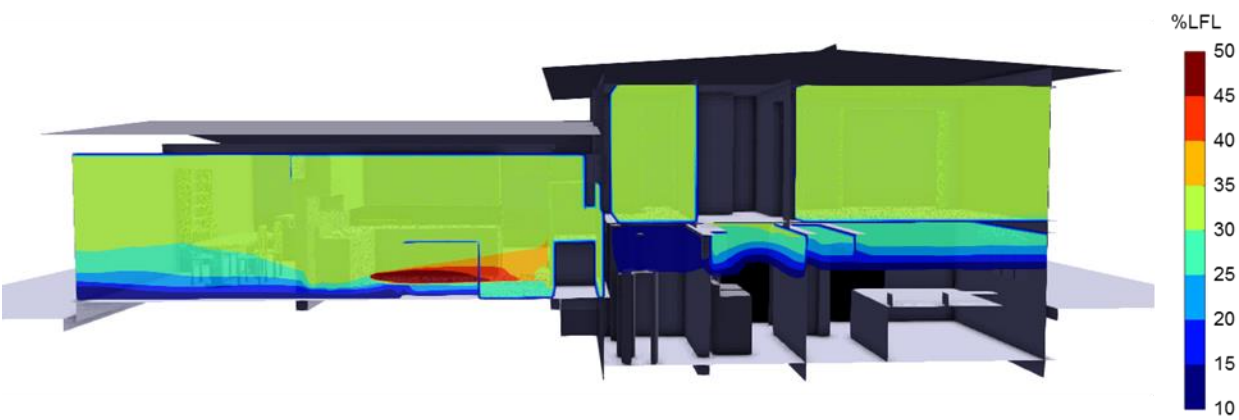

Figure 4.1: Example free-jet NG release at the range in split-level house kitchen.

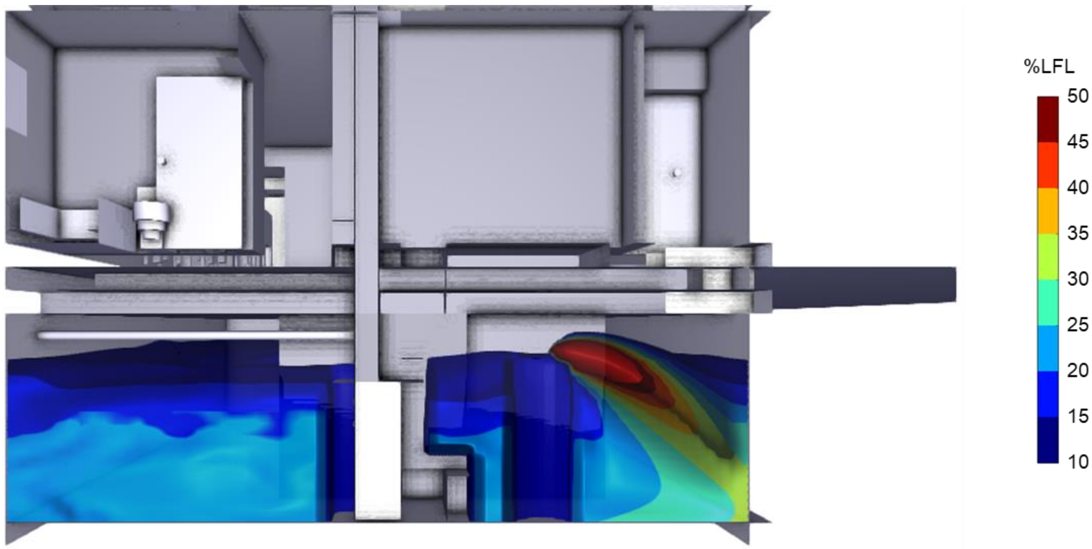

Figure 4.2: Example free-jet LPG release at the water heater in the colonial house basement.

4.2.1.1 NG Releases – Category A

For NG, these are the free jet releases modeled at the range in each kitchen. For all simulations with this leak type, Table 4.4 shows the percentage of sensors in each location "bin" that did not activate prior to either threshold hazard condition occurring. Results for 10% LFL and 25% LFL alarm threshold are shown on the left and right respectively. The bins are delineated based on horizontal straight-line distance from the leak source ranging up to 10 ft, and distance from the ceiling ranging from 4 in to 18 in. As the table shows, all sensors in all bins in all simulations activated prior to either threshold hazard condition, thus detector performance is insensitive to installation location for these modeled releases as long as the sensor is within 10 ft or closer to the leak source and 18 in or closer to the ceiling.

Table 4.4: Percentage of sensors that *did not* activate prior to threshold hazard conditions for NG category A leaks.

NG - Category A Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from ceiling (in)	Distance from leak (ft)						Distance from ceiling (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	0.0%	0.0%	0.0%	0.0%	0.0%		0	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%		12	0.0%	0.0%	0.0%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%		18	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4.5 provides the average normalized time to detection for the detectors that activated prior to the threshold hazard conditions (i.e., all sensors in this case). Results for 10% LFL and 25% LFL alarm threshold are shown on the left and right respectively. Average normalized times to detection are also insensitive to installation location within the bounds considered. As expected, earlier detection occurs when the alarm threshold is 10% LFL compared to 25% LFL.

Table 4.5: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for NG category A leaks.

NG - Category A Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from	Distance from leak (ft)						Distance from	Distance from leak (ft)				
ceiling (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10		ceiling (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	4.0%	4.0%	4.4%	4.5%	4.2%		0	32.3%	32.3%	32.7%	35.1%	36.3%
6	4.3%	3.3%	4.9%	5.9%	5.5%		6	45.9%	30.9%	31.7%	33.8%	30.0%
12	5.0%	3.4%	5.0%	6.1%	5.6%		12	47.5%	31.2%	31.0%	34.2%	30.1%
18	5.3%	3.5%	5.1%	5.9%	5.7%		18	47.7%	31.2%	30.8%	34.2%	30.2%

4.2.1.2 LPG Releases – Category A

For LPG, category A releases are the free-jet releases modeled above the water heaters in the various geometries. Table 4.6 shows the percentage of detectors in each bin that did not activate prior to the threshold hazard conditions. Results for 10% LFL and 25% LFL alarm thresholds are shown on the left and right respectively. As with the NG releases, all sensors in all bins in all simulations activated prior to either threshold hazard condition, thus, for these leaks, detector performance is insensitive to installation location as long as the detector is within 10 ft of the leak source and 18 in of the floor.

Table 4.6: Percentage of sensors that *did not* activate prior to threshold hazard conditions for LPG category A leaks.

LPG - Category A Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from	Distance from leak (ft)						Distance from	Distance from leak (ft)				
floor (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10		floor (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	0.0%	0.0%		4	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
8	0.0%	0.0%	0.0%	0.0%	0.0%		8	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.0%	0.0%	0.0%	0.0%	0.0%		10	0.0%	0.0%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%		12	0.0%	0.0%	0.0%	0.0%	0.0%
14	0.0%	0.0%	0.0%	0.0%	0.0%		14	0.0%	0.0%	0.0%	0.0%	0.0%
16	0.0%	0.0%	0.0%	0.0%	0.0%		16	0.0%	0.0%	0.0%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%		18	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4.5 provides the average normalized time to detection for the detectors that activated prior to the threshold hazard conditions (i.e., all sensors in this case). Average normalized detection times were again lower for the lower detector alarm threshold of 10% LFL. When the alarm threshold was 25% LFL, higher average normalized detection times of approximately 60% were observed for detector locations 8-10 ft from the leak source. These results are exclusively related to the LPG leaks at the water heater in the basement of the colonial house because in the other geometries, there were no detectors within this distance range from the leak sources. In the colonial basement the large open volume resulted in roughly uniform concentrations within 18 inches of the floor at this distance and thus a near-linear increase in concentration with time at these locations (i.e., time to 25% LFL is approximately 60% the time to 40% LFL).

Table 4.7: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for propane leaks with activation at 25% LFL for category A leaks.

LPG - Category A Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	1.1%	3.0%	2.2%	3.8%	18.2%		4	1.3%	21.5%	9.6%	20.6%	62.1%
6	1.0%	3.1%	2.2%	3.8%	18.3%		6	1.4%	24.3%	12.1%	23.0%	62.2%
8	1.0%	3.1%	2.2%	3.8%	18.5%		8	1.4%	26.2%	13.3%	23.9%	62.5%
10	1.0%	3.3%	2.2%	3.8%	18.7%		10	0.9%	28.0%	15.0%	25.0%	62.6%
12	1.0%	3.3%	2.2%	3.9%	18.9%		12	0.8%	29.0%	15.9%	25.3%	62.8%
14	1.0%	3.5%	2.2%	4.3%	19.1%		14	1.0%	30.5%	16.8%	25.8%	62.9%
16	0.9%	3.8%	2.4%	4.4%	19.2%		16	1.0%	31.3%	18.3%	27.1%	63.0%
18	0.9%	3.9%	2.5%	4.9%	19.7%		18	0.7%	32.3%	20.1%	27.5%	63.1%

4.2.2 Category B Results

Category B releases result in moderately high amounts of mixing and include free-jet releases of NG at higher leak heights (Figure 4.3) and LPG at lower leak heights (Figure 4.4).

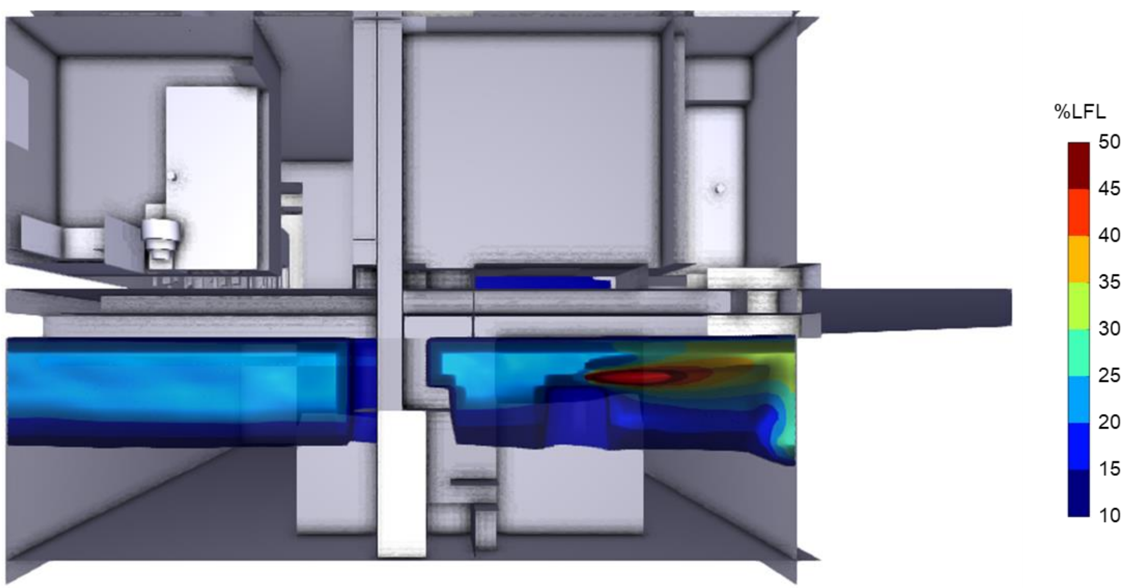

Figure 4.3: Example free-jet NG release at the water heater in the colonial house basement.

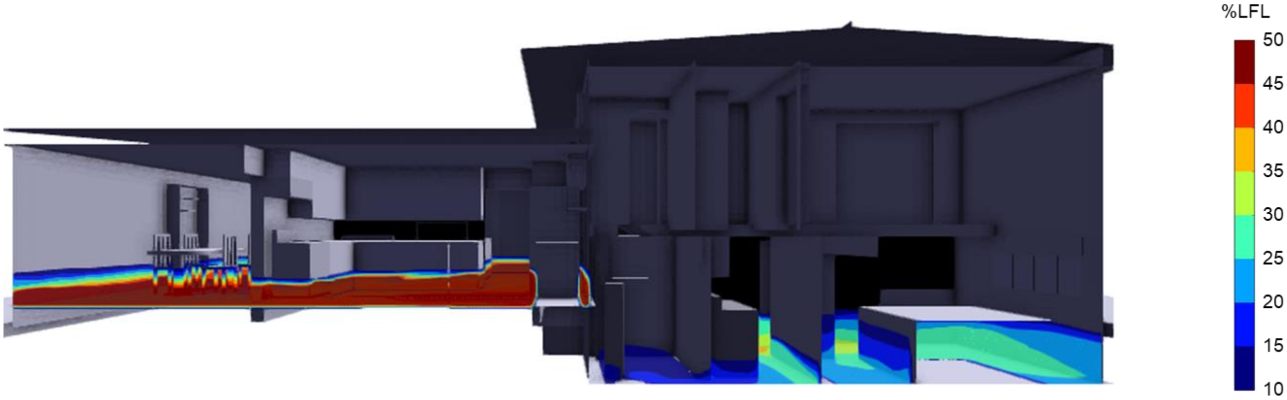

Figure 4.4: Example free-jet LPG release at the range in the split-level house kitchen.

4.2.2.1 NG Releases – Category B

For NG, category B releases are the free jet releases modeled at the water heaters in each geometry. Table 4.8 provides the percentage of sensors in each bin that did not activate prior to the threshold hazard conditions. As observed for the Category A NG releases, detector performance is insensitive to installation location for these modeled releases as long as the detector is within 10 feet of the leak source and 18 inches of the ceiling.

Table 4.9 shows the average normalized times to detection, which are again similar to those observed for the Category A NG releases.[3]

Table 4.8: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category B natural gas leaks.

NG - Category B Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from ceiling (in)	Distance from leak (ft)						Distance from ceiling (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	0.0%	0.0%	0.0%	0.0%	0.0%		0	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%		12	0.0%	0.0%	0.0%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%		18	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4.9: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category B natural gas leaks.

[3] The non-monotonic variation in normalized time to detection occurs because of the differences in the size of the rooms containing the water heaters in the three geometries and the number of sensors that we were able to place in those rooms. The higher average normalized times to detection are driven by the results in the large open basement in the colonial house. In these simulations, there were no sensors in the 0-2 ft and 4-6 ft bins at 6-18 inch heights and thus those bins show much shorter times to detections because those are solely the results for the detectors in the small utility room in the split-level house and utility closet in the townhouse.

NG - Category B Leak Average normalized time to detection											
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**				
Distance from ceiling (in)	Distance from leak (ft) 0 - 2	2 - 4	4 - 6	6 - 8	8 - 10		Distance from ceiling (in)	Distance from leak (ft) 0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	12.0%	9.8%	12.2%	15.7%	17.5%		0	46.0%	38.9%	45.3%	54.1%	55.8%
6	0.3%	13.0%	0.5%	2.1%	11.2%		6	0.9%	43.4%	3.8%	29.9%	46.7%
12	0.3%	13.4%	0.5%	2.6%	12.3%		12	0.9%	43.7%	3.6%	33.7%	49.2%
18	0.3%	13.7%	0.6%	3.8%	13.0%		18	0.9%	43.9%	3.8%	37.6%	51.1%

4.2.2.2 LPG Releases – Category B

For LPG, category B releases are the free-jet releases modeled at the range in each kitchen. Table 4.10 shows the percentage of detectors in each bin that did not activate prior to the threshold hazard conditions. For these LPG releases, non-activation percentages of 20-40% are observed for certain detectors locations 14-18 inches above the floor when the alarm threshold is 25% LFL.[4] Table 4.11 shows the average normalized times to detection for the detectors that activated prior to the threshold hazard conditions. In general, sensors located within 12 inches from the floor mostly activate before threshold hazard conditions and have low normalized times to detection.

Table 4.10: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category B LPG leaks.

LPG - Category B Leak Detector non-activation % prior to THCs											
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**				
Distance from floor (in)	Distance from leak (ft) 0 - 2	2 - 4	4 - 6	6 - 8	8 - 10		Distance from floor (in)	Distance from leak (ft) 0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	1.4%	0.0%		4	0.0%	0.0%	0.0%	3.4%	0.0%
6	0.0%	0.0%	0.0%	1.4%	0.0%		6	0.0%	0.0%	0.0%	3.4%	0.0%
8	0.0%	0.0%	0.0%	1.4%	0.0%		8	0.0%	0.0%	0.0%	3.4%	0.0%
10	0.0%	0.0%	0.0%	1.4%	0.0%		10	0.0%	0.0%	0.0%	3.4%	0.0%
12	0.0%	0.0%	0.0%	1.4%	0.0%		12	0.0%	0.0%	6.1%	4.1%	0.0%
14	0.0%	0.0%	0.0%	1.4%	0.0%		14	11.9%	0.0%	27.3%	11.6%	0.0%
16	7.1%	0.0%	9.1%	1.4%	0.0%		16	26.2%	0.0%	27.3%	11.6%	3.0%
18	28.6%	0.0%	18.2%	6.2%	0.0%		18	38.1%	0.0%	27.3%	21.9%	3.0%

[4] At these heights, the non-monotonic variations with distance are caused by geometry influences and limitations on sensor placements, especially with respect to the direction of the jet leak. More specifically, the distance bins group detectors based on straight-line horizontal distance from the leak and therefore detectors at different locations such as 4 ft away in the direction of the leak or in the opposite direction are grouped in the same bin. Because of the finite places to place detectors in the geometries modeled, there are not always detectors in each bin, nor is there consistently detectors a certain distance from the leak in numerous directions from the leak. This leads to some of the non-monotonic, and at sometimes, non-intuitive results that this study presents. We have however investigated all of these instances and have been able to explain each of them as being related to geometry influences and limited places to put detectors (even when placing over 200 detectors in each simulation).

Table 4.11: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category B LPG leaks.

