

NIST Technical Note 1870

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List of Acronyms

EMS	Emergency Medical Services
FDS	Fire Dynamics Simulator
HGL	Hot Gas Layer
HRR	Heat Release Rate
HRRPUA	Heat Release Rate per Unit Area
LODD	Line of Duty Death
NIST	National Institute of Standards and Technology
PPE	Personal Protective Equipment
SCBA	Self Contained Breathing Apparatus
SFPE	Society of Fire Protection Engineers

List of Symbols

ft	foot
m	meter
min	minute
Pa	Pascal
psi	pound per square inch
s	second
W	Watt
k	thermal conductivity
ρ	density
c_p	specific heat

Abstract

Fire Dynamics Simulator (FDS), which is a fire model that is developed and maintained by the National Institute of Standards and Technology (NIST), was used to provide insight into the dynamics of a fire that occurred on February 24, 2012, within a single-story, single-family residential structure in Riverdale Heights, MD, that resulted in the serious injury of two Prince George's County firefighters. The inputs for the FDS simulation are documented in this report and are based on the fire scenario, including the building geometry, interior furnishings, and ventilation conditions. The fire started in the basement which generated ventilation limited (fuel rich) fire conditions in the basement area. After the front door was opened, the interior stairwell, aided by strong winds blowing into the basement, acted as a chimney for hot gases in the basement to flow towards regions of lower pressure, out through the front door. The temperature of the gases in the interior stairwell was estimated to be in excess of 400 °C (750 °F). Two firefighters were located in the flow path between the interior stairwell door and the front door of the structure, were exposed to these elevated temperatures, and suffered serious burn injuries. Five additional firefighters were injured during fire operations on the first floor.

Section 1

Introduction

Part of the function of the Fire Research Division at the National Institute of Standards and Technology (NIST) is to develop and apply technology, measurements, and standards to improve the understanding of the behavior, prevention, and control of fires to enhance fire fighting operations and equipment, fire suppression, fire investigations, and disaster response. NIST has previously used the Fire Dynamics Simulator (FDS) fire model to provide insight into the fire development and thermal conditions of fires that have resulted in line of duty deaths (LODDs) [1–7]. The objective of these studies has been to improve the safety and effectiveness of firefighters.

On February 24, 2012, a fire in an uninhabited residential structure injured seven Prince George's County firefighters. NIST examined the fire dynamics of this incident at the request of the Prince George's Country Fire/Emergency Medical Services (EMS) Department. Computer simulations of the fire incident were conducted using the NIST Fire Dynamics Simulator [8] and Smokeview [9] software to provide insight into the fire development and thermal conditions that likely existed inside the residence during the fire. The specific objectives of the simulations detailed in this report are:

1. To examine the effect of the flow path (including temperature, pressure, and fire conditions) in this single-story residential structure with a basement using physics-based calculations.
2. To provide visualizations of the fire behavior that are representative of the conditions that members of the Prince George's Fire Department likely experienced during the course of their interior operations.
3. To provide a basis for analyzing tactical operations in terms of fire dynamics.

This document describes the input and the results of the FDS (version 6.1.1) simulations. The simulations were developed using a combination of knowledge of the fire scenario and appropriate engineering approximations and assumptions. Analysis of the simulation results focuses on the hazardous conditions that developed following the development of a flow path inside of the structure. This document is organized as follows: Section 2 provides a summary of the fire incident, Section 3 describes the relevant model input parameters and assumptions that were used to develop the simulations, Section 4 presents the simulation results, and Section 5 discusses the simulation results as they relate to firefighter safety and effectiveness. Appendix A contains dimensioned drawings of the basement and first floor of the structure.

Section 2

Fire Incident Summary

The account of events for this incident was documented by the Safety Investigation Team of the Prince George's County Fire/EMS Department [10]. At 21:11 hours on February 24, 2012 Prince George's Fire/EMS Department responded to a residential structure fire in Riverdale Heights, Maryland with a fire in the basement [10]. For the purpose of this analysis, the details regarding the timeline are considered to be approximate values. The Prince George's County report [10] includes narratives of actions of the response personnel. Note that term following the apparatus number (e.g. Truck 809 Can) refers to the seating assignment and operational duties of the firefighters on board. The following narrative of the incident, focused on the events which led to serious burn injuries to two emergency-personnel, was taken from the Prince George's County report [10]:

Truck 809 responded from quarters, as the first due truck company, and arrived on 57th Avenue right behind Engine 807B. When Truck 809 stopped to let Engine 807B layout, Truck 809 Can dismounted the truck and had to walk up the street as it pulled away. Truck 809 Officer observed a lot of smoke moving extremely fast through the front yard and across the street upon exiting the truck. Truck 809 Officer and Truck 809 Forcible Entry proceeded directly to the front door . . . of the structure. Both of them entered the structure with full PPE, including SCBA, but without the protection of a hose line. Truck 809 Officer and Truck 809 Forcible Entry began primary searches on the first floor. At some point during the primary search, as conditions worsened, the front door closed, trapping Truck 809 Officer and Truck 809 Forcible Entry inside the structure. This situation could not have occurred if a charged hose line was operating inside the structure at the time the door slammed shut. They were the only firefighters operating on the first floor at that time.

Truck 809 Forcible Entry was unable to self-evacuate, and remained trapped inside. Due to rapidly deteriorating conditions, Truck 809 Officer was forced to self-rescue through another small window on [the front of the structure].

After exiting the structure, Truck 809 Officer [alerted other firefighters] that a firefighter was trapped inside. Truck 809 Officer then proceeded to the front door . . . in an attempt to search for and rescue Truck 809 Forcible Entry, who was trapped inside. At this point multiple firefighters on the exterior assisted Truck 809 Officer in the search, rescue, and removal of Truck 809 Forcible Entry. Both Truck 809 Officer and Truck 809 Forcible Entry sustained serious injuries and were transported to MedStar/Washington Hospital Center.

From a combination of on-scene video and the narrative accounts from the Prince George's County Fire/EMS Department report [10], Table 2.1 shows an overview of the timeline of events. Table 2.1 represents the best estimate of the events.

Table 2.1: Abridged Prince George's Fire/EMS approximate fire event timeline [10].

Incident Time [hh:mm:ss]	Fire Behavior / Fireground Operation
21:08:26	First 911 call is made.
21:11:03	Dispatch for a "box" alarm assignment- four engine companies, two truck companies, one rescue squad, and a commanding officer.
21:12:55	First unit (Engine 807B) arrived on-scene.
21:13:44	Volunteer Chief 809A establishes incident command (IC).
21:13:56	Truck 809 arrived on-scene.
21:14:00	Front door opened.
21:14:42	Truck 809 personnel enter structure.
21:15:47	Basement door opened and water applied to fire. Front door blown closed.
21:15:51	Lower pane of front egress window broken.
21:16:01	Top pane of front egress window broken.
21:16:16	Truck 809 officer bailout through front window.
21:16:44	Front door opened.
21:17:15	Truck 809 forcible entry firefighter rescued.

Section 3

Model Description

Fire Dynamics Simulator [8] is a computational fluid dynamics (CFD) model that solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires. Within a CFD model, the room or building is divided into small three-dimensional rectangular control volumes or computational cells. The cells are contained together within one larger volume known as a computational domain. The CFD model computes the density, velocity, temperature, pressure, and species concentration of the gas in each cell. Based on the laws of conservation of mass, momentum, and energy, the model tracks the generation and movement of fire gases. One of the most important advantages of FDS is that it is mathematically verified [11] and validated against fire test data to ensure that it provides the expected results, given sufficient input data [12]. A complete description of the FDS model is provided in the FDS Technical Reference Guide [13].

Smokeview is a software tool designed to visualize simulation results from FDS [9]. Smokeview visualizes smoke and other attributes of the fire simulation using traditional scientific methods such as displaying tracer particle flow, two dimensional (2D) or three dimensional (3D) shaded contours of gas flow data such as temperature and flow vectors showing flow direction and magnitude. Smokeview allows the fire and fire movement to be visualized. This is done by displaying a series of partially transparent planes where the transparencies in each plane (at each grid node) are determined from soot densities computed by FDS. Smokeview also visualizes static data at particular times using 2D or 3D contours of data such as temperature and flow vectors showing flow direction and magnitude.

Input data from various sources must be collected and documented to simulate a fire using FDS or any other fire model. For the simulation results presented in this document, information was obtained from two primary sources. The following information was gathered from the fire scene: the geometry of the building and the compartments being modeled, the size and location of exterior and interior ventilation openings, and documentation of fire damage to the building. The following information was gathered from witnesses, first responders, reports, and recorded media such as fire ground radios or videos: information on the timing of the fire development, the sequence and approximate timing of ventilation openings to the outside, and weather conditions at the time of the fire.

The analysis of the simulation results is focused on the impact of ventilation. Specifically on the interior conditions of the first floor following the establishment of a flow path through door control and how wind impacted these conditions. Based on the goals of the analysis and the information

collected, several engineering approximations were made. For example, heavy smoke conditions were reported at the front of the house at the time of arrival [10]; however, the exact ignition time, fire growth rate, and heat release rate (HRR) of the fire were not known. The ignition time and growth rate were estimated to reduce the amount of required calculation time while adhering to the event timeline (Table 2.1) and documented observations. The HRR of the fire was estimated using documentation of the potential fuel load within the structure and relevant literature.

3.1 Geometry

The structure involved in this fire incident was a single-story, single-family structure with a basement. The structure was platform-framed wood construction with a gable roof.¹ The structure had a first floor footprint of 9.14 m (30 ft) by 7.77 m (25.5 ft) with the basement being slightly smaller, 9.14 m (30 ft) by 7.16 m (23.5 ft), as shown in Fig. 3.2. This resulted in a first floor area of 71 m² (764 ft²) and a basement floor area of 65 m² (700 ft²). The interior walls were composed of gypsum board over wood framing [10]. There was a single flight of stairs in the center of the structure which connected the first floor to the basement.

The structure was built on a sloped landscape such that on the front side of the structure the first floor was located at street level but the basement was below street level (Fig. 3.1). On the rear side of the structure, the slope allowed the basement to be a walkout. Therefore, access to the structure could be made on the front side to the first floor and on the rear side to the basement.



Figure 3.1: Photograph taken from front side street level showing the slope down to basement on the rear side of the structure (left) and Smokeview rendering of model representation of sloped landscape (right).

The fire, which is described in Section 3.2, started in the basement and spread to the stairs

¹Platform-framed construction means that floor joists are completely covered with a sub-floor. This forms a platform from which walls are built.

which connect to the first floor. The door at the top of the stairs was open at the time of the fire. Discussion of the fire's impact on the interior conditions is provided in Section 4. Figure 3.3 shows the exterior of the front and rear of the structure after the incident. Note that the majority of the damage occurred in the basement of the structure. Fully dimensioned drawings of the interior of the basement and first floor are shown in Figs. A.1 and A.2, respectively.

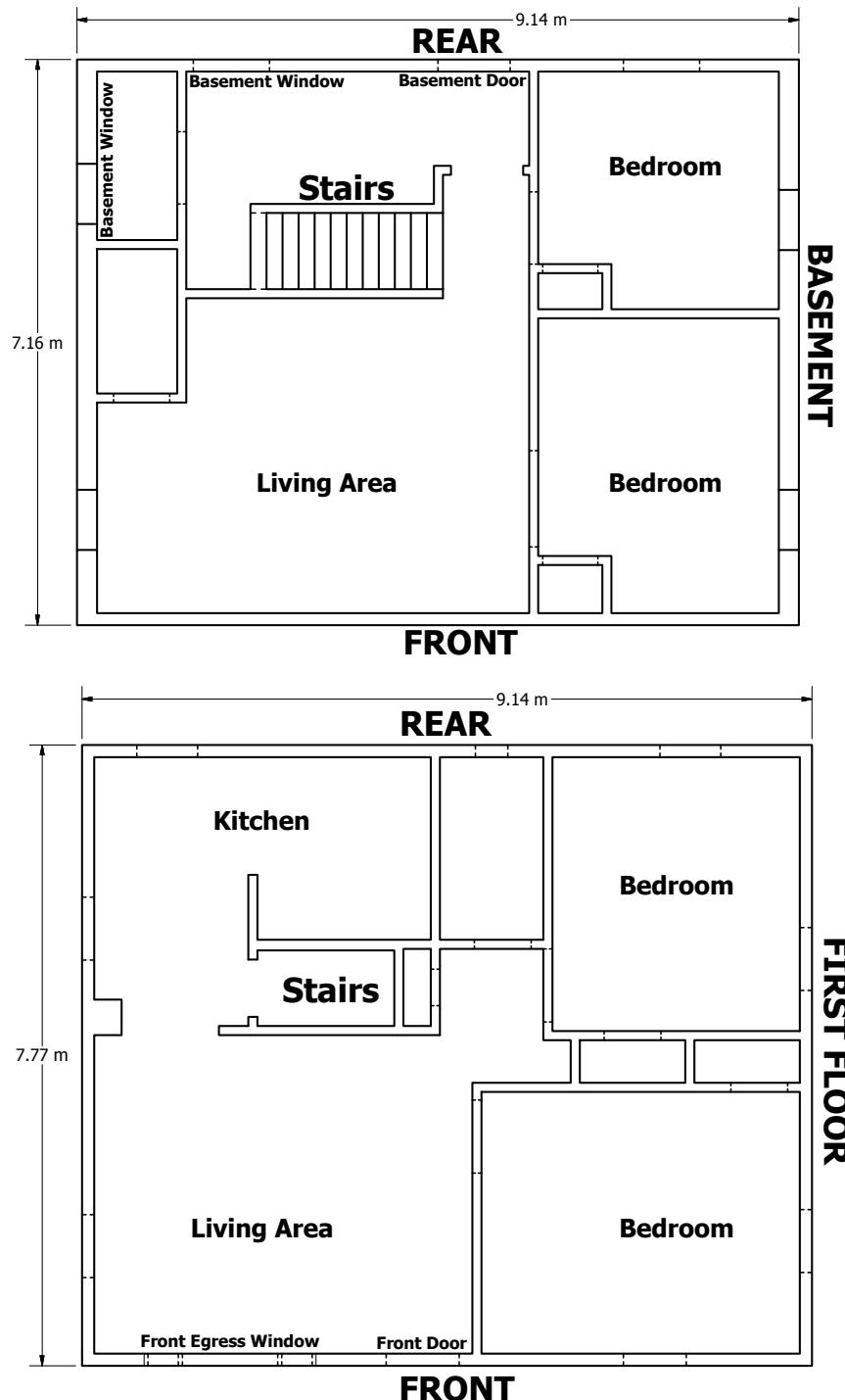


Figure 3.2: Plan view of basement (top) and first (bottom) floor of structure. Stairs and key windows and doors are identified using measurements collected by NIST.



