UNIVERSITY OF WATERLOO | FACULTY OF ENGINEERING

IMPACTS OF OXYGEN DEPRIVATION AND NOXIOUS GAS CIRCULATION DURING FIRE DEVELOPMENT IN ENERGY EFFICIENT HOMES

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A report prepared for
BC Housing

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1 Introduction

Fires in single family homes contribute the highest incident of fire-related fatalities in British Columbia and Canada. There is limited information available on the evolution and circulation of toxic fire gases that result from furniture fires in homes and even less on how the generation of these gases may be exasperated by the air-tightness found in newer energy efficient homes. This research was designed to systematically investigate temperatures and hot gas movement, particularly with respect to oxygen deprivation, carbon monoxide and other gas species distributions in a two-storey, energy efficient structure during a fire.

2 Objectives

Significant research has been done around energy efficiency in dwellings; however, there have been few, if any, studies aimed toward understanding the evolution of interior conditions during fires and the potential impact of air-tightness on fire development in single family homes. The majority of research that has been completed considers only situations involving well-ventilated fires with a primary focus on the evolution of smoke and fire gases within single rooms.

This research is designed to study fire development under different ventilation, fuel and air recirculation conditions to evolve new scientific understanding of ventilation-limited fires. For this, fire-induced, ventilation-limited environments and conditions leading to variations in temperature, carbon monoxide and other potentially noxious gases within a fire room, as well as in adjacent rooms on the same and different floors in a two-storey structure will be documented in a series of furniture fire burns. Results will provide insight toward the following key objectives:

- to establish improved understanding of any differences in fire dynamics associated with ventilation-limited fires when compared to better-ventilated fires
- to define any differences in fire conditions associated with different types of fuels and ventilation configurations, and thus
- to evaluate the impact of ventilation-limited conditions on the available time to evacuate from a dwelling during a fire as a function of the stage of fire development, and
- to identify risk factors that may impact the fire service in ventilation-limited fire condition in single family structures.

The results obtained will expand industry knowledge of fires in more complex environments, and those reflective of single family homes. They will enable better risk assessment of homes relative to the level of air-tightness, use of heat and energy recovery ventilators, positioning of smoke alarms, and control of furniture and furniture materials. The overall findings will thereby provide a foundational basis for future work, including: much-needed data for fire models, an assessment of furniture fire development, the impact of building air leakage during early fire growth, the probability of fire spread, and guidance with respect to ventilation and firefighter response. Finally, it will open the way for potential opportunities to further study, address or mitigate risk in adverse fire conditions.

This report includes a description of the experimental design, including an overview of key experimental techniques that were used, description of the full-scale live fire characterization tests that were conducted and a presentation, summary and discussion of specific results obtained as compared to expectations. Finally, conclusions and recommendations for future work are presented.

3 Research Design

The current work aims to improve scientific understanding of the above stated objectives though experimental investigation. As such, this research probes thermal and gas species distributions, airflow patterns and resulting interactions between rooms as ventilation-limited conditions develop during a fire situated in one room of a multi-compartment structure. The structure and ventilation conditions are configured, and fire situations chosen, such that the fire substantially impacts the environmental conditions throughout the structure when compared to the more typically studied, well-ventilated fires early in their development.

Full-scale live fire tests are conducted at the University of Waterloo (UW) Live Fire Research Laboratory in an instrumented two-story burn house enclosure similar to a typical residential dwelling. The burn house is configured to mimic modern, well-sealed and energy efficient homes since the focus of these tests is on under-ventilated fires as they develop in modern residential structures. The fuel is comprised of upholstered furniture and side tables to mimic a typical living room setup. Experiments are designed to study behaviour of developing fires as they interact with the multi-compartment structure with and without ventilation to the exterior, and with and without mechanical ventilation. For this, the burn house is configured with an HVAC system designed to supply typical airflow to each compartment (room). The use of an HVAC system allows for analysis of the effects of ventilation on the fire and also the effects of the fire on different elements of the HVAC system. In particular, it is of interest how the different ventilation conditions lead to greater oxygen depletion and carbon monoxide generation in the fire room and thus impact conditions in the adjoining rooms as well.

The original experimental design consisted of up to 24 tests using different configurations of mechanical air supply (0%, 100%, 200% outdoor air, and recirculation), different fuels (solid fuel, upholstered furniture and heptane) and different combinations of natural ventilation (near field, intermediate field, far field). The scope and breadth of experiments was greatly impacted by instrumentation availability and continuing COVID-19 restrictions throughout the course of the research. Therefore, this report focuses on results from two series of experiments: a mechanical ventilation (MV) series and a fuel volatility (FV) series. The MV series consists of four tests, studying the effects of mechanical ventilation, in which fires were fueled by the same furniture type under four different configurations of mechanical air supply (0%, 100%, 200% outdoor air and full air recirculation). The FV series consists of 10 tests studying the behaviour of the fire and the environments created in the structure when burning different fuels, each with the 100% outdoor air ventilation (supply and exhaust) configuration.

Instrumentation throughout the burn house has been continuously upgraded since initial testing in 2015 to provide additional time and spatially resolved measurements of important parameters such as smoke and toxic species production and movement during the fires. The present research utilizes the full suite of instrumentation, which includes: vertical rakes of thermocouples to chart temperature distributions, radiometers, smoke detectors, sets of electrochemical sensors for oxygen, carbon monoxide, and carbon dioxide concentrations at various locations in each room/storey of the burn house, weigh scales to measure fuel mass burning rate, and bidirectional pressure probes to measure smoke flow. Mixing and interactions of recirculating air and smoke between compartments are also followed. Video cameras are positioned strategically to allow for real time tracking of overall fire development and conditions in the structure from multiple angles. The instrumentation package is designed to allow for analysis of the overall interior fire environments that evolve on both storeys in the burn structure, as well as specific details of the fire and other key experimental parameters.

4 Details of Experimental Design and Techniques

This section outlines details of the experimental layout and instrumentation for the series of tests considered in this report. In total, four large-scale fire tests are performed in the University of Waterloo Burn House with the same furniture fuel load and varying levels of ventilation for the MV series and 10 large-scale fire tests are performed with varying fuels and the same level of ventilation for the FV series.

4.1 Fire Compartment Setup

The University of Waterloo Burn House, shown in Fig. 1, is a two-story steel structure designed and constructed to perform large-scale fire experiments in a typical residential setting. A floor plan of the burn house is shown in Fig. 2. The burn house has a total floor area of approximately 120m^2 and a total volume of approximately 290m^3. The main floor has a ceiling height of 2.4m and the second floor ceiling height is 2.6m.

The structural frame is constructed of 102mm steel H and I beams and is clad with 3.18mm Corten steel on the exterior. Steel stud interior walls on the main floor are finished with 15.9mm thick type X gypsum board. An additional protective layer of 12.7mm thick concrete board is added on top of the gypsum board in the fire room to further protect the structure from direct fire exposure. The seams between concrete board panels are sealed with Pyromix high temperature mortar. The fire room ceiling also contains 100mm thick mineral wool batt insulation behind the gypsum board to protect the steel frame from heat exposure. The interior walls up the staircase and throughout the second floor are not covered in gypsum board, leaving the steel structure exposed.

Figure 1: External view of the burn house structure.

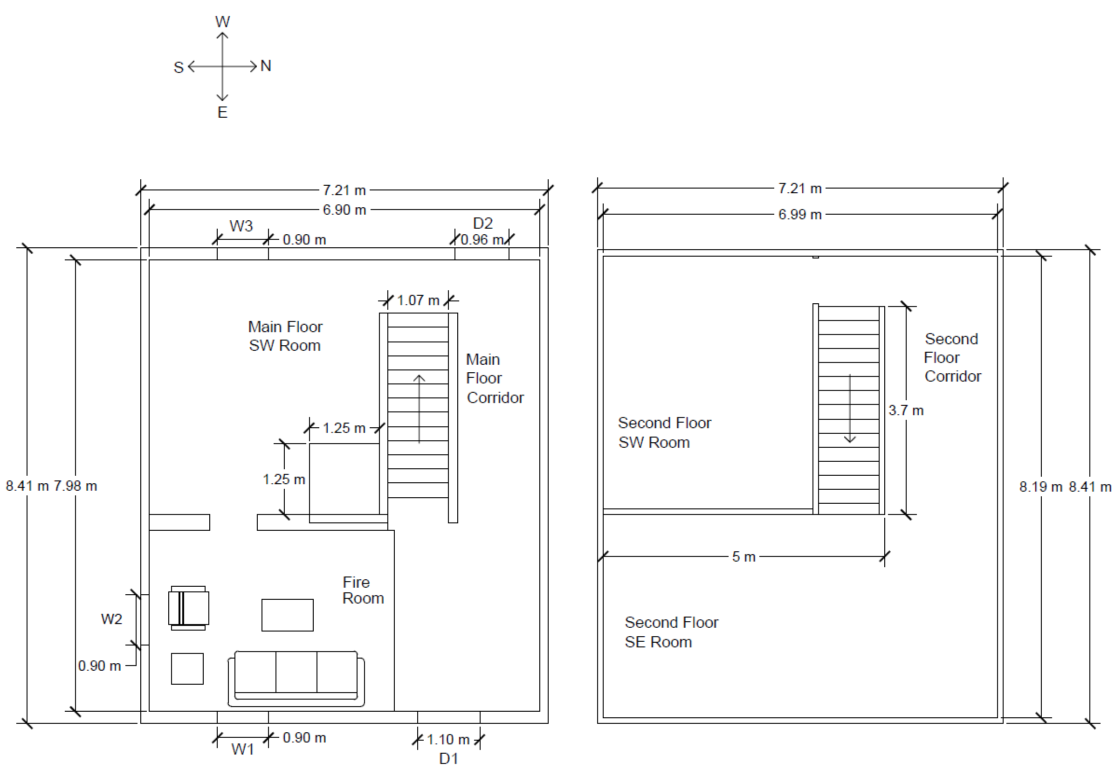


Figure 2: Floor plan layout of the main and second floors of the burn house.

The main floor has two compartments, the fire room and the southwest (SW) room. Door 1 (D1) is located on the east wall of the burn house and Door 2 (D2) is located on the west wall. A corridor connects the fire room to D2 and to the SW room from its northwest corner. Another doorway connects the fire room and SW room along the mid-wall of the structure. There are three windows (0.9 x 0.6m, double pane slider type) on the main floor. Two are located in the fire room, labelled W1 and W2, and one in the SW room, labelled W3. An open staircase, located between the corridor and SW room, leads to the second floor.

The second floor has an additional two compartments, labelled the second floor SW room and the second floor south-east (SE) room. At the top of the staircase there is a landing which connects to a corridor leading to the SE room and a door opening into the SW room.

4.2 Fuel Load

The fuel load is designed to mimic a typical living room layout. The fuel package consists of primary and secondary fuels. The fire is initiated on the primary fuel and, depending on the evolution of the environment within the fire compartment, spreads to the secondary fuels.

4.2.1 MV Series Fuel

For consistency, all four MV tests use the same fuel load arranged in the same configuration. The items comprising the fuel are listed as follows.

Primary fuel:

- Cloth Couch, purchased from Canada and meeting US California Bureau of Electronic and Appliance Repair, Home Furnishings and Thermal Insulation Technical Bulletin 117-2013 and containing no added flame retardants [1]. Measures 2.41x0.98x 0.83m (WxDxH) and weighs approximately 75kg when fully assembled.

Secondary fuels:

- Cloth Chair, purchased from Canada and meeting the requirements of [1] and containing no added flame retardants. Measures 0.71x0.98x0.83m and weighs approximately 20kg when fully assembled.
- Coffee table, measures 0.90x0.55x0.45m and weighs approximately 8.5kg when fully assembled.
- Side table, measures 0.55x0.55x0.45m and weighs approximately 3.5kg when fully assembled.

The arrangement of the fuel in the fire room prior to a test is shown in Fig. 3. The couch is located 0.15m from the W1 wall and 1.26m from the W2 wall. The chair is located 0.25m from the W2 wall and 1.5m from the W1 wall. The coffee table is located 0.35m in front of the couch and 2m from the W2 wall (roughly centered on the couch). The side table is located 0.2m from the side of the couch and 0.4m from the side of the chair.

Figure 3: View of the fire room setup prior to a test.

The fire is ignited on the left cushion of the three-cushion couch (when facing toward the front of the couch) using a Type 4 wood crib and 1.4 ml of isopropanol, in accordance with ignition methods specified in the BS 5852 Furniture Flammability Standard [2]. The standard includes a series of "miniature" wood cribs that constitute a series of calibrated ignition sources and range from Type 4 to Type 7 with increasing side. The Type 4 crib, is placed approximately 0.32m from the arm of the couch as shown in Fig. 4.

Figure 4: Position of the ignition crib on a couch cushion.

4.2.2 FV Series Fuel

The fuels for each FV test are listed in Table 1 along with the miniature crib ignition method. In the cases with furniture, the secondary fuels are a chair and two tables. The chairs are the same material and construction as the test couch, and the tables are the same as described for the MV series. For the wood crib tests, there is a secondary wood crib containing 36 sticks in the position of the chair, and there are no tables in the test. The heptane test contains only the primary heptane fuel and no secondary fuels. The positioning of the furniture and ignition source is maintained as closely as possible to the MV series for consistency.

The wood cribs are constructed with standard 2x2 inch spruce lumber cut to 24 inches (0.61m) in length. The sticks are stacked in a grid with six sticks per layer, and each stick is spaced so that the crib measures 24x24 inches (WxD). The cribs are positioned so that each crib is in approximately the same location as the cushions of a couch test. The first wood crib is ignited using a Type 5 igniter crib located in its centre at the bottom.

For Test FV2, the 5L of heptane fuel is equally split between four 0.38x0.27m aluminum trays placed on the couch load cell in a 2x2 configuration. The trays are located in a position similar to that of the first cushion of the couches, with their east most edge situated 0.3m from the W1 wall and their south most edge positioned 2.65m from the W2 wall. The fuel is ignited using the spark from a handheld butane barbeque lighter.

Ignition of the couch fires in the FV tests depends on the level of fuel volatility, which is affected by the nature of the base materials, as well as the differing levels and types of fire retardant used and controls in the design of the test couches. In all cases, ignition occurs on the left cushion of the couch (when facing toward the front of the couch) approximately 0.32m from the arm of the couch as shown in Fig. 4 for the MV test series. For most couches, one of a selection of standard wood cribs are used with isopropanol as specified in the BS 5852 Furniture Flammability Standard [2] as described below. Ignition of one couch was also attempted using a propane burner method based on the State of California Flammability Test Procedure for Seating Furniture [3]. In each test, ignition of the couch is initially attempted using a Type 4 igniter crib as in the MV series; however, when this does not ignite the fuel such that self-sustained combustion is established, the cushions are exchanged and the next larger size of wood crib, Type 5 followed by Type 7, are tried in turn. An exception to this is the two leather couch tests FV4 and FV7 where a Type 5 crib was used initially followed by a Type 7 crib if it did not ignite. This was because this couch-type only had two wider cushions, as opposed to three.

Test FV0 is a calibration test used to determine the proper fuel load (wood crib size) and ignition method for the wood cribs. Ignition failed with a Type 4 crib, so a Type 5 crib was used. In Test FV5, ignition attempts failed with all three - Type 4, Type 5, and Type 7 cribs specified in [2] so the couch did not burn. The couch in Test FV7 failed to ignite with the initial Type 5 ignitor crib, so a Type 7 crib was used to establish the fire. Finally, attempts were made to ignite the US cloth couch in Test FV8 with both a Type 7 crib and the propane burner method [3], but both failed, so again the couch did not burn.

Table 1: FV test series fuels and ignition methods.

Test	**Primary Fuel**	**Ignition Method**
FV0	Wood cribs 3x 24 sticks	Crib Type 5
FV1	Wood cribs 1x 36 sticks & 2x 18 sticks	Crib Type 5
FV2	Heptane 5L total 4 trays	Butane Lighter
FV3	Canadian non-fire retardant faux-leather	Crib Type 4
FV4	Canadian non-fire retardant leather	Crib Type 5
FV5a,b,c	UK fire retardant cloth	Cribs 4, 5, and 7 did not sustain ignition
FV6	UK fire retardant faux-leather	Crib Type 4
FV7	UK fire retardant leather	Crib Type 5 and 7
FV8a,b	US fire retardant cloth	Crib 7 and propane burner did not sustain ignition
FV9	US fire retardant faux-leather	Crib Type 7

4.3 Ventilation Conditions

The ventilation conditions employed during the tests are designed to mimic standard mechanical ventilation configurations in modern homes. For this, the burn house is configured as a home with modern airtight construction. To obtain the well-sealed environment, all windows and doors are closed for the duration of the tests and any gaps are sealed with fibrefrax or spray foam insulation. Leak testing was done, by RDH Building Science Laboratories, to evaluate the condition of the house and identify any potential openings within the house that required sealing. Due to the age of the house and type of construction (steel), perfect seals were not entirely possible. However, the leak testing identified areas requiring additional sealing, and observations of smoke during calibration tests were used to further identify areas that were subsequently sealed. All combined, the house may be considered to approach, at best, an Energy Star designation. A substantial house sealing effort was implemented to eliminate leakage paths as much as practical, however the house was not, retested for leaks. Following several of the calibration and early MV tests, it was elected that further validation was not considered necessary given the similarity of the findings.

The mechanical ventilation is powered by two fans attached to a series of 0.127m (5 inch) diameter metal HVAC ducts. Each floor of the burn house is equipped with two supply ports and one exhaust port as shown in Fig. 5. On the main floor, the supply ports are located in the centre of the SW room and in the fire room above the doorway leading to the SW room. The main floor exhaust is located in the corridor. On the second floor, the supply ports are located in the centre of the second floor SW room and in the second floor SE room near the wall separating the SW and SE rooms. The second floor exhaust is located in the second floor corridor immediately above the exhaust on the floor below.

Figure 5: Images of HVAC vent locations at (a) first floor SW room, (b) fire room, (c) second floor SW room, (d) second floor SE room, and (e) second floor exhaust.