LPG - Category B Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	3.2%	1.7%	5.4%	6.5%	5.1%		4	3.2%	1.8%	7.9%	7.0%	6.2%
6	3.1%	1.7%	5.4%	6.7%	5.2%		6	3.3%	1.8%	9.2%	7.4%	6.2%
8	2.8%	1.0%	5.6%	6.8%	5.2%		8	4.8%	1.8%	11.9%	8.6%	6.3%
10	2.9%	1.0%	6.2%	7.5%	5.3%		10	7.7%	1.8%	16.9%	10.2%	6.3%
12	5.2%	1.0%	8.6%	8.1%	5.4%		12	12.2%	1.8%	18.1%	12.6%	6.4%
14	9.8%	1.7%	10.4%	8.7%	5.4%		14	10.2%	2.6%	6.6%	7.4%	6.5%
16	10.3%	1.8%	10.5%	10.6%	5.5%		16	20.7%	2.8%	7.8%	9.0%	6.6%
18	7.6%	1.8%	8.3%	9.7%	5.7%		18	17.6%	2.5%	13.6%	11.7%	6.8%

The non-zero percentages at all heights at the 6-8 ft distance are the result of detectors that were placed directly above a supply register in the colonial house (see Figure 4.5).

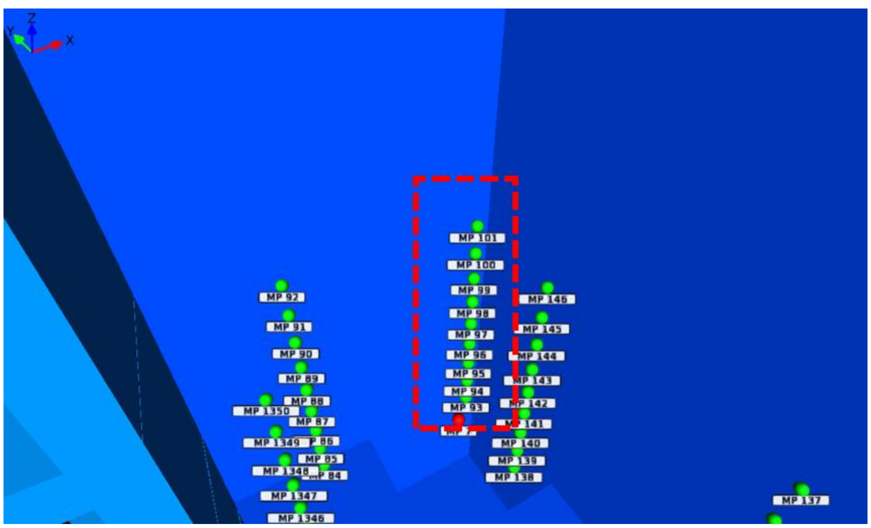

Figure 4.5: Sensors which did not activate prior to threshold hazard conditions in the colonial house – sensors located directly above an HVAC supply register.

Non-activations were observed for detectors placed directly above the leak (0-2 ft from the leak source and 14-18 in above the floor). The momentum of the free-jet release causes LPG to accumulate first in the area toward which the leak faces and less so directly above the leak.

For detectors 14-18 in above the floor, the relatively higher non-activation percentages at 4-8 ft compared to 8-10 ft are the result of non-activation of detectors along the wall parallel to the leak direction in the split-level geometry (see left image of Figure 4.6). As shown in the right image of Figure 4.6, the directional free-jet release of LPG causes the LPG to first accumulate on the other side of the kitchen, and the sensors in the 8-10 ft bin are located in this region, thus showing the influence of leak direction when a free-jet release occurs.

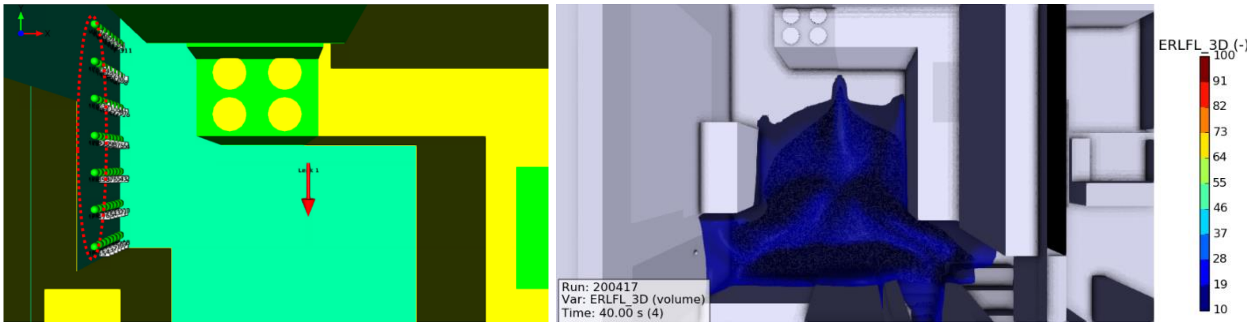

Figure 4.6: Sensors located in the split level kitchen, perpendicular to the leak direction. Circled sensors located near the upper range of distance from the floor had difficulty detection prior to threshold hazard conditions.

4.2.3 Category C Results

Category C releases result in moderately low amounts of mixing and include impinged low-momentum releases of NG at lower leak heights (Figure 4.7) and LPG at higher leak heights (Figure 4.8).

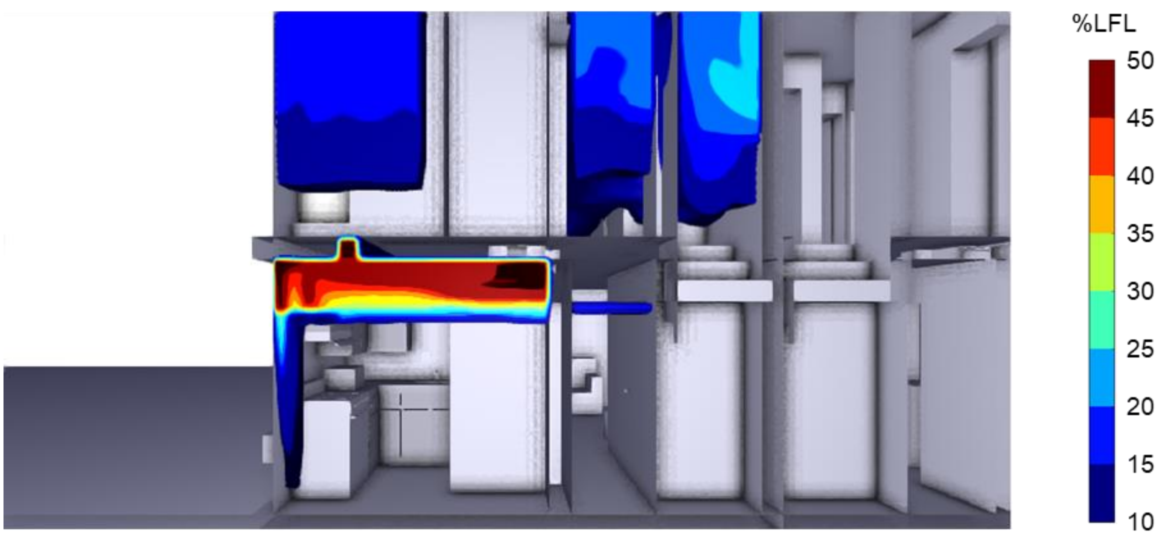

Figure 4.7: Example impinged low-momentum NG release at the range in the townhouse kitchen.

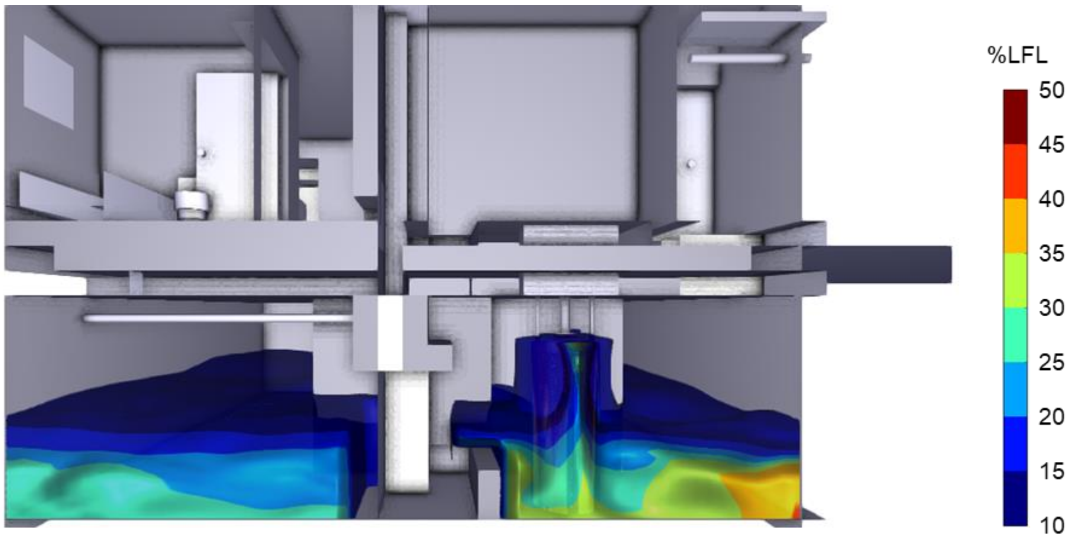

Figure 4.8: Example impinged low-momentum LPG release at the water heater in the colonial house basement.

4.2.3.1 NG Releases – Category C

For NG, category C releases are the impinged releases modeled at the range in each kitchen. Table 4.12 provides the percentage of sensors in each bin that did not activate prior to the threshold hazard conditions. Table 4.13 provides the average normalized times to detection for the detectors that activated prior to the threshold hazard conditions. For these releases, as observed for release categories A and B, detector performance is insensitive to installation location as long as the detector is within 10 feet of the leak source and 18 inches of the ceiling (non-zero values explained below). Average normalized times to detection are once again low, ranging from 2% to 5% when the alarm threshold is 10% LFL and 3% to 15% when the alarm threshold is 25% LFL.

Table 4.12: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category C NG leaks.

NG - Category C Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from ceiling (in)	Distance from leak (ft)						Distance from ceiling (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	0.0%	0.0%	0.0%	0.0%	0.0%		0	0.0%	0.0%	0.0%	0.3%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.7%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%		12	0.0%	0.0%	0.0%	0.7%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%		18	0.0%	0.0%	0.0%	0.7%	0.0%

Table 4.13: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category C natural gas leaks.

NG - Category C Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from	Distance from leak (ft)						Distance from	Distance from leak (ft)				
ceiling (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10		ceiling (in)	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	1.7%	1.8%	2.4%	3.4%	3.6%		0	3.2%	5.9%	8.3%	12.6%	14.7%
6	4.4%	2.8%	2.7%	3.3%	2.3%		6	5.2%	6.5%	6.8%	7.1%	5.3%
12	4.5%	3.0%	3.0%	3.4%	2.5%		12	7.8%	9.7%	8.2%	7.0%	5.4%
18	4.6%	3.8%	4.0%	3.8%	2.6%		18	11.6%	11.3%	11.7%	9.2%	6.6%

The non-zero percentages in the 6-8 ft bins when the alarm threshold is 25% LFL are the result of detectors that were placed directly below a supply register in the colonial house (see Figure 4.9). When the mechanical ventilation was active, these sensors failed to detect before the threshold hazard condition of 350 ft^3 (10 m^3) above 40% LFL.

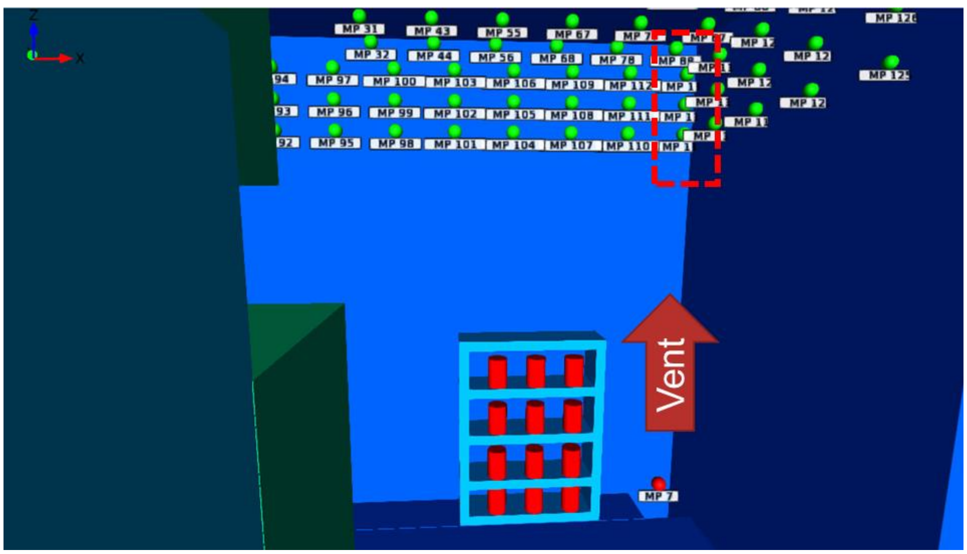

Figure 4.9: Locations that did not activate prior to threshold hazard conditions in the colonial house kitchen – located above the HVAC supply register.

4.2.3.2 LPG Releases – Category C

For LPG, category C releases are the impinged low-momentum releases modeled at the water heaters in the various geometries. Table 4.14 shows the percentage of detectors in each bin that did not activate prior to the threshold hazard conditions. The percentage of non-activation are similar to what was observed for the category B releases, with certain bins at the higher heights having non-activation percentages of ~ 10-40% when the detector alarm threshold is 10% LFL and ~ 5-50% when the detector alarm threshold is 25% LFL.[5] While the percentage values are similar,

[5] The non-monotonic behavior with detector distance from the leak source seen in Table 4.14 is once again the result of geometry factors, leak directionality factors, and limited detector placement locations. For example, in the split-

non-activations were mainly the result of the 10 ft^3 (0.3 m^3) above LFL threshold hazard condition being reaching prior to detection, whereas for the category B releases, it was the 350 ft^3 (10 m^3) above 40% LFL threshold hazard condition that occurred prior to some of the detectors activating.

Table 4.14 shows the average normalized times to detection for the detectors that activated prior to the threshold hazard conditions. Average normalized time to detection is generally insensitive to detector height, with slightly lower values observed for detectors placed closest to the ground. Lower values are also generally observed for detectors closer to the leak source.

Table 4.14: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category C LPG leaks.

LPG - Category C Leak Detector non-activation % prior to THCs											
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**				
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)			
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	0.0%	0.0%		4	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
8	0.0%	0.0%	0.0%	0.0%	0.0%		8	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.0%	0.0%	0.0%	0.0%	0.0%		10	0.0%	0.0%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%		12	0.0%	0.0%	10.5%	0.0%	0.0%
14	0.0%	0.0%	10.5%	0.0%	0.0%		14	0.0%	3.6%	26.3%	0.0%	0.0%
16	0.0%	0.0%	26.3%	0.0%	0.0%		16	0.0%	7.1%	42.1%	0.0%	0.0%
18	0.0%	0.0%	36.8%	0.0%	0.0%		18	0.0%	10.7%	47.4%	0.0%	0.0%

Table 4.15: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category C LPG leaks.

LPG - Category C Leak Average normalized time to detection											
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**				
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)			
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	13.3%	5.2%	26.5%	23.0%	20.3%		4	14.7%	10.0%	28.2%	33.4%	61.8%
6	13.2%	5.2%	27.6%	23.4%	20.3%		6	14.8%	10.3%	28.9%	33.8%	62.2%
8	13.0%	6.4%	28.3%	23.8%	20.5%		8	14.8%	11.7%	29.6%	34.2%	62.5%
10	12.8%	6.6%	29.6%	24.3%	20.9%		10	14.7%	13.2%	34.5%	34.7%	62.8%
12	12.7%	7.9%	31.7%	24.8%	21.2%		12	14.6%	17.1%	33.4%	35.3%	63.4%
14	12.1%	10.6%	29.3%	25.5%	21.6%		14	15.7%	16.3%	31.0%	36.6%	65.1%
16	12.3%	11.2%	28.3%	30.0%	22.3%		16	15.5%	16.8%	30.4%	41.2%	65.3%
18	12.1%	15.9%	32.6%	31.0%	22.6%		18	24.9%	13.9%	26.2%	46.2%	66.7%

4.2.4 Category D Results

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level utility closest when the release rate is 110 SCFH (highest leak rate modeled), the initial dynamics of the release cause considerable concentrations of LPG to bank upward in the corner of the small room, thus activating the detectors in this corner, which are > 6 ft away from the leak, before activating sensors that are closer to the leak. For this release rate of 110 SCFH in the small utility closet, the 10 ft^3 (0.3 m^3) above 100% LFL is reached in less than 1 minute and thus the results are sensitive to the initial dynamics of the release and the detector location relative to the leak direction and preferential flow paths.

Category D releases result in the least amount of mixing and include impinged low-momentum releases of NG at higher leak heights (Figure 4.10) and LPG at lower leak heights (Figure 4.11).

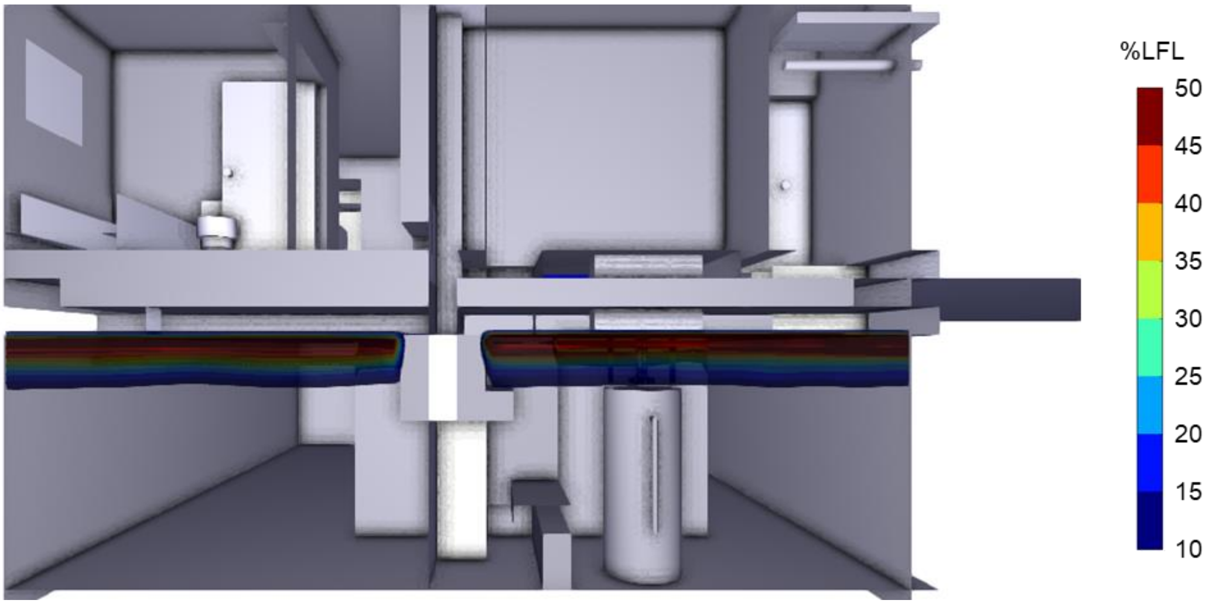


Figure 4.10: Example impinged low-momentum NG release at the water heater in the colonial house basement.