Figure 3.3: Photographs showing the front (top) and rear (bottom) exterior of the structure after the incident.

3.2 Fire

To estimate the type of fuel, fire size, and structure ventilation, on-scene videos and post-incident reports were used. Based on these sources of information, the FDS model includes two source fire locations in the basement: one fire in the kitchen area and one in the adjacent bathroom (Fig. 3.4). At the time of the fire, the structure was unfurnished so the dominant fuel was wood: wood paneling on walls, exposed ceiling joists, sub-floor, cabinets, and stairs.

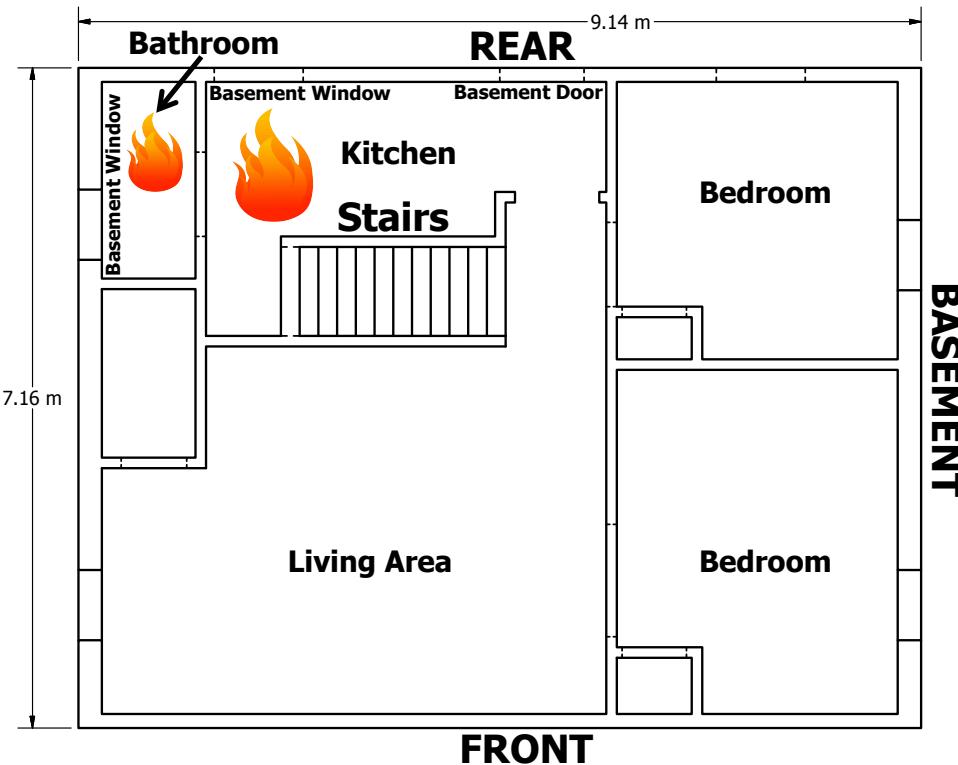
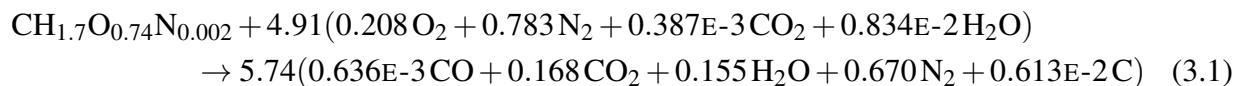


Figure 3.4: Plan view of the basement indicating the location of the two fires in the FDS model.

Wood fuel can be represented by the chemical formula, $\text{CH}_{1.7}\text{O}_{0.74}\text{N}_{0.002}$, with specified yields of carbon monoxide ($y_{\text{CO}} = 0.004 \text{ kg/kg}$) and soot ($y_{\text{C}} = 0.015 \text{ kg/kg}$) [14]. The product yields are expressed in terms of the amount of carbon monoxide or soot emitted per unit mass of fuel consumed (kg/kg) and can be found in the Society of Fire Protection Engineers (SFPE) Handbook [14]. A balanced chemical reaction for wood combustion can be written as:



The value for the heat of combustion of wood used in this simulation was 16,400 kJ/kg, based on data provided in the SFPE Handbook [14]. The heat of combustion quantifies the amount of energy per unit mass of the fuel. The following text defines Eq. 3.1 for an FDS input file with the desired fuel and reaction properties discussed above:

```

&SPEC ID='WOOD', FORMULA='CH1.700.74N0.002' /

&REAC ID = 'wood'
  FUEL = 'WOOD',
  HEAT_OF_COMBUSTION = 16400,
  SOOT_YIELD = 0.015,
  CO_YIELD = 0.004/

```

Note that using the input lines above will invoke the simple chemistry reaction mechanism in FDS in which fuel and air react to form only CO₂, CO, H₂O, soot, and N₂. If the inclusion for other combustion products is desired, then the user must explicitly define those species and the chemical reaction that produces them [8]. Based on the above input lines, FDS uses the default, mixing-controlled fast chemistry combustion model. This mechanism states that the rate of fuel consumption is proportional to both the local limiting reactant concentration and the local rate of mixing. Extinction is based on the critical flame temperature approach [13]. While FDS provides users with the option to use a more complex finite-rate combustion mechanism, there is not sufficient evidence in this case to justify deviating from the default specifications.

To estimate the heat release rate per unit area (HRRPUA) of wood, Babrauskas and Grayson [15] conducted experiments in a cone calorimeter² to determine the 5-min average of the HRRPUA for several different types of wood over a range of radiant heat fluxes. The results of that study indicate that the HRRPUA for different types of wood is approximately 50 kW/m².

To calculate the total fire size, the appropriate burning area of the basement needed to be determined. Based on the floor plan of the structure and post-incident images, two distinct fires were considered: 1 source in the basement bathroom and 1 source in the basement kitchen. The bathroom fire was estimated to be comprised of wood paneling along the four walls (17.3 m² or 186 ft²) and wood subfloors and studs along the ceiling (2.9 m² or 31 ft²). This resulted in 20.2 m² (217 ft²) of wood burning surface area or a 1 MW fire using a 50 kW/m² HRRPUA. The remainder of the wood combustible load in the basement was lumped into the localized kitchen fire. The ceiling and wall areas included in the basement kitchen, stairway, and main living area totaled approximately 86 m² (926 ft²). This resulted in a 4.3 MW fire.

Initial simulations were conducted using a HRR for the two fires totaling 5.3 MW, however, the fire behavior did not align with observations made during the fire incident or post-incident images. Specifically there was insufficient fuel to drive the basement to an underventilated condition. One reason is that while the structure was unoccupied at the time of the fire [10], there were additional fuels that were not accounted for: transient fuels, sparse kitchen cabinetry, and an unknown bathroom vanity among other fuels. A second reason is that the 50 kW/m² HRRPUA used to estimate the fire size does not account for an observed increase in burning rate during wind driven fires [17, 18]. It is not clear how to quantify the impact of wind on burning rate within a structure from first principles, so several iterations of the model with increased fire sizes were run. The final estimated fire size was a 1.8 MW fire in the bathroom and a 6.8 MW fire in the kitchen. This resulted in a total peak specified fire size of 8.6 MW.

Since the time at which the fire started is not known relative to the notification of a fire or how fast the fire spread, several simplifications were made. The fires started at the beginning of the

²The cone calorimeter is an experimental apparatus used to gather data about ignition time, mass loss, combustion products, and heat release rate among other properties associated with burning small samples of materials [16].

simulation and increased to a value of 8.6 MW in 10 s. The 10-s ramp up time was used to prevent abrupt changes in the velocity at the fire boundary condition in FDS. Since the actual ignition time is unknown, the fire was ramped quickly to reflect the conditions determined from reports and post-incident images. The second assumption is that the sources of the gas phase wood fuel have constant areas at fixed locations in the basement (1 source for the kitchen, 1 source for the bathroom). At 207 s, using a simple decay model, the fire size decreases linearly to 25 % of its peak value in 60 s. This is to account for the impact of firefighters putting water on the basement fire (Table 2.1). The following lines define the source fires in the FDS input file:

```
&SURF ID='burner1', HRRPUA = 2000, COLOR='BURNT ORANGE', RAMP_Q='BURN' /
&SURF ID='burner2', HRRPUA = 4500, COLOR='BURNT ORANGE', RAMP_Q='BURN' /

&RAMP ID='BURN', T = 0, F = 0. /
&RAMP ID='BURN', T = 10, F = 1.0 /
&RAMP ID='BURN', T = 207, F = 1.0 /
&RAMP ID='BURN', T = 267, F = 0.25 /
&RAMP ID='BURN', T = 300, F = 0.25 /

&OBST XB=0.6,1.2,5,6.5,0.0,0.4, SURF_IDS='burner1','INERT','INERT' / Burner1
&OBST XB=2.5,4,5.0,6.0,0.0,0.4, SURF_IDS='burner2','INERT','INERT' / Burner2
```

Note that the coordinates here are unique for the vents are specific to the input files used for these simulations. The key point is the 2-D planar area.

Figure 3.5 shows the overall prescribed design fire for this scenario, which is the sum of the HRRs of the two source fires. In this figure, the text indicates the prescribed steady peak HRR and the decay phase associated with firefighter water application. Note that the prescribed HRR can be different than the simulated HRR calculated by FDS based on the amount of available fuel, oxygen, and ventilation. A comparison of the prescribed HRR and the simulated HRR is discussed in Section 4.1.

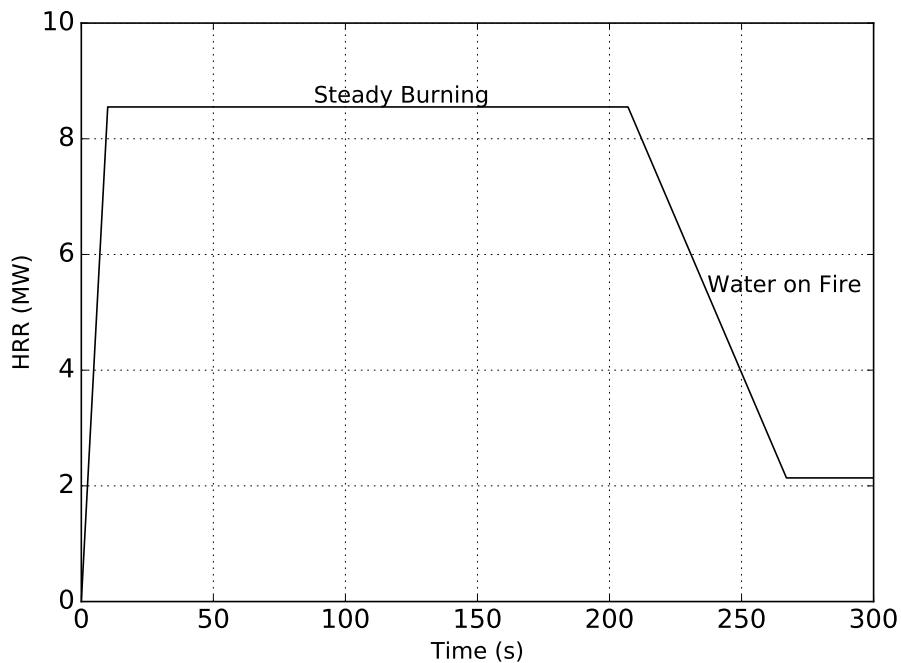


Figure 3.5: Prescribed HRR vs. time for the simulation. The text labels indicate the prescribed steady peak HRR and the decay phase associated with firefighter water application. Time zero represents 21:21:20, see Table 4.1.