Two Continental MBI150/125 centrifugal in-line fans, one supply and one exhaust are located on the exterior of the structure. The fans are capable of producing up to 0.16 m^3/s (340 cfm) of flow at 3050 rpm. In these tests, they are fitted with a speed controller to help regulate the flow into the structure. The flows through each supply and exhaust port are balanced immediately before each test by setting the fan to the appropriate speed and adjusting the balancing dampers located near each vent inside the structure. Flow velocities are then measured and recorded at each supply and exhaust port prior to each test to verify the fan speed settings, and confirm that proper balancing has been achieved. An acceptable range of flow rates is specified for each test to account for the sensitivity of these adjustments.

In the ventilation configuration with 100% flow recirculation, only one fan is used and any duct sections that are not in use are capped to close off the open ends. The suction side of the fan is then connected to the exhaust ducts and the discharge side of the fan is connected to the supply ducts to recirculate the exhaust flow directly back into the burn structure.

Each of the tests is conducted with different mechanical ventilation configurations or settings, as follows:

- Test MV1 is configured for no mechanical ventilation. The ends of each duct are capped on the exterior of the structure and the structure remains sealed for the duration of the test.
- Test MV2 is configured for mechanical ventilation in all locations, with 100% outdoor air. Each supply port is set at a flow rate between 0.011-0.013 m^3/s (port velocity of 0.85-1.0 m/s) and each exhaust port is set to a flow rate between 0.022-0.025 m^3/s (velocity of 1.7-2.0 m/s). Therefore, the total supply flow is between 0.043-0.051 m^3/s, which corresponds to approximately 0.53-0.63 air changes per hour (ACPH).
- Test MV3 is similar to Test MV2 with twice the flow rate. In this test each supply port is set at a flow rate between 0.022-0.025 m^3/s (port velocity of 1.7-2 m/s) and each exhaust port is set to a flow rate between 0.043-0.051 m^3/s (velocity of 3.4-4.0 m/s). Therefore, the total flow rate is between 0.086-0.101 m^3/s, which corresponds to 1.07-1.26 ACPH, approximately double that of the configuration in Test MV2.
- Test MV4 is configured for 100% recirculation (no exhaust) with the same supply port flow rates as used in Test MV2.
- All FV series tests are conducted with the same ventilation configuration as Test MV2.

4.4 Instrumentation and Data Collection

The UW burn house is instrumented with various sensor types for continuous measurement and recording of the evolving fire environments. This includes gas temperature, fire heat flux, fuel weight, gas flow velocity, and concentrations of various gases. Oxygen, carbon dioxide, and carbon monoxide form the basic suite of species concentration measurements. Other concentration measurements include total unburned hydrocarbons, NO_x, and a selection of other toxins. The structure is monitored by video for the full test, facilitating video recording of the fire and smoke development from multiple angles. Reference ambient conditions such as external air temperature, barometric pressure, wind, and relative humidity are recorded for each test via Cole-Parmer or equivalent weather sensors.

4.4.1 Gas Temperatures

Gas temperatures are measured using 20 AWG Type-K (chromel-alumel) thermocouples. Each thermocouple bead is made by twisting the ends of the exposed thermocouple wires, for an exposed bead diameter of approximately 1mm. The wires themselves are insulated with Nextel ceramic fiber and sheathed with an Inconel overbraid to provide abrasion resistance, as well as protection from moisture and continuous high temperature exposure of the wires. These thermocouples are rated for 980°C continuous and 1090°C short-term service [4]. Each thermocouple is tested using a hand-held lighter prior to each burn to ensure proper response.

The location of the thermocouples and thermocouple rakes can be seen in Fig. 6 marked by the green 'x' symbols. On the main floor, there are three rakes located above the couch and one above the chair, with each rake containing four thermocouples. One rake containing two thermocouples is located in the doorway between the SW room and the fire room, another containing eight thermocouples is located off to the side of the fire room, one containing four thermocouples is located in the corridor, and one containing six thermocouples is located in the SW room. On the second floor there are three rakes, one in each compartment and one in the corridor, each containing four thermocouples. In addition to these rakes, there are also thermocouples adhered to W1 and W2 in the fire room. Each window has two thermocouples on the inside (fire room side) and two on the outside to provide temperature data when those windows crack.

4.4.2 Heat Flux Gauges

Two water-cooled Vatell TG1000-1 Gardon heat flux gauges (HFG) are placed in the fire room as shown by the pink dots in Fig. 6. One gauge, denoted HF2, is positioned on the wall approximately 2m across from the couch, 2.55m from the W2 wall, and 0.79m above the floor (roughly in line with the centre couch cushion). The other, denoted HF0, is located on the floor of the fire room 4.33m from the W2 wall and 1.61m from the W1 wall. This HFG is facing the ceiling to measure the radiation emitted by the fire plume. Both gauges were originally provided with a voltage-heat flux calibration curve and have a typical accuracy of 3% FS. Each heat flux gauge is tested using a hand-held lighter prior to each burn to ensure proper response.

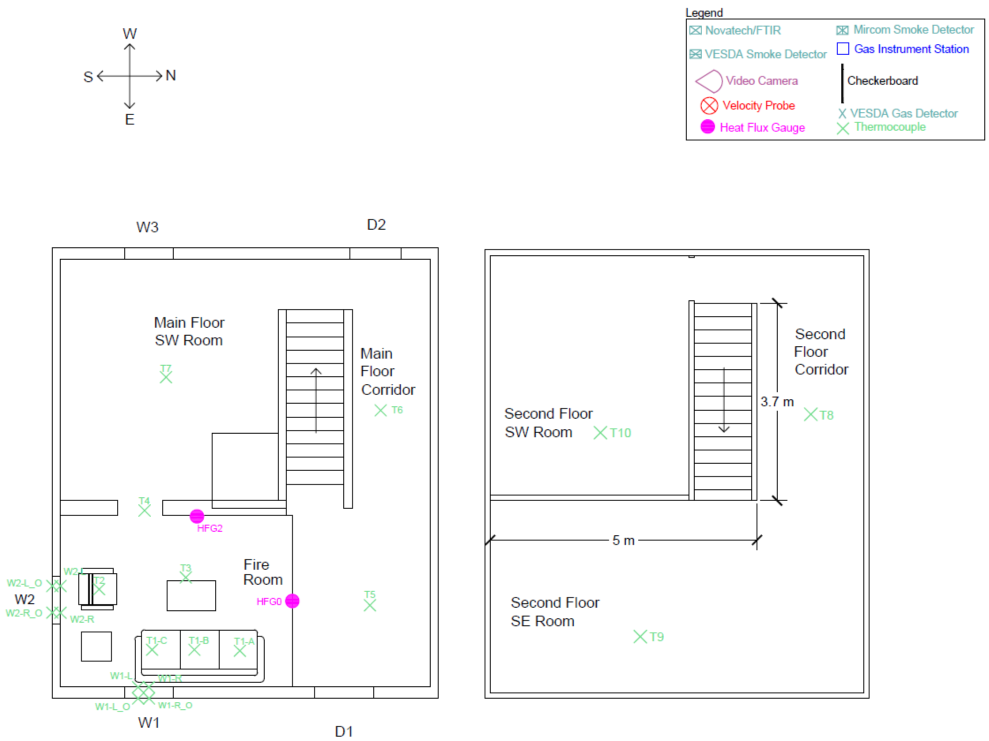


Figure 6: Floor plan layout showing locations of thermocouples and heat flux gauges.

4.4.3 Load Cells

The couch is placed on four MARS MSB-60 load cells each measuring 0.45x0.45m with a maximum capacity of 60kg (for a total combined capacity of 240kg). The four load cells are wired together and configured so the measured mass output is the sum of the four individual readings. Each load cell is individually protected with a layer of fiberfrax insulation installed carefully to ensure proper movement of the scales throughout a test. A 1.2x2.4m sheet of 15.9mm type-X gypsum board that has been wrapped with aluminum foil is placed on top of the insulation (across all load cells) to act as a platform to hold the couch. The gypsum board provides protection to the load cells from heat and burning debris during each test.

The chair is placed on a single MARS MSB-120 load cell, measuring 0.61x0.76m with a maximum capacity of 120kg. This load cell is protected with the same layers of insulation and gypsum board as used under the couch (described above).

The load cells for the couch and chair are calibrated before each test using weights with known masses as measured on a calibrated lab scale. The span weight of the cells is first set at a value 50% higher than the anticipated sample weight, and then the maximum output value is set to 25% higher than the sample weight. Recorded values are later used to convert measured values of output voltage to mass of the chair or couch, respectively.

4.4.4 Gas Velocity

Gas velocities are measured throughout the structure using bidirectional differential pressure probes. The probes measure a spatially averaged vector velocity value at the probe location based on the pressure difference between the two sides of the probe. A rake of probes is located in each doorway of the structure as shown in Fig. 7 marked by the red crossed circle symbol. Probe rakes A4 and A8 (at the bottom and top of the stairs, respectively) each have 8 pressure probes installed at heights of 0.4m, 0.65m, 0.9m, 1.15m, 1.4m, 1.6m, 1.8m and 2.0m above the floor. Rake A9 located at the entrance to the second floor SW small bedroom has 4 pressure probes installed 0.4m, 0.9m, 1.15m and 1.6m above the floor. The remainder have two probes, each positioned at 0.4m and 1.6m above the floor. All pressure probes protrude roughly 15cm into the opening of each doorway.

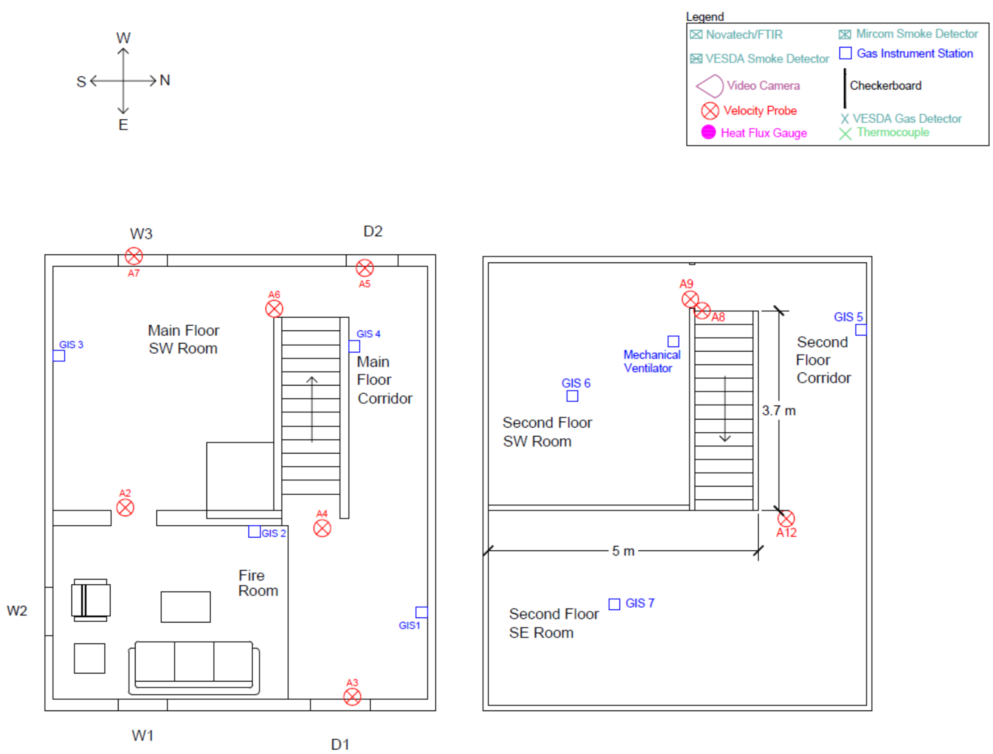


Figure 7: Floor plan showing locations of the velocity probes and custom gas sensors.

Additional probes are positioned in the HVAC ducts to measure supply and exhaust velocities. Two probes are located in the main supply duct for the first floor, one upstream of the SW room supply vent and one between the SW room and fire room supply vents. One probe is located in the main supply duct for the second floor, upstream of the SW room supply vent. The exhaust ducts are fitted with velocity probes in the vertical section of duct located on the exterior of the structure. Two probes are used for the exhaust, one for the first floor and one for the second floor exhaust ducts.

Each probe is connected to an individually calibrated Setra 267 differential pressure transducer with a range of ±25kPa and 0.5% FS accuracy. Each probe is also paired with a thermocouple to measure the gas temperature necessary to correct for gas density in the velocity calculations. The response of each probe is tested prior to each burn and zero reference voltages are found using the average measurement from the first 60 seconds of the baseline collected prior to each test.

4.4.5 Gas Concentrations

Concentrations of oxygen (O_2), nitrogen oxides (NO_2 and NO), hydrogen Chlorides (HCl), hydrogen cyanide (HCN), carbon monoxide (CO), ammonia (NH_3), carbon dioxide (CO_2), methane (CH_4), and volatile organics (VOC) are measured using custom-built gas sampling units shown in Fig. 8. These units also contain relative humidity and temperature sensors to complete monitoring of the fire environment.

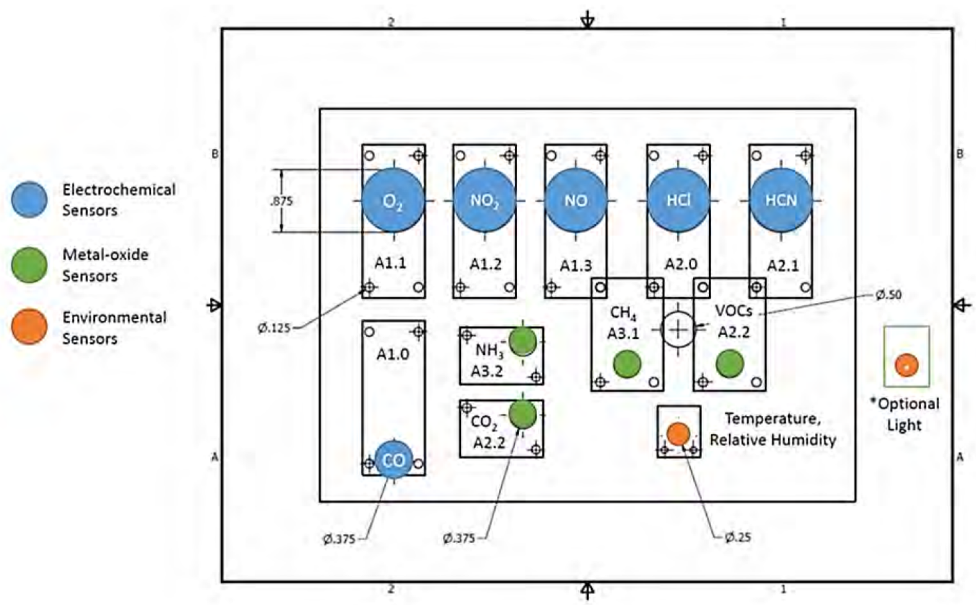


Figure 8: Custom Built Gas Sampling Unit.

In the burn house, there are seven gas sampling stations (shown by the blue squares in Fig. 7), each containing up to three of these custom units at heights of 0.3, 0.9, and 1.5m above the floor. Stations 1 and 2 in the fire room have only two units at the 0.3m and 0.9m heights due to the extremely harsh environment that develops at higher elevations. Station 7 in the second floor SE room has only two stations at the 0.9m and 1.5m heights, since the environment at the lower levels was shown to be relatively homogeneous in earlier tests. All other stations have three units. Station 3 in the main floor SW room is shown in Fig. 9 as an example. The use of multiple units allows for building a spatially enhanced picture of gas concentrations throughout the structure in a relatively budget friendly manner.

Each unit operates with an on-board Arduino microcontroller which simultaneously stores and outputs digital signals at a rate of four bits/second. The output data is sent directly via Ethernet to a laptop that runs a LabView program to retrieve and convert the raw output to a voltage from each sensor. These raw voltages are then converted into concentrations using calibration curves provided by the manufacturer [5]. Each gas sensor unit is tested prior to each burn to ensure that each individual gas sensor is operational.

Figure 9: Image of gas sampling station 3 in the main floor SW room.

Additional gas concentration measurements are taken with a Novatech P-695 gas analysis system complete with Servomex Servopro 4900 paramagnetic and IR analyzers to measure concentrations of O_2, CO and CO_2, a Baseline 8800H to measure total unburned hydrocarbon (THC), and TML-41H chemiluminescence analyzers to determine NO_x, NO and NO_2 (derived) concentrations. For tests MV1, MV2, and MV4, the Novatech sampling port is located at the 0.9m height in the main floor SW room adjacent to the custom gas unit at this location. The sampling port is moved to the 1.5m height in the same location for Test MV3 and all FV series tests. These measurements are complementary to, and provide a cross-check for, the measurements from the custom units. The Novatech system is calibrated according to operating procedures on the day of each test [6]. The calibration provides a linear voltage to concentration calibration curve for each gas using a zero value based on sampling of pure nitrogen and a span value obtained using a mixture containing known concentrations of the gases of interest.

A Thermo Fisher Scientific Nicolet 6700 Fourier Transform Infrared Spectrometer (FTIR) is also used in Test MV3 and the FV series tests. The FTIR sampling port is located at the same position as the Novatech sampling port, 1.5m height adjacent to the custom gas unit in the main floor SW room, for Test MV3. FTIR data is collected in a stand-alone computer running OMNIC 8.3 software and set to complete one sample scan every nine seconds. Results from the FTIR include concentrations of CO_2, CO, HCl, HBr, NO, NO_2, HCN, as well as a range of other gases. These measurements are again intended to be complementary to the measurements from the custom gas sensing units.

4.4.6 Data Acquisition System

Data acquisition from the thermocouples, load cells, pressure transducers, heat flux gauges, and Novatech is accomplished using a National Instruments Compact FieldPoint distributed data logging system that allows remote placement of the analogue to digital (A/D) signal conversion hardware. Four modular backplanes (NI cFP-1808) in conjunction with a sufficient number of Compact FieldPoint modules are utilized to facilitate the required temperature (NI cFP-TC-125) and analog voltage or current (NI cFP-AI-110) measurements. The backplanes communicate with a local network switch using gigabit Ethernet and a conventional Ethernet protocol is then used to transfer the digitized signals back to a central computer running LabVIEW. Data is collected at 1.125 second increments (0.89 Hz) and saved to Comma Separated Value (CSV) files in the present work. All channels are recorded simultaneously.