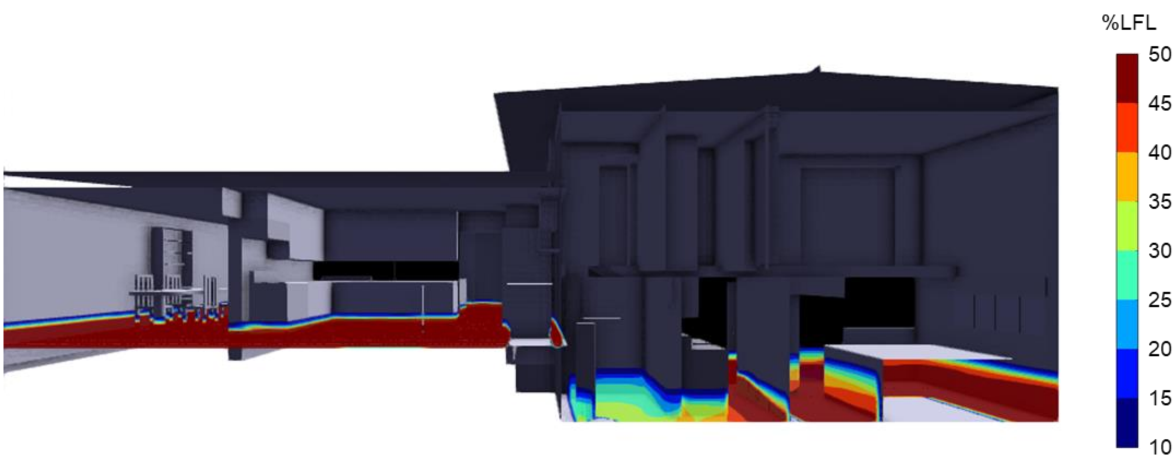


Figure 4.11: Example impinged low-momentum LPG release at the range in the split-level house kitchen.

4.2.4.1 NG Releases – Category D

For NG, category D releases are the impinged releases modeled above the water heaters in the various geometries. Table 4.16 provides the percentage of detectors in each bin that did not activate prior to the threshold hazard conditions. Table 4.17 provides the average normalized times to detection for the detectors that activated prior to the threshold hazard conditions.

As seen in Table 4.16, all detectors placed 6 inches or closer to the ceiling activate prior to the threshold hazard conditions, even for an alarm threshold of 25% LFL. There is a marked increase in the percentage of non-activations when detectors are installed 12 inches and lower from the ceiling. Furthermore, the increase is greater when the detector alarm threshold is 25% LFL. As seen previously for other leak categories, detector locations closer the leak and ceiling have lower normalized times to detection, and thus provide the most time to respond to an alarm.[6] For the 25% alarm threshold, roughly half of the non-activations were the result of the 10 ft^3 (0.3 m^3) above LFL threshold hazard condition being reaching prior to detection, with the other half being the result of the 350 ft^3 (10 m^3) above 40% LFL threshold hazard condition being reaching prior to detection.

Table 4.16: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D NG leaks.

NG - Category D Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							Detector Alarm Threshold - 25%					
Distance from ceiling (in)	Distance from leak (ft)						Distance from ceiling (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	0.0%	0.0%	0.0%	0.0%	0.0%		0	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
12	6.3%	19.8%	1.2%	0.0%	0.0%		12	50.0%	49.5%	7.1%	66.7%	66.7%
18	75.0%	59.3%	31.8%	66.7%	66.7%		18	100.0%	83.5%	47.1%	100.0%	100.0%

Table 4.17: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for natural gas leaks with activation at 25% LFL for category D leaks.

NG - Category D Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							Detector Alarm Threshold - 25%					
Distance from ceiling (in)	Distance from leak (ft)						Distance from ceiling (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	2.5%	5.7%	5.1%	6.0%	11.7%		0	2.8%	6.5%	6.7%	14.0%	28.7%
6	9.3%	5.4%	16.7%	2.5%	11.9%		6	9.3%	10.4%	18.5%	15.8%	41.3%
12	36.8%	39.8%	18.8%	11.8%	32.0%		12	59.5%	62.6%	28.2%	83.3%	76.0%
18	84.3%	39.1%	22.3%	54.1%	55.0%		18	N/A	13.8%	11.9%	N/A	N/A

Figure 4.12 through Figure 4.14 show detector locations that did not activate before threshold hazard conditions occurred. Note that the locations with non-activation in the split-level utility room (Figure 4.14) were below the height of the door opening.

[6] Refer to footnote 2 for explanation of why average normalized times to detection are sometimes lower in bins with higher percentages of non-activation.

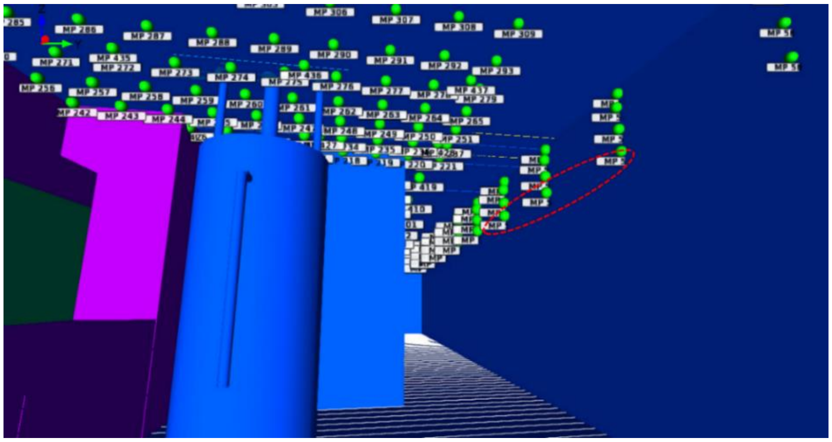


Figure 4.12: Locations that did not activate prior to threshold hazard conditions in the colonial house basement - sensors located on the opposite wall of the stairwell up to the main level.

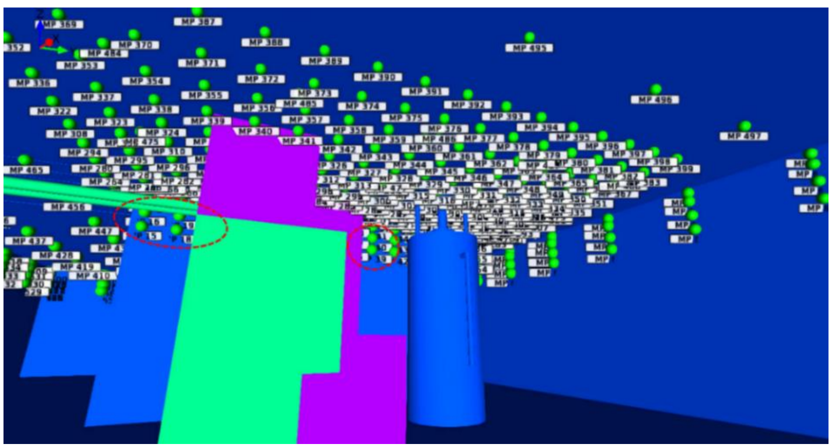


Figure 4.13: Locations that did not activate prior to threshold hazard conditions in the colonial house basement - sensors located farther from the leak and lower on the wall.

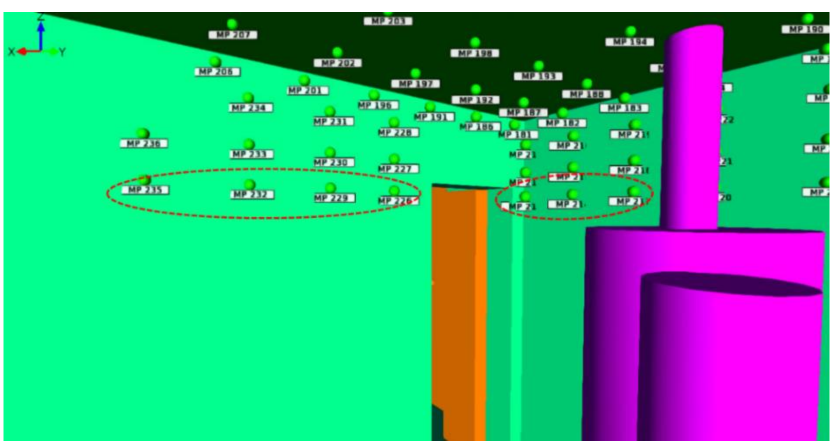


Figure 4.14: Locations that did not activate prior to threshold hazard conditions in the split level appliance closet - sensors located lower on the wall and near door openings.

4.2.4.2 LPG Releases – Category D

For LPG, category D releases are the impinged low-momentum releases modeled at range in each kitchen. Table 4.18 shows the percentage of detectors in each bin that did not activate prior to the threshold hazard conditions. For an alarm threshold of 10% LFL, detectors located within 6 ft of the leak and 6 inches from the floor activated before the threshold hazard conditions in all simulations. For an alarm threshold of 25% LFL, this was true only for detectors located within 4 ft of the leak and 4 inches from the floor. For the 25% alarm threshold, all of the non-activations were the result of the 10 ft^3 (0.3 m^3) above LFL threshold hazard condition being reached prior to detection. Very high levels of non-activation occurred when detectors were placed higher up from the floor. In addition (as discussed below) detectors can be placed further from the leak when they are not placed in obstructed pathways, over registers or at doorway openings. Although having less of an impact compared to increased height from the floor, increased distance from the leak also resulted in higher numbers of non-activation as expected for these types of leaks resulting in low lying layers of gas with high concentrations.

Table 4.18: Percentage of sensors that *did not* activate prior to threshold hazard conditions for propane leaks with activation at 25% LFL for category D leaks.

LPG - Category D Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							**Detector Alarm Threshold - 25%**					
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	4.2%	18.8%		4	0.0%	0.0%	2.6%	9.0%	18.8%
6	0.0%	0.0%	0.0%	6.3%	18.8%		6	26.7%	50.0%	15.4%	15.3%	22.9%
8	57.8%	72.2%	7.7%	6.3%	20.8%		8	66.7%	94.4%	53.8%	30.6%	29.2%
10	64.4%	83.3%	64.1%	22.9%	35.4%		10	82.2%	100.0%	92.3%	60.4%	47.9%
12	86.7%	88.9%	87.2%	59.7%	50.0%		12	100.0%	100.0%	100.0%	83.3%	60.4%
14	86.7%	88.9%	100.0%	84.0%	62.5%		14	100.0%	100.0%	100.0%	91.7%	72.9%
16	86.7%	88.9%	100.0%	87.5%	70.8%		16	100.0%	100.0%	100.0%	93.8%	87.5%
18	86.7%	88.9%	100.0%	88.9%	83.3%		18	100.0%	100.0%	100.0%	94.4%	95.8%

Table 4.19 and Table 4.20 show the 10% and 25% LFL alarm threshold data in Table 4.18 broken out by geometry. For each geometry, the height of the leak is indicated by a dashed red line. Bins that did not have any detectors in them are labeled as “N/A”. As the tables show, detectors placed below the leak height more readily activated before threshold hazard conditions.

Table 4.19: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D LPG leaks in each geometry - alarm threshold of 10% LFL. The red line indicates the height of the leak in these scenarios.

LPG - Category D Leak Colonial House Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 10%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	N/A	5.7%	33.3%
6	0.0%	0.0%	N/A	8.6%	33.3%
8	57.8%	86.7%	N/A	8.6%	33.3%
10	64.4%	86.7%	N/A	18.1%	73.3%
12	86.7%	86.7%	N/A	55.2%	86.7%
14	86.7%	86.7%	N/A	82.9%	86.7%
16	86.7%	86.7%	N/A	84.8%	86.7%
18	86.7%	86.7%	N/A	84.8%	86.7%

LPG - Category D Leak Split Level House Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 10%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	N/A	0.0%	0.0%	0.0%	66.7%
6	N/A	0.0%	0.0%	0.0%	66.7%
8	N/A	0.0%	0.0%	0.0%	66.7%
10	N/A	66.7%	20.0%	0.0%	66.7%
12	N/A	100.0%	66.7%	33.3%	66.7%
14	N/A	100.0%	100.0%	33.3%	66.7%
16	N/A	100.0%	100.0%	33.3%	100.0%
18	N/A	100.0%	100.0%	100.0%	100.0%

LPG - Category D Leak Townhouse Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 10%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	N/A	N/A	0.0%	0.0%	6.7%
6	N/A	N/A	0.0%	0.0%	6.7%
8	N/A	N/A	12.5%	0.0%	10.0%
10	N/A	N/A	91.7%	38.9%	13.3%
12	N/A	N/A	100.0%	75.0%	30.0%
14	N/A	N/A	100.0%	91.7%	50.0%
16	N/A	N/A	100.0%	100.0%	60.0%
18	N/A	N/A	100.0%	100.0%	80.0%

Table 4.20: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D LPG leaks in each geometry - alarm threshold of 25% LFL. The red line indicates the height of the leak in these scenarios.

LPG - Category D Leak Colonial House Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	N/A	12.4%	33.3%
6	26.7%	53.3%	N/A	20.0%	33.3%
8	66.7%	100.0%	N/A	32.4%	53.3%
10	82.2%	100.0%	N/A	57.1%	86.7%
12	100.0%	100.0%	N/A	81.9%	86.7%
14	100.0%	100.0%	N/A	89.5%	86.7%
16	100.0%	100.0%	N/A	91.4%	100.0%
18	100.0%	100.0%	N/A	92.4%	100.0%

LPG - Category D Leak Split Level House Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	N/A	0.0%	6.7%	0.0%	66.7%
6	N/A	33.3%	26.7%	33.3%	100.0%
8	N/A	66.7%	46.7%	33.3%	100.0%
10	N/A	100.0%	80.0%	66.7%	100.0%
12	N/A	100.0%	100.0%	66.7%	100.0%
14	N/A	100.0%	100.0%	100.0%	100.0%
16	N/A	100.0%	100.0%	100.0%	100.0%
18	N/A	100.0%	100.0%	100.0%	100.0%

LPG - Category D Leak Townhouse Only Detector non-actication % prior to THCs					
Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	N/A	N/A	0.0%	0.0%	6.7%
6	N/A	N/A	8.3%	0.0%	10.0%
8	N/A	N/A	58.3%	25.0%	10.0%
10	N/A	N/A	100.0%	69.4%	23.3%
12	N/A	N/A	100.0%	88.9%	43.3%
14	N/A	N/A	100.0%	97.2%	63.3%
16	N/A	N/A	100.0%	100.0%	80.0%
18	N/A	N/A	100.0%	100.0%	93.3%

Figure 4.15 through Figure 4.20 show detectors locations that did not activate before threshold hazard conditions. These locations included above a supply register for the HVAC system in the colonial house (Figure 4.15), near doorway openings into adjacent rooms (Figure 4.16 and Figure 4.17), locations obstructed from the leak (Figure 4.15 and Figure 4.18), and generally the higher height detector locations throughout all geometries (Figure 4.15 through Figure 4.20). Note that in the colonial house, most of the detector non-activations in the 6-8 ft bins 6 inches and lower were the result of detector locations above the supply register and behind the shelf obstruction seen in Figure 4.15. Also, note that in the split-level house, the one detector non-activation in the 4-6 ft bin at 4 inches from the ground for the 25% LEL alarm threshold was the result of this detector being placed just past the doorway into the dining room.

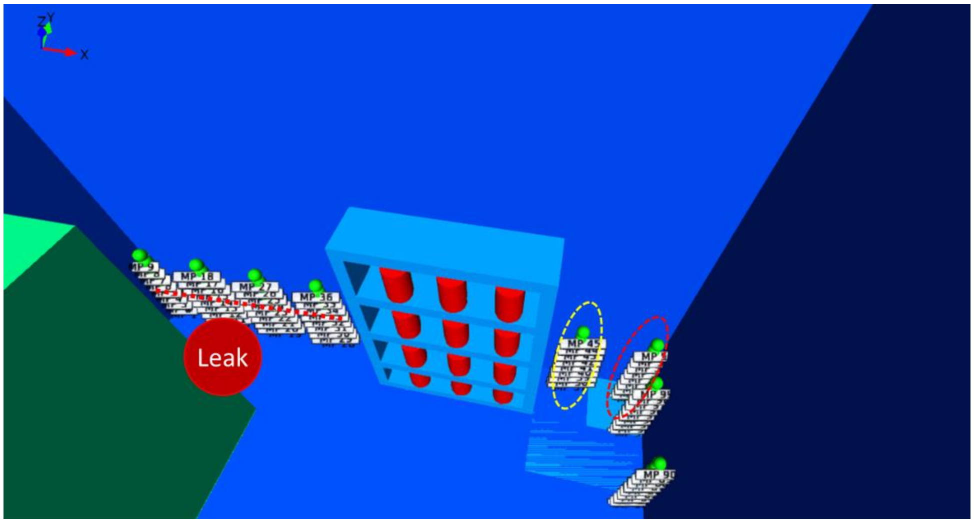


Figure 4.15: Locations which did not activate prior to threshold conditions in the colonial kitchen – detectors above the horizontal dashed red line, those circled in yellow behind the shelf obstruction, and those circled in red above the HVAC supply register.