3.3 Materials

While the fires were represented as fuel sources with a constant area (Section 3.2), from a heat transfer perspective, it is important to define the material properties (density, thermal conductivity, and specific heat) to account for heat transfer and energy storage in the ceiling, walls, and floor. In this study, the material properties of gypsum board [19] were specified on the finished walls and ceilings on the main two floors of the structure, and the material properties of wood [20] were specified on the unfinished portions of the structure. The following lines define these materials in the FDS input file:

```
&MATL ID = 'GYPSUM BOARD'
    FYI = 'Wakili - Journal of Fire Sciences 2007'
    CONDUCTIVITY = 0.28
    SPECIFIC_HEAT = 1.0
    DENSITY = 810. /

&MATL ID = 'WOOD MAT'
    FYI = 'Incropera and DeWitt, Fundamentals of Heat and Mass Transfer'
    CONDUCTIVITY = 0.12
    SPECIFIC_HEAT = 1.38
    DENSITY = 510. /
```

3.4 Ventilation

The simulation in this study accounts for changes in the ventilation due to a combination of fire department operations (opening doors), fire acting on the structure (fire breaching windows) and wind (restricting flow, closing doors). The ventilation times and ventilation areas represent the best understanding of the incident. The estimated times of ventilation changes for doors and windows are provided in Table 3.1.

During the time when the firefighters exited the structure or were rescued from the structure, the state of some windows and doors in the structure was known. The state of the vents (opened versus closed) resulted in the establishment of a flow path in the interior stairwell leading from the basement to the first floor. The exact time of operation for other doors/windows was not known. Therefore, the two basement windows on the left rear corner of the structure were assumed to be open at the start of the simulation. The states of the front door and front window were specified at certain times based on observations (i.e. forcible entry, wind effects, forced window breakage) from post-incident reports.

Structure leakage has been shown to be important when modeling enclosure fires [21]. The open rear basement windows at the start of the simulation were significantly larger than the typical total effective area of leakage of a structure of this type. Therefore, any leakage in the structure would have a negligible impact on the fluid mechanics within the structure and is not included in this study.

In addition to the state of openings within the structure, outlined in Table 3.1, an 8.9 m/s (20 mph) wind velocity boundary condition was assumed. The flow direction of the wind was assumed from the rear toward the front of the structure, perpendicular to the rear of the structure.

Table 3.1: Timeline of ventilation changes in the simulation.

Baseline Simulation [s]	Ventilation Area [m ²]	Type	State of Opening	Side of Structure
0	1.40	Window	Opened	Rear
0	0.39	Window	Opened	Left
100	1.84	Door	Opened	Front
207	1.84	Door	Closed	Front
207	1.84	Door	Opened	Rear
211	0.26	Window	Opened	Front
221	0.26	Window	Opened	Front
267	1.84	Door	Opened	Front

Based on local weather conditions, mean wind velocities ranged between 4.5 m/s (10 mph) and 8.9 m/s (20 mph) with gusts up to 13.4 m/s (30 mph) with a direction that angled toward the back left of the structure [10]. The following lines define the wind boundary condition in the FDS input file:

```
&SURF ID='wind', VEL=-8.94, RAMP_V='WIND RAMP', COLOR='INVISIBLE' /
&VENT MB = 'YMAX', SURF_ID = 'wind' /
&RAMP ID='WIND RAMP', T=0,F=0.25 /
&RAMP ID='WIND RAMP', T=10,F=0.50 /
&RAMP ID='WIND RAMP', T=20,F=0.75 /
&RAMP ID='WIND RAMP', T=30,F=1.00 /
```

Note that there is a 30 s ramp time to reach peak wind speed. This was included to prevent an abrupt change at the FDS domain boundary. Since the front door does not open until 100 s into the simulation there was sufficient time to for the airflow to stabilize.

3.5 Numerical Mesh

For the simulation, a measure of how well the flow field is resolved can be estimated by using the non-dimensional expression $D^*/\delta x$. Here, D^* is the characteristic fire diameter, δx is the nominal size of a mesh cell, and \dot{Q} is the total heat release rate of the fire:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{3}} \quad (3.2)$$

From the FDS User's Guide [8], the characteristic fire diameter is related to the characteristic fire size via the relation $Q^* = (D^*/D)^{5/2}$. Here, D is the physical diameter of the base of the fire specified in the simulation. Following Eq. 3.2 and using a grid cell size of 10 cm (3.9 in), the characteristic fire diameter to cell size ($D^*/\delta x$) ratio is 12 for the 1.8 MW bathroom fire and 20 for the 6.75 MW basement fire. Based on validation work performed for the U.S. Nuclear Regulatory Commission, $D^*/\delta x$ values ranged between 4 and 16 [22] and produced results that were adequate for engineering calculations. The grid resolution used in this model is within or exceeds typical engineering $D^*/\delta x$ values.

As discussed in Section 3.1, the structure has dimensions of 9.14 m (30 ft) by 7.62 m (25 ft) and a total height of 7.31 m (24 ft). To sufficiently resolve the wind boundary condition, the computational domain was extended beyond the volume of the structure. The large domain led to the use of two separate grid resolutions, a 10 cm (3.9 in) resolution and a 20 cm (7.8 in) resolution. The 10 cm resolution encompassed the structure with a total volume 14 m (46 ft) by 12 m (39ft) by 8 m (26 ft) that required a total of 1.3 million computational cells. As a result, all of the input model geometry lengths, ventilation openings (holes, doors, and windows), and fire areas will snap to the nearest 10 cm. The 20 cm grid resolution extended the computational domain 5 m to the left and right sides and 4 m behind the 10 cm mesh to provide sufficient computational domain for the wind profile to develop around the structure. The mesh is coarser to cut down on computational time and because high accuracy in the fluid mechanics of the air flow far from the structure is not important in the analysis of this simulation. The 20 cm resolution resulted in an additional 216 000 computational cells.

Figure 3.6 shows the front and rear of the structure and surrounding domain rendered in Smokeview with the 10 cm and 20 cm meshes. Note the finer mesh (smaller cells) surrounding the structure and the coarser mesh on each side. The domain was divided into 12 equally sized 10 cm meshes that surrounded the structure (each containing 150 000 grid cells) plus 4 equally sized 20 cm meshes to the left and right of the structure (each containing 32 000 grid cells) and one 20 cm mesh in the rear of the structure (containing 56 000 grid cells) for a total of 17 meshes. Multiple meshes allowed the simulation to be processed in parallel, which reduced the amount of required calculation time to approximately 3 days from over 1 week with a uniform 10 cm mesh. Figure 3.7 shows the entire structure within the computational domain that has been divided into multiple meshes. The boundary between the twelve 10 cm meshes and five 20 cm meshes is indicated by the **bold** lines.

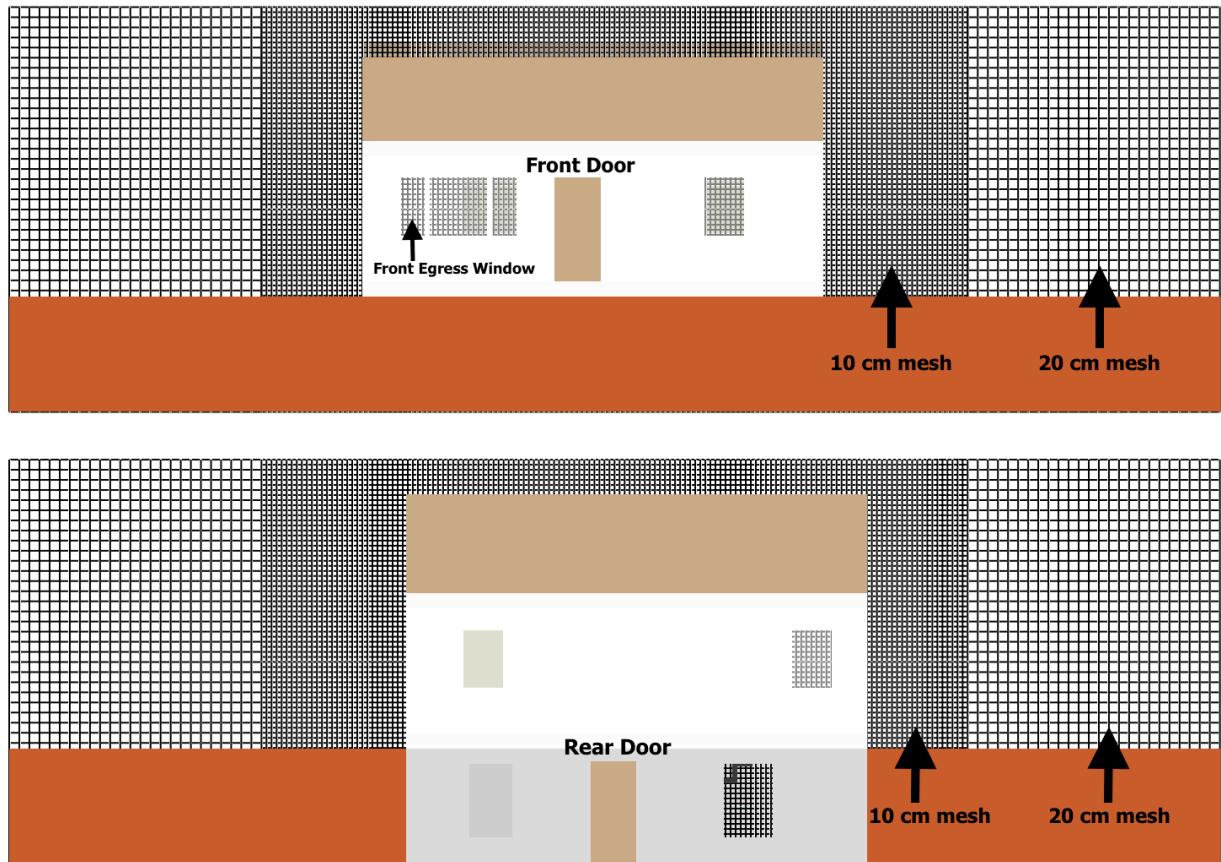


Figure 3.6: Front (top) and rear (bottom) of the structure with 10 cm computational mesh surrounding the structure and 20 cm mesh to the left and right of the structure.

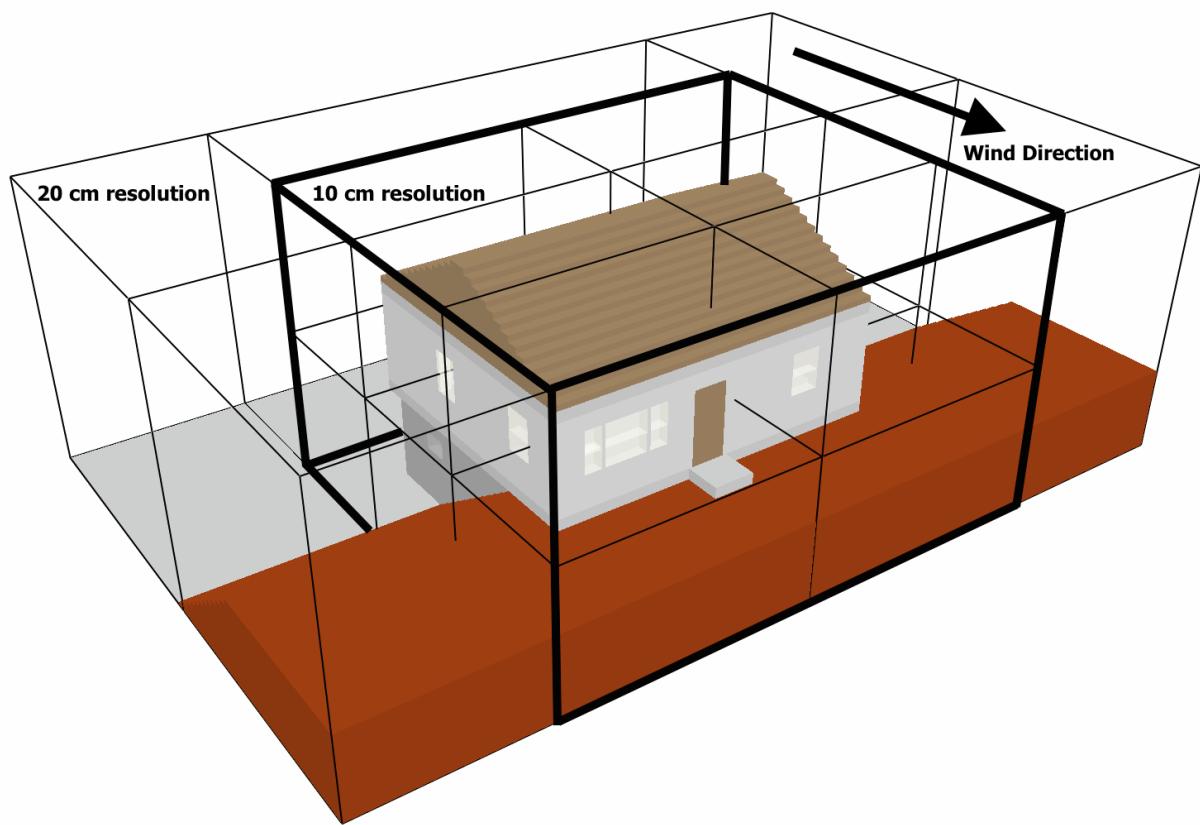


Figure 3.7: Overhead front-left view of the structure within the computational domain (with 17 meshes). The entire computational domain was 24 m (79 ft) by 16 m (53 ft) by 8 m (26 ft).