Overall, the instrumentation and data logging system employed in these tests has many advantages including: reducing the required lengths of expensive thermocouple wire; minimizing the travel distance of analogue signals for improved noise immunity; and allowing the control and data storage computer to be located tens of meters from the large fire experiments.

4.4.7 Video Collection

A QSee high definition analog video recorder (DVR) is used to record simultaneous inputs from 16 Lorex CVC7572-780p, hybrid colour-night vision security cameras. These have proven to be cost-effective cameras to employ during fire testing due to their low cost and relatively good image resolution in both well-lit and unlit environments. Camera locations and angles are represented by the magenta coloured cone symbols in Fig. 10. The cameras are used to visually track the development of the fire, the spread of flames, smoke layer progression, and smoke flow during each test.

Smoke layer progression is visually monitored early in the tests using a novel method developed at the UW Fire Research Facility [7]. For this, black and white squares, each 305mm on a side, are painted onto gypsum board panels as can be seen on the left-hand side of Fig. 3. The boards are mounted vertically in each location as shown in Fig. 10. A camera is positioned at a known distance away and directly in front of each board and aligned to be as nearly perpendicular as possible to the painted surface of the board. Video recording of the smoke layer progression with time across the squares on the board are then used to visually deduce the depth and thickness of the smoke during a test. If needed at a later date for refinement of the present models, methods outlined in [7] can be used to conduct additional detailed analysis of individual images from the recorded traces in order to determine specific values for rate of smoke descent and relative smoke density with time.

The DVR, video feed monitor(s), DAQ, and LabVIEW computers are all located in a control room at a safe distance from the burn house. This provides one weather-safe, central location from which to operate all instrumentation and monitor the tests.

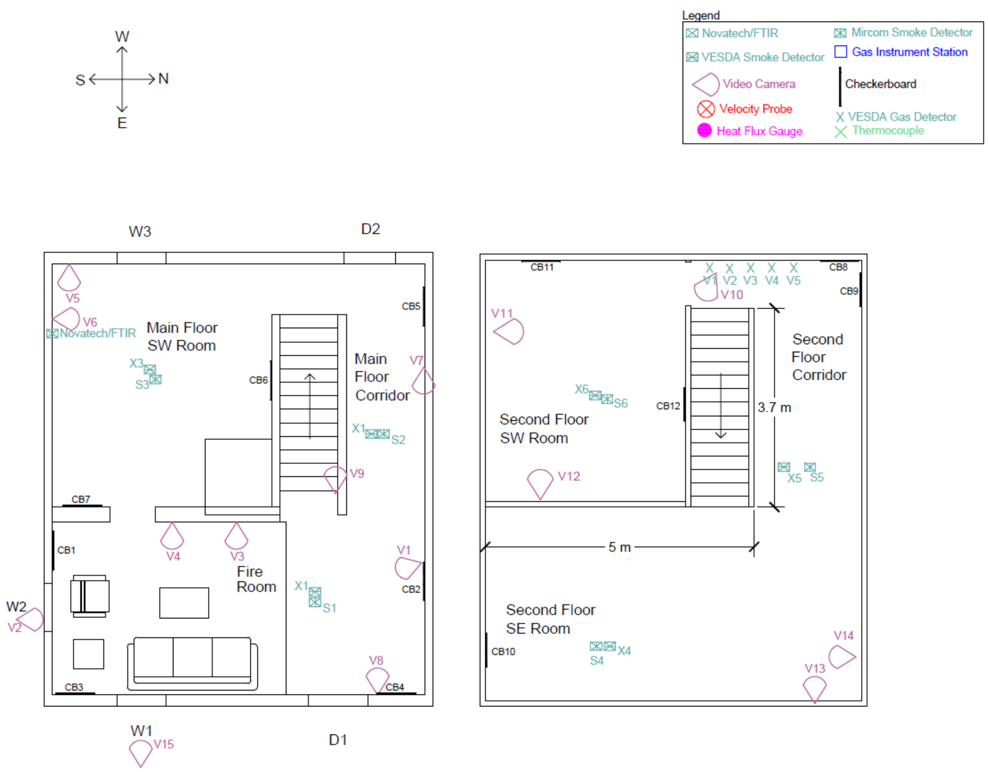


Figure 10: Floor plan showing locations of the cameras and checkerboards.

4.4.8 Smoke Detection

The burn house is fitted with a Mircom Flex-net smoke detection system. The Mircom system consists of an FX-2000 control panel and six analog detectors positioned near the ceiling, as shown in Fig. 10. Each detector contains an optical smoke sensor and a heat sensor. A signal is sent to the control panel once a threshold value is reached at either sensor, triggering an alarm. The alarm emits an audible alert and a visual strobe, as would typically be used to notify occupants of fire. Data from the Mircom system, including detector activation time, is collected in a stand-alone computer connected to the control panel via USB connection.

4.4.9 Transducer Uncertainty

Type K thermocouples are known to have a standard manufacturer's uncertainty of 2°C and an expanded uncertainty of 4°C when including the complete data acquisition system. The response time for a 24 gauge exposed bead thermocouple is less than 1 second in air moving at about 20 m/s, so the delay in thermocouple response will be on the order of 1-2 seconds for these experiments as well [4].

Gas velocity and concentration data are known to be subject to higher levels of variability than thermocouple data. Typical uncertainty bounds for bidirectional velocity probes are on the order of 10% [8] while typical errors for concentration data lie in a similar range, on the order of 10-15% depending on the analyzers used and measurement conditions in a specific test [9]. The accuracy of the novel electrochemical sensors used in the present work remains under investigation.

The load cells have a manufacturer's specified total error of 0.05% of applied load [10].

4.5 Test Procedure

Each test is comprised of three stages: pre-test, during test, and post-test. The procedures are broken down into a series of steps as recorded on a test day checklist to ensure consistency.

In the pre-test procedure all equipment and instrumentation is checked for proper operation and daily calibrations/checks are performed as outlined in the previous section. The fuels are vacuumed to clean off any dust collected during storage and then weighed individually. After weighing, the fuels are placed into position on the load cells. The mechanical ventilation system is then turned on to the appropriate setting for the test configuration, as listed in Table 2, and flow rates are measured and recorded.

The test starts by recording at least five minutes of baseline data from all instrumentation, with the burn house evacuated of any occupants. Starting times for each recording system and the start of data collection are recorded relative to a master clock. Once the baseline data is collected, the ignition crew makes entrance to the fire room through D2 and places the initial wood crib in position on the couch. At ignition, 1.4 ml of isopropanol is dispensed on the cotton wick at the base of the wood crib. A countdown is initiated and the crib is ignited using a standard butane lighter. Once the crib is ignited, D2 is left open for 30 seconds to allow for evacuation of the ignition crew. All key times related to ignition are recorded.

The fire is allowed to burn uninterrupted until one of several events occur:

- the flammable components of the entire fuel load are burned out,
- flashover of the burn room occurs, or
- the fire self-extinguishes

During this time, an observer records all key events that take place, such as open/closed doors and cracks forming in any of the windows.

In the event that the couch does not ignite with the initial wood ignition crib, the cushions are rearranged to switch cushion 1 with one of the other couch cushions and the procedure is repeated with a wood ignition crib of the next largest size. For test FV8, where the couch cushion did not ignite with the largest wood crib, a propane burner is applied as outlined for the fuel volatility test series above.

After extinction (or suppression), the fire service ventilates the structure by opening D1, then a window on the second floor directly above D2, and then D2 itself. A positive pressure ventilation fan is placed in front of D2 and is turned on to aid in the evacuation of smoke and hot gases from the structure. Once clear, the fire service makes entrance into the fire room to remove any remaining unburnt fuel.

Data logging systems and instrumentation are run for an additional 30 minutes after extinction to capture baseline measurements post-fire. After 30 minutes the equipment is shut down and those times are again recorded. Any remaining fuel is weighed on the calibrated lab scale as a cross check on the load cells to determine the total amount of fuel burnt.

Table 2 restates key test conditions. All MV series tests contain the same fuel load (Couch and chair) with varying levels of ventilation (No mechanical ventilation, 100% supply and exhaust, 200% supply and exhaust, and 100% recirculation). The FV series of tests are conducted with the same ventilation configuration (100% supply and exhaust) and varying fuel loads.

Table 2: Matrix of key test conditions.

Test	**Ventilation**	**Fuel - Couch**	**Fuel - Chair**
MV1	No HVAC - intake and exhaust air vents sealed	Canadian cloth	Canadian cloth
MV2	HVAC All Locations	Canadian cloth	Canadian cloth
MV3	HVAC All Locations (2x supply and 2x exhaust)	Canadian cloth	Canadian cloth
MV4	HVAC All Locations (100% recircultation)	Canadian cloth	Canadian cloth
FV1-9	HVAC All Locations	Varies, see Table 1	

5 Mechanical Ventilation Experimental Results

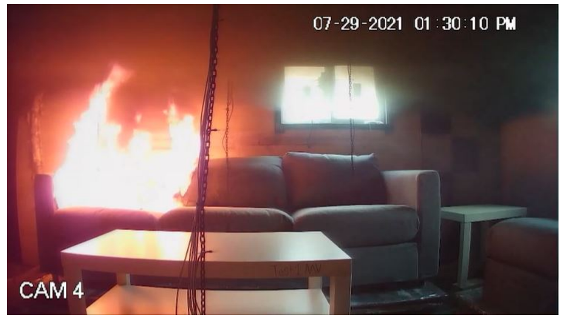
This section presents and discusses important results from the MV series compartment fire tests. These include detailed time-varying thermocouple temperature, fire fuel mass loss, gas species concentration and differential pressure (velocity) data, as well as smoke progression and video to highlight the key findings of the study. The combined results convey key comparisons in a concise manner as they pertain to particular discussion points around the impact of different ventilation rates on fire-induced, ventilation-limited environments in a two-storey structure. In particular, they document fire development and smoke flows, along with variations in temperature, oxygen, carbon monoxide and other potentially noxious gas concentrations within the fire room, as well as in adjacent rooms on the same and different floors of the structure.

The following four figures (Figs. 11 - 14) show images of the fire room though the view of camera 4 looking at the couch. Images are taken at four key times after ignition: 1) when smoke descends to the top of W1, 2) when the second/middle cushion ignites, 3) at the peak mass loss rate (MLR), and 4) when O_2 concentrations on the second floor drop to 15 % (as measured at the 0.9m height of gas sensor station 7 in the SW room). The times to each event are listed in the figures as minutes:seconds after ignition. These times are also summarized in Table 3. The first three events occur at nearly the same time for all tests while the fourth event occurs at later times with increasing ventilation. The fire initially grows in size. Then, as might be expected, the peak in MLR seems to correspond with the time when the descending smoke layer begins to interfere with the fire plume. The room continues to fill with smoke and by the time oxygen levels decrease to 15 % on the second floor, the smoke in the fire room is thick enough to obstruct the view of the camera.

Table 3: Summary of fire event times (m:ss) for the MV tests.

Test	**Event 1** (smoke descends to W1)	**Event 2** (second cushion ignites)	**Event 3** (peak MLR)	**Event 4** (15% O_2 on second floor)
MV1	2:50	4:10	6:00	7:30
MV2	3:00	4:26	5:40	8:16
MV3	2:55	4:10	6:24	9:13
MV4	2:55	4:10	5:55	7:35

(a) Smoke to top of W1 at 2:50.



(b) Second cushion ignites at 4:10.

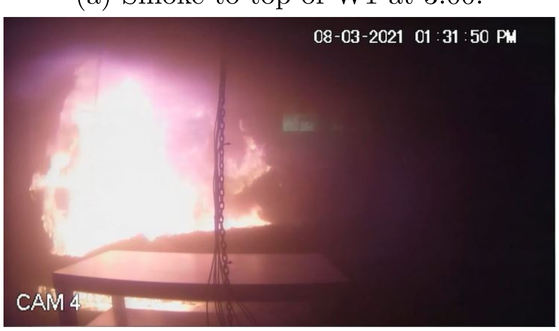
(c) Peak MLR at 6:00.

(d) 15% O_2 on second floor at 7:30.

Figure 11: Images of couch fire for Test MV1.

(a) Smoke to top of W1 at 3:00.

(b) Second cushion ignites at 4:26.



(c) Peak MLR at 5:40.

(d) 15% O_2 on second floor at 8:16 sec.

Figure 12: Images of couch fire for Test MV2.

(a) Smoke to top of W1 at 2:55.

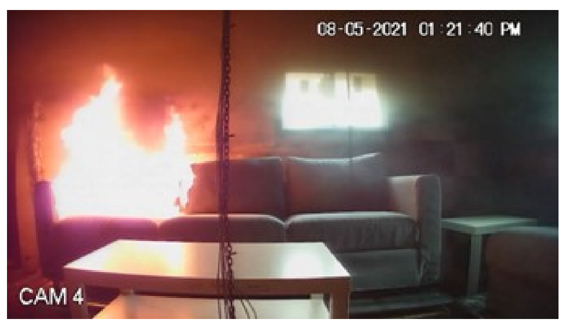
(b) Second cushion ignites at 4:10.

(c) Peak MLR at 6:24.

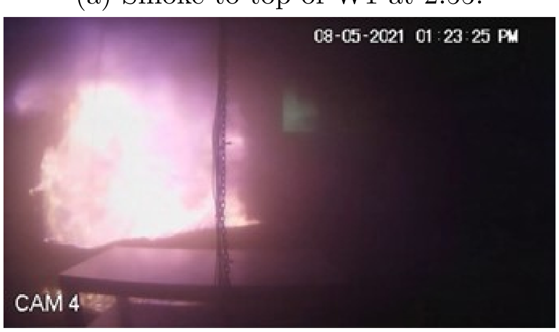
(d) 15% O_2 on second floor at 9:13.

Figure 13: Images of couch fire for Test MV3.

(a) Smoke to top of W1 at 2:55.



(b) Second cushion ignites at 4:10.



(c) Peak MLR at 5:55.

(d) 15% O_2 on second floor at 7:35.

Figure 14: Images of couch fire for Test MV4.

5.1 Mass and Mass Loss Rate

Figure 15 shows the decrease in mass of the couch as it burns in each MV test versus time, where time zero is set to the time of ignition. This plot focuses on the first 15 minutes of the tests to show the details of the mass loss more clearly. Similar time varying profiles of mass loss, and total mass loss, were recorded in all four tests. There is an incipient period for approximately the first two minutes and 20 seconds of each test, as the fire establishes itself on the first couch cushion. As the fire grows across the first, and any subsequent, cushions, the mass of the couch rapidly decreases before levelling off at approximately eight minutes and 20 seconds after ignition when the fire has decayed to near extinction.

Measured values of MLR with time are plotted in Fig. 16, again for the first 15 minutes after ignition. For a well-ventilated fire the MLR can be multiplied by the effective heat of combustion to determine the heat release rate (HRR) of the fire. As such, the MLR curves are also a representation of the fire size for well ventilated fires. In contrast, for an under-ventilated fire such as the fires in these studies, taking the product of the MLR and an effective heat of combustion of the fuel (measured in well-ventilated conditions) can result in significant overestimation of the fire size because the combustion efficiency (heat of reaction) is reduced [11]. Since the time varying heat of reaction and combustion efficiency are not known for the present tests, the MLR curves are plotted to demonstrate that each test has similar fire sizes with similar trends in fire growth and decay. The only significant difference between tests appears to be that there is a slightly longer time spent near the peak MLR with increasing ventilation. With that said, the mass results between all four tests are comparable, given the natural variability of large-scale furniture fire experiments.

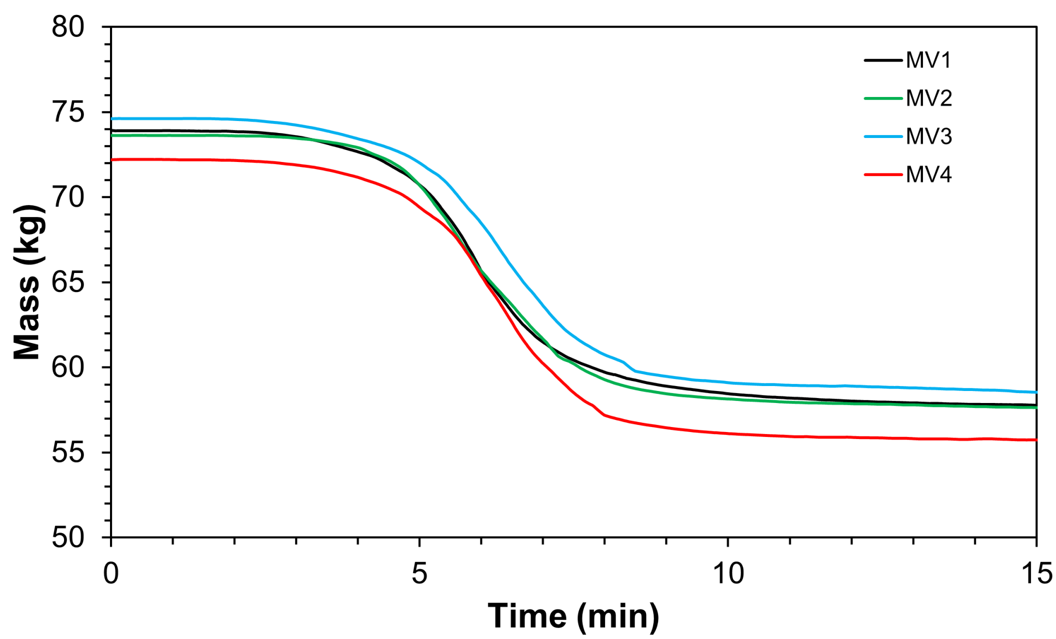


Figure 15: Couch mass versus time plot for each test.