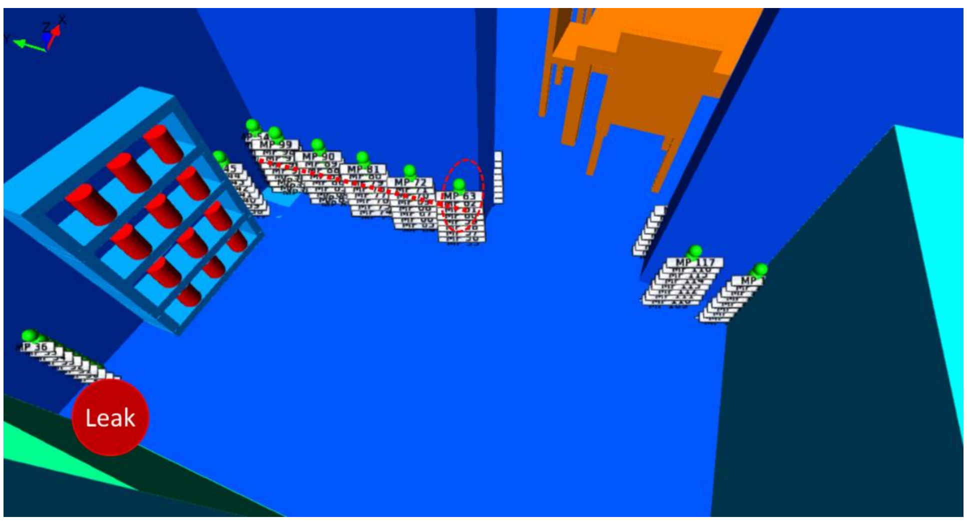


Figure 4.16: Locations which did not activate prior to threshold conditions in the colonial kitchen. – detectors above the horizontal dashed red line and those circled near the door opening.

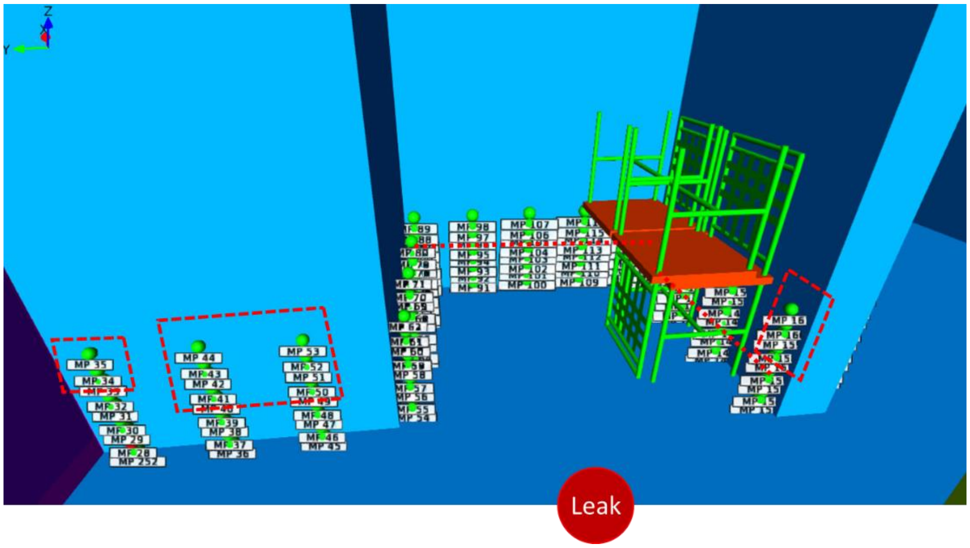


Figure 4.17: Locations which did not activate prior to threshold conditions in the townhouse kitchen – detectors above the horizontal dashed red line and those contained within the boxes.

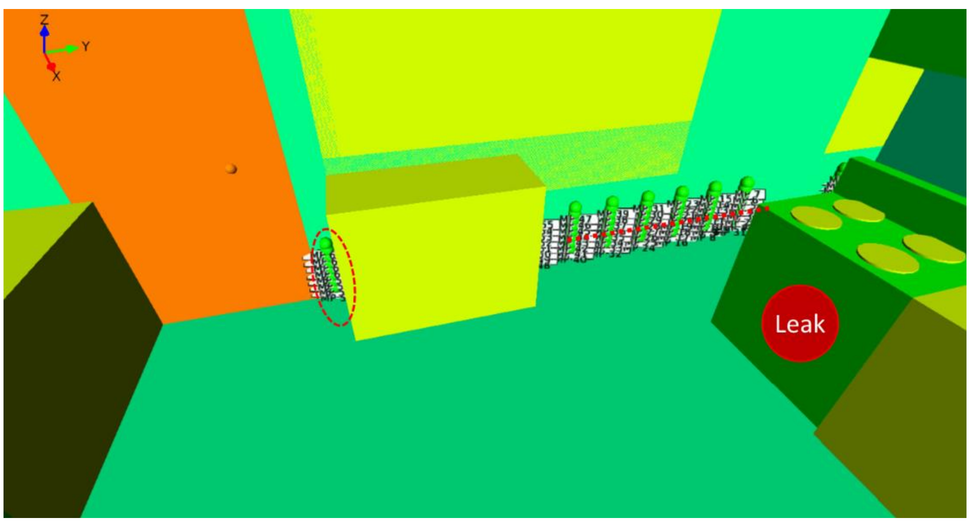


Figure 4.18: Locations which did not activate prior to threshold conditions in the split level kitchen - detectors above the horizontal dashed red line and those circled next to the cabinet.

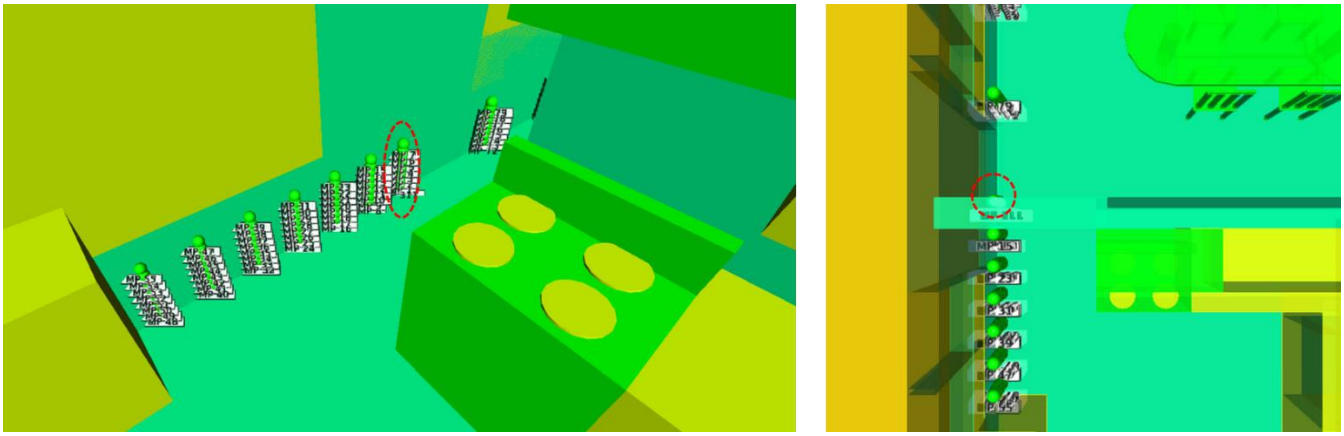


Figure 4.19: Locations which did not activate prior to threshold conditions in the split level kitchen - detectors circled just past the doorway to the dining room.

Figure 4.20: Locations which did not activate prior to threshold conditions in the townhouse kitchen - detectors above the horizontal dashed red line and those contained within the boxes.

Table 4.21 shows the percentage of non-activations when excluding the detector locations in the colonial house above the supply register and behind the shelf (circled in red and yellow respectively in Figure 4.15) and the locations in the split-level house just past the doorway into the dining room (Figure 4.19). All remaining detectors located within 8 ft of the leak and 6 inches from the floor activated prior to threshold hazard conditions when the alarm threshold was 10% LFL. Furthermore, all detectors located within 8 ft of the leak and 4 inches from the floor activated when the alarm threshold was 25% LFL.

Table 4.21: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D LPG leaks when excluding obstructed locations and locations above a supply register for both alarm thresholds of 10% and 25% LFL.

LPG - Category D Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	0.0%	18.8%		4	0.0%	0.0%	0.0%	0.0%	18.8%
6	0.0%	0.0%	0.0%	0.0%	18.8%		6	26.7%	50.0%	13.9%	6.1%	22.9%
8	57.8%	72.2%	8.3%	0.0%	20.8%		8	66.7%	94.4%	50.0%	20.2%	29.2%
10	64.4%	83.3%	61.1%	17.5%	35.4%		10	82.2%	100.0%	91.7%	54.4%	47.9%
12	86.7%	88.9%	86.1%	58.8%	50.0%		12	100.0%	100.0%	100.0%	80.7%	60.4%
14	86.7%	88.9%	100.0%	86.8%	62.5%		14	100.0%	100.0%	100.0%	91.2%	72.9%
16	86.7%	88.9%	100.0%	89.5%	70.8%		16	100.0%	100.0%	100.0%	93.9%	87.5%
18	86.7%	88.9%	100.0%	91.2%	83.3%		18	100.0%	100.0%	100.0%	94.7%	95.8%

Table 4.22 provides the average normalized times to detection for the detectors that activated prior to the threshold hazard conditions. Bins that had no detectors activate before threshold hazard conditions are shown as "N/A". Following the general trends observed for the previous release categories, detectors placed closer to the leak and closer to the ground generally provide more time to respond to an alarm.

Table 4.22: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for LPG leaks with activation at 25% LFL for category D leaks.

LPG - Category D Leak Average normalized time to detection												
Detector Alarm Threshold - 10%							Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)						Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	8.3%	19.5%	46.0%	54.7%	62.1%		4	9.3%	20.0%	47.8%	57.5%	63.1%
6	11.1%	23.9%	47.5%	56.9%	63.0%		6	15.0%	29.6%	56.0%	61.1%	63.0%
8	26.6%	47.6%	51.9%	59.4%	63.5%		8	13.4%	75.0%	66.6%	65.8%	66.8%
10	31.0%	53.1%	60.1%	63.0%	65.4%		10	18.5%	N/A	79.1%	67.8%	65.9%
12	79.8%	41.4%	74.7%	62.9%	64.7%		12	N/A	N/A	N/A	56.6%	62.9%
14	79.8%	41.8%	N/A	45.1%	65.7%		14	N/A	N/A	N/A	41.3%	74.2%
16	79.8%	63.4%	N/A	38.8%	66.6%		16	N/A	N/A	N/A	39.9%	73.8%
18	79.8%	85.6%	N/A	38.5%	70.9%		18	N/A	N/A	N/A	46.3%	88.9%

4.2.4.3 Sensitivity of results to chosen threshold hazard conditions

To evaluate the sensitivity of the results to the chosen threshold hazard conditions, we post-processed the results for category D LPG leaks again, but this time with an adjusted threshold hazard condition of 20 ft^3 (0.6 m^3) above LFL instead of 10 ft^3 (0.3 m^3) above LFL. These specific leaks were chosen here because all the detector non-activations previously seen were the result of the 10 ft^3 (0.3 m^3) above the LFL threshold hazard condition being reaching prior to detection.

Table 4.23 and Table 4.24 compare the percentage of detectors with alarm thresholds of 10% LFL and 25% LFL that did not activate prior to the original threshold hazard condition of 10 ft^3 (0.3 m^3) above LFL (left tables) and the modified condition of 20 ft^3 (0.6 m^3) above LFL (right tables).

As the tables show, the percentages shift slightly in some of the bins, but the relative comparisons between detector locations and overall trends generally remain consistent.

Table 4.23: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D LPG leaks with detector alarm threshold of 25% LFL. The left table shows results for a threshold hazard condition of 10 ft^3 (0.3 m^3) above LFL and the right table shows results for a threshold hazard condition of 20 ft^3 (0.6 m^3) above LFL.

Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	2.6%	9.0%	18.8%
6	26.7%	50.0%	15.4%	15.3%	22.9%
8	66.7%	94.4%	53.8%	30.6%	29.2%
10	82.2%	100.0%	92.3%	60.4%	47.9%
12	100.0%	100.0%	100.0%	83.3%	60.4%
14	100.0%	100.0%	100.0%	91.7%	72.9%
16	100.0%	100.0%	100.0%	93.8%	87.5%
18	100.0%	100.0%	100.0%	94.4%	95.8%

Detector Alarm Threshold - 25%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	4.2%	4.2%
6	26.7%	33.3%	10.3%	7.6%	4.2%
8	66.7%	83.3%	25.6%	17.4%	12.5%
10	82.2%	94.4%	74.4%	43.8%	33.3%
12	100.0%	100.0%	84.6%	70.1%	41.7%
14	100.0%	100.0%	94.9%	85.4%	54.2%
16	100.0%	100.0%	97.4%	88.2%	72.9%
18	100.0%	100.0%	100.0%	88.9%	83.3%

Table 4.24: Percentage of sensors that *did not* activate prior to threshold hazard conditions for category D LPG leaks with detector alarm threshold of 10% LFL. The left table shows results for a threshold hazard condition of 10 ft^3 (0.3 m^3) above LFL and the right table shows results for a threshold hazard condition of 20 ft^3 (0.6 m^3) above LFL.

Detector Alarm Threshold - 10%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	4.2%	18.8%
6	0.0%	0.0%	0.0%	6.3%	18.8%
8	57.8%	72.2%	7.7%	6.3%	20.8%
10	64.4%	83.3%	64.1%	22.9%	35.4%
12	86.7%	88.9%	87.2%	59.7%	50.0%
14	86.7%	88.9%	100.0%	84.0%	62.5%
16	86.7%	88.9%	100.0%	87.5%	70.8%
18	86.7%	88.9%	100.0%	88.9%	83.3%

Detector Alarm Threshold - 10%					
Distance from floor (in)	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
4	0.0%	0.0%	0.0%	4.2%	4.2%
6	0.0%	0.0%	0.0%	4.2%	4.2%
8	57.8%	33.3%	0.0%	4.2%	4.2%
10	64.4%	83.3%	38.5%	9.7%	16.7%
12	86.7%	88.9%	69.2%	40.3%	33.3%
14	86.7%	88.9%	82.1%	70.8%	39.6%
16	86.7%	88.9%	82.1%	77.1%	47.9%
18	86.7%	88.9%	84.6%	83.3%	62.5%

One outcome that does change however for these category D LPG releases is the performance of sensors farther away from the release. When the threshold volume above LFL is made larger the sensors farther away more readily detect before the threshold volume is reached. This is because detectable LPG concentrations (i.e., 10% and 25% LFL) now extend farther from the leak when the threshold volume is reached. This is illustrated in Figure 4.21 which shows a top-down view of the volumes above 25% LFL (i.e., detectable volume shown as blue) and 100% LFL (i.e., hazard volume shown as red) when the threshold hazard conditions of 10 ft^3 (left image) and 20 ft^3 (right image) above LFL are reached. As also shown in the figure, the sensors obstructed by the base cabinets (shown as a green circle) still fail to activate prior to the larger threshold hazard condition forming, thus showing the importance of an unobstructed path between the detector and leak source.

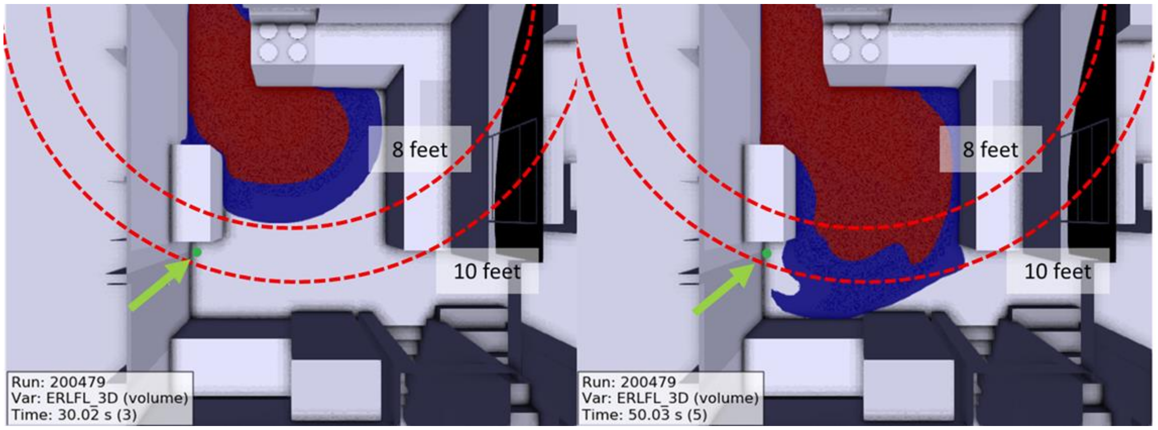


Figure 4.21: Above 25% LFL concentration (blue) and above 100% LFL concentration (red) when the threshold hazard conditions of 10 ft^3 (left image) and 20 ft^3 (right image) above LFL are reached.

4.3 Supplemental detector locations

This section compares the performance of supplemental gas detector locations in rooms or areas near the room where the gas-fired appliance is located. Detector locations are grouped by room or area such as "dining room", "hallway", "staircase", etc., instead of horizontal straight-line distance from the leak source to the sensor as this variable becomes less meaningful when there are walls separating the two (i.e., the actual gas migration distance is larger). In this section, results are presented: separately for each geometry, only for alarm thresholds of 25% LFL; and only as the percentage of detectors that do not activate prior to threshold hazard conditions. Results for only category C and D releases are presented, as it was generally found for category A and B releases that the performance of a supplemental detector is insensitive to installation location as long as installed at appropriate distances from the ceiling for NG and floor for LPG.