3.6 Summary of Model Input Parameters

Table 3.2 shows a summary of the model input parameters for the simulation that was conducted as part of this study. In reality, the quantities associated with model input parameters are not fixed values; rather, a model input parameter can be thought of as a point estimate from a distribution of possible input parameters with some associated amount of uncertainty. Any change in an input parameter (such as the HRR) for a given scenario results in a change in the output quantity (such as the hot gas layer (HGL) temperature).

For example, according to the McCaffrey, Quintiere, and Harkleroad [23] empirical correlation, the HGL temperature in a well-ventilated compartment fire is proportional to the HRR raised to the two-thirds power. Following this relationship, a 7.5 % increase in the HRR would result in a 5 % increase in the HGL temperature [24]. More detailed discussion on the propagation of parameter uncertainty in fire models is available in a validation study that was sponsored by the U.S. Nuclear Regulatory Commission [24].

Table 3.2: Relevant fire model input parameters.

Parameter	Description	Discussion
Simulation Time	5 min	–
Grid Cell Size	10 cm around house 20 cm for wind	Section 3.5
Ambient Temperature*	20 °C (68 °F) Formula: $\text{CH}_{1.7}\text{O}_{0.74}\text{N}_{0.002}$	–
Reaction: Wood [14]	CO Yield: 0.004 kg/kg Soot Yield: 0.015 kg/kg Heat of Combustion: 16,400 kJ/kg	Section 3.2
Peak HRR	Basement Fire: 6.75 MW Bathroom Fire: 1.8 MW	Section 3.2
Material: Wood [20]	k : 0.12 W/(m · K) ρ : 510 kg/m ³ c_p : 1.38 kJ/(kg · K)	Section 3.3
Material: Gypsum Board [19]	k : 0.28 W/(m · K) ρ : 810 kg/m ³ c_p : 1.0 kJ/(kg · K)	Section 3.3
Wind	8.9 m/s (20 mph)	Section 3.4

*Initial interior temperatures were assumed to be 20 °C; exterior temperatures were 10 °C [10].

Section 4

Model Results

To examine the results of the simulation, it is important to link the timelines from the fire scene to the simulation times. Table 4.1 shows the fireground timeline [10] along with the corresponding simulation times.

Table 4.1: Fire incident and simulation event timeline.

Incident Time (hh:mm:ss)	Simulation Time (s)	Fire Behavior / Fireground Operation
21:08:26		First 911 call is made.
21:11:03		Dispatch for a “box” alarm assignment- four engine companies two truck companies, one rescue squad, and a commanding officer.
21:21:20	0	FDS simulation begins.
21:12:55		First unit (Engine 807B) arrived on-scene.
21:13:44		Volunteer Chief 809A establishes incident command (IC).
21:13:56		Truck 809 arrived on-scene.
21:14:00	100	Front door opened.
21:14:42		Truck 809 enters structure.
21:15:47	207	Front door closed over. Basement door opened and water applied to fire.
21:15:51	211	Lower pane of front egress window broken.
21:16:01	221	Top pane of front egress window broken.
21:16:16		Truck 809 officer bailout through front window.
21:16:47	267	Front door opened.
21:17:15		Truck 809 forcible entry firefighter rescued.

For specific information regarding ventilation areas used in the simulation, refer to Table 3.1.

4.1 Heat Release Rate

In FDS, a HRR must be specified, which results in a specified amount of fuel vapor (or pyrolyzate) being released from a fuel surface. FDS then determines the amount of combustion that occurs throughout the simulation based on the amount of available fuel and oxygen at a given location. As a result, the prescribed HRR that was input into the simulation can be different than the HRR calculated by FDS based on the ventilation conditions.

Figure 4.1 shows the HRR in the structure vs. time based on the fires described in Section 3.2. In this figure, the solid line represents the prescribed HRR that was input into the simulation (based on a prescribed mass flux), and the dashed line represents the HRR inside the structure that was calculated by FDS based on the ventilation conditions. The vertical lines represent the times at which ventilation occurred: front door opening and closing as well as the breaking of a front window for emergency escape. See Table 3.1 for a detailed list of the ventilation that occurred during the incident. The maximum size of the fire specified in this study was selected such that the conditions aligned with observations and fuel loads from the actual fire incident.

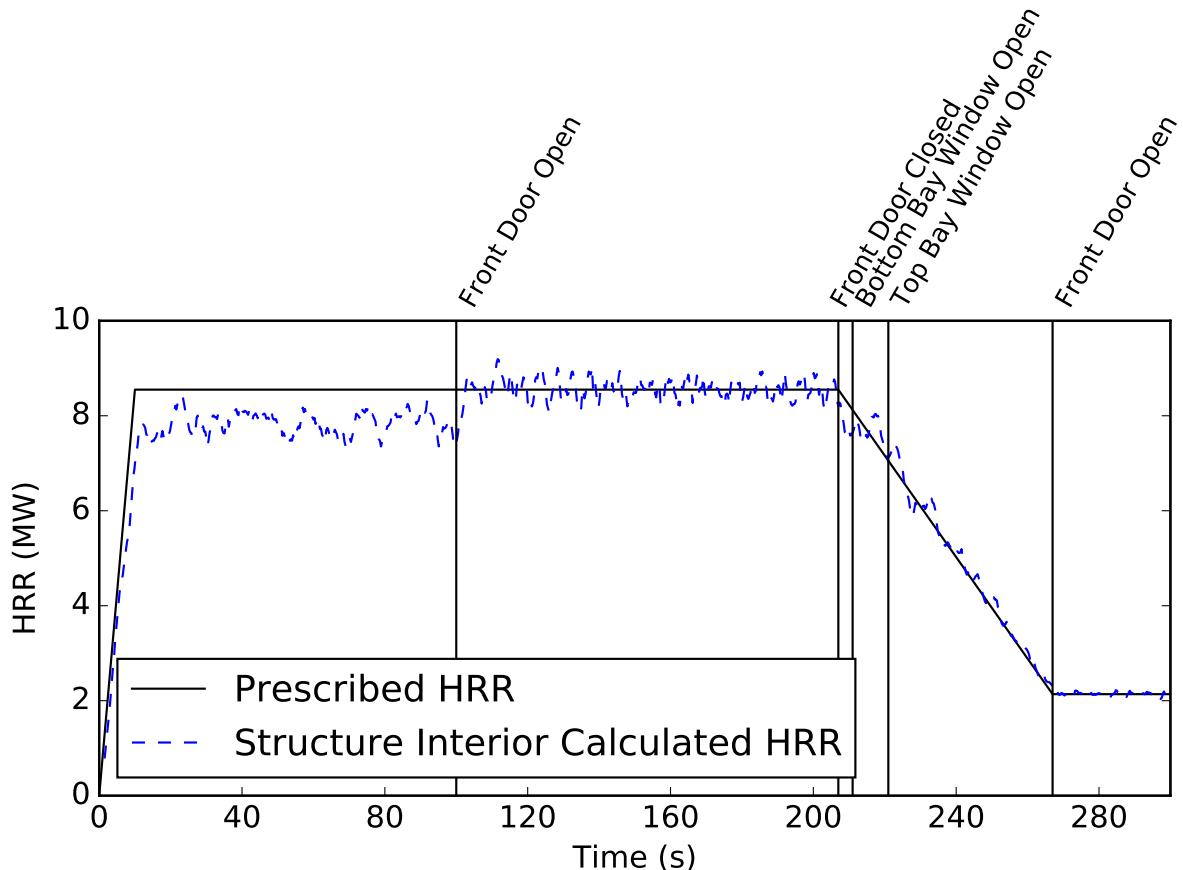


Figure 4.1: Comparison of prescribed and calculated interior HRRs from the FDS simulation. The vertical lines indicate the times when ventilation occurred.

In Fig. 4.1, the prescribed HRR that was input into the simulation is different than the HRR calculated by FDS based on the ventilation conditions. From 0 s to approximately 9 s, the calculated HRR was in approximate agreement with the prescribed HRR because there was an adequate amount of oxygen for all of the fuel to combust. The differences in prescribed versus predicted HRR is a result of either fuel accumulation within the structure not combusting because of a lack of oxygen or combustion occurring exterior to the structure where fuel and oxygen can mix and react. Fig. 4.2 shows the total calculated HRR within the computational domain (includes combustion occurring exterior to the structure) compared to the prescribed HRR curve.

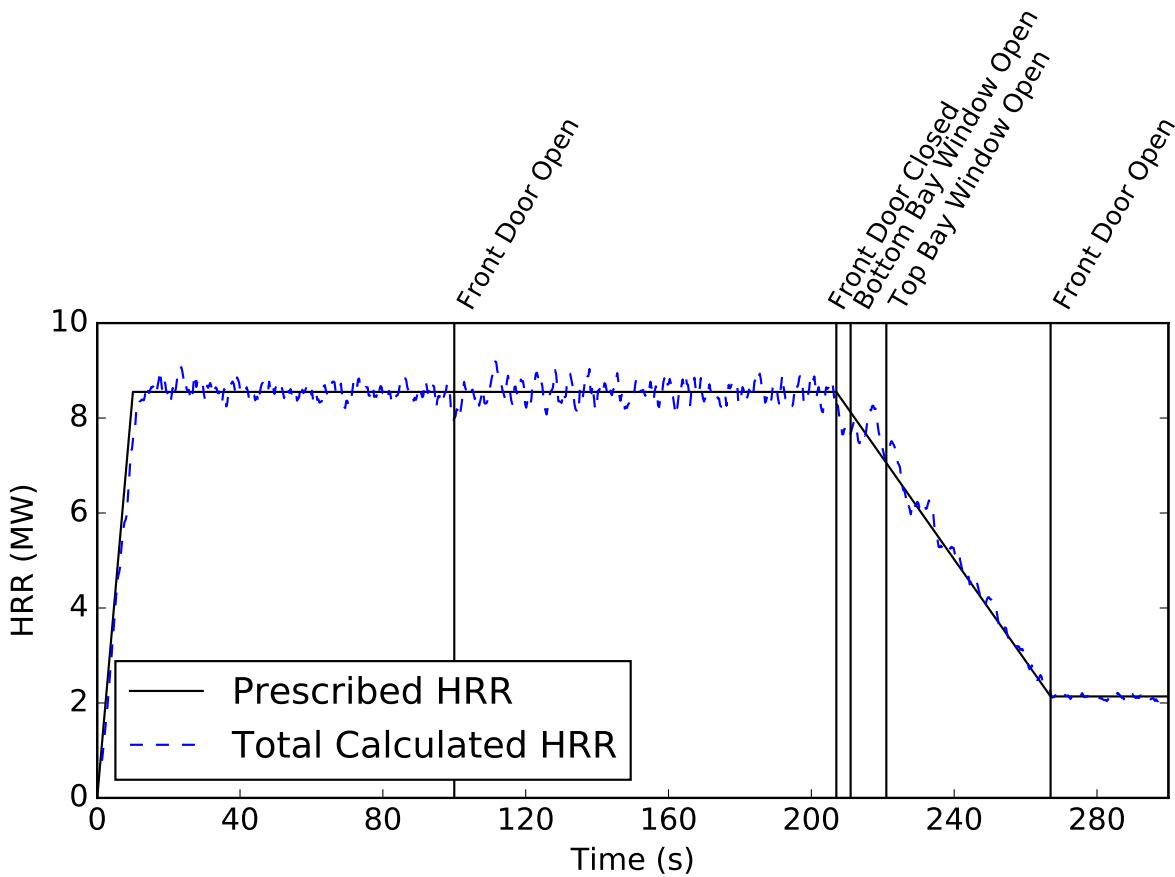


Figure 4.2: Comparison of total prescribed and calculated HRRs within the entire computational domain from the FDS simulation. The vertical lines indicate the times at which ventilation occurred.