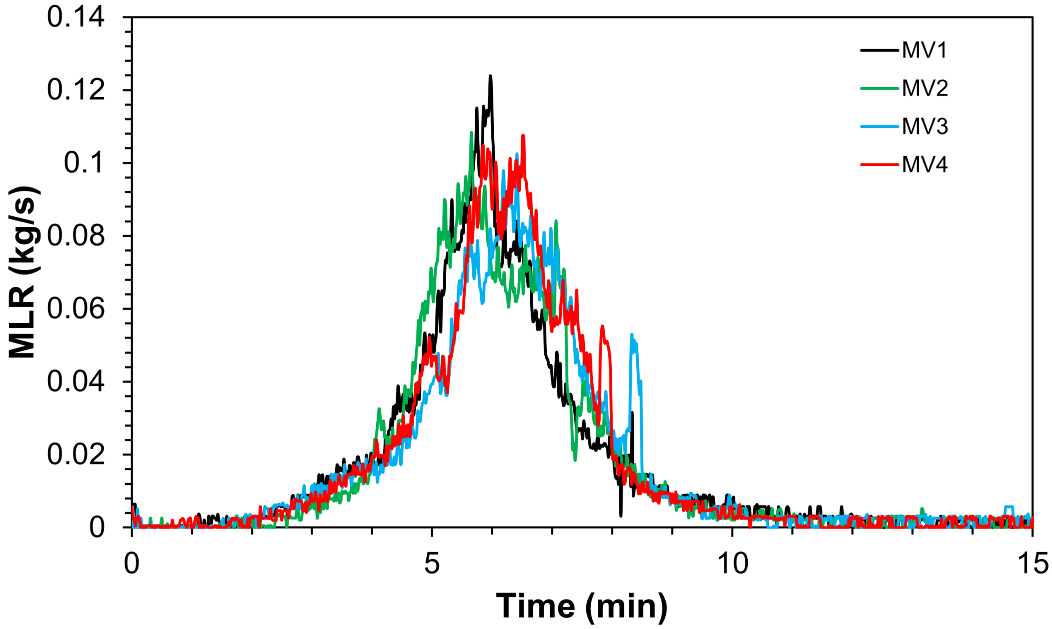


Figure 16: Couch mass loss rate versus time plot for each test.

5.2 Fire Room Oxygen Concentration

An important difference between tests is observed in comparisons of the time varying O_2 concentrations in the fire room. Figure 17 compares the O_2 concentration with time at the 0.9m height of gas sensor station 1 in the fire room. In all the tests, the O_2 concentrations begin to decrease at similar times after ignition indicating that it took similar lengths of time (incipient periods) for the fire to establish on a couch independent of ambient HVAC conditions. They continue to decrease over time, until reaching similar minimum O_2 concentrations near 3% as the fire begins to self-extinguish. They remain at these low levels for a period of time, before increasing again towards ambient concentrations.

Tests 1, 2, and 4 show similar rates of consumption of O_2 from the fire room, which, when coupled with examination of the mass loss rates in these fires (Fig. 16), suggests very comparable patterns of fire growth and heat release rate. Test MV3, with 200 % ventilation, exhibits a significantly slower rate of O_2 consumption, likely due to the increased amount of outside air being introduced into the fire room in that test. Each test remains at the low concentration of O_2 for some period of time until the fire room cools enough for pressures throughout the house to rebalance. The rebalancing of pressures causes gases to flow into the fire room with consequent increase in O_2 concentrations as well.

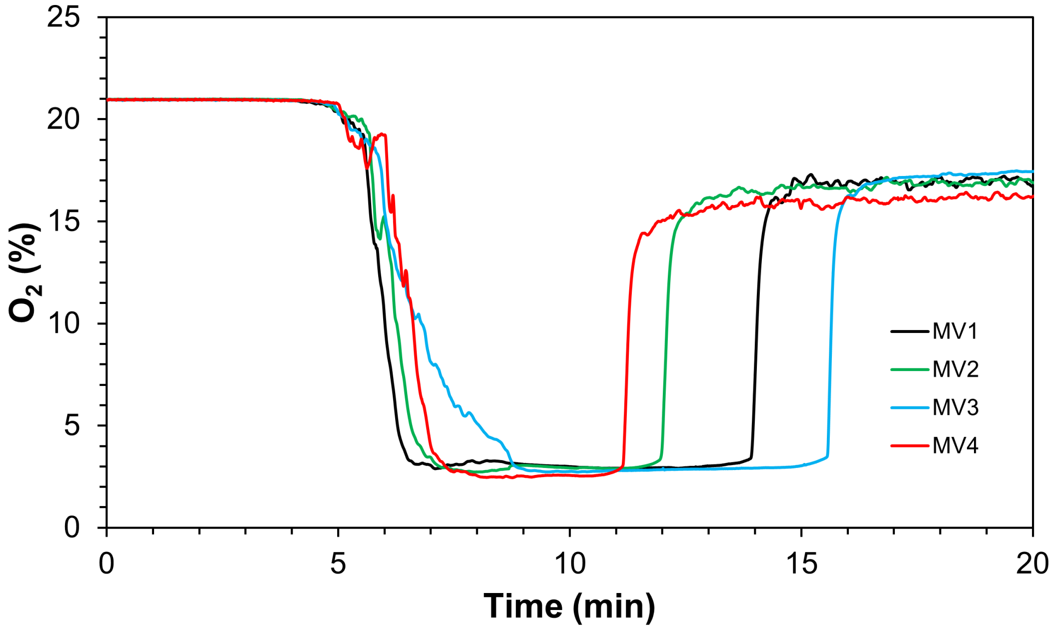
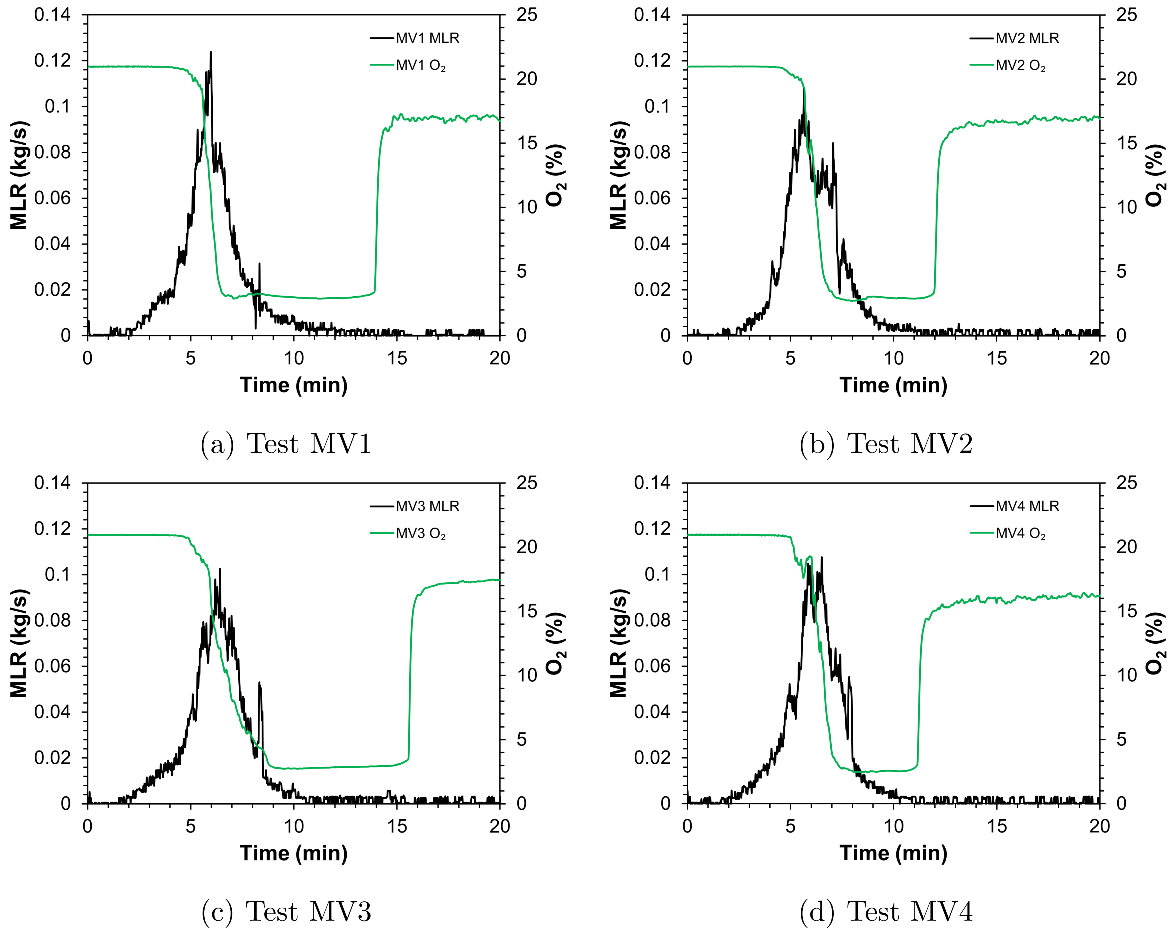


Figure 17: Oxygen concentrations in the fire room for all tests.

Once the pressure rebalance occurs, O_2 recovery is rapid in all cases, climbing back to 15-17% in 50-60 seconds and then remaining at this level until the end of a test. The O_2 recovery, being this rapid, remains to be investigated further. After recovery, the house reaches an equilibrium where all locations in the house have similar O_2 concentrations. The concentrations of O_2 return to ambient levels once the doors are opened to the outside at the end of the tests.

The O_2 profiles at the same location in the fire room are plotted against the MLR curves for each test in Fig. 18. It can be seen that the O_2 concentration begins to decrease significantly near the time of the peak MLR. It is important to note that the fire continues to burn, albeit at a steadily decreasing rate, throughout the period of decreasing O_2 concentration. This signals the potential for simultaneous build-up of CO and unburned hydrocarbons in a heated fire environment leading to a possible range of rapid fire growth situations should fresh air be introduced into the environment. Interestingly, the O_2 concentrations do not begin to increase again until the MLR has decayed to nearly zero, indicating that the fire is nearly extinguished at that time.



(a) Test MV1

(b) Test MV2

(c) Test MV3

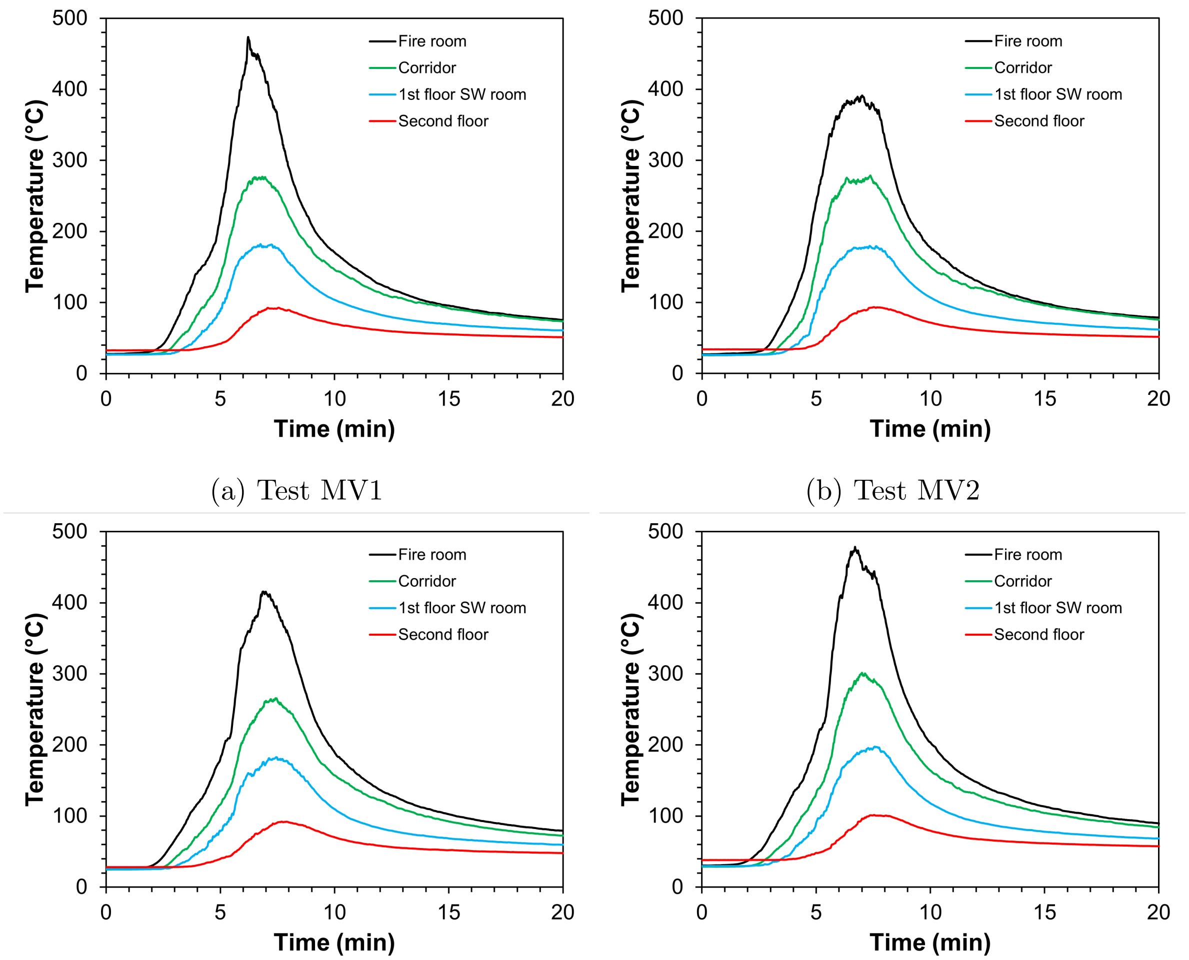
(d) Test MV4

Figure 18: Plots of MLR and O_2 concentrations versus time for all tests.

5.3 Compartment Temperatures

Time-variations in temperature at select heights on the thermocouple (TC) rake T3 in the fire room, rake T6 in the corridor of the first floor, rake T7 in the SW room of the first floor, and rake T10 in the SW room of the second floor are presented in this section. In general, stratified thermal environments develop in each of the rooms, with the highest temperatures occurring near the ceiling and the lowest occurring near the floor. On the lower floor, temperature gradients from floor to ceiling vary significantly depending on proximity to the burn room so several representative thermocouple rakes have been selected for discussion in this section. In contrast, on the second floor, the conditions are fairly well-mixed across all compartments, therefore a single location was chosen to represent temperatures on that floor.

Figure 19 shows temperature versus time plots at an approximate height of 2m above the floor for each stated location above. This height was chosen to present temperature results indicative of the hot smoke layer near the ceiling in each area. As expected, temperature profiles follow similar trends with time as do the fire MLR profiles. The maximum temperature in the fire room occurs near the time of peak fire MLR; at other locations, the times of peak temperature are delayed from this time depending on their distance from the fire room. In all cases, the highest temperatures are measured in the fire room followed by temperatures in the corridor, in the first floor SW room, and then on the second floor in that order. Measured temperature-time profiles are comparable across all tests. Peak temperatures measured on the first floor are within approximately 50^{o}C of each other at each location across ventilation conditions, while temperatures measured on the second floor are even more consistent. In Tests MV1 and MV4, where there is no ventilation and 100% recirculation respectively, the peak temperatures are slightly higher. This can be attributed to the fact that there is no fresh, and thus cooler, air being introduced into the compartments during those tests. In all cases, there is a period of time over which the combination of decreasing O_2 and relatively high temperature, if coupled to build-up of CO and unburned hydrocarbons could lead to dangerous situations for both occupants and emergency responders.



(a) Test MV1

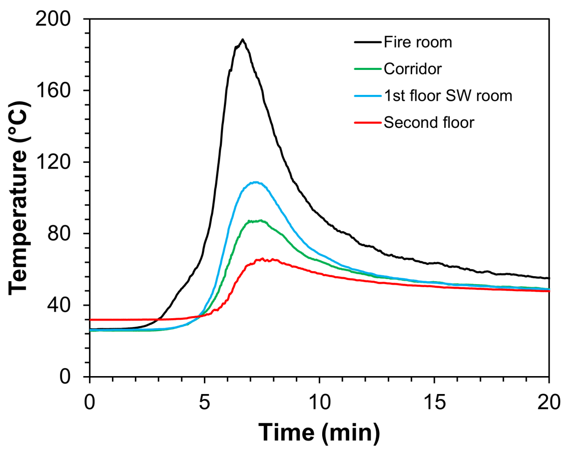
(b) Test MV2

(c) Test MV3

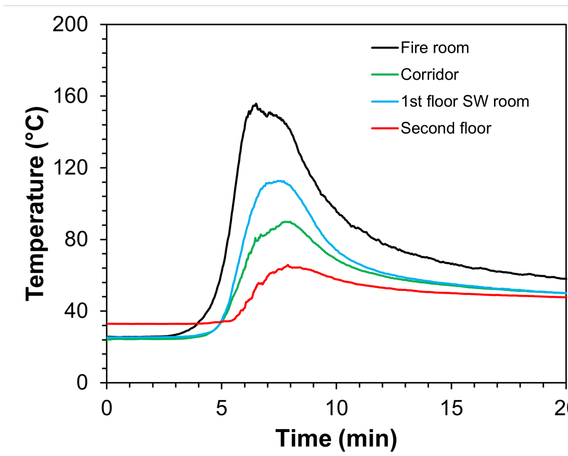
(d) Test MV4

Figure 19: Plots of temperature versus time at 2m above the floor at various locations for all tests.

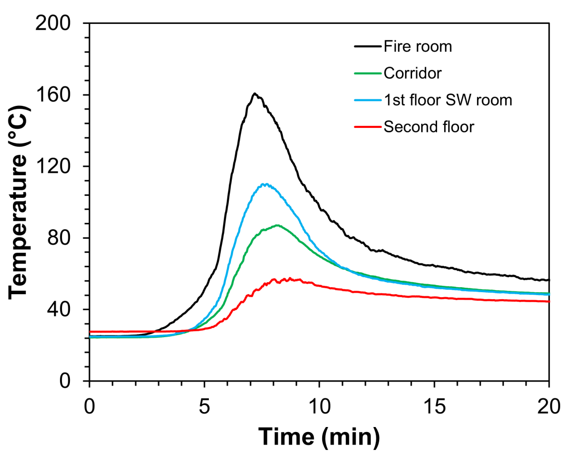
Similar patterns are seen in temperatures recorded closer to the floor over the duration of each test. Figure 20 shows plots of temperature with time measured at approximately 0.7m above the floor at the same locations as in Fig. 19. These temperature traces represent the temperature evolution in the lower layers near the floor in each area. Comparison of Fig. 20 and Fig. 19 highlights that there is less difference in temperature between compartments in the lower levels of the structure. Further, the temperatures are obviously much cooler at the floor than nearer to the ceiling in the main floor fire room, corridor and SW room. In contrast, there is much less difference between the floor and the ceiling temperatures on the second floor. Interestingly, in these lower layers, the temperatures in the SW room on the first floor are higher than those in the corridor. While the detailed reasons for this have not been fully investigated, it is likely due to the relative values of gas flow and cold air exchange in the corridor when compared to the SW room.