4.3.1 NG Releases - Category C

Table 4.25 provides the percentage of detectors that did not activate prior to the threshold hazard conditions for category C NG releases from the range in the two-story townhouse configuration. Table 4.26 shows the same for the split-level house. Sensors that were located in the neighboring room had very low non-activation percentages. For detectors farther away from the leak source in terms of the gas migration path (i.e., top of the stairs), the non-activation percentages increased, however sensor placement in the stairwell still maintained a reasonably low non-activation percentage as long as they were close to the ceiling. The NG buoyantly mixes and dilutes with air as it migrates up the stairs and thus concentrations are reduced at the top of the stairs thus delaying detector activation at this location.

Table 4.25: Percentage of sensors in adjacent areas in the townhouse that *did not* activate prior to threshold hazard conditions for category C NG leaks and a detctor alarm threshold of 25% LFL.

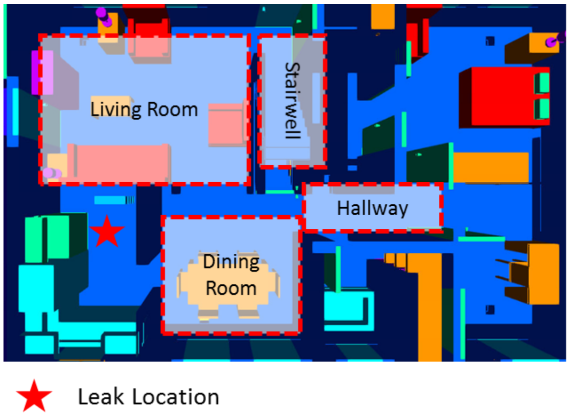
NG - Category C - Townhouse Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL			
Distance from ceiling (in)	Location		
	Front Room	Stairwell	Upstairs Hallway
0	0.0%	10.0%	33.3%
6	0.0%	11.1%	33.3%
12	0.0%	11.1%	33.3%
18	2.8%	22.2%	33.3%

Table 4.26: Percentage of sensors in adjacent areas in the split-level house that *did not* activate prior to threshold hazard conditions for category C NG leaks and a detctor alarm threshold of 25% LFL.

NG - Category C - Split Level Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL		
Distance from ceiling (in)	Location	
	Dining Room	Stairwell
0	0.0%	0.0%
6	0.0%	16.7%
12	0.0%	33.3%
18	0.0%	50.0%

Table 4.27 provides the results for the category C NG releases in the colonial house at the range. All detectors placed in the neighboring dining room and hallway activated prior to threshold hazard conditions. Some of the detectors in the living did not activate when there was a header between the dining room and living room as this header allowed NG to accumulate to threshold hazard conditions before it could migrate into the living room. More non-activations were observed in the stairwell, again because of the buoyant mixing and therefore generally lower concentrations in this area and because it is the location away from the leak out of the locations considered.

Table 4.27: Percentage of sensors in adjacent areas in the colonial house that *did not* activate prior to threshold hazard conditions category C NG leaks and a detctor alarm threshold of 25% LFL.

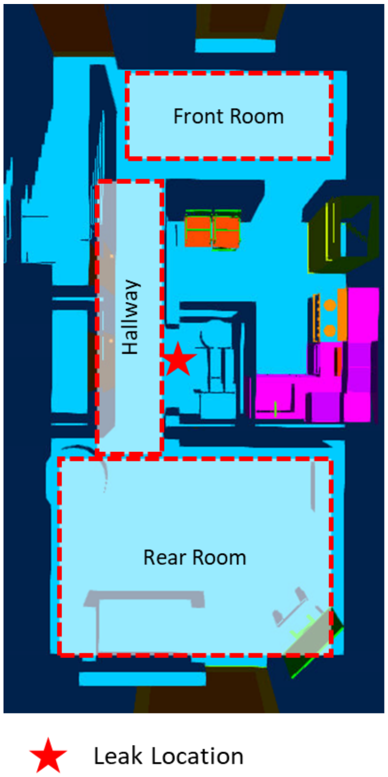


NG - Category C - Colonial Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL				
Distance from ceiling (in)	Location			
	Dining Room	Hallway	Living Room	Stairwell
0	0.0%	0.0%	12.0%	33.3%
6	0.0%	0.0%	15.0%	27.8%
12	0.0%	0.0%	15.6%	27.8%
18	0.0%	0.0%	17.8%	38.9%

4.3.2 LPG Releases – Category C

Table 4.28 provides the results for the category C LPG releases in the townhouse at the water heater. Detectors placed in the hallway just outside the utility closet performed generally the best, with sensors lower to the floor performing better. Detectors in the rear room and the front room has similar performance with the rear room somewhat better because of slightly closer proximity to the leak source. If for this scenario there was also an LPG-fired range in the kitchen, a single secondary sensor installation placed in the front room would be able to provide supplemental detection for leaks both at the water heater and range.

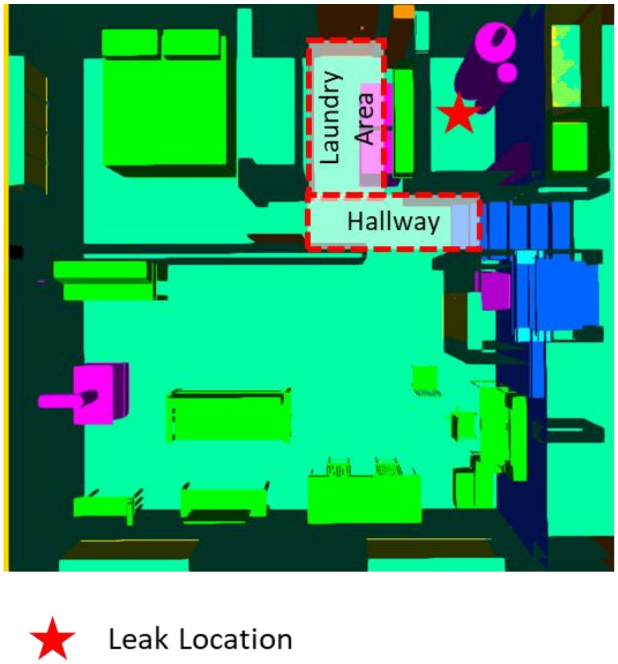
Table 4.28: Percentage of sensors in adjacent areas in the townhouse that *did not* activate prior to threshold hazard conditions for category C LPG leaks and a detctor alarm threshold of 25% LFL.



LPG - Category C - Townhouse Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL			
Distance from floor (in)	Location		
	Front Room Walls	Rear Room Walls	Hallway Walls
4	53.0%	44.4%	18.5%
6	55.6%	44.4%	20.4%
8	58.1%	47.6%	20.4%
10	61.5%	47.6%	24.1%
12	63.2%	49.2%	26.9%
14	65.0%	60.3%	32.4%
16	66.7%	63.5%	38.9%
18	68.4%	66.7%	54.6%

Table 4.29 provides the results for the category C LPG releases in the split-level utility room at the water heater. Detectors in the neighboring laundry room performed better than those in the hallway which was further away from the utility room. Note that the hallway could be considered a better place to place a supplemental sensor compared to the laundry room as it would provide better performance in detecting a leak from an LPG-range in the kitchen if the goal of the supplemental detector was to provide detection redundancy for potential leaks occurring at more than one gas-fired appliance located in different areas of the residence.

Table 4.29: Percentage of sensors in adjacent areas in the townhouse that *did not* activate prior to threshold hazard conditions for category C LPG leaks and a detctor alarm threshold of 25% LFL.

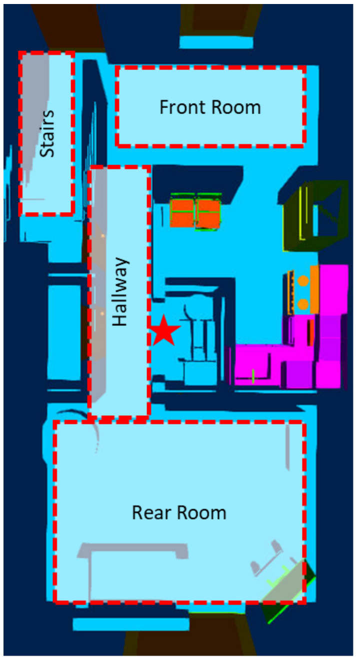


LPG - Category C - Split Level Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL		
Distance from floor (in)	Location	
	Hallway	Laundry Area
4	50.0%	0.0%
6	50.0%	0.0%
8	50.0%	0.0%
10	50.0%	16.7%
12	50.0%	16.7%
14	50.0%	16.7%
16	100.0%	33.3%
18	100.0%	33.3%

4.3.3 NG Releases – Category D

Table 4.30 provides the results for the category D NG releases in the townhouse at the water heater. Near or on the ceiling in the hallway was the most effective supplemental location. Sensors placed lower in height in the hallway, however, performed worse than those at similar distances from the ceiling in other rooms/areas in the house. The hallway ceiling is lower relative to the ceiling height in other rooms. This means that sensors placed 18 inches from the ceiling in the hallway are at a lower relative height than sensors placed 18 inches from the ceiling in the front room, thus why detectors at 12-18 inches from the ceiling in the hallway had reduced performance compared to those similarly installed from the ceiling in the rear and front rooms.

Table 4.30: Percentage of sensors in adjacent areas in the townhouse that *did not* activate prior to threshold hazard conditions for category D NG leaks and a detctor alarm threshold of 25% LFL.

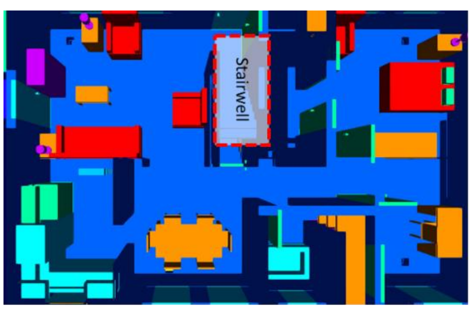


★ Leak Location

NG - Category D - Townhouse Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL					
Distance from ceiling (in)	Location				
	Front Room	Rear Room	Hallway	Stairwell	Upstairs Hallway
0	60.0%	62.5%	2.8%	86.7%	100.0%
6	61.1%	65.6%	33.3%	88.9%	100.0%
12	63.9%	66.7%	85.9%	88.9%	100.0%
18	94.4%	66.7%	100.0%	100.0%	100.0%

Table 4.31 shows the results for the category D NG releases in the basement of the colonial house. For this case, we only evaluated the performance of detectors in the stairwell. Overall, high percentages of non-activation were observed, indicating the overall ineffectiveness of a supplementary detector for these releases due to the size of the basement volume.

Table 4.31: Percentage of sensors in adjacent areas in the colonial house that *did not* activate prior to threshold hazard conditions for category D NG leaks and a detctor alarm threshold of 25% LFL.



★ Leak location – in open basement

NG - Category D - Colonial Basement Door Closed Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL	
Distance from ceiling (in)	Location
	Basement Stairs
0	77.8%
6	66.7%
12	83.3%
18	83.3%

4.3.4 LPG Releases – Category D

Table 4.32 and Table 4.33 show the results for category D LPG releases from the range in the townhouse and split-level house. High percentages of non-activation again indicate that overall ineffectiveness of a supplementary detector for category D releases, and further show the importance of having a properly placed detector in the room where the gas-fire appliance is located. Similar results were observed in the colonial house as well.

Table 4.32: Percentage of sensors in adjacent areas in the townhouse that *did not* activate prior to threshold hazard conditions for category D LPG leaks and a detctor alarm threshold of 25% LFL.

LPG - Category D - Townhouse Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL	
Distance from floor (in)	Location Front Room Walls
4	96.2%
6	96.2%
8	98.7%
10	98.7%
12	100.0%
14	100.0%
16	100.0%
18	100.0%

★ Leak Location

Table 4.33: Percentage of sensors in adjacent areas in the split level house that *did not* activate prior to threshold hazard conditions for category D LPG leaks and a detctor alarm threshold of 25% LFL.

LPG - Category D - Split Level Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL		
Distance from floor (in)	Location	
	Dining Room Walls	Stairs Going Down
4	72.2%	66.7%
6	72.2%	100.0%
8	83.3%	100.0%
10	83.3%	100.0%
12	88.9%	100.0%
14	100.0%	100.0%
16	100.0%	100.0%
18	100.0%	100.0%

★ Leak Location

In summary, the results show that supplemental sensors can provide reliable detection redundancy for the category A, B, and C releases modeled, both NG and LPG, when used in conjunction with a primary detector located in the room where the gas-fire appliance is located. Performance is generally better when detectors are placed in rooms or areas closest to the room where the leak can occur. For the category D releases modeled, both NG and LPG, a supplementary detector provides poor detection performance, thus highlighting the importance of a properly placed sensor in the room where the gas-fired appliance is located.

If only one supplemental detector is used, it may be most beneficial to place it in a location that can detect leaks from multiple gas-fired appliances located in different rooms of the residence. Supplemental sensors placed along common gas migration paths (e.g., stairwells, interconnecting hallways and rooms/areas equidistant from all possible leak locations) are effective locations to for this purpose.

4.4 Special considerations

4.4.1 Header Height

Doorway header heights are a geometry detail that can significantly influence how NG disperses throughout a residence when released, especially for releases with low levels of mixing. These headers, when present, act as barriers that contain the layer of NG at the ceiling and prevent it from spreading into neighboring rooms or upper floors until it has grown in thickness enough to pass below the header. When there are no headers, the layer of NG at the ceiling can spread sooner to other rooms and floors above and thus there can be a significant delay before the layer at the ceiling builds in thickness, even in the room where the leak occurs. This is potentially significant in terms of appropriate detector installation heights for NG. Thus, matrix tables are provided below which show the performance of detectors based on installation heights and doorway header height.

Table 4.34 provides the percentage of detectors that did not activate prior to threshold hazard conditions during category D NG leaks from the water heater in the split-level house. The header that is varied in height is between the utility room and the neighboring laundry room. In these simulations, all sensors 6 in or closer to the ceiling detected prior to threshold hazard conditions, even when there was not a door header. When the door header was present detectors 12 in from the ceiling had good performance, however when there was no header these same detectors had poor performance. All of the sensors at 18 in from the ceiling failed even when there was a 16 in header, thus indicating that detectors should not be placed below the highest door opening.

Table 4.34: Percentage of sensors that *did not* activate prior to threshold hazard conditions for natural gas leaks in the split level house with activation at 25% LFL for category D evaluated by header height.

NG - Category D - Split Level Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL			
Distance from ceiling (in)	Header Height		
	0 in	8 in	16 in
0	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%
12	72.2%	14.8%	7.4%
18	100.0%	100.0%	100.0%

For the large open basement of the colonial house, there were no headers to vary. The results of these dispersion simulations in the base, however, are approximately what would occur in a large open floorplan without headers above doorway openings in partition walls. Table 4.35 shows that detector performance is very sensitive to detector installation height. The detectors placed 18 inches below the ceiling consistently failed to activate prior to the threshold hazard conditions, and all sensors 6 in or closer to the ceiling detected prior to threshold hazard conditions for the large open geometry.

Table 4.35: Percentage of sensors that *did not* activate prior to threshold hazard conditions for natural gas leaks in the colonial basement with activation at 25% LFL for category D evaluated by header height.

NG - Category D - Colonial Non-Activation % Prior to THCs Alarm Threshold @ 25% LFL	
Distance from ceiling (in)	Header Height
	0 in
0	0.0%
6	0.0%
12	66.7%
18	100.0%

4.4.2 Sensors near windows

Detectors placed near windows may have reduced performance because of the diluting effect of exterior air infiltration. This was confirmed in the townhouse simulations which had air infiltration pathways around the windows and external winds imposed. Figure 4.12 shows the detectors placed throughout the front room and near the window during the NG releases (left) and LPG releases (right). The influence of exterior air infiltration at windows is most pronounced during releases that are well-mixed. Concentrations are generally lower near the window because of exterior air infiltration and pathways for the fuel-gas to leak outside and thus average normalized times to detection are higher for the detectors near the window compared to those in the front room that are not near the window. This is shown in Table 4.36 for category A NG releases and Table 4.37 for category A LPG releases.

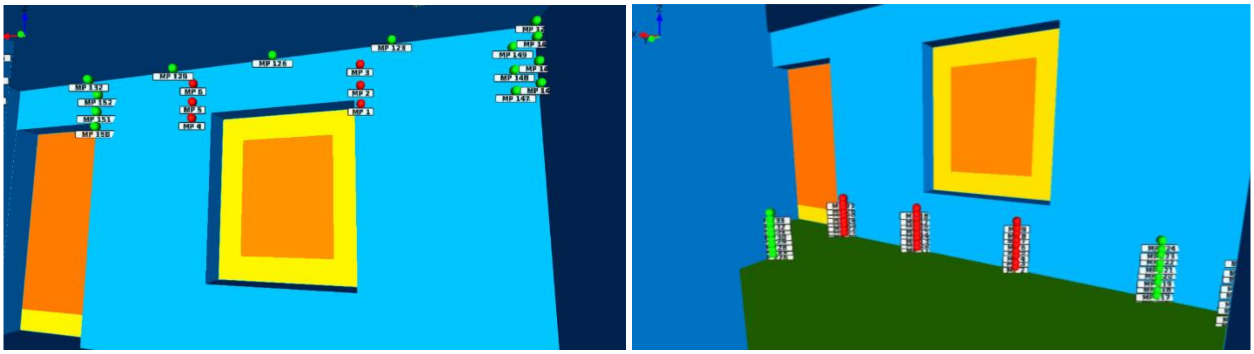


Figure 4.22: Detectors placed throughout the front room and near the window during the NG releases (left) and LPG releases (right).

Table 4.38: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category A natural gas leaks with activation at 25% LFL for sensors located in the front room and near windows for the townhouse geometry.

NG - Category A Leaks (110 SCFH) Average normalized time to detection Detector Alarm Threshold - 25%		
Distance from ceiling (in)	Front room walls	Sensors located near windows
6	53.3%	60.2%
12	58.8%	62.0%
18	60.3%	63.1%

Table 4.39: Average normalized time to detection for sensors that activated prior to threshold hazard conditions for category B LPG leaks with activation at 25% LFL for sensors located in the front room and near windows for the townhouse geometry.