A comparison of the differences between the HRR inside the structure (Fig. 4.1) and the total HRR (Fig. 4.2) over the first 100 s of the simulation indicated that on average there was the equivalent of an approximate 0.7 MW fire(s) occurring through open external vents (basement windows). This aligns with observed post-fire damage and post-incident report [10]. Fig. 4.3 shows a post-fire image of the back left corner of the structure as well as a Smokeview rendering of the fire from the FDS simulation prior to the front door being opened by firefighters.



Figure 4.3: External post-fire image of damage to the basement (top) and FDS model showing external fire prior to the front door of the structure being opened (bottom).

After 100 s of simulation time, 5.5 min after the first 911 call, firefighters open the front door to make entry to the first floor of the structure. The change in ventilation to the structure impacted the HRR. After the door was opened combustion no longer took place outside of the structure, as shown in Fig. 4.4, however the basement HRR was lower than the total HRR within the domain.

The differences in HRR between the total HRR and the basement HRR can be accounted for

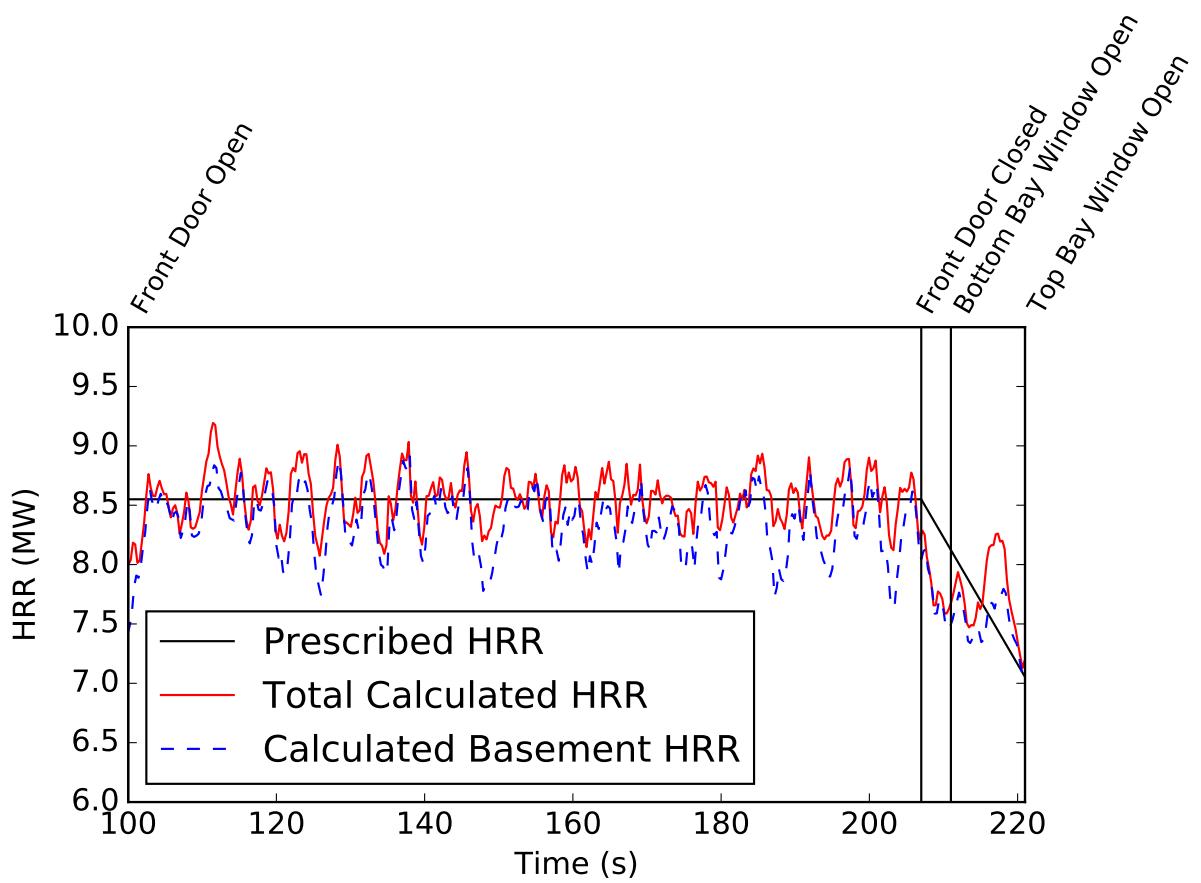


Figure 4.4: Comparison of prescribed, total calculated domain HRR and basement calculated HRRs from the simulation. The vertical lines indicate the times when ventilation changed.

in combustion occurring on the first floor of the structure. Fuel that was combusting outside of the structure due to a lack of oxygen combusts on the first floor of the structure as the open front door allows flow to occur within the structure and fuel to mix with available oxygen and react (Fig. 4.5).

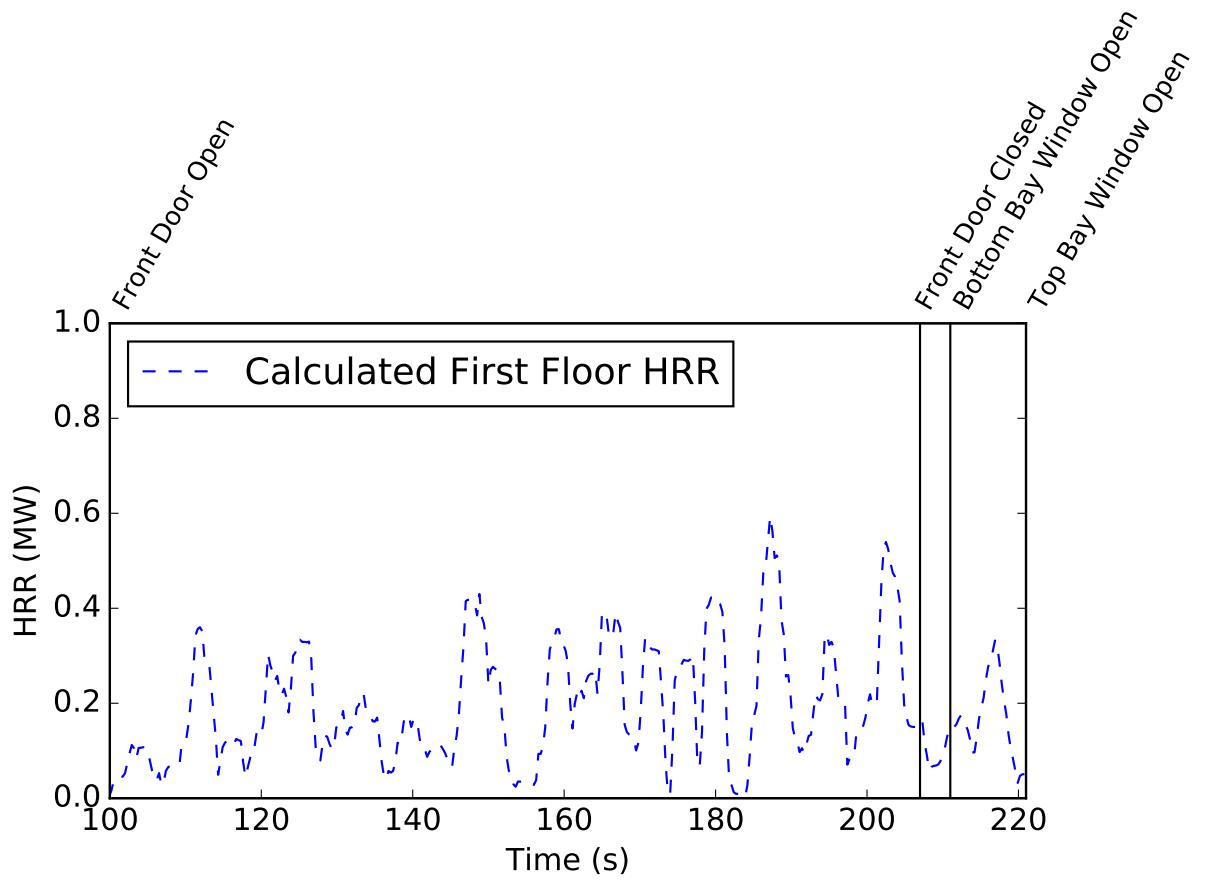


Figure 4.5: First floor calculated HRR from the simulation. The vertical lines indicate the times when ventilation changed.

4.2 Pressure

The growth of the fire combined with a 8.9 m/s (20 mph) wind flowing normal to the rear of the structure caused the pressure to rise within the structure. Hot gases which may have built up within the structure will flow from high pressure to low pressure. Based on the event timeline, the front door was opened 100 s into the simulation, which would create a low pressure relief on the first floor. Due to firefighters entering the structure through the front door, the simulated pressure on the first floor prior to and just after opening the door is important. Figure 4.6 shows the calculated pressure conditions in the structure just before and after the front door was opened (100 s) in the simulation.

In the top snapshot in Fig. 4.6, the pressure profile shows an overpressure of approximately 200 Pa (2.9×10^{-2} psi), 1 s prior to the door being opened. This pressure may be on the conservative side (over-prediction) because of wind speed fluctuations, wind direction, and small amounts of structure leakage. One second after the door was opened (bottom snapshot in Fig. 4.6), the pressure on the first floor drops to between 75 Pa (1.1×10^{-2} psi) and 85 Pa (1.2×10^{-2} psi). Without the presence of wind, the pressure in the first floor prior to the door opening was approximately 18 Pa (2.6×10^{-3} psi) and after the door was opened the pressure drops to between 5 Pa (7.3×10^{-4} psi) and 10 Pa (1.4×10^{-3} psi).

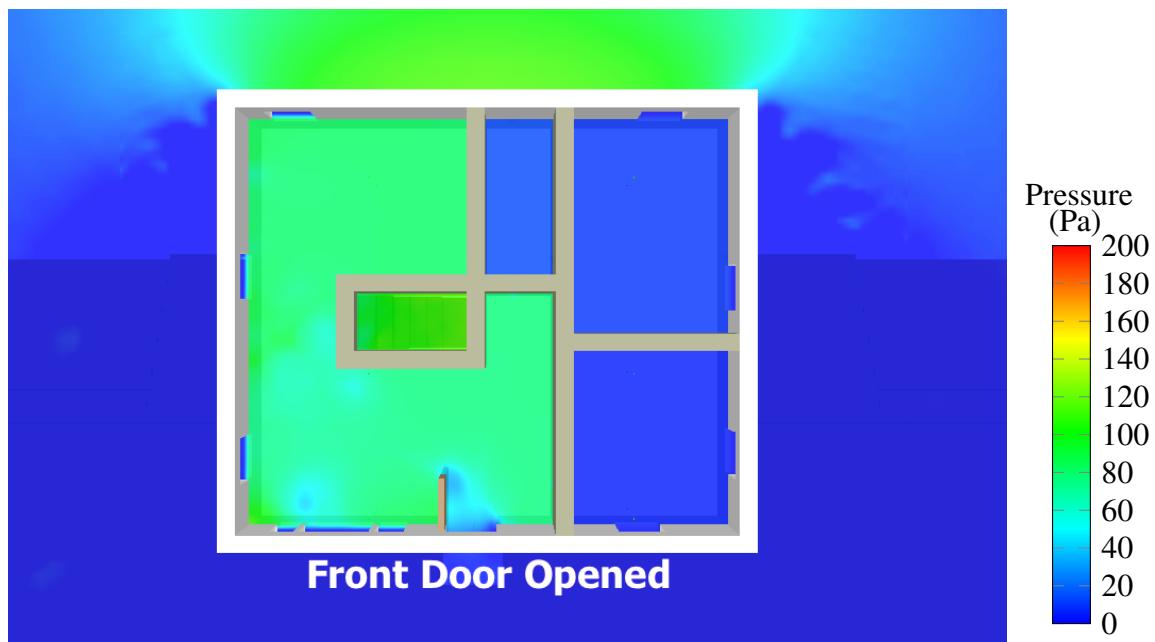
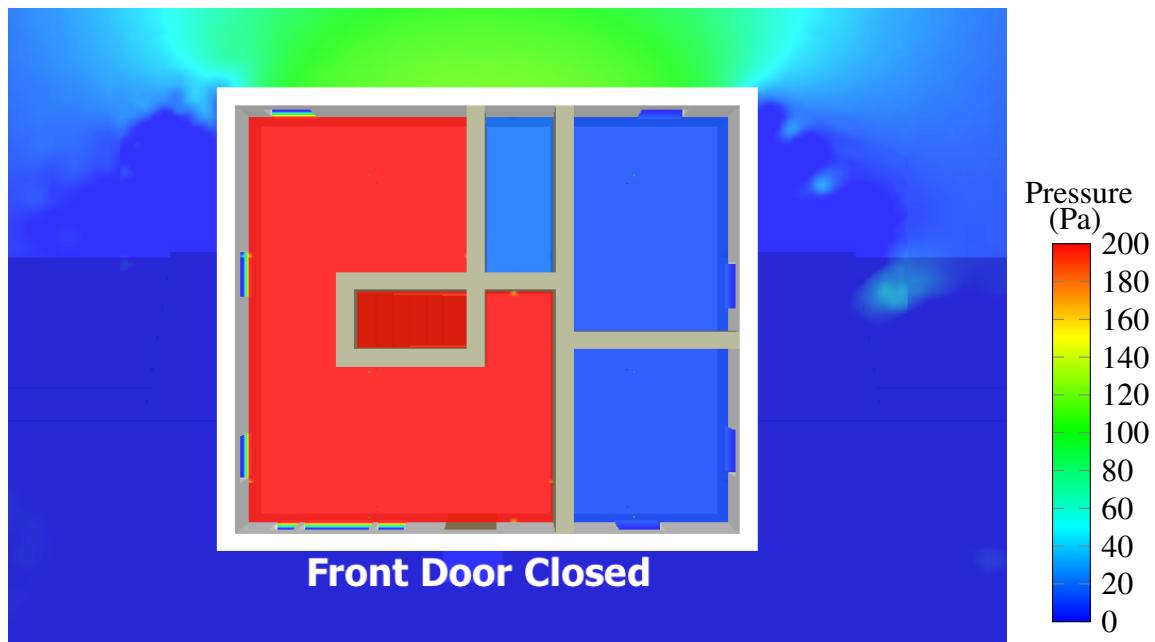


Figure 4.6: Calculated pressure contours on the first floor of the structure 1 s prior to (top) and 1 s after (bottom) firefighter entry through the front door at 0.91 m (3 ft) above the floor.