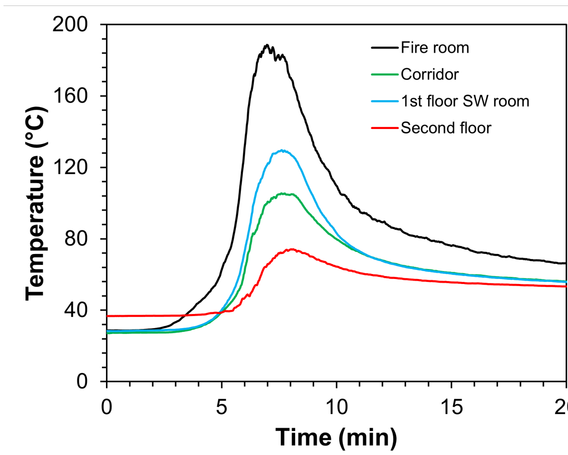
(a) Test MV1



(b) Test MV2



(c) Test MV3



(d) Test MV4

Figure 20: Plots of temperature versus time at 0.7m above the floor at various locations for all tests.

5.4 Effects on HVAC

Flow velocities and gas temperatures in the supply ducts are monitored to investigate the potential for back flow into any of the ducts during these fire tests. Results for each of the four tests are plotted in Figs. 21 to 23 and Fig. 25. Each plot includes the data from three locations corresponding to instrumentation positions in the main ducts supplying the fire room, first floor SW room, and the second floor in each test, as stated in Section 4.4.4. A positive velocity represents flow into the compartment of interest, and a negative velocity represents flow out of the compartment and back into that duct. Note that the probes labelled first floor SW room and second floor are upstream of both supply vents on their respective floors. Therefore, the flow rates at these locations are nominally twice that of the specified flow rate at each supply vent and the centreline velocity measured by these probes would be nearly twice (if not slightly higher than) the velocity specified at each supply vent.

In Test MV1, Fig. 21, there is no mechanical ventilation, so the velocities measured inside and near the outlets of the ducts are a result of smoke flow generated only by the fire. As the fire grows and smoke builds up near the ceiling of the first floor, some smoke flows into all of the supply ducts from the fire room. As the fire peaks, at around six minutes after ignition, the data suggests that the expanding hot smoke flows preferentially into the duct in the fire room, while air is actually drawn through the ducts in the SW room on the first floor and the supply duct on the second floor. The flow velocities in the ductwork reach maximum values shortly after the peak of the fire with balanced velocities of around 1.3 m/s into the fire room supply duct and out of the first floor SW room supply duct and a lower velocity of 0.7 m/s from the second floor supply duct. Temperatures in the ducts are consistent with these trends. Peak temperatures are measured at around the same time as peak velocities are reached, with a higher temperature of approximately 350^{o}C in the fire room duct (approximately 100^{o}C cooler than the upper layer fire room temperature at this time), 130^{o}C in the first floor SW room duct (approximately 30^{o}C cooler than the upper layer SW room temperature at this time), and 80^{o}C in the second floor duct (approximately 10^{o}C cooler than the upper layer second floor temperature at this time).

Due to the ventilation conditions represented, Test MV2 (Fig. 22) has nominal supply duct flow velocities of 0.85-1 m/s throughout the test. As the fire grows, velocities measured inside and near the outlets of all of the ducts decrease as smoke is generated and pressure builds up near the duct inlet. Velocity into the fire room supply duct reverses to negative value (inflow) while those in the SW room and second floor ducts reach their minimum values near the peak of the fire at five minutes and 40 seconds after ignition. After the fire peaks, the fire gases continue to flow into the fire room duct with a value near -0.6 to -0.7 m/s for a period of time. Some air appears to be drawn through the duct into the SW room on the first floor though to a slightly lesser degree than for test MV1 with no ventilation. In contrast, the flow velocity at the duct on the second floor, which changes direction to suggest smoke inflow around the peak of the fire, appears to return to the initial supply velocity for the remainder of the test. Temperatures in the ducts remain much lower in Test MV2 when compared to Test MV1 with peak temperatures reaching 200^{o}C in the fire room duct and 90^{o}C in the first floor SW room duct. The temperature remains nearly constant at the original ambient value in the second floor duct for the duration of the test. Near the end of the test, the velocities in all of the ducts return to the flow values set at the beginning of the test.

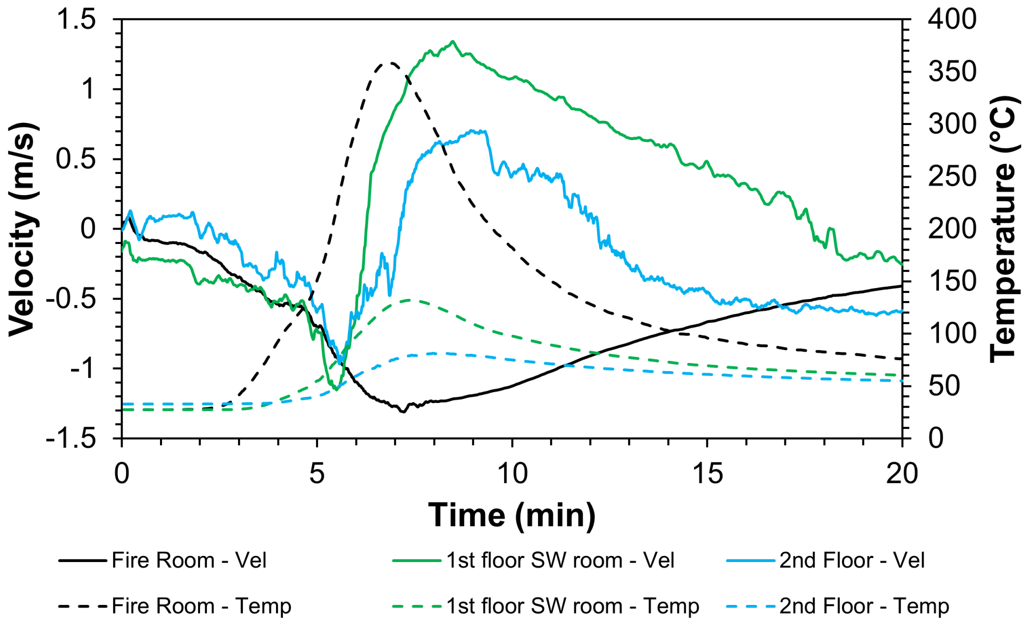


Figure 21: MV1 supply duct velocities and temperatures.

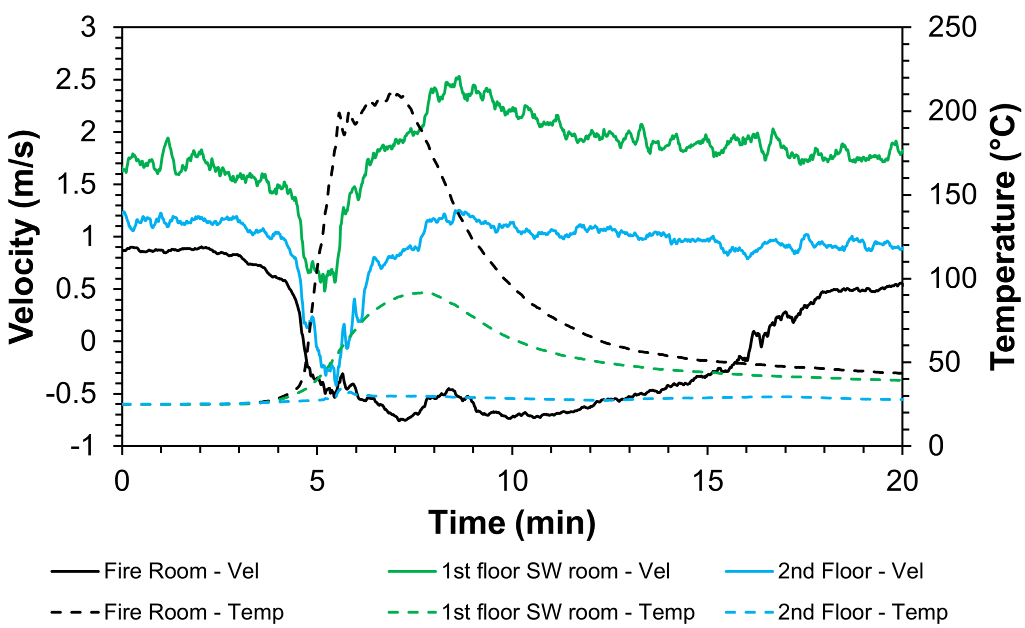


Figure 22: MV2 supply duct velocities and temperatures.

Test MV3, Fig. 23, has nominal supply duct velocities of 1.7-2 m/s. The fire has little effect on the velocities measured inside the supply ducts in this test, likely due to the increased ventilation supply flow rates for this test. The supply duct velocities at all three locations decrease slightly at six minutes and 24 seconds, just before the peak of the fire is reached, but quickly recover to their original velocities. Temperatures in the ducts are much lower than in either of the previous tests, reaching maximum values of approximately 100^{o}C in the fire room duct and 45^{o}C in the first floor SW room duct. The second floor duct shows a very gradual increase in temperature (approximately 7^{o}C) throughout the duration of the test. For Test MV3, additional velocity probes and thermocouples are fitted in the exhaust ducts. Results show that exhaust velocities increase up to 34% as the fire grows, which is consistent with pressurization of the house due to volume expansion of the hot smoke.

The supply velocities in Test MV3 are positive for the entire duration of the test. This means that smoke does not enter the ductwork and there is always a flow of air into the compartments. Video recordings from Test MV3 show that smoke is pushed down to the floor by the supply air flow once the smoke layer descends to a level near the height of the HVAC supply vents. Figure 24 shows a snapshot from camera 5 in the first floor SW room where smoke can be seen flowing away from the region near the opening of the supply duct and impinging on the floor in a jet like manner. This phenomenon is not seen in the fire room, which is likely explained by the fire room duct being oriented to direct airflow across the room instead of downwards towards the floor. The orientation allows the smoke to impart more normal stresses on the supply port and hence, has more of an ability to resist the momentum imparted by the duct flow.

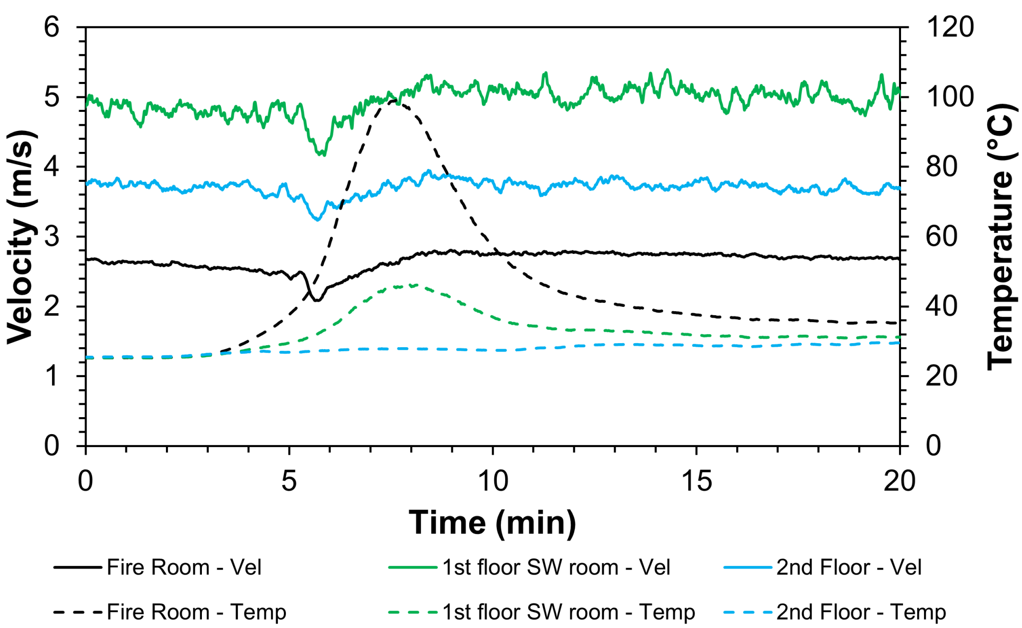


Figure 23: MV3 supply duct velocities and temperatures.

Figure 24: Images of smoke flow out of the first floor SW room supply duct in Test MV3.

Test MV4, Fig. 25, has 100% recirculating flow with the same flow rate of exhaust gas and exhaust gas supply back into the structure as for Test MV2. The overall trends and values of velocities measured in the ducts during Test MV4 are comparable to those of Test MV2, with a slightly more pronounced change in velocity at 8-9 minutes after ignition (1-2 minutes prior to the fire extinguishing). This could be due to the slightly higher temperatures of the supply in Test MV4. Peak gas temperatures in the supply ducts reach 260^{o}C in the fire room duct, 110^{o}C in the first floor SW room duct, and 45^{o}C in the second floor duct, which are all slightly higher than those in Test MV2, consistent with recirculation of hotter exhaust gases back into the supply stream in Test MV4.

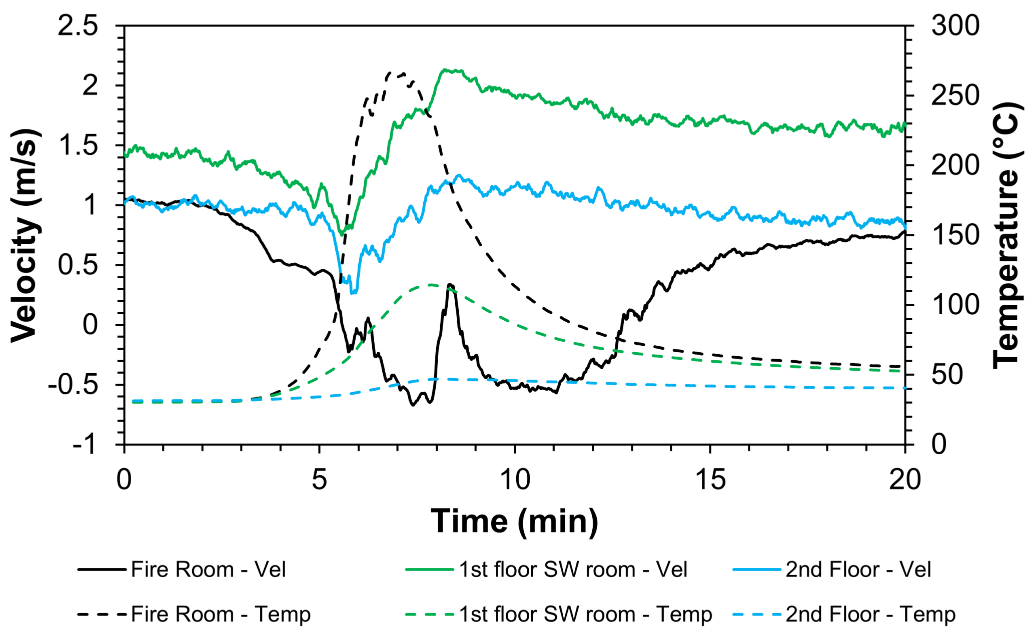


Figure 25: MV4 supply duct velocities and temperatures.

5.5 Gas Flow Patterns

Hot smoke and gas flows throughout the structure are similar for all tests. To illustrate the patterns and similarities in these flows, results are shown for Tests MV1 and MV3 which had the largest difference in mechanical ventilation. Gas flow through four doorways between compartments in the structure are plotted as a function of height for five times after ignition in Fig. 26 for Test MV1 and Fig. 27 for Test MV3. The five individual plots in each figure correspond to the time when smoke descends to the top of W1 (representing the period of early fire growth), the time when the second couch cushion ignites, the time of peak MLR, the time when 15% O_2 is reached on the second floor (as measured at the 0.9m height of gas sensor station 6 in the SW room), and the time when a flow reversal occurs near the end of the test respectively. In all cases, a positive velocity represents flow out of the fire room on the main floor or away from the landing on the second floor and a negative velocity represents flow towards the second floor landing or into the fire room. Velocities presented in this section represent the flows within the structure that are induced by the fire, since the probes are zeroed using baseline measurements taken prior to the test with the HVAC system already set to the given test configuration. A visual representation of flow directions through doorways is shown on the floor plans of the structure in Appendix A.

The figures illustrate very similar flow patterns and velocities over the duration of Tests MV1 and MV3. During the early stages of fire development gas flow through the structure favours the direction into the fire room. As the fire continues to grow and smoke collects in the fire room, the net flow shifts toward flow out of the fire room. In reality, a two-way flow develops with the hotter upper layer gases and smoke flowing out of the fire room into the adjacent compartments and cooler lower layer gases flowing towards/into the fire room.

Peak velocities occur near the time of peak MLR of the fire, with a slight delay in some locations due to the transport time of the smoke. After the peak of the fire, velocities begin to decrease with less flow out of and into the fire room. Eventually, the environment cools sufficiently that there is a flow reversal and the net flow changes again from out of, to into, the fire room as pressures throughout the structure rebalance. Measured gas velocities are fastest in the staircase, reaching peak values near 4m/s (up the stairs) and -2m/s (down the stairs) at the time of peak fire size. Maximum velocities in most other locations reach between -1 and 1m/s depending on the direction of flow.