LPG - Category B Leaks (70 SCFH) Average normalized time to detection Detector Alarm Threshold - 25%		
Distance from floor (in)	Front room walls	Sensors located near windows
4	56.2%	49.4%
6	46.7%	52.0%
8	48.5%	54.1%
10	49.2%	56.5%
12	58.5%	61.1%
14	46.0%	62.0%
16	47.6%	66.7%
18	34.3%	70.6%

4.4.3 Mixed-use and multi-family residential buildings

There may be the potential for larger leaks and gas migration between units in mixed-use occupancies and residential building types that use centralized furnaces and boilers to provide heat and hot water to the entire building. Thus, it is of interest to understand whether the findings presented thus far are applicable when there is the potential for higher leak rates and gas migration into a residence when leaked in a neighboring utility room. A reduced subset of simulations was conducted in a mixed-use occupancy with a higher leak rate and with passive flow paths so that gas could migrate out of the room where the leak occurs and into neighboring rooms. These simulations were performed in a mixed-use geometry that we had built for a previous project. The scenario modeled is an NG leak in a utility room with a restaurant located above it and gas migration paths from the utility room to the restaurant. Note that this "restaurant" space above the utility room can be considered representative of an apartment, just with different furniture. Figure 4.23 shows a top-down view of the two floors of the geometry.

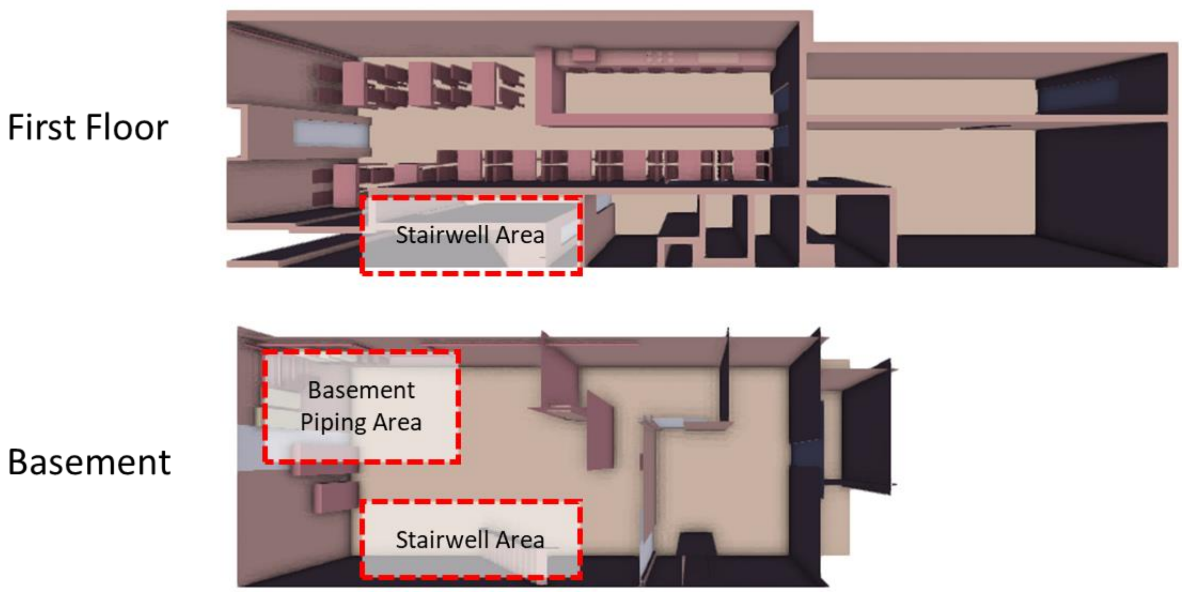


Figure 4.23: Mixed-use occupancy geometry.

Similar to the other geometries, detectors were located in both the basement and in the first-floor restaurant. The leak originated from the gas supply piping in the basement. In this geometry, there is piping that extends up from the basement to the apartment style units above the restaurant. The area surrounding where the piping penetrates the floor was assumed to have a small amount of open area for some gas migration directly through the floor. In addition, simulations were run with the stairwell door from the basement to the main restaurant closed.

Simulations were conducted with impinged low-momentum NG leaks near the ceiling (category D leaks) in the basement with both the basement door open and closed. The NG leak rate was assumed to be 300 SCFH.

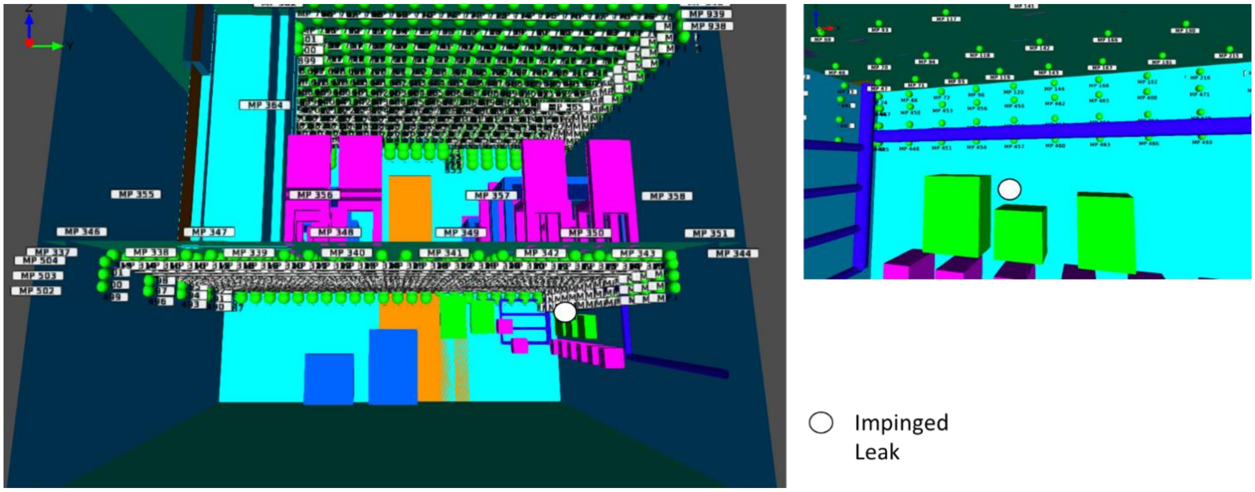


Figure 4.24: Mixed use sensor locations and leak location.

The sensors that were closer to the ceiling and closer to the leak in the room of origin generally performed better, thus the general trends observed in these simulations are similar to those observed in the single-family and townhouse simulations.

Table 4.40: Percentage of sensors that *did not* activate prior to threshold hazard conditions for a category D natural gas leak in the basement of a mixed use structure.

NG - Category D Leak Detector non-activation % prior to THCs												
Detector Alarm Threshold - 10%							Detector Alarm Threshold - 25%					
Distance from	Distance from leak (ft)						Distance from	Distance from leak (ft)				
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10			0 - 2	2 - 4	4 - 6	6 - 8	8 - 10
0	0.0%	0.0%	0.0%	0.0%	0.0%		0	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%		6	0.0%	0.0%	0.0%	0.0%	0.0%
12	40.0%	50.0%	0.0%	0.0%	0.0%		12	60.0%	75.0%	28.6%	50.0%	50.0%
18	40.0%	75.0%	71.4%	100.0%	100.0%		18	40.0%	75.0%	85.7%	100.0%	100.0%

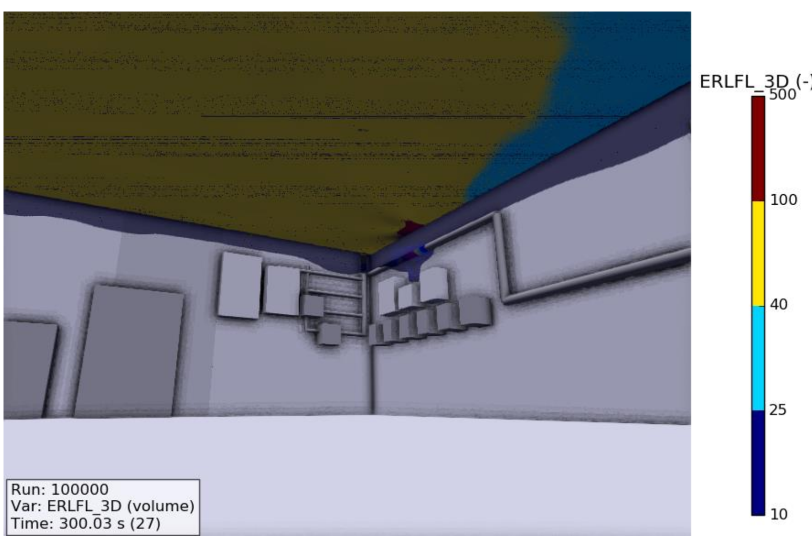


Figure 4.25: Example 300 SCFH leak from the meter area of the mixed-use basement.

The detectors placed 6 inches or closer in the basement were consistently able to detect prior to threshold hazard conditions for this larger leak. The layout of the geometry allows for gas migration directly through the floor to the main restaurant level. As the gas migrates from the basement upwards, the equivalent leak at the piping penetration on the main level of the restaurant resembles a low momentum leak at floor level, i.e., a category C leak in the previously presented residences (Figure 4.26). Thus, detector location recommendations developed from the results of the single-family and townhouse simulations are generally applicable for releases in mixed-use and multi-family residential buildings where higher leak rates are possible and there is the potential for gas migration between various spaces. However, a larger simulation set specific to these geometries and leak scenarios would help confirm these findings.

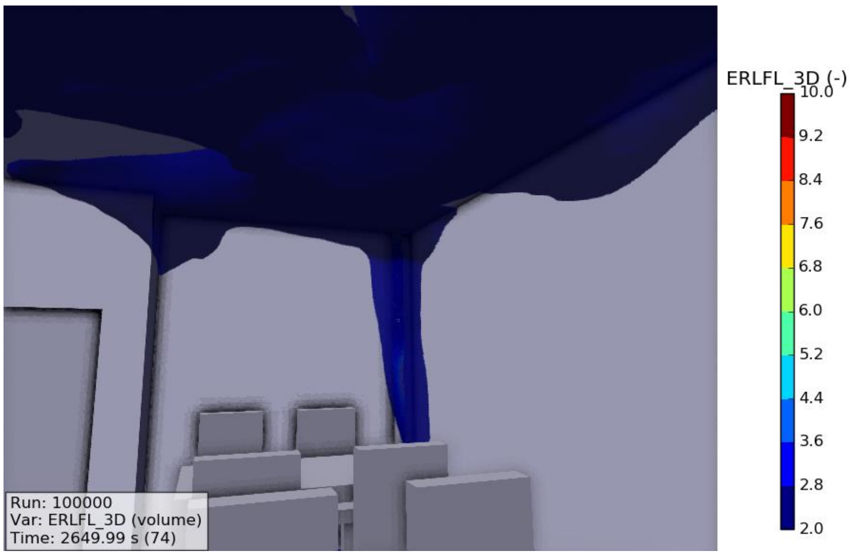


Figure 4.26: Leak through pipe floor penetration on the main restaurant level of the mixed use structure.

Should a secondary sensor placement be included in the room above the common basement of the mixed-use structure, it should be placed along common gas migration pathways. These pathways may include piping or electrical wire penetrations through the floor.

5 Summary of Findings

The results of this study highlight the importance of requiring a gas detector in the same room as permanently installed fuel-gas appliances. For these detectors, generally better performance was observed when: the detector was placed closer to the leak source, there was an unobstructed path between the detector and the leak source, and when the detector alarm threshold was lower (i.e., 10% LFL compared to 25% LFL). Generally poorer performance was observed when a detector was located: near HVAC supply registers; near passive openings such as doors and windows; and near openings to adjacent areas (e.g., door openings and stairwells).

Proper detector installation location is most critical for detecting impinged low-momentum NG leaks near the ceiling and impinged low-momentum LPG leaks near the floor (i.e., category D leaks). These types of releases create pockets or layers with concentrations significantly higher than elsewhere in the space where a release occurs and thus it is important for detectors to be placed where these pockets or layers are likely to form, and not in obstructed pathways, over registers or at doorway openings. A major observation from the simulations in this study is that if a sensor placement is adequate for these releases with minimal mixing, it is also adequate other releases with more mixing (i.e., categories A, B and C).

For natural gas, the closer the detector was to the ceiling the more likely it was to detect a leak and the more time it provided for occupants to respond to an alarm before hazardous conditions occurred. Based on the applied threshold hazard conditions, detectors placed 6 inches or closer to the ceiling had significantly improved performance compared to those placed farther down in height when the detector alarm threshold was 10% LFL and 25% LFL. If a sensor cannot be placed this close to the ceiling, it should be placed at least above the highest doorway opening.

For liquefied petroleum gas, the closer the detector was to the floor the more likely it was to detect a leak and the more time it provided for occupants to respond to an alarm before hazardous conditions occurred. Based on the applied threshold hazard conditions, and provided certain installation locations are avoided (e.g., excluding locations with an obstructed path to the leak source, locations over registers, or at doorway openings), detectors placed closer than 8-10 feet from the leak and at no more than 6 inches above the floor had significantly improved performance for the alarm threshold of 10% LFL. When the alarm threshold was 25% LFL, improved performance occurred when sensors were placed closer than 8-10 feet from the leak and no more than 4 inches above the floor.

Additional gas detectors in rooms or areas remote from where a gas-fired appliance was located generally alarmed after a properly placed detector in the room where the gas-fired appliance was located. These additional or supplemental detectors mainly provide detection redundancy and the best places to put them include rooms or areas directly adjacent to the room containing the gas-fired appliance, and along pathways to upper and lower floors when the fuel is NG and LPG, respectively.

6 Future Work

Recommended future work falls into two categories: additional CFD modeling to further build the technical bases for detector installation location recommendations in various residential occupancies, and even commercial buildings; and experiments to validate the input assumptions used in the modeling, and the results of the modeling.

Additional simulations would verify that the recommendations developed from the simulations in this report are applicable to a broader range of leaks, specifically in a broader range of residences and buildings. For example, to further expand modeling of mixed-use geometries and add areas such as machine rooms of hotels or multi-family dwellings. Furthermore, it would be prudent to model NG leaks closer to the ceiling than done in the present work. The results may suggest that NG detectors need to be closer to the ceiling (e.g., 4 inches instead of 6 inches), just as releases of LPG less than 1 foot from the floor showed that detector performance was better at 4 inches from the floor compared to 6 inches from the floor. We could also model more leak scenarios anticipated to be challenging to detect and thus potentially identify other useful installation location recommendations. These scenarios could include additional header scenarios, floor joists in a basement with gas piping / equipment, beam ceilings, vaulted ceilings, tall ceilings, cathedral ceilings, ceilings with HVAC supply registers (for NG releases), an evaluation of the effectiveness of detectors for crawl spaces for houses with LPG containers, etc. In addition, we could perform simulations to evaluate the ignition consequences from the 10 ft^3 (0.3 m^3) LFL threshold hazard condition versus other threshold conditions if warranted in different geometries.

Lastly, given the increased sensitivity of detector placement to category D releases for LPG, it is strongly recommended to perform additional simulations with low-momentum LPG releases near the floor in a wider variety of geometrical layouts to further strengthen recommendations on specifically where to avoid placing detectors and to evaluate whether acceptable detector performance could be achieved at farther distances from the leak source so long as certain installation locations are avoided (e.g., excluding locations with an obstructed path to the leak source, locations over registers, near doorways, etc.) or certain detector alarm thresholds are mandated.

Future work could include reduced-scale and full-scale experiments to validate the input assumptions and results of the CFD modeling, or modeling of existing experimental data for gas leaks in residential structures that were determined for software validation purposes. Reduced-scale testing could quantify the degrees of leak impingement that are possible and/or likely. This would be useful for understanding the likelihood of the category D releases occurring, and whether not it is more accurate to model impinged releases as having reduced momentum as opposed to no momentum. Full-scale leak tests with non-flammable tracer gases would provide experimental data for which FLACS dispersion simulations could be validated against.

This full-scale testing would first start with a methodology that we have previously implemented to characterize air infiltration into occupancies where leak tests will be performed. The first step is to perform a blower door test to determine the air change rates and infiltration paths. In addition, specific leak paths such as attic eaves, leaky windows, etc. will need to be thoroughly documented so that they can be accurately modeled in the CFD geometry. Once this is done, we can perform real releases with non-flammable gases (such as CO_2 to simulate propane because they have the same molecular weight) and install inexpensive oxygen sensors throughout the occupancy to indirectly measure the concentration of the tracer gas. These types of tests would further confirm that the CFD results are accurate, thus further confirming that it is appropriate to establish recommendations based on the CFD results.

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2. Cleaver, R., M. Marshal, and P. Linden, *The build-up of concentration within a single enclosed volume following a release of natural gas.* Journal of hazardous materials, 1994. **36**(3): p. 209-226.
3. Baines, W. and J. Turner, *Turbulent buoyant convection from a source in a confined region.* Journal of Fluid mechanics, 1969. **37**(1): p. 51-80.
4. Marshall, M. *The effect of ventilation on the accumulation and dispersal of hazardous gases*. in *Institution of chemical engineers/Symposium series*. 1983.
5. Hall, J.R., *Fires starting with flammable gas or flammable or combustible liquid*. 2014: National Fire Protection Association.
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9. ASHRAE, *Fundamentals handbook.* IP Edition, 2013. **21**.

Appendix A – Detector Location Placements

Townhouse NG Releases

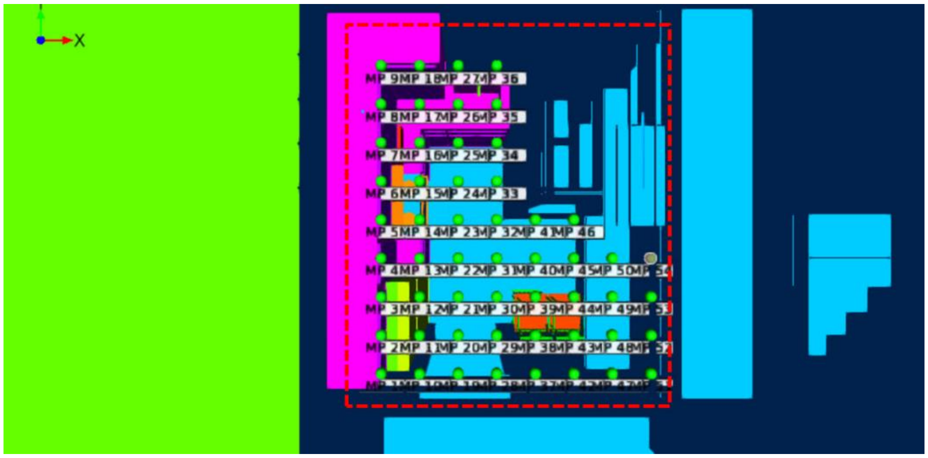

Figure A.1: Detectors on the ceiling in the kitchen.