4.3 Velocity

Gases flow from a region of high pressure towards a region of lower pressure. Once the front door opened, the gases in the basement at an elevated temperature and pressure flowed upward into the interior stairwell and exited the structure via the front door. The velocity contours shown in Fig. 4.7 indicate the magnitude of flow velocities within the structure before and after the front door was opened.

In Fig. 4.7, the velocity profile within the high-hazard area (first floor) is shown via two snapshots in time to illustrate the change in the interior conditions 0.91 m (3 ft) above the floor. The first snapshot is shown at a simulation time of 99 s, which is 1 s before the front door was opened, and the second snapshot is shown at a simulation time of 101 s, which is 1 s after the front door was opened. The velocity contours shown indicate that prior to the front door being opened, there was minimal flow on the first floor. However, after the front door was opened, a flow path was established forcing the combustion products from the basement fire to flow to the first floor through the interior stairwell. The simulation calculated the flow exiting the structure to be approximately 11 m/s (25 mph).

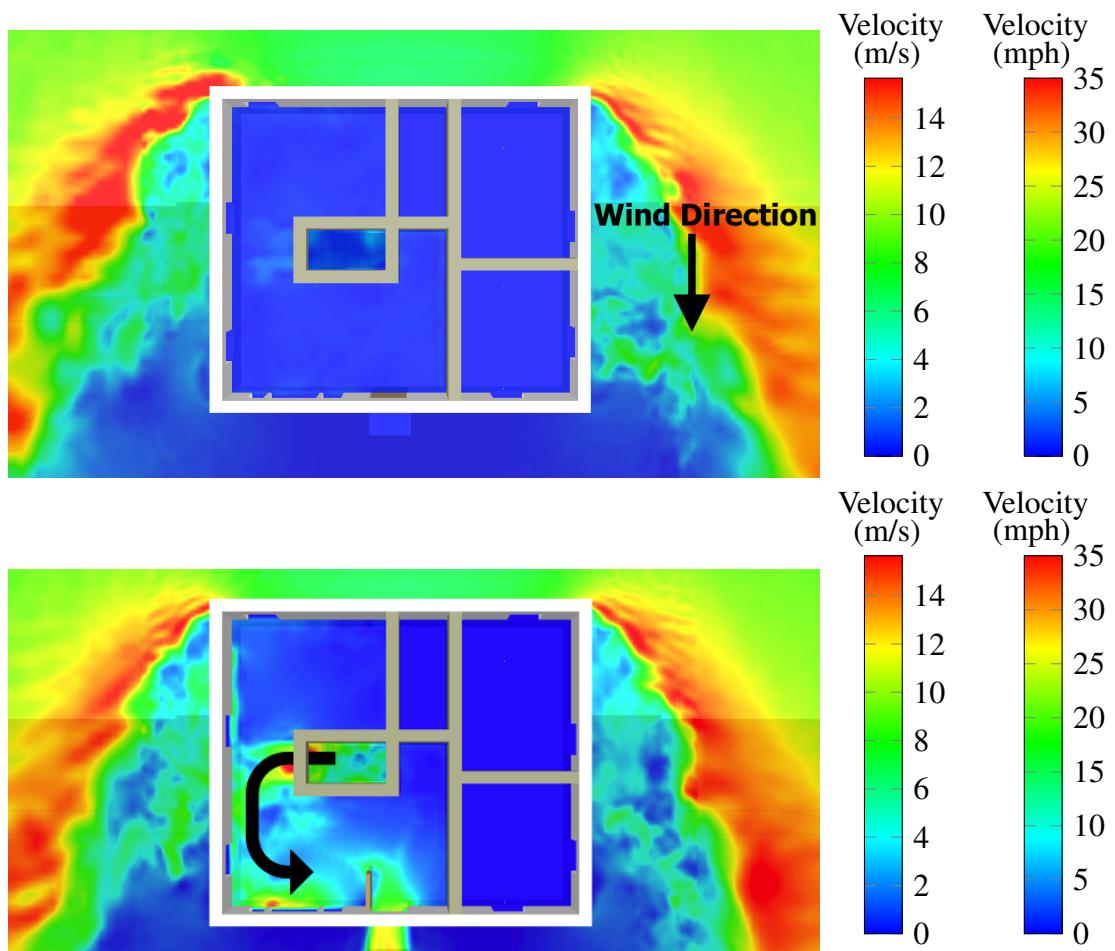


Figure 4.7: Calculated velocity contours on the first floor of the structure 1 s prior to (top) and 1 s after (bottom) firefighter entry through front door 0.91 m (3 ft) above the floor. Arrows indicate direction.

4.4 Temperature

Analysis of the temperatures from the simulation focused on the high-hazard area of the structure: the first floor area between the front door and the top of the interior stairwell. The temperature contours shown in Fig. 4.8 indicate the gas temperatures within the structure 1 s before the front door was opened 0.91 m (3 ft) above the floor. The overlaid arrows represent the gas flow: the length of the lines represents the magnitude of the speed and the direction of the arrow represents the flow direction. Prior to the door opening, the open living area and kitchen on the first floor were approximately 60 °C (140 °F), while the peak temperatures were concentrated near the interior stairwell, 105 °C (220 °F). Note that there was very minimal flow throughout the first floor. Figures 4.9 and 4.10 show gas temperature contours at 0.91 m (3 ft) above the floor, 1 s and 5 s after the front door was opened.

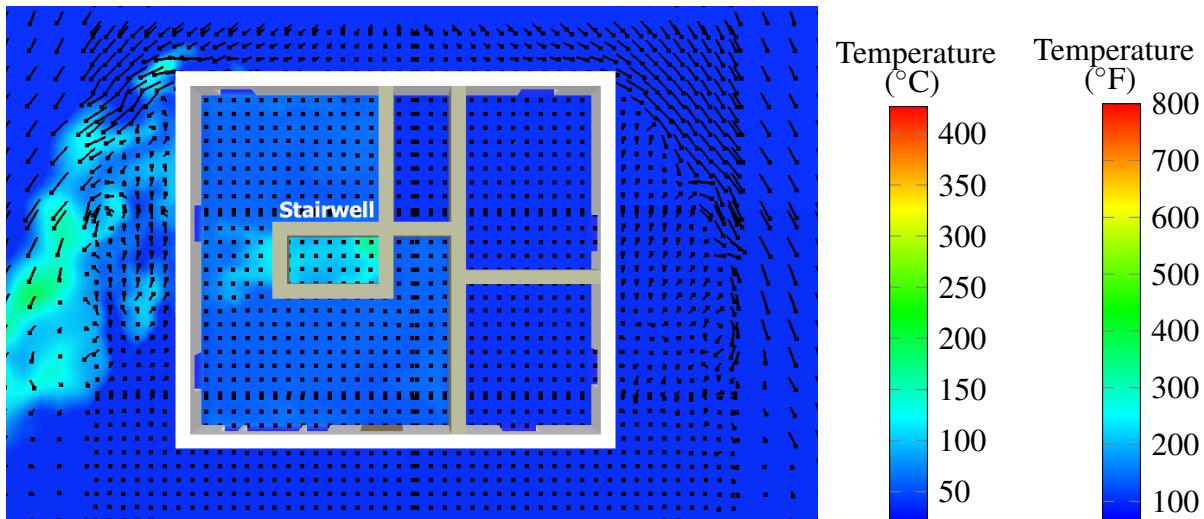


Figure 4.8: Calculated temperature contours on the first floor of the structure 1 s prior to firefighter entry through front door 0.91 m (3 ft) above the floor.

After the front door is opened, hot fire gases from the basement begin to flow through the interior stairwell into the first floor. Figure 4.9, 1 s after the front door was opened, shows that the temperature contours at the top of the stairwell have increased to approximately 200 °C (392 °F) with a hot spot that approached 425 °C (800 °F). Figure 4.10, 5 s after the front door was opened, shows more significant increases in temperature. The area at the top of the stairs is between 375 °C (700 °F) and 425 °C (800 °F). The gas temperatures 0.91 m (3 ft) above the floor at the front door have also increased to approximately 230 °C (450 °F) and show increased flow velocities.

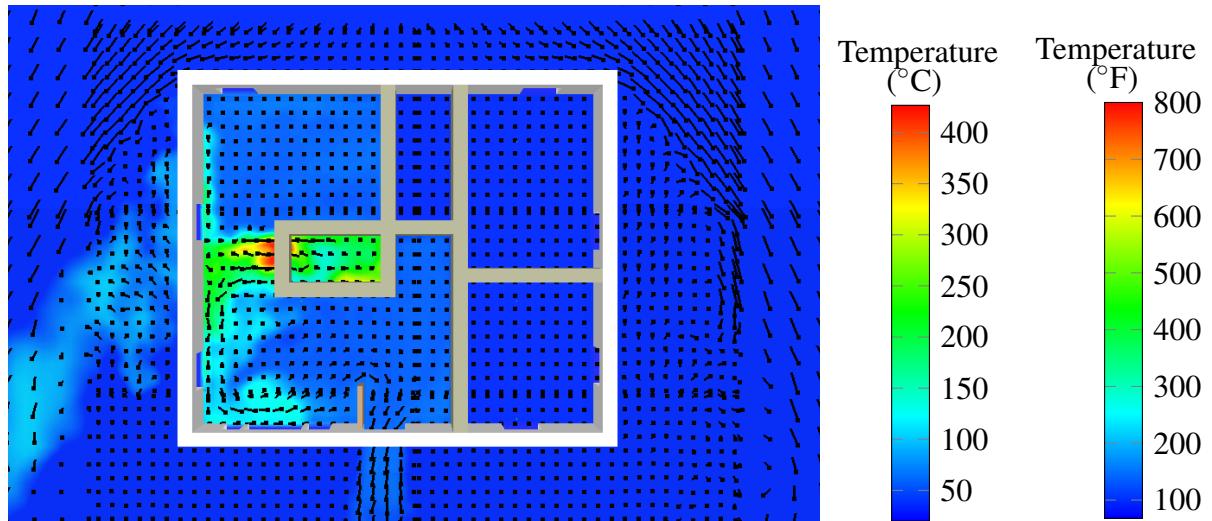


Figure 4.9: Calculated temperature contours on the first floor of the structure 1 s after firefighter entry through front door 0.91 m (3 ft) above the floor.

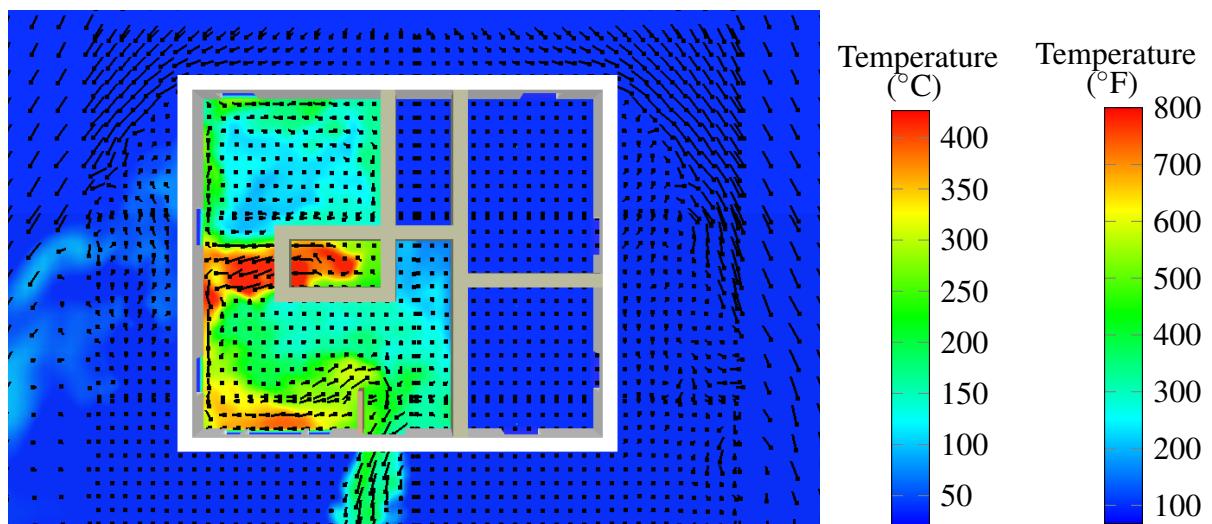


Figure 4.10: Calculated temperature contours on first floor of the structure 5 s after firefighter entry through front door 0.91 m (3 ft) above the floor.