The staircase is a particularly interesting region which is characterized by mixing of smoke and lower layer air. It also facilitates the flow of a significant amount of air into the fire to sustain burning. On the first floor, conditions are stratified, as shown by the large temperature differences between locations near the ceiling (Fig. 19) and near the floor (Fig. 20). On the second floor conditions are fairly well-mixed, shown by only slight differences in temperature at different heights. The differences in stratification of the environments on the two floors can, at least in part, be attributed to the intense mixing facilitated between flows up and down the stairs. Figure 28 shows plots comparing the flow at the top and bottom of the stairs for Test MV1. The magnitude of the velocities at both locations are low in the early stages of the fire, but increase to significantly faster values by the time the fire reaches its peak MLR. The flow profiles at the top and bottom of the stairs are similar throughout the duration of the test, clearly showing the significant flow of smoke up the stairs to the second floor and the simultaneous exchange of lower cooler air towards the fire room.

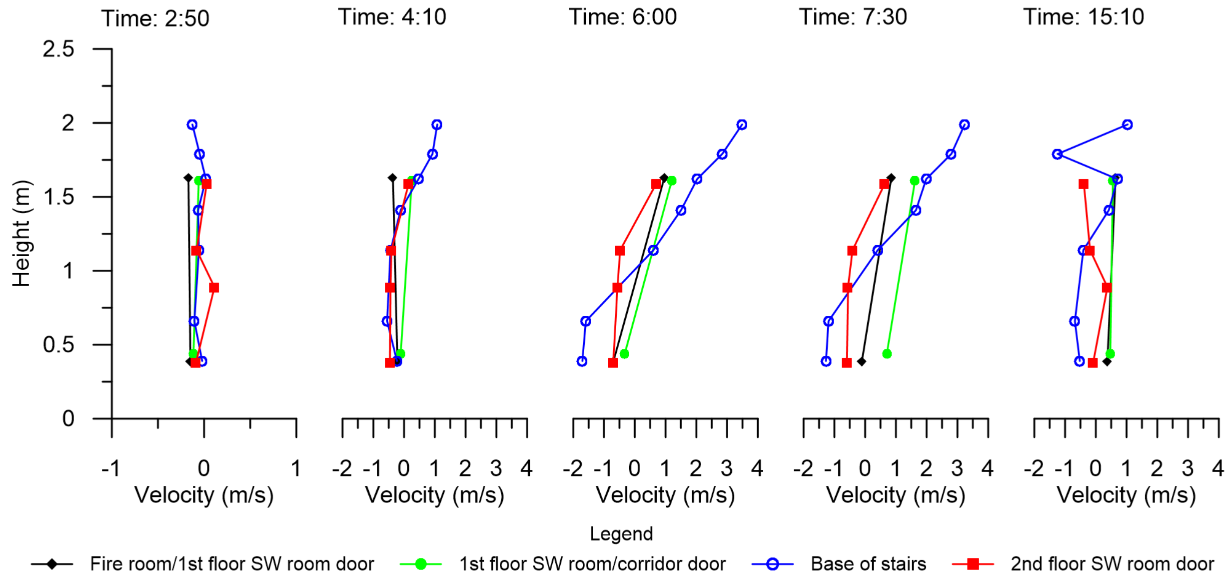


Figure 26: Plots of gas flow velocities through doorways in Test MV1 when smoke reaches the top of W1, when the second cushion ignites, at peak MLR, when 15% O_2 is reached on the second floor, and when flow reversal occurs.

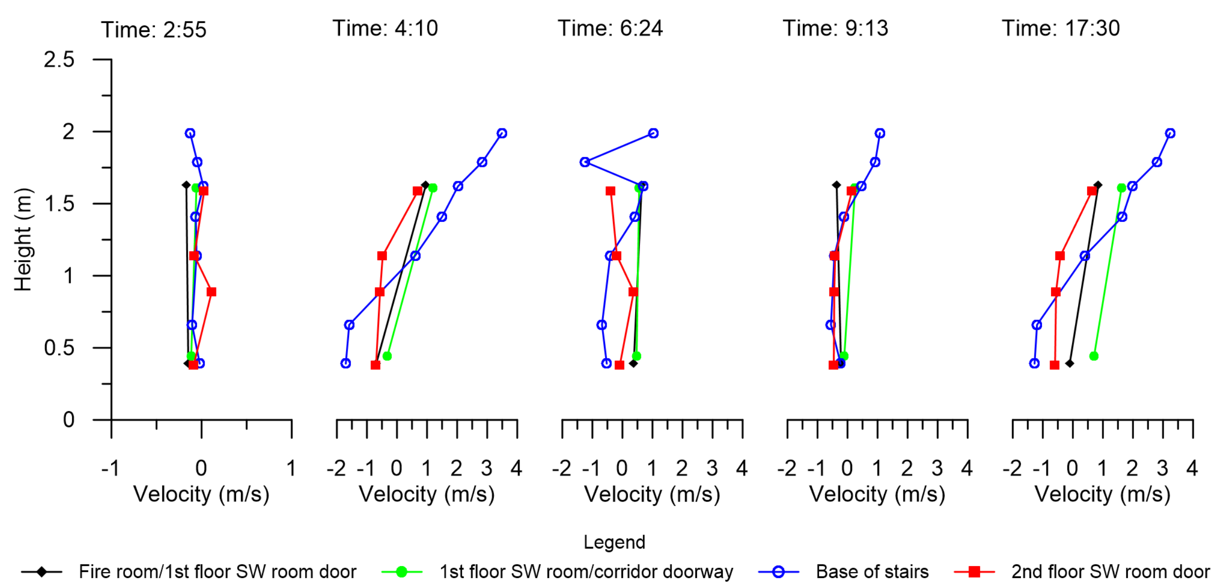


Figure 27: Plots of gas flow velocities through doorways in Test MV3 when smoke reaches the top of W1, when the second cushion ignites, at peak MLR, when 15% O_2 is reached on the second floor, and when flow reversal occurs.

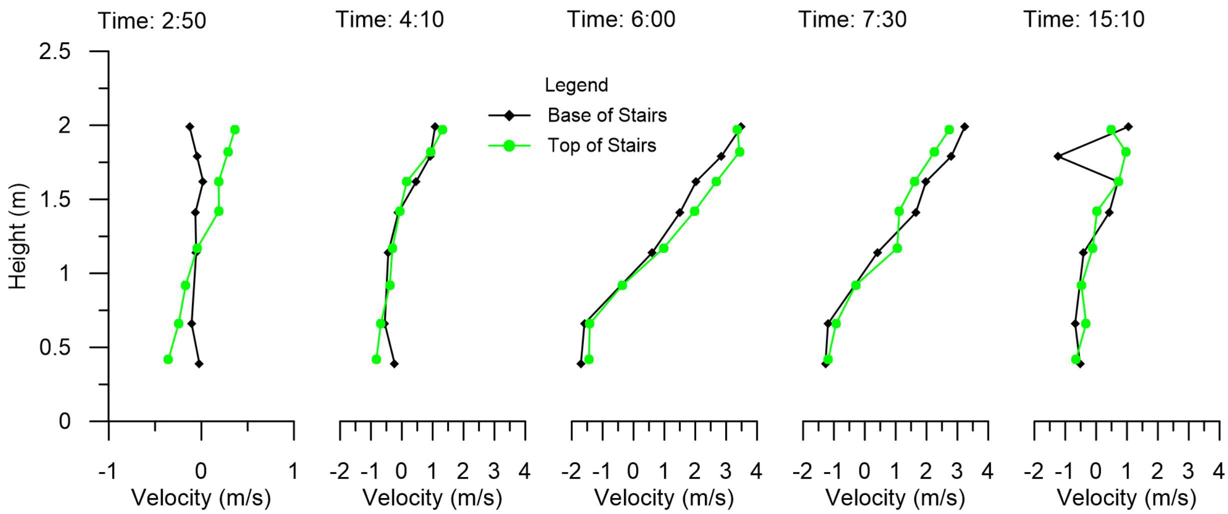


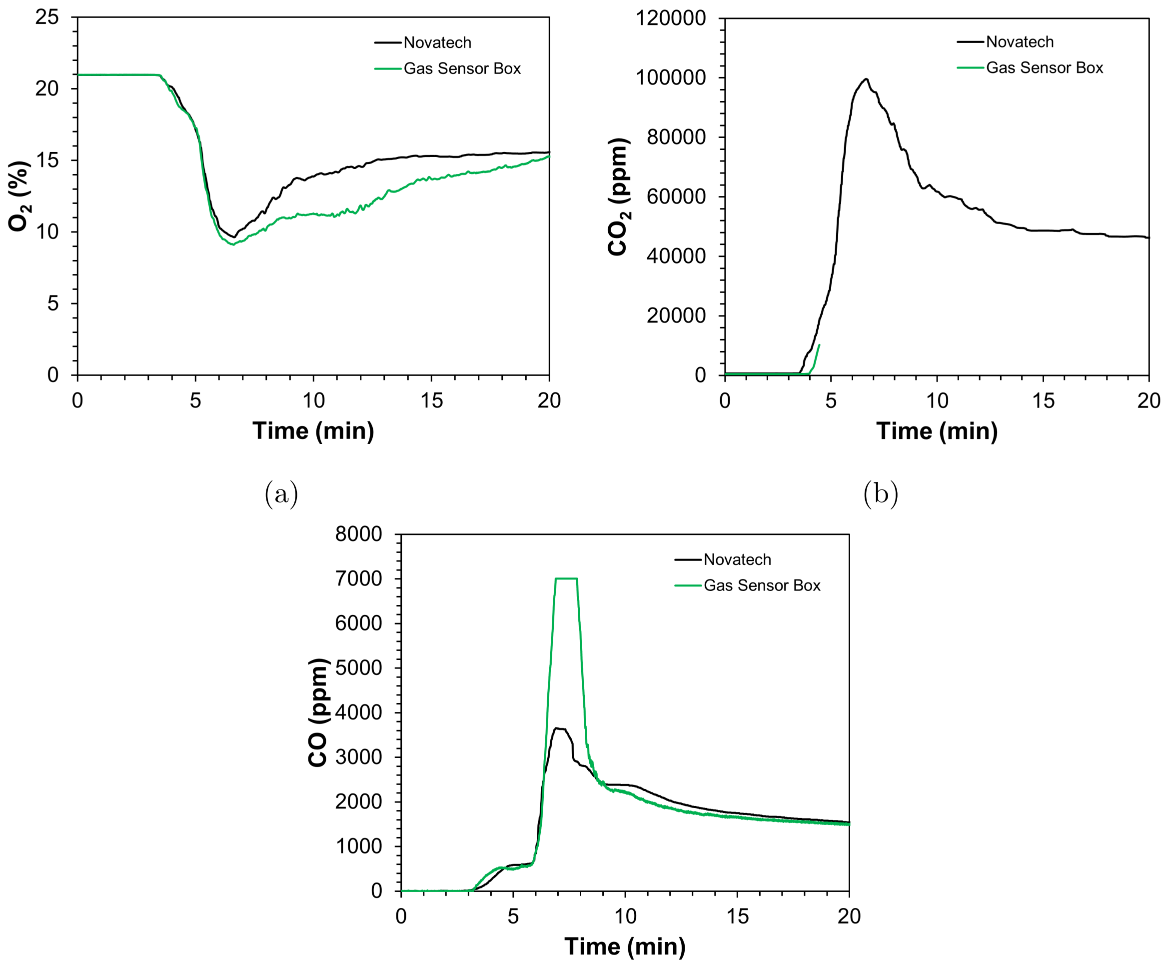
Figure 28: Plots of gas flow velocities in the staircase in Test MV1 when smoke reaches the top of W1, when the second cushion ignites, at peak MLR, when 15% O_2 is reached on the second floor, and when flow reversal occurs.

5.6 Gas Concentrations

5.6.1 Instrumentation Comparison

Gas concentrations are discussed largely based on measurements obtained using the custom-built electrochemical gas sensing units, described in Section 4.4.5. Before providing details, however, this section discusses how the measurements from these units compare to measurements collected using the Novatech P-695 which is a known and reliable gas analysis instrument specifically as it speaks to the ability of the electrochemical gas sensing units to provide accurate measurements of the harsh environment inside the burn house. Figure 29 shows comparison plots of O_2, CO_2, and CO concentrations measured using the gas sensing unit in the first floor SW room and the Novatech positioned immediately adjacent to the unit. Oxygen and CO_2 measurements are compared from Test MV1 and CO measurements are compared for Test MV3 due to a faulty CO sensor in Test MV1.

The O_2 concentration profiles between the two instruments show good agreement, especially in the phase of decreasing concentration as the fire grows and consumes oxygen, until the time when minimum concentration is reached. Discrepancies in measured concentration as the O_2 concentration begins to increase again after the minimum suggests that the electrochemical gas sensing units are unable to respond to subsequent increases in oxygen concentration at the same rate as the Novatech, although the longer term steady concentrations are again very similar between the two instruments.



(c)

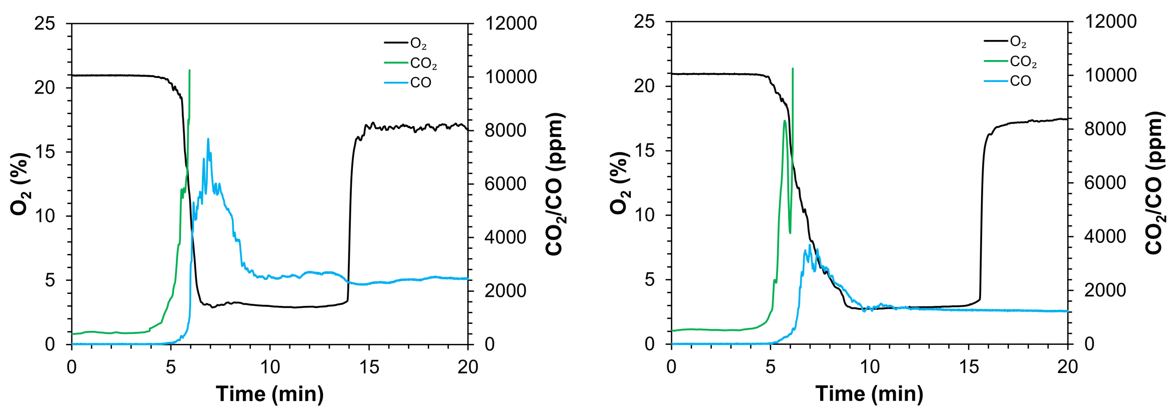
Figure 29: Comparison plots between the gas sensing unit and Novatech in the first floor SW room.

The CO_2 plot shows that the gas sensing unit is not able to respond to the steep increases in CO_2 that characterize the fire growth. In addition, they cannot measure high enough concentrations of CO_2 to provide reasonable values of peak CO_2 concentrations, particularly in locations close to the fire. When the concentration of CO_2 reaches approximately 10,000 ppm the sensors saturate and their measurements are unreliable for the remainder of the test. For this reason plots of CO_2 concentration generally show the initial increase in values with growth of the fire but are truncated at the time when saturation occurs. In reality, the peak concentrations of CO_2 are not well captured in these tests since they can reach values that are significantly higher than 10,000 ppm as shown by measurements using the Novatech analysis system.

Measurements of CO obtained using the electrochemical gas sensing unit agree well with measurements from the Novatech for the first six minutes and 40 seconds of Test MV3 and again from roughly eight minutes and 20 seconds after ignition to the end of the test. During the time between six and eight minutes, the CO concentration at this location rapidly increases, reaches a peak, and then begins to decrease. Again, due to the steep change in concentration, the electrochemical gas sensing unit appears to significantly overshoot the peak concentration in comparison to values measured using the Novatech system. As a result, peak values of CO may be overestimated so plots are truncated at some times and/or some locations within the structure.

5.6.2 Fire Room Gas Concentrations

Time varying concentrations of O_2 in the fire room have previously been discussed in relation to the fire development and profiles of fire MLR for Tests MV1 and MV3. Figure 30 shows the same time varying profiles of O_2 concentration, measured at the 0.9 m height at gas sensor station 1 in the fire room, overplotted with time varying concentrations of CO_2 and CO measured at the same location. As anticipated during the time that the fire is rapidly growing, the concentration of CO_2 begins to rapidly increase at the same time as concentrations of O_2 begin to decrease. Similar minimum O_2 concentrations of around 3% are measured in both Tests MV1 and MV3; however, the rate of decrease of O_2 depletion with time is lower in Test MV3 due to the higher rate of ventilation, as previously discussed. The increase in CO concentrations is slightly delayed relative to changes in O_2 and CO_2 concentrations for both tests. This is consistent with the fact that CO production necessarily increases as combustion efficiency decreases due to decrease of O_2 available to the fire. Further, the additional ventilation in Test MV3 results in a lower peak CO concentration, 3700 ppm, compared to that seen in Test MV1 with no ventilation in which CO concentrations peak at 7700 ppm.



(a) Test MV1

(b) Test MV3

Figure 30: Plots of O_2, CO_2, and CO at 0.9 m in the fire room for tests 1 and 3.

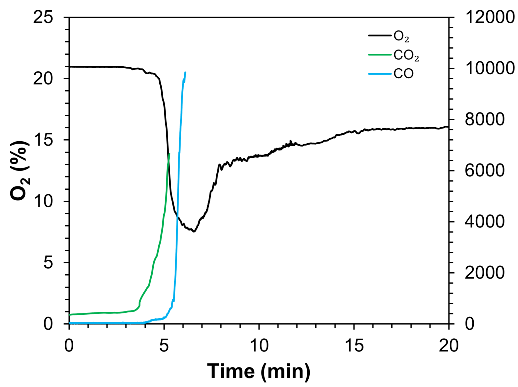
5.6.3 Comparison Between the First and Second Floors

Figure 31 compares the concentrations of O_2, CO_2, and CO at the 0.9 m height of gas sensor station 4 in the first floor corridor and 5 in the second floor corridor for Tests MV1 and MV3 in order to highlight potential differences in the environments that evolve on the two floors of the structure during the fires. Both tests show similar trends over time, though they differ slightly in minimum values of O_2 concentration and peak CO concentration. The CO_2 sensors indicate steep and comparable increasing values at the time when the fire begins to grow but are not fast enough to follow the rise in concentration and/or saturate after some time, necessitating truncation of the curves before the peak values are recorded. Unfortunately, the first floor CO sensors similarly cannot follow the steep increases in concentration, so those curves are also truncated. Thus, the peak values on the plots are not indicative of actual peak concentrations of CO on the first floor during the tests. In contrast, the sensors do appear to follow the trends in CO concentration over time on the upper level, leading to estimated peak values of 3200 ppm and 1400 ppm in Tests MV1 and MV3 respectively.