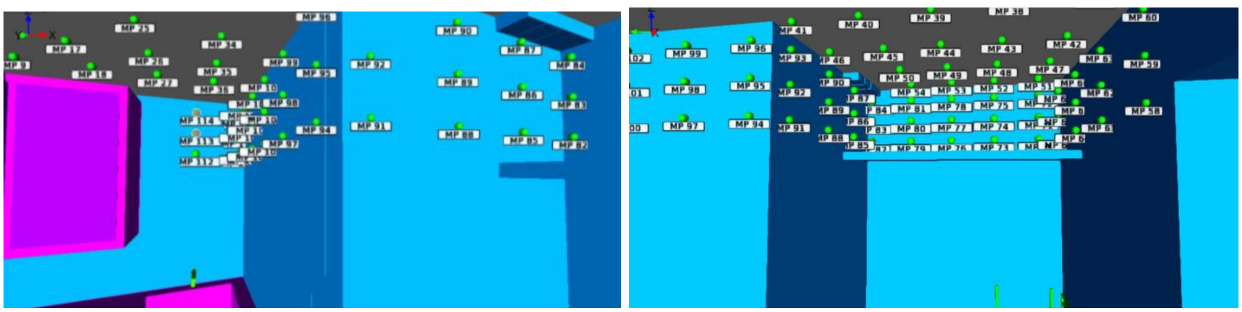

Figure A.2: Detectors on the walls in the kitchen.

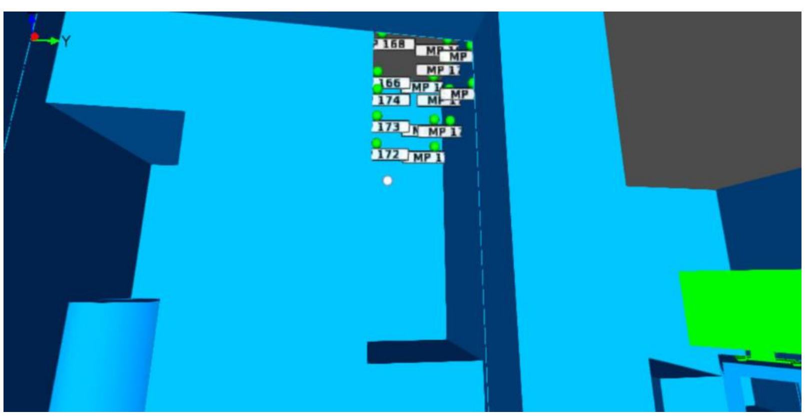

Figure A.3: Detectors in the utility closet.

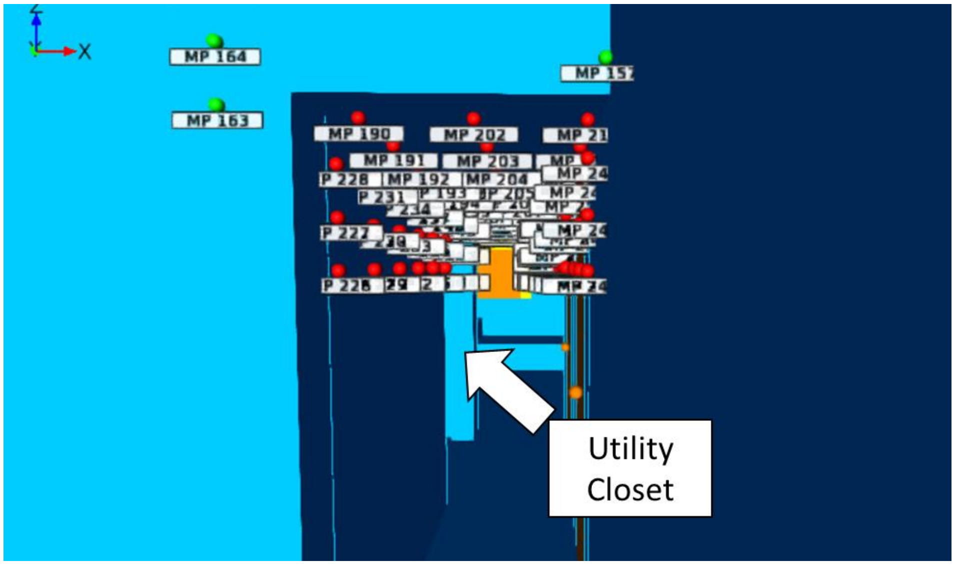

Figure A.4: Detectors on the ceiling and walls in the first-floor hallway.

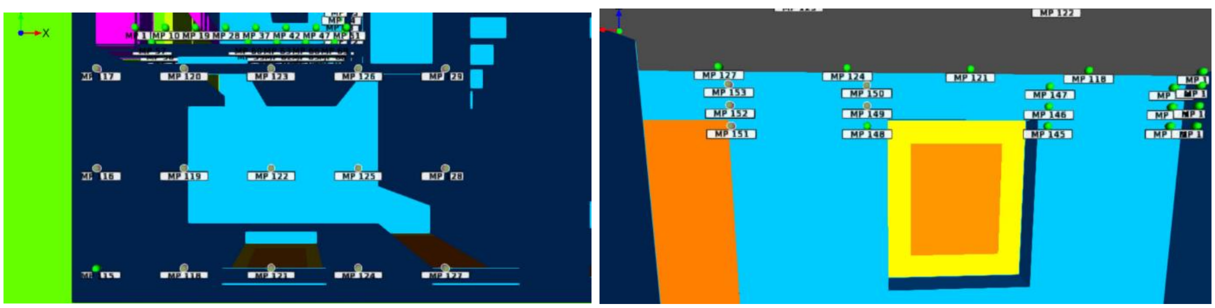

Figure A.5: Detectors in the front dining room.

Figure A.6: Detectors in the rear living room.

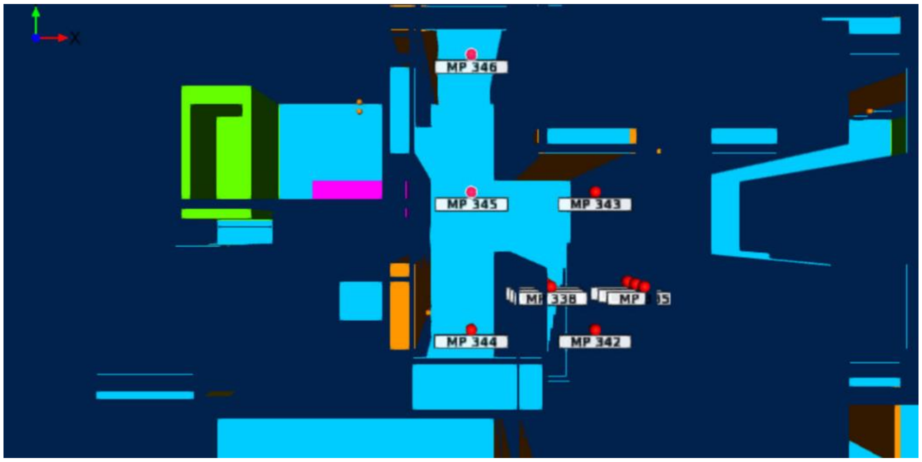

Figure A.7: Detectors in the stairwell and in the second-floor hallway.

Townhouse LPG Releases

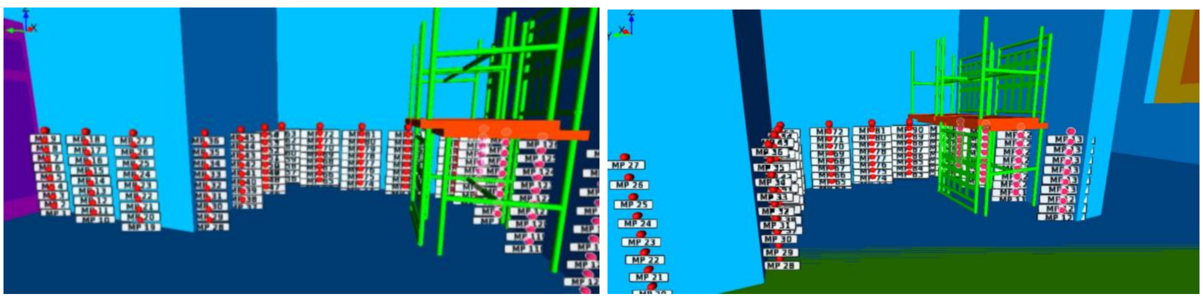

Figure A.8: Detectors on the walls in the kitchen.

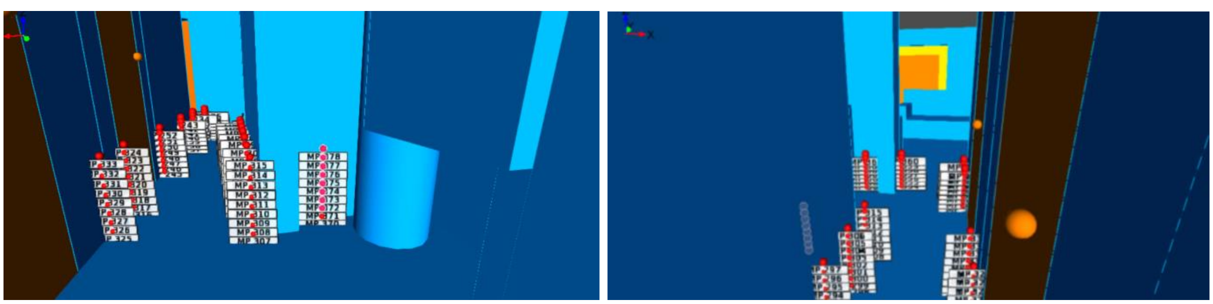

Figure A.9: Detectors on the walls in the utility closet and first-floor hallway.

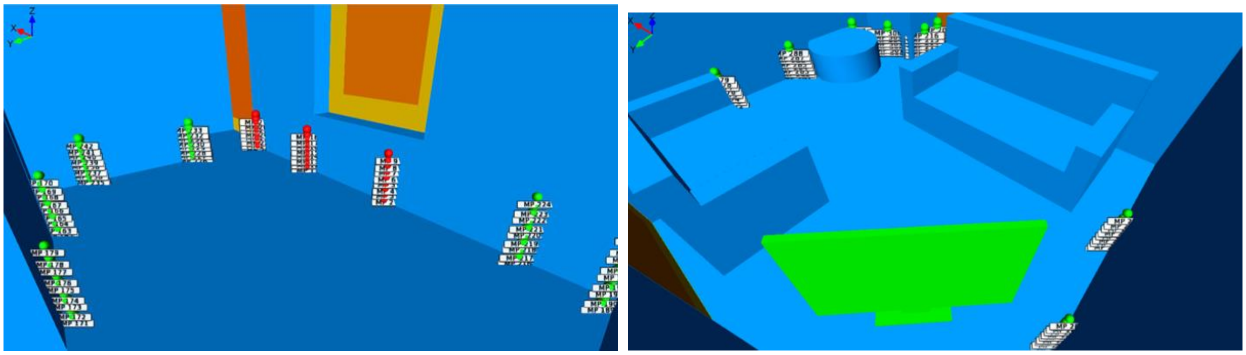

Figure A.10: Detectors in the front dining room (left image) and rear living room (right image).

Colonial House NG Releases

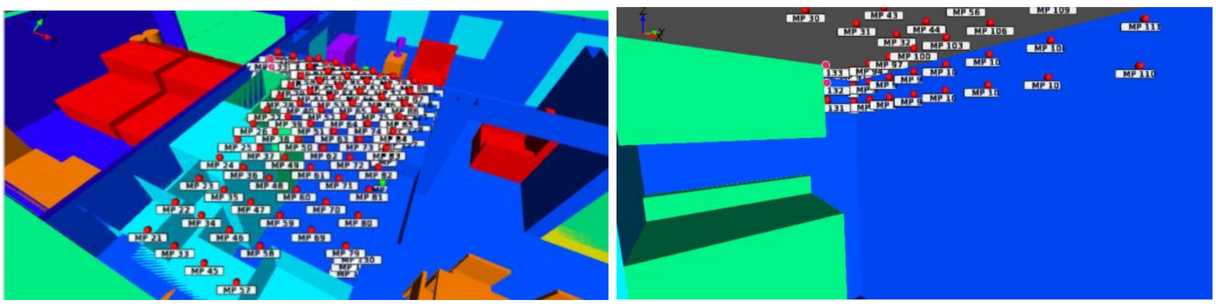

Figure A.11: Detectors on the ceiling (left image) and walls (right image) in kitchen.

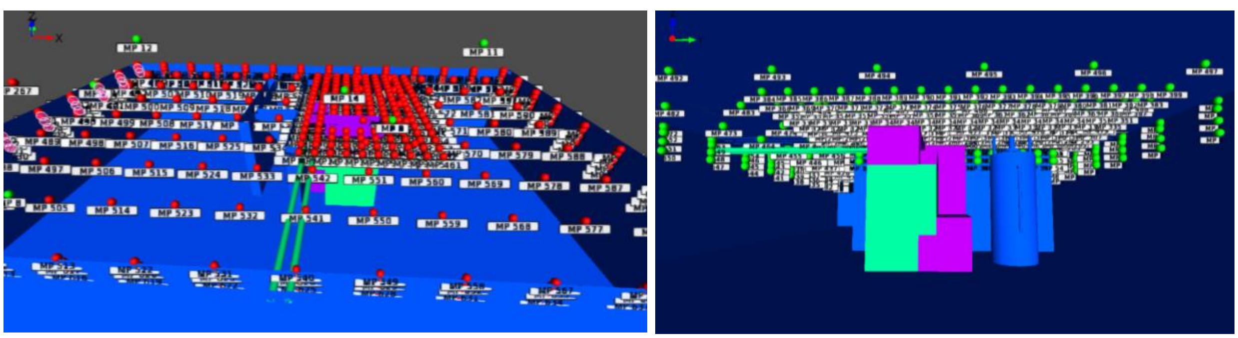

Figure A.12: Detectors on the ceiling and walls in the basement.

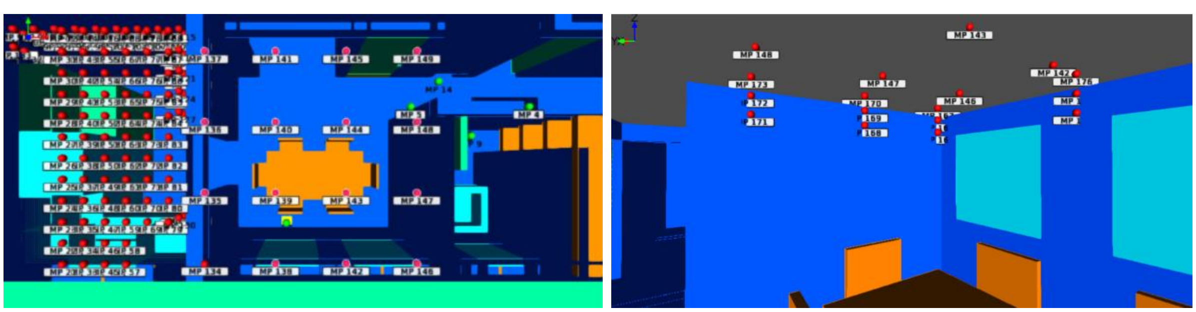

Figure A.13: Detectors in the dining room.

Figure A.14: Detectors in the living room.

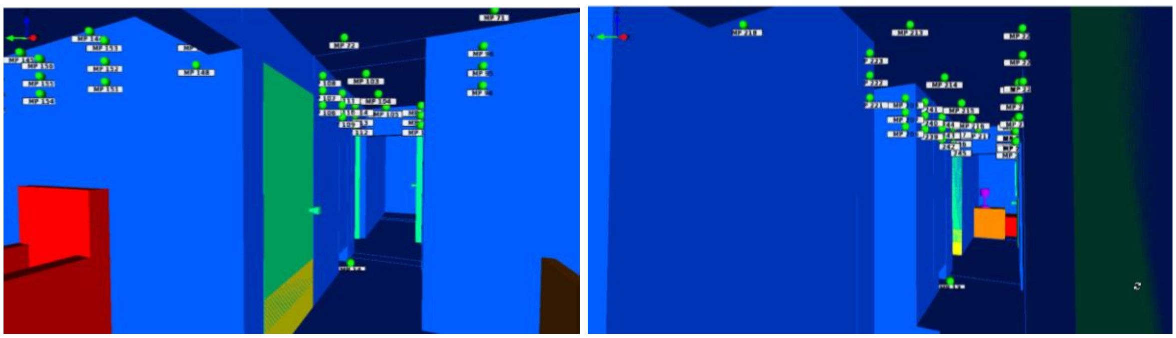

Figure A.15: Detectors in the first-floor hallway (left image) and second-floor hallway (right image).

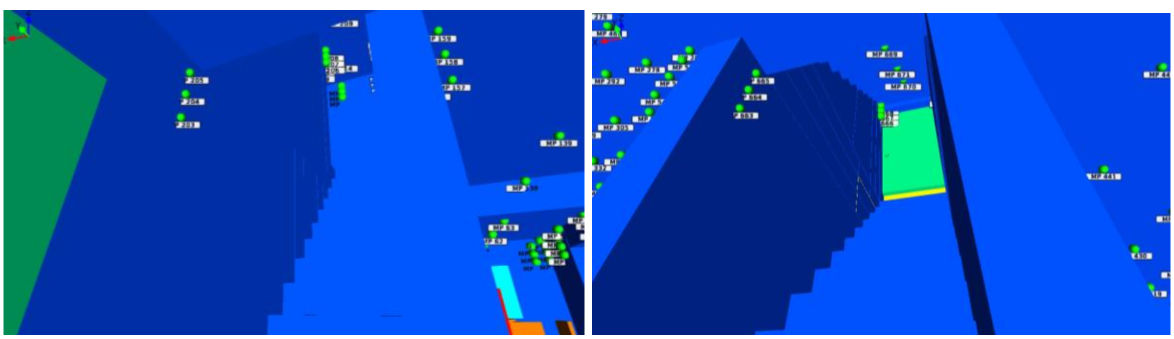

Figure A.16: Detectors in the stairwell from the basement to the first floor (left image) and in the stairwell from the first floor to the second floor (right image).