Section 5

Discussion

The results of the simulation are discussed in the following sections. Section 5.1 addresses the results of the simulation as they relate to the flow path that was established in the interior stairwell through the front door. Section 5.2 examines the model results as they relate to the hazardous conditions and exposure temperatures on the first floor. Section 5.3 discusses tactical considerations and outcomes of the fire incident as they relate to the fire dynamics and flow path conditions that have been observed in recent analyses, modeling, and full and bench-scale experimental research.

5.1 Simulated Flow Path

The incident report from Prince George's County Fire/EMS [10] indicated that two firefighters from Truck 809 were seriously injured after making entry to the first floor. The interior conditions forced one firefighter to bail out through a first floor window on the front side of the structure and the other firefighter to be rescued through the front door. From Section 4.4, the conditions on the first floor were initially tenable. After the front door was opened, however, the simulation results indicated that a high hazard area existed in the first floor that exceeded the conditions that would put a firefighter at risk for burn injuries (temperatures greater than 260 °C or 500 °F) [25].

The simulation results indicate that a flow path was established between the open vents (windows) on the rear side of the basement and front side of the structure (through the front door of the first floor) after the front door was opened. Strong winds (8.9 m/s (20 mph)) pushed air into the rear side of the basement through window failures and combined with buoyant combustion gases to pressurize the structure. Opening the front door provided a pressure relief; this resulted in a rapid change in the conditions within the structure and the establishment of a flow path. After the front door was opened, the combustion gases at elevated temperature and pressure in the basement flowed towards lower pressure regions outside of the structure on the leeward side (front of structure) via the interior stairwell. The two injured firefighters were located in the flow path on the first floor between the top of the interior stairwell and the front door.

To examine the impact of opening the front door on the establishment of a flow path, flow conditions were examined along the centerline of the interior stairwell doorway and through the centerline of front door. Figure 5.1 shows the flow vectors at the first floor stairwell doorway 1 s before the front door was opened. Note that the length and direction of the arrows indicate the magnitude and direction of the flow, respectively. The color of the arrows correspond to the

values from the included temperature scales. Therefore, a short blue arrow represents slow moving, cool gas while a long red arrow represents fast moving, high temperature gas. Prior to the door opening, there was minimal flow through the first floor stairwell door and the temperature peak was approximately 125 °C (257 °F) as shown in Figure 5.1. One second after the door opened, Figure 5.2, there was noticeable flow through both the stairwell doorway and through the front door. Simulated temperatures at the stairwell increased to approximately 200 °C (392 °F) and temperatures through the doorway were approximately 100 °C (212 °F). These values are also shown in planar contours 1 m above the floor in Figs. 4.7 and 4.9 for velocity and temperature, respectively.

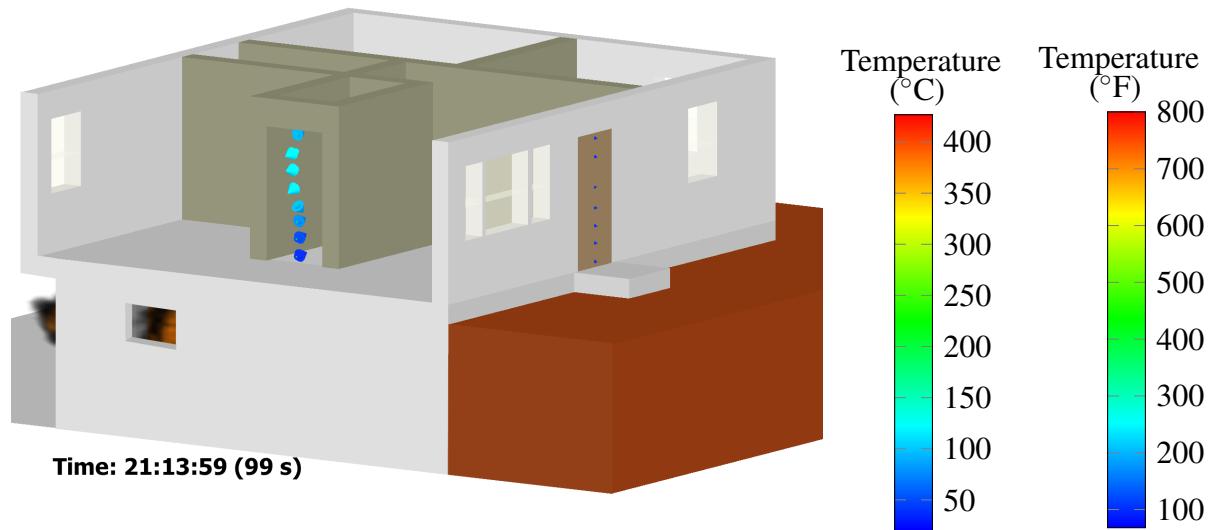


Figure 5.1: Flow path vectors at front door and top of stairwell 1 s before the front door was opened.

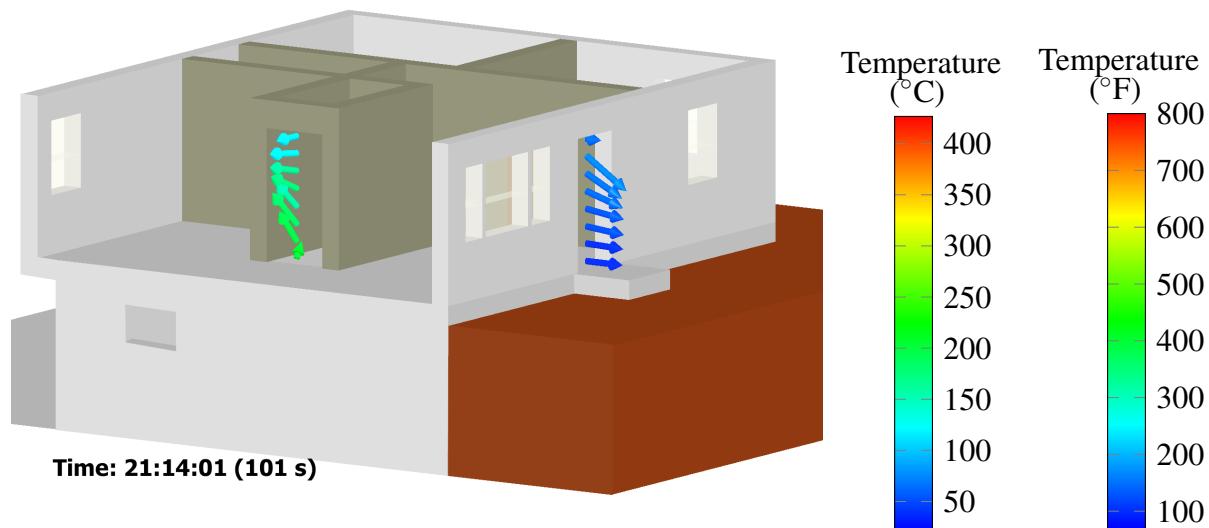


Figure 5.2: Flow path vectors at front door and top of stairwell 1 s after the front door was opened.

At the estimated time of firefighter entry to the first floor (142 s into the simulation at 21:14:42; see Table 4.1), the simulated flow magnitudes through the first floor (stairwell and front doors) remained similar to the conditions just after opening the front door. Velocities through both the doorway at the top of the stairs and the front door were approximately 13 m/s (29 mph), which was faster than the imposed wind speed (9 m/s or 20 mph) because of the addition of the buoyancy of the fire plume. The model temperatures increased through the stairwell doorway to between 400 °C and 425 °C (750 °F to 800 °F) and through the front door to approximately 375 °C (700 °F). From the approximate timeline (Table 4.1), the front door was forced closed due to airflow pushing against it, 207 s into the simulation. Figures 5.4 and 5.5 show the conditions 1 s prior to and after the front door closed. The figures show that while the closed door stopped significant flow through the stairwell door and onto the first floor, the temperature hazard for the firefighters (temperatures at or above 400 °C or 750 °F) remained.

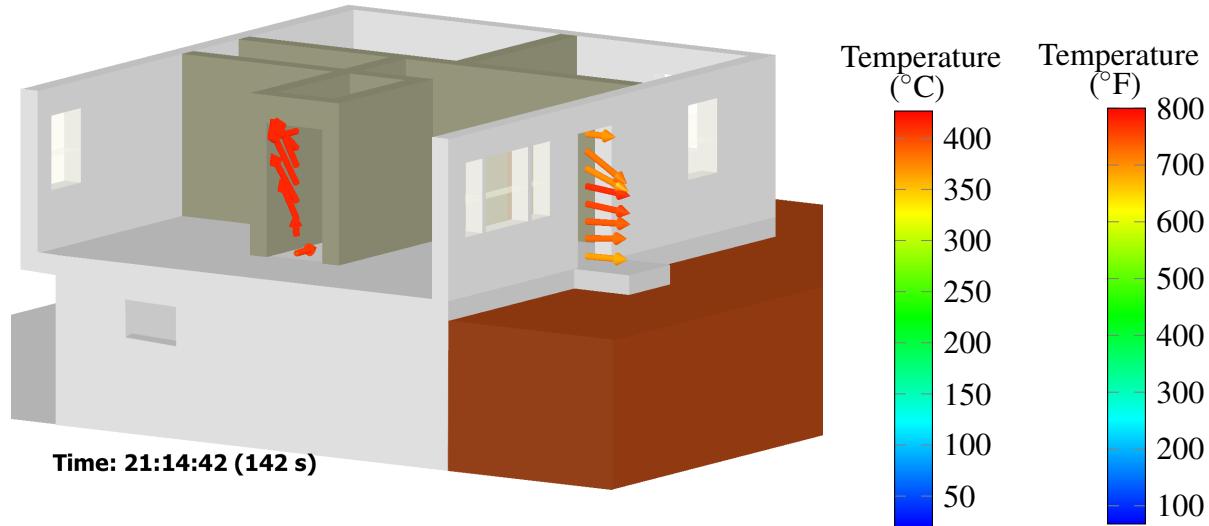


Figure 5.3: Flow path vectors at the front door and the top of the stairwell 42 s after the front door was opened, at the estimated time of first floor entry.

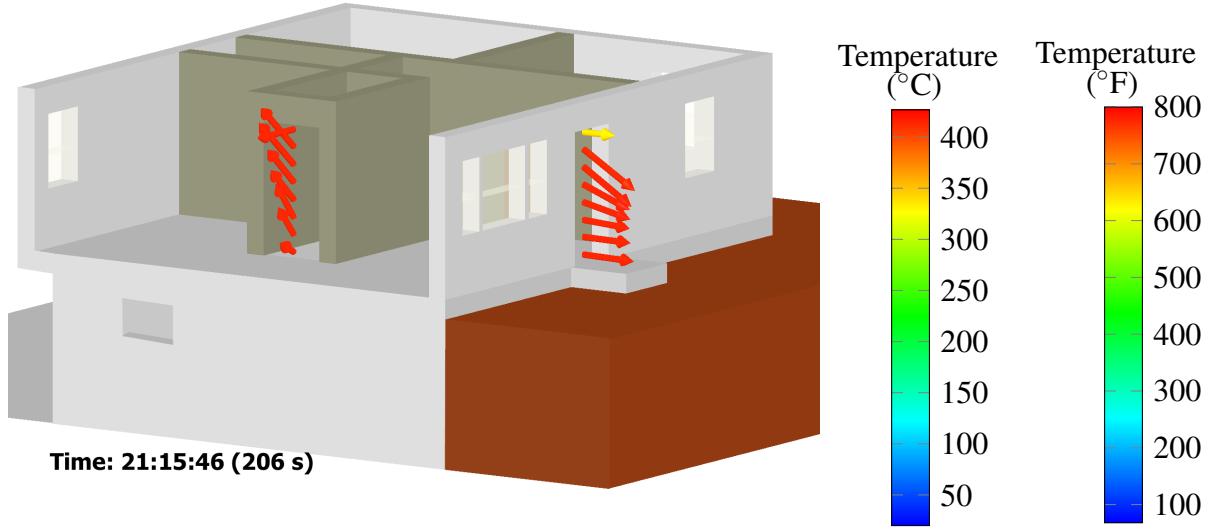


Figure 5.4: Flow path vectors at the front door and the top of stairwell 1 s before the front door was closed.