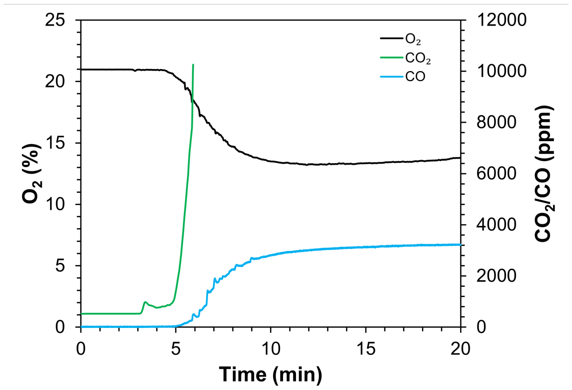
Oxygen concentrations in the first floor corridor decrease rapidly with time, following a similar profile to that measured in the fire room and shown previously in Fig. 30. In contrast to the low minimum measured concentrations of O_2 near 3% in the fire room and closer to the fire, the minimum O_2 concentration in the first floor corridor is 7.5% in Test MV1 with no ventilation and slightly higher at 9.5% in Test MV3.

In the second floor corridor the profiles of O_2 depletion and increasing CO concentration show a much more gradual change than those measured in the first floor corridor likely due to mixing that occurs on the longer path between the fire and the second floor corridor. Consistent with this, minimum O_2 concentrations at this location are also higher, near 13.0% for Test MV1 and 14.8% for Test MV3. Consistent with mixing as well, the maximum CO concentrations at this location are lower than those near the fire. Overall, Test MV3 shows higher levels of minimum O_2 concentration (less depletion of oxygen with time) and lower concentrations of CO as is expected due to the continual supply of fresh outdoor air to the spaces by the HVAC system during that test.

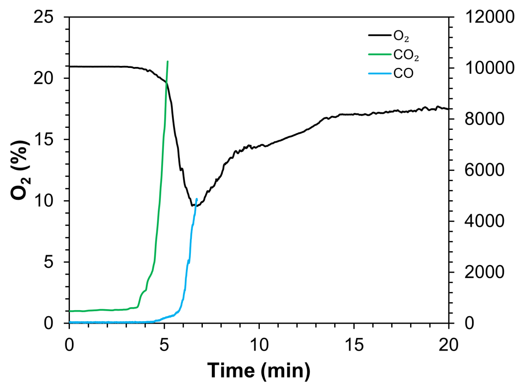
A significant difference in concentration at each height is also observed between the first and second floors. The first floor has a much more stratified environment from floor to ceiling both in terms of concentration and temperature. This is because the hot smoke layer first fills the volumes near the ceiling of the fire room and adjacent compartments on the first floor and then descends gradually down into the room from the ceiling as smoke continues to be produced by the fire. When it descends down to the opening, smoke travels up the staircase to the second floor but there the environment is much less stratified and fairly well-mixed due to the upward and downward flows in the staircase as described previously. Figure 32 illustrates the difference in stratification on the first and second floors via plots of O_2 concentrations measured by gas sensor station 3 in the first floor SW room and station 5 in the second floor corridor for Test MV1. As shown in the plot, the minimum O_2 concentrations in the first floor SW room at each height occur at nearly the same time although at 0.3 m above the floor the minimum concentration is 10.5%, while at 0.9 m it is 9.1%, and at 1.5 m it is much lower at 2.8%. In the second floor corridor, minimum O_2 concentrations at all three heights show little difference in value, ranging between 13 and 14%.



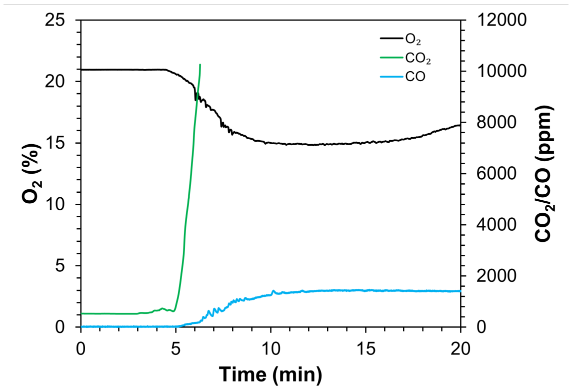
(a) Test MV1 - First Floor Corridor



(b) Test MV1 - Second Floor Corridor

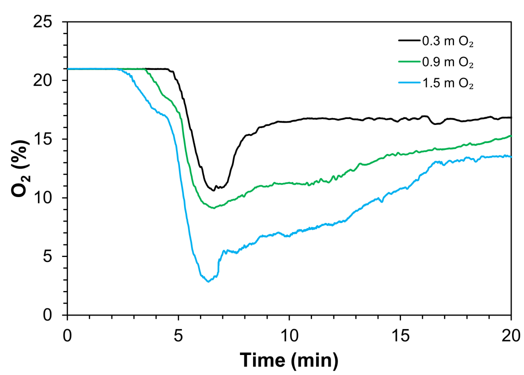


(c) Test MV3 - First Floor Corridor

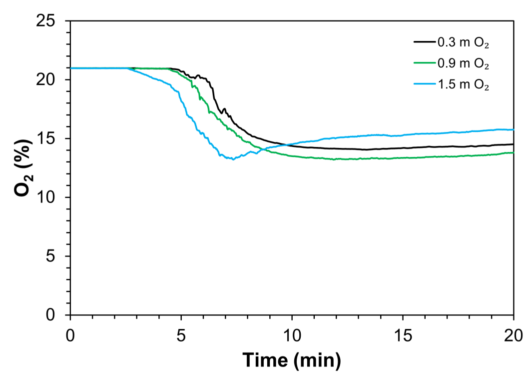


(d) Test MV3 - Second Floor Corridor

Figure 31: Plots of O_2, CO_2, and CO at 0.9 m in the first and second floor corridors for tests 1 and 3.



(a) Station 3 - first floor SW room



(b) Station 5 - second floor corridor

Figure 32: Plots of O_2 with height in first floor SW room and second floor corridor for Test MV1.

5.7 Smoke Detector Activation

As specified in Section 4.4.8, there are six smoke detector locations at 1) the fire room, 2) first floor corridor, 3) first floor SW room, 4) second floor SE room, 5) second floor corridor, and 6) second floor SW room.

Activation times from ignition for the Mircom system detectors are shown graphically in Fig. 33 for all four MV tests. Locations are numbered as listed above. It can be seen that there is little variation in activation time between tests at each location. More specifically, the detection times of each are within one minute of each other at each detector location. As would be expected, the detectors closest to the fire (in the fire room) activate first in all tests, between 2-3 minutes after ignition, and detectors on the second floor activate a significant amount of time later. In some cases, the second floor detectors activate up to two minutes after the first detector activation. At this time, approximately four minutes after ignition, the fire has begun to grow rapidly. A large delay in activation time between floors can allow for the buildup and circulation of toxic gases close to the floor, especially with enhanced mixing up the staircase. This highlights the importance of having interconnected smoke detectors and alarms to alert occupants to a fire as early as possible, giving occupants more time to escape.

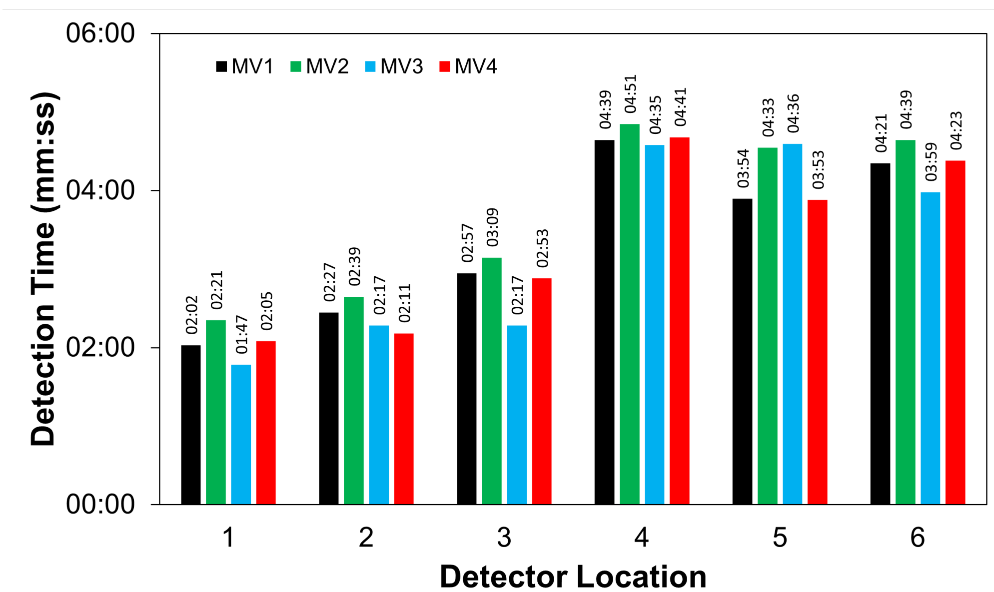


Figure 33: Smoke detector activations times at each location for MV series tests.

In all MV tests, the detectors activate between 2-5 minutes after ignition. Other results show that at two minutes the fire is just beginning to grow and the environment in the structure is beginning to develop. At this point, the smoke has yet to propagate to the second floor, O_2 concentrations are near ambient, temperatures have yet to rise, and toxic gas concentrations have not yet increased. Near the other end of this range, closer to five minutes, the fire has progressed to fully involve the first couch cushion and ignite the second. Oxygen concentrations are decreasing rapidly, temperatures are rising above 100^{o}C, and smoke is building up throughout the structure.

The period shortly after smoke detectors have activated, between approximately 5-10 minutes after ignition, is the period of severe under ventilation of the fire leading to particularly dangerous conditions for both occupants and firefighters. During this period temperatures reach their peak values throughout the structure and flows of smoke out of the fire room to other compartments reach maximum values, while O_2 concentrations decrease to their minimum levels in conjunction with other gas concentrations reaching maximum values. While further analysis of the detailed environments encountered in the various compartments during these tests is required, it appears that the potential exists for a range of rapid fire growth events to occur if a source of O_2 becomes available, for example during firefighter entrance or occupant egress.

6 Fuel Volatility Experimental Results

A final set of tests are run to characterize differences in the fire behaviour and environments established during a series of tests designed to study differences in the volatility and chemical makeup of fuels used in the FV test series. Due to variations in fuel characteristics, the fire growth and gaseous species production varies largely from test to test in this series with a few key results presented here.

6.1 Fire Growth

Differences in fire growth rates over time for each fuel included in the FV series can be seen through comparison of the times to peak fire MLR listed in Table 4. The time to peak MLR is much longer for less volatile fuels such as the wood cribs and fire retardant couches. The heptane pool fire grows fastest, as would be expected with a liquid fuel, while the wood cribs lead to slow growing and longer burning fires, taking the longest to reach peak values of MLR. In general, fires that ignited and spread exhibit times to peak MLR that fall between those of the heptane and wood crib fires. Also as anticipated, the couches constructed of fire retardant materials take longer times to reach peak fire MLR, since it often takes more time for the flames to initially establish in the fire retardant materials.

Similar to the MV tests, all the fires in the FV series also burn to extinction. The couch fires extinguish due to depletion of the oxygen in the structure, whereas the heptane fires extinguish when all the fuel is consumed and the wood crib fires extinguish due to a decrease in temperature which hindered propagation of the flames. Differences in rates of fire growth, decay, and extinction highlight, and are consistent with, the differences in burning characteristics of the different fuels.

Test FV6 is an interesting test since it takes a significantly longer time to reach peak MLR compared to any other test, at over 25 minutes. In this test, the flame from the Type 4 crib is able to establish itself on the faux-leather covering the cushion, but is not able to penetrate down to the foam. Therefore, the flame spreads slowly across the surface of the cushion until it reached the corner where the seat cushion, arm rest, and back cushion meet. From there, the flame is able to grow as it burns up the thinner covering material on the arm rest, thus creating enough heat for the fire to penetrate into the cushion. Following this, the fire continues to grow and extinguish due to depletion of oxygen in a similar manner as observed in the other tests.

Table 4: Time to peak MLR for each FV test.

Test	**Primary Fuel**	**Time to Peak MLR (mm:ss)**
FV0	Wood cribs 3x 24 sticks	13:54
FV1	Wood cribs 1x 36 sticks & 2x 18 sticks	13:57
FV2	Heptane 5L total 4 trays	2:07
FV3	Canadian non fire retardant faux-leather	7:41
FV4	Canadian non fire retardant leather	10:29
FV5	UK fire retardant cloth	N/A
FV6	UK fire retardant faux-leather	25:16
FV7	UK fire retardant leather	12:00
FV8	US fire retardant cloth	N/A
FV9	US fire retardant Leather	9:40

In two tests, namely FV5 and FV8, the couch does not ignite. Perhaps of most interest is FV5, since it is the UK fire retardant version of the Canadian couches burned in the MV tests. Images showing the burn patterns from a front and top view are shown in Figs. 34 and 35, respectively. The images show the impact of attempting to ignite the couch with successively larger Type 4, V, and VII ignition cribs. The burn patterns corresponding to the largest Type 7 crib clearly show that the fabric and part of the foam in the cushion has been burned through; however, even with this extensive burn through, a self-sustained flame is not created, and the fire extinguishes shortly after the ignition crib is consumed. It should be noted that this is the only couch that had a barrier liner in addition to fire retardant surface fabric and foam.

Figure 34: Front view of the FV5 couch showing burn patterns for each igniter crib.

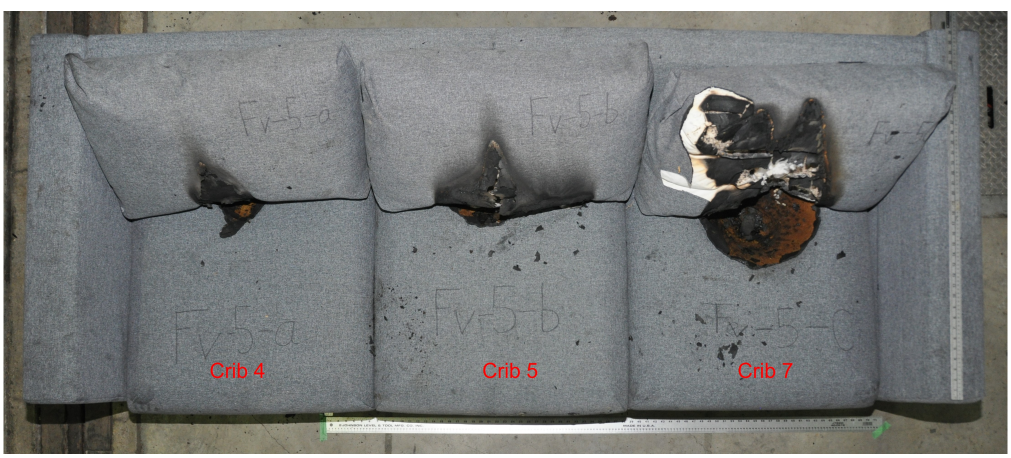


Figure 35: Top view of the FV5 couch showing burn patterns for each igniter crib.

6.2 Comparison of Environments

Differences in burning characteristics of each fuel coupled to differences in the chemical formulations of the fuels lead to creation of significantly different environments in the structure during the FV series fires. Difference in the overall environments are highlighted through the tabulation of minimum O_2 concentrations and times to minimum O_2 concentration listed in Table 5 for the fire room and the second floor SW room, all taken at the 0.9m height above the floor.

Table 5: Comparison of minimum O_2 concentrations in the FV tests.

	Fire Room		**Second Floor**	
Test	**Min. O_2 (%)**	**Time to Min. O_2 (mm:ss)**	**Min. O_2 (%)**	**Time to Min. O_2 (mm:ss)**
FV0	19.4	27:00	18.9	30:18
FV1	17.7	23:18	17.5	28:24
FV2	7.8	7:05	17.5	3:01
FV3	4.6	9:23	13.3	10:35
FV4	4.7	11:32	13.3	12:23
FV5	20.9	N/A	20.9	N/A
FV6	15.6	33:25	15.4	34:31
FV7	4.2	13:54	15.2	13:58
FV8	20.9	N/A	20.9	N/A
FV9	6.6	10:31	12.6	13:04

In general, the slower growing fires (wood cribs and couch used in Test FV6) are characterized by higher minimum concentrations of O_2 in the fire room, as well as longer times to reach the corresponding minimum concentrations. In these fires, unlike the fires in the other FV series tests and those discussed in the MV series, the minimum O_2 concentrations in the fire room are comparable, with 0.5% maximum difference, to those on the second floor. Such small differences may even be attributed to the uncertainty in concentration measurements, especially with higher temperatures in the fire room. The slower growth of the fire, therefore, appears to consistently provide more time for mixing and diffusion of smoke and gaseous species throughout the structure, leading to more uniform species concentrations across all locations.

Faster growing fires (heptane and the other couches) lead to lower minimum O_2 concentrations than the slow growing fires and shorter times are also taken to reach the minimum values in these fires. The concentrations of O_2 on the second floor are higher compared to those measured in the fire room, similar to the trends already discussed for the MV tests. Since faster growing fires consume O_2 at a higher rate, there is less time for diffusion and mixing, leading to larger differences in concentration between locations. This clearly shows that differences in fire behaviour, driven by differences in fuel volatility and composition, will lead to the development of significantly different environments across locations throughout the structure.

6.3 Smoke Detector Activation

Smoke detector activation times after ignition are shown in Fig. 36 for Test FV3 (Canadian non fire retardant faux-leather) and FV6 (UK fire retardant faux-leather). Large differences in activation times are seen at locations on the second floor and in the first floor SW room. In the fire room and first floor corridor, the activation times are less than one minute apart. The result is significant, since the fire in FV6 develops much more slowly than the fire in FV3, presumably giving occupants more time to escape the structure in the FV6 scenario.