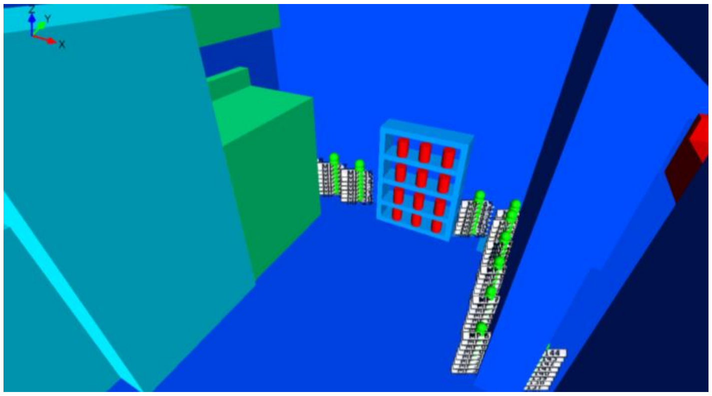

Figure A.17: Detectors in the kitchen.

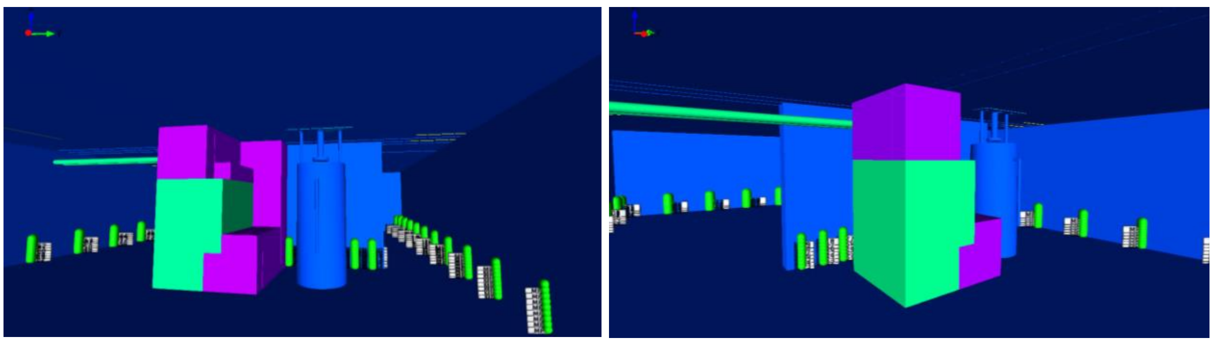

Figure A.18: Detectors in the basement.

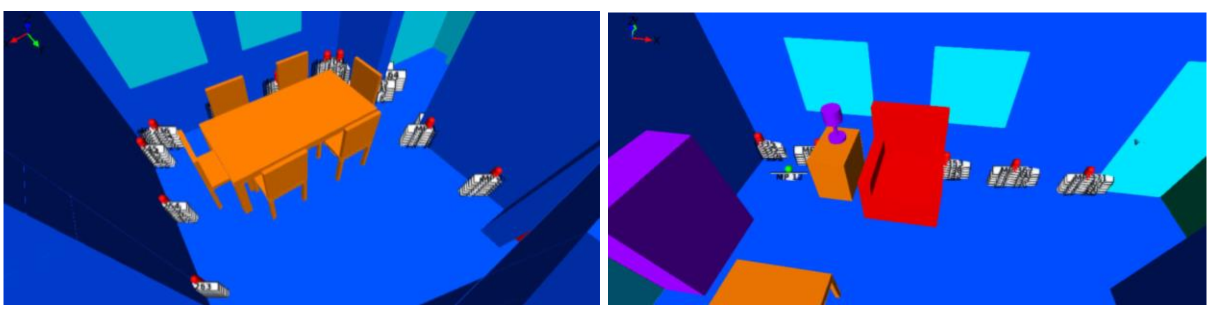

Figure A.19: Detectors in the dining room (left image) and living room (right image).

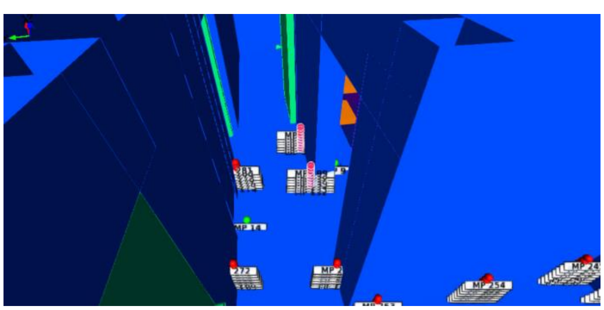

Figure A.20: Detectors in the first-floor hallway.

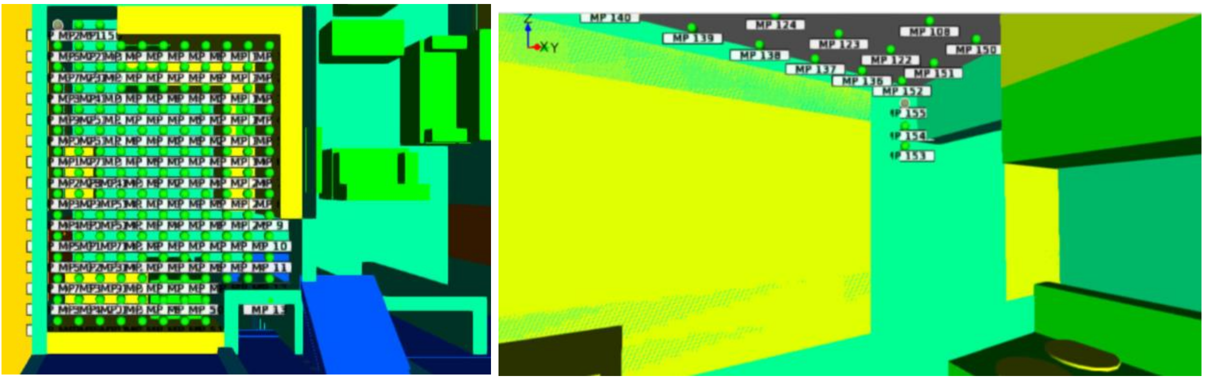

Figure A.21: Detectors on the ceiling in the kitchen

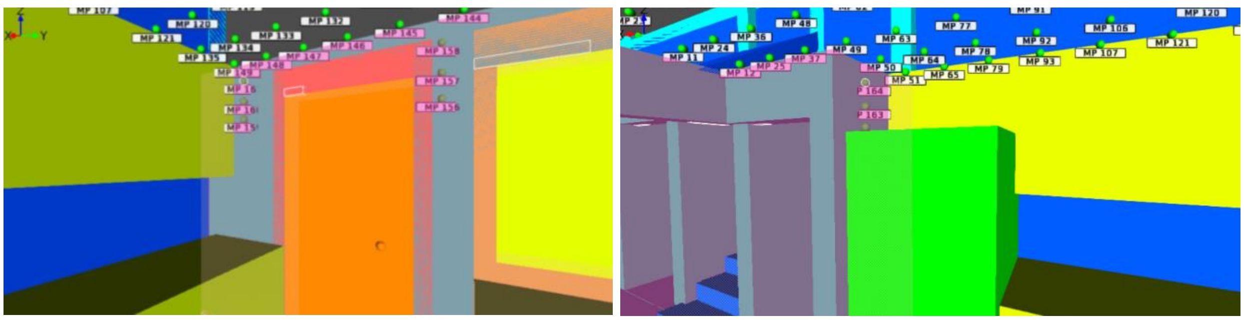

Figure A.22: Detectors on the walls in the kitchen.

Figure A.23: Detectors on the ceiling in the utility room.

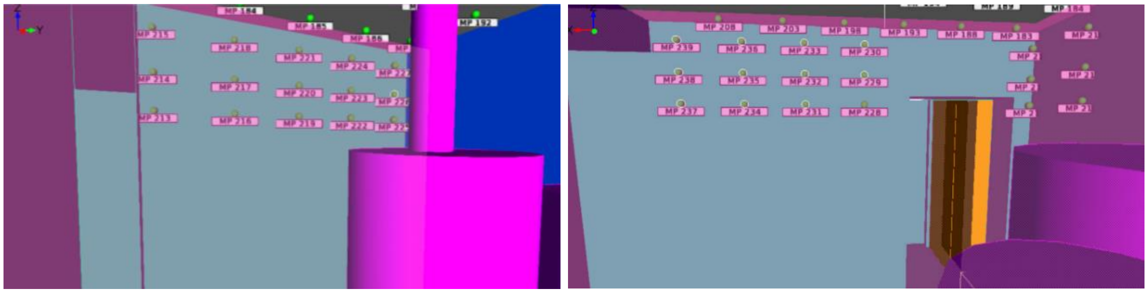

Figure A.24: Detectors on the walls in the utility room.

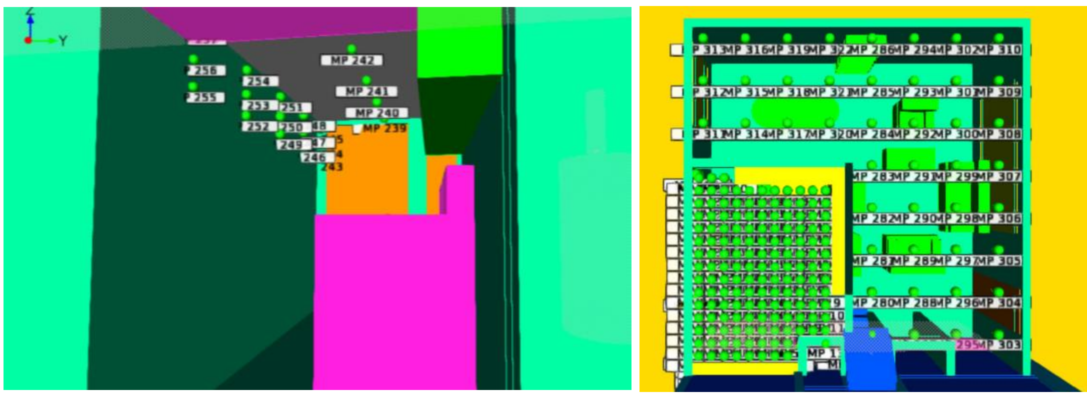

Figure A.25: Detectors in the laundry room (left image) and living/dining room (right images).

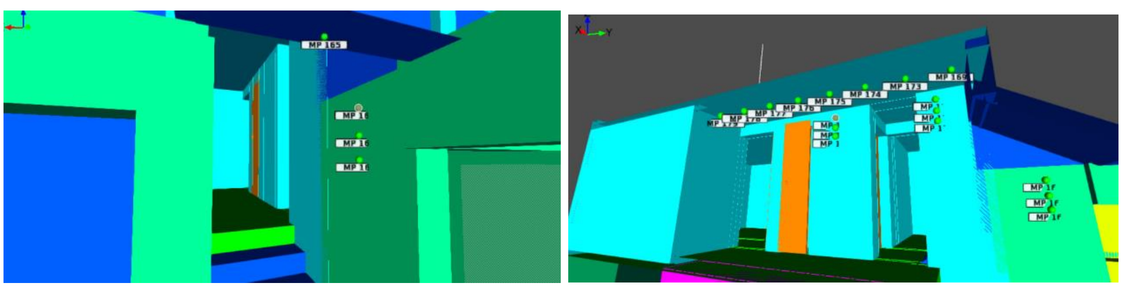

Figure A.26: Detectors near the stairwell (left image) and in the upper-level hallway (right image).

Split-Level House LPG Releases

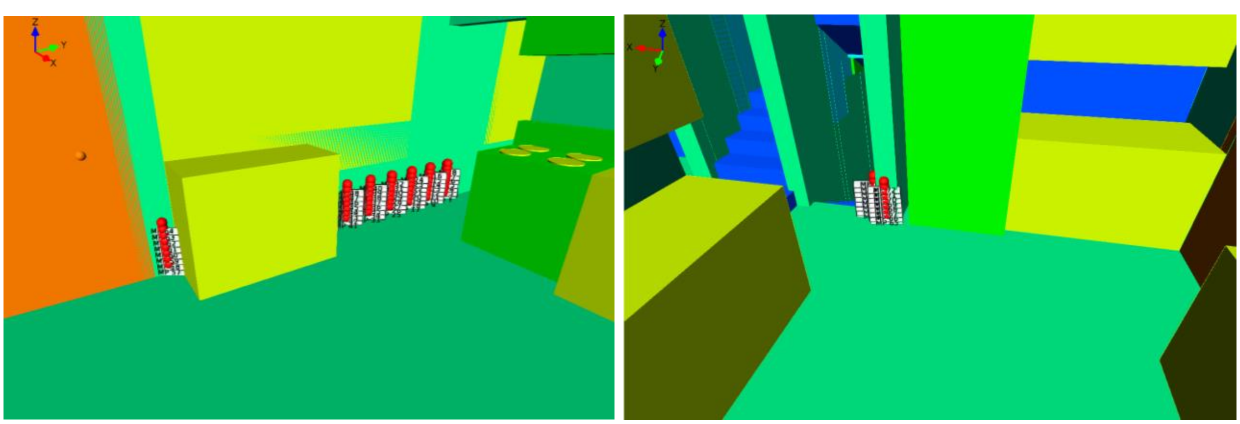

Figure A.27: Detectors in the kitchen.

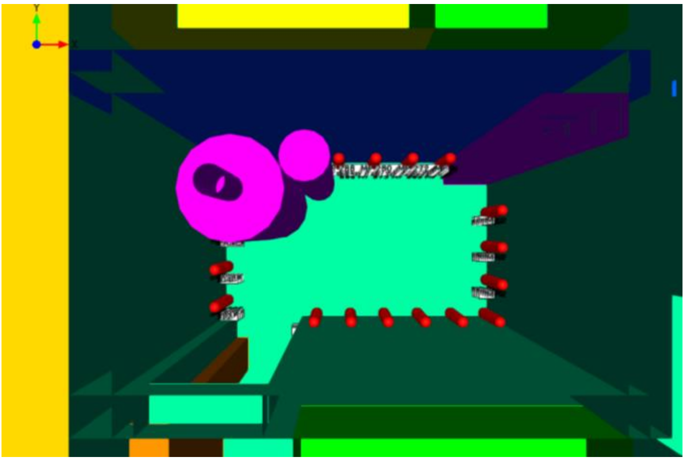

Figure A.28: Detectors in the utility room.

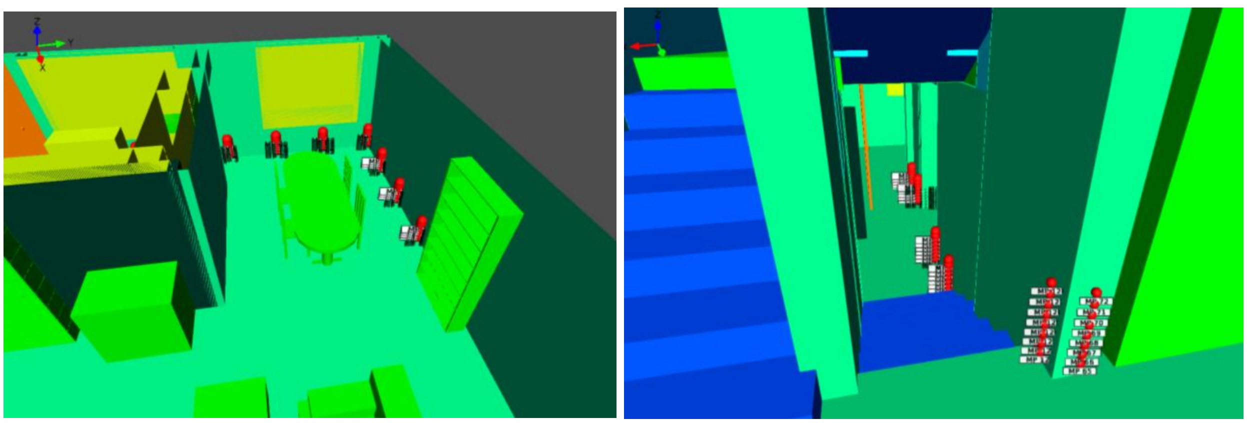

Figure A.29: Detectors in the dining room adjacent to the kitchen (left image) and in the stairwell and lower-level hallway (right image).

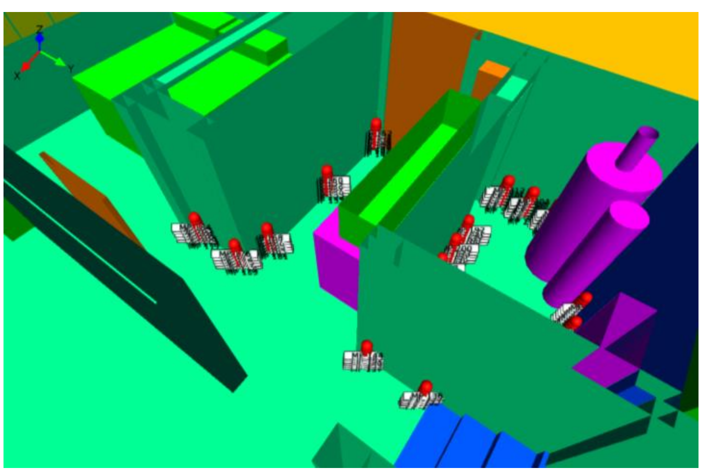

Figure A.30: Detectors in the laundry room and lower-level hallway.