In Test FV3, the delay in activation between locations is similar to that of the MV series of tests, where the second floor detectors activate up to two minutes after those on the first floor. In Test FV6, there is a significantly higher delay time (up to 20 minutes) between detector activation on the main and second floor. This can be explained by the combination of decreased smoke production with a smaller fire due to the fire retardants in the couch of FV6, and the cooling of smoke hindering propagation up to the second floor due to the smaller fire size in FV6. At the same time, further analysis of the details in the environment is necessary, since it is possible in FV6 that gaseous species are building up in the environment for some time during this delay period even though there may be insufficient particulate loading to trigger the detectors on the upper floor. When the second floor detectors activate approximately 22 minutes after ignition in FV6, the fire has developed to near its peak size, as indicated by the time to peak MLR (25 minutes after ignition). This further highlights the importance of interconnected smoke detectors and alarms, as occupants on the second floor could be alerted by the earlier detector activation on the lower floor.

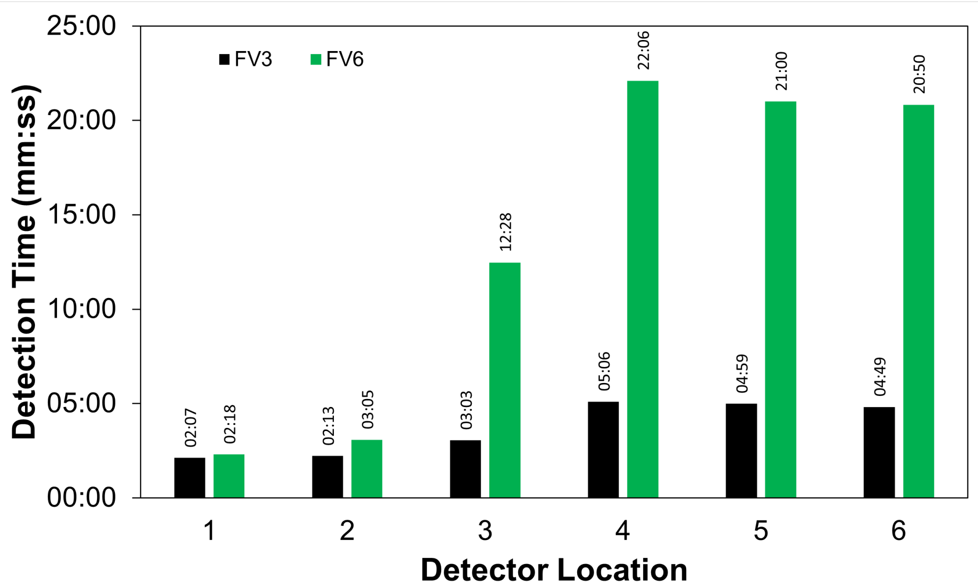


Figure 36: Smoke detector activations times at each location for tests FV3 and FV6.

7 Conclusion

Four furniture fire tests were conducted to investigate fire development, smoke flow, and environmental development in a two-storey structure under different ventilation and air recirculation conditions. Time varying distributions of temperature and major species concentration (oxygen, carbon monoxide and carbon dioxide) in the fire room, as well as in adjacent rooms and corridors on the same and different floors were presented. Results from an additional series of ten tests are presented to highlight several key characteristics of fire and environmental development during fires fueled by materials of different volatility and composition as well.

Based on the experimental data and results outlined, several interesting conclusions can be drawn related to the development of the fire environment throughout the structure.

- The early stages of fire growth appear to be fairly consistent across the range of ventilation configurations tested in the MV series of tests. Differences in the fire environment that develops during each test do, however, tend to become significant after the fires have reached peak values of MLR.
- The peak values of compartment temperature are slightly higher in the configurations of no external ventilation and 100% recirculation than for situations when 100% or 200% outdoor air is supplied.
- The O_2 concentrations decrease more slowly throughout the structure and lower peak concentrations of CO are measured as ventilation levels increase.
- For the level of ventilation tested in the FV series, slower growing fires tend to result

in higher minimum values of O_2 concentration and more uniform spatial distribution of species concentration throughout the structure.

- Flow patterns in areas such as the staircase in the present structure tend to promote mixing of hot smoke and fire gases from the upper layers of the fire compartment to areas closer to the floor in the upper compartments.
- Smoke detection times vary widely depending on both location of detector and fuel type, pointing to the potential importance of detector position within a floor area and having interconnected smoke detectors on both levels of a multi-compartment, multi-storey structure.
- The buildup of smoke and heat, coupled with low O_2 concentrations shortly after smoke detector activation, indicate a risk of rapid fire growth, and consequent safety concerns for emergency responders should outside air be introduced into the fire environment during this period.
- Overpressure from the fire in the burn room counter-flowed the air velocity in the ducts of two of the three ventilated MV tests. However, the MV3 test with double the supply air did not counterflow from the burn room. Further research is required in this area, but early findings suggest that any risk of back-pressure in the duct can be managed with increased air supply.

The results obtained expand existing knowledge of the environment encountered during ventilation-limited fires, particularly in more complex environments, and those reflective of single family homes. They point to several potential areas of risk relative to level of air-tightness and ventilation pathways, positioning of smoke alarms, and control of furniture and furniture materials. Overall, the findings have provided a starting point for additional work in this area, including the addition of much-needed data for fire models, new assessment of furniture fire development, original evaluation of some of the impacts of building air leakage during early fire growth and better definition of the probability of fire spread, as well as guidance with respect to ventilation and firefighter response. Finally, while it lays a foundation, it also opens the way for many opportunities by which to further study, address or mitigate risk in adverse fire conditions.

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Appendix A

The following figures show vectors of the gas flow measured for Test MV1 at the five key times used throughout this report. Velocity measurements are from the bottom probe (blue) and top probe (red) at each location.

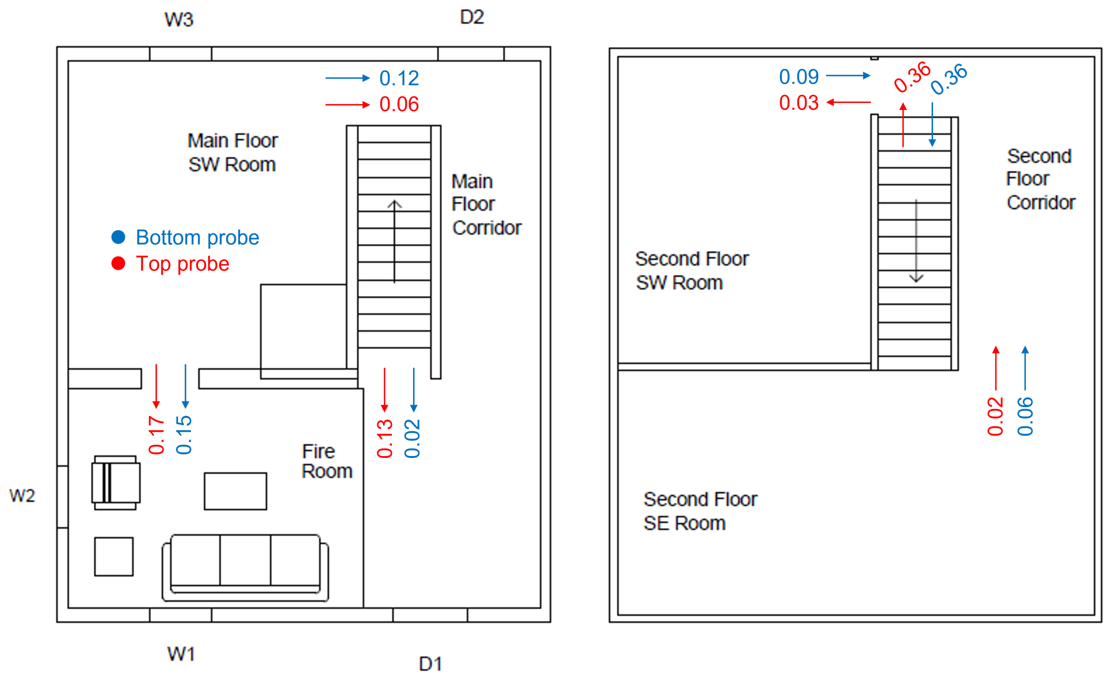

Figure 37: Flow direction and velocities for Test MV1 at 2:50 after ignition, when smoke descends to the top of W1.

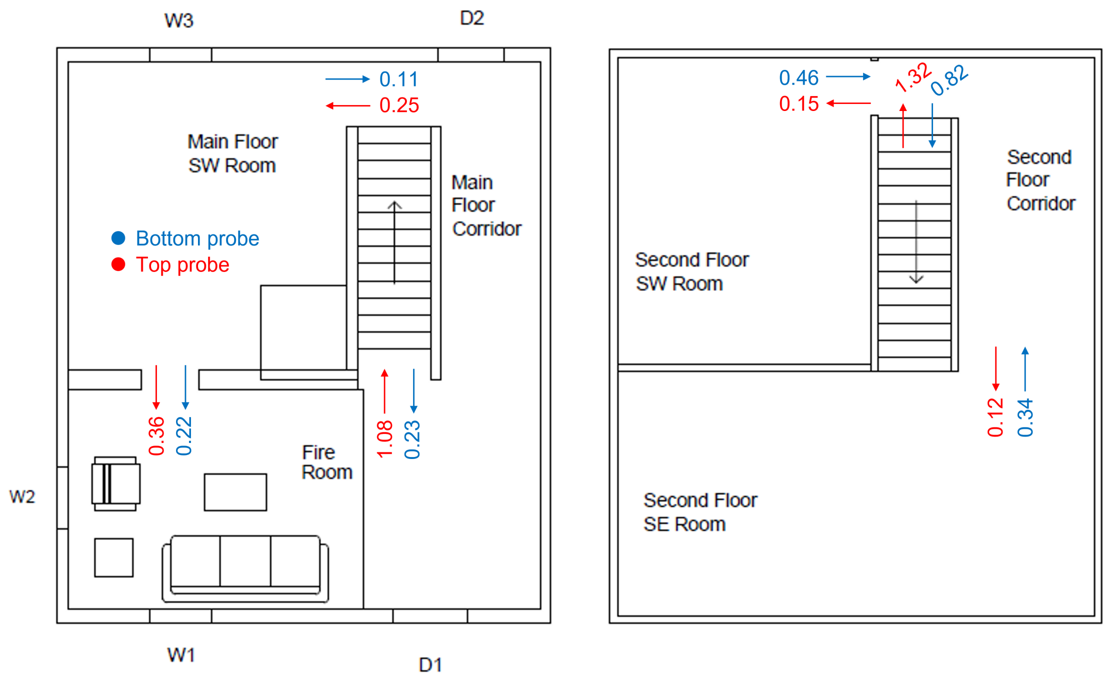

Figure 38: Flow direction and velocities for Test MV1 at 4:10 after ignition, when the second cushion ignites.

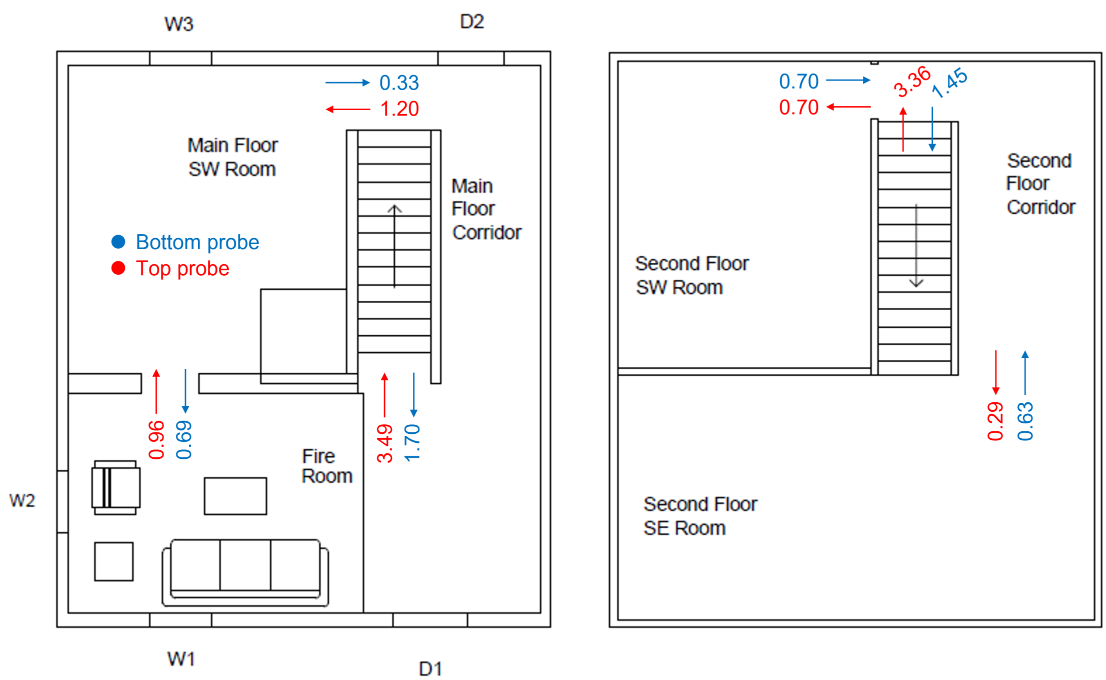

Figure 39: Flow direction and velocities for Test MV1 at 6:00 after ignition, when peak MLR is reached.

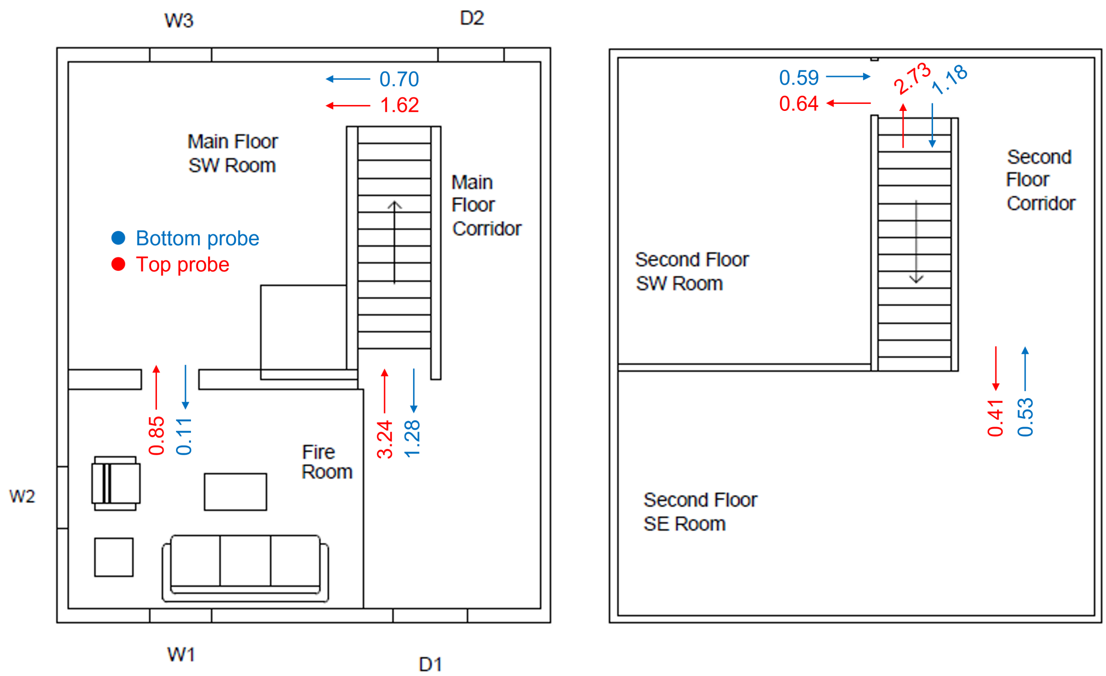

Figure 40: Flow direction and velocities for Test MV1 at 7:30 after ignition, when peak MLR is reached.

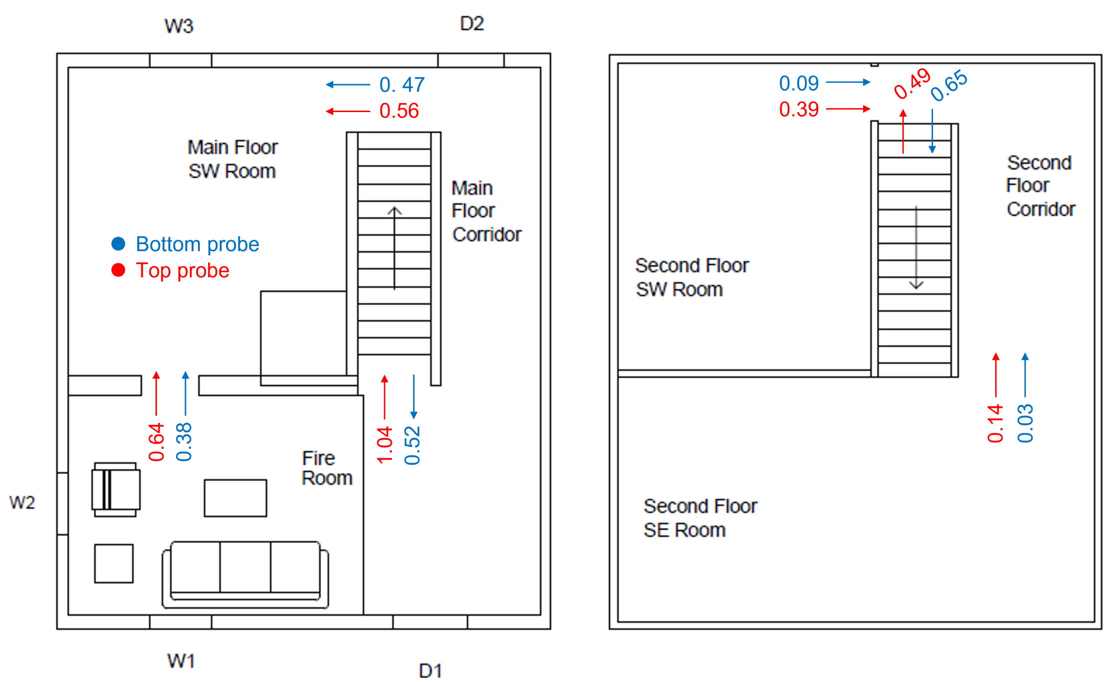

Figure 41: Flow direction and velocities for Test MV1 at 15:10 after ignition, near the time of flow reversal.