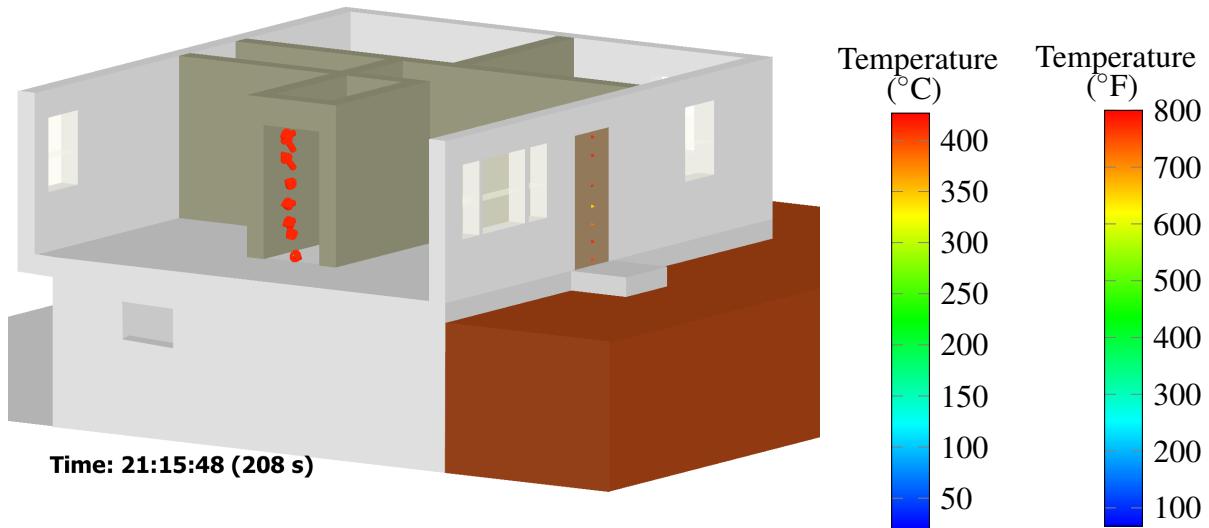


Figure 5.5: Flow path vectors at the front door and the top of stairwell 1 s after the front door was closed.

5.2 Assessing the Hazard

A person is susceptible to second-degree burn injuries if skin temperatures exceed 55 °C (130 °F) [26]. Although firefighters wear protective gear, gear only offers a finite amount of protection. The polycarbonate material in the facepiece of a self-contained breathing apparatus begins to soften when the material temperature reaches approximately 140 °C (284 °F) [27]. Structural fire fighting coats and pants are tested to withstand temperatures up to 260 °C (500 °F) or 10 kW/m² [25] for less than 2.5 min. Exposure to elevated temperatures can result in a significant amount of heat transferred to the firefighter, putting him or her at risk.

Figures 5.6 to 5.8 show two simulated interior views of temperature contours at particular snapshots in time. The top image is a planar view through the middle of the front door (from the front to the back of the house), which shows the conditions in the living area on the first floor and the conditions in the basement just past the bottom of the stairs. The bottom image shows temperature contours through the middle of the interior stairwell which connected the basement to the first floor of the structure (looking from the rear of the structure towards the front). Prior to the front door being opened, (Fig. 5.6) shows that temperatures in excess of 200 °C (400 °F) were confined to the basement of the structure: specifically the rear of the structure and under the stairwell. One second after the door was opened, hazard in the structure increased with the most drastic change occurring at the top of the stairwell as peak simulated temperatures exceeded 400 °C (750 °F). At the approximate time firefighters made entry to the first floor, Fig. 5.8, the conditions within the flowpath (interior stairwell through front door) had become more severe with simulated temperatures in excess of 400 °C (750 °F), for which a fully protected firefighter would be susceptible to burn injuries. These high-hazard conditions within the flowpath remained until the HRR was reduced by the simulated action of applying water on the fire.

Based on these results and the simulation results shown in Sections 4.3 and 4.4, after the front door was opened, the simulated flow path temperatures in the interior stairwell were in excess of 400 °C (750 °F) and the flow velocities were in excess of 9 m/s (20 mph). The conditions in the interior stairwell changed from tenable to high-hazard very rapidly following the opening of the front door. Within the structure, the hot gases and smoke were moving along the flow path from the basement towards the door located on the front side of the structure via the interior stairwell. The simulated temperatures are consistent with the post-incident conditions that were documented in the interior stairwell.

Ongoing research and experimental work is being conducted by NIST to gain a better understanding of convective heat transfer to firefighter personal protective equipment, including fire-fighting gear, helmets, self-contained breathing apparatuses, etc. The goal of this ongoing research is to parameterize various flow path conditions (elevated temperatures and velocities) and determine their effect on the rate of heat transfer and amount of energy storage in firefighting safety equipment.

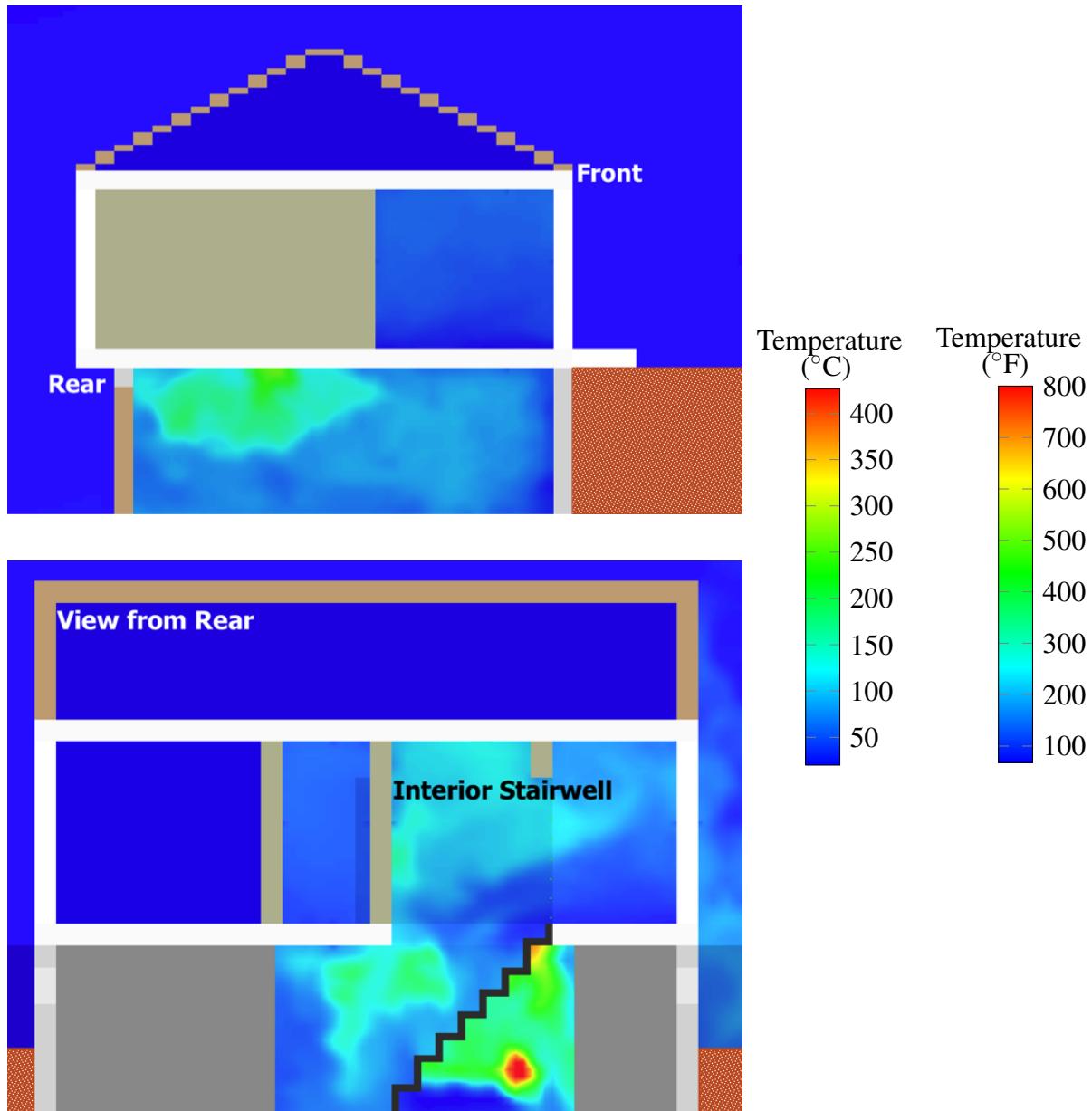


Figure 5.6: Interior temperature contours 1 s before the front door was opened (21:13:59). The top snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the front door. The bottom snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the interior stairwell doorway.

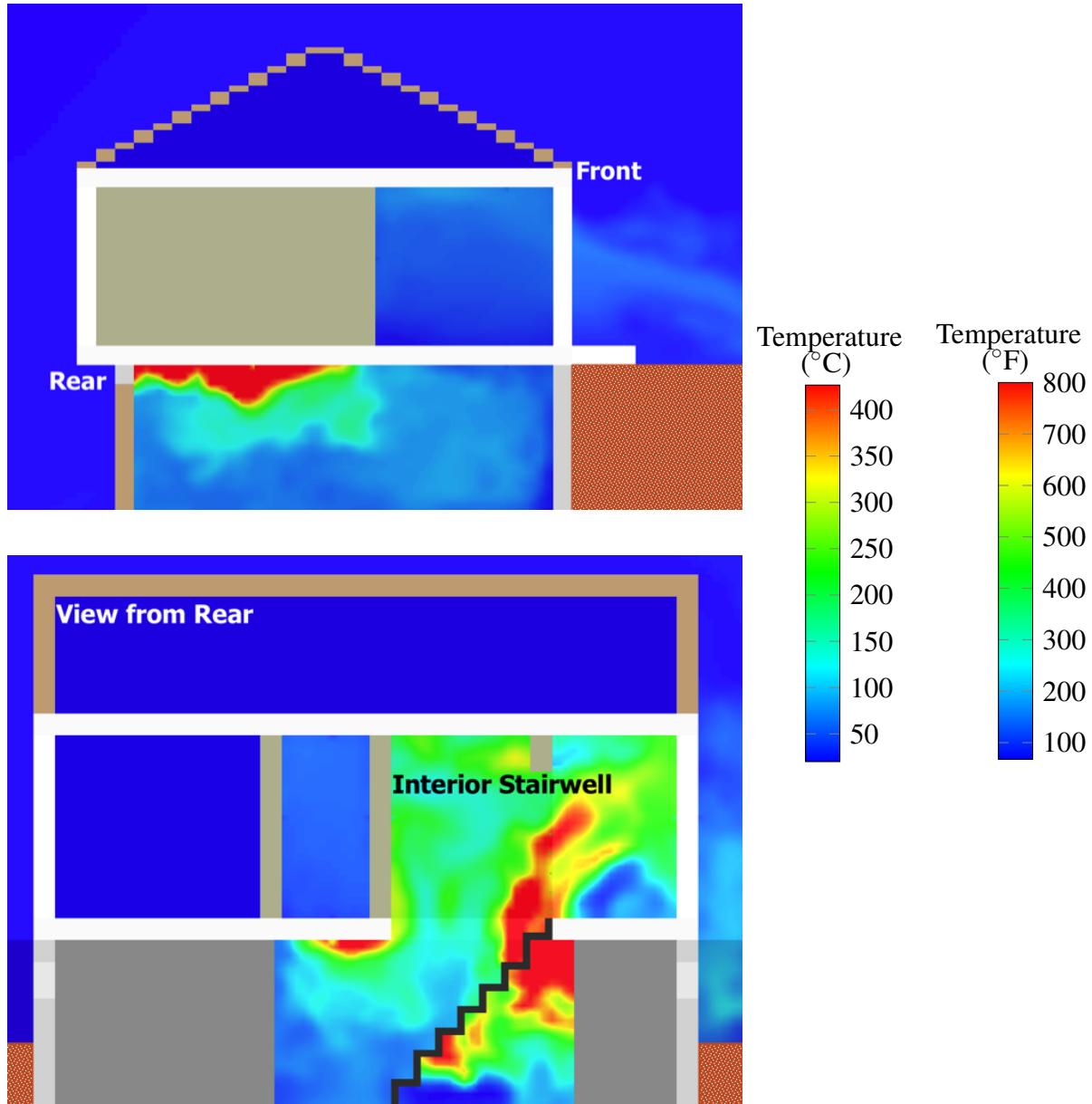


Figure 5.7: Interior temperature contours 1 s after the front door was opened (21:14:01). The top snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the front door. The bottom snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the interior stairwell doorway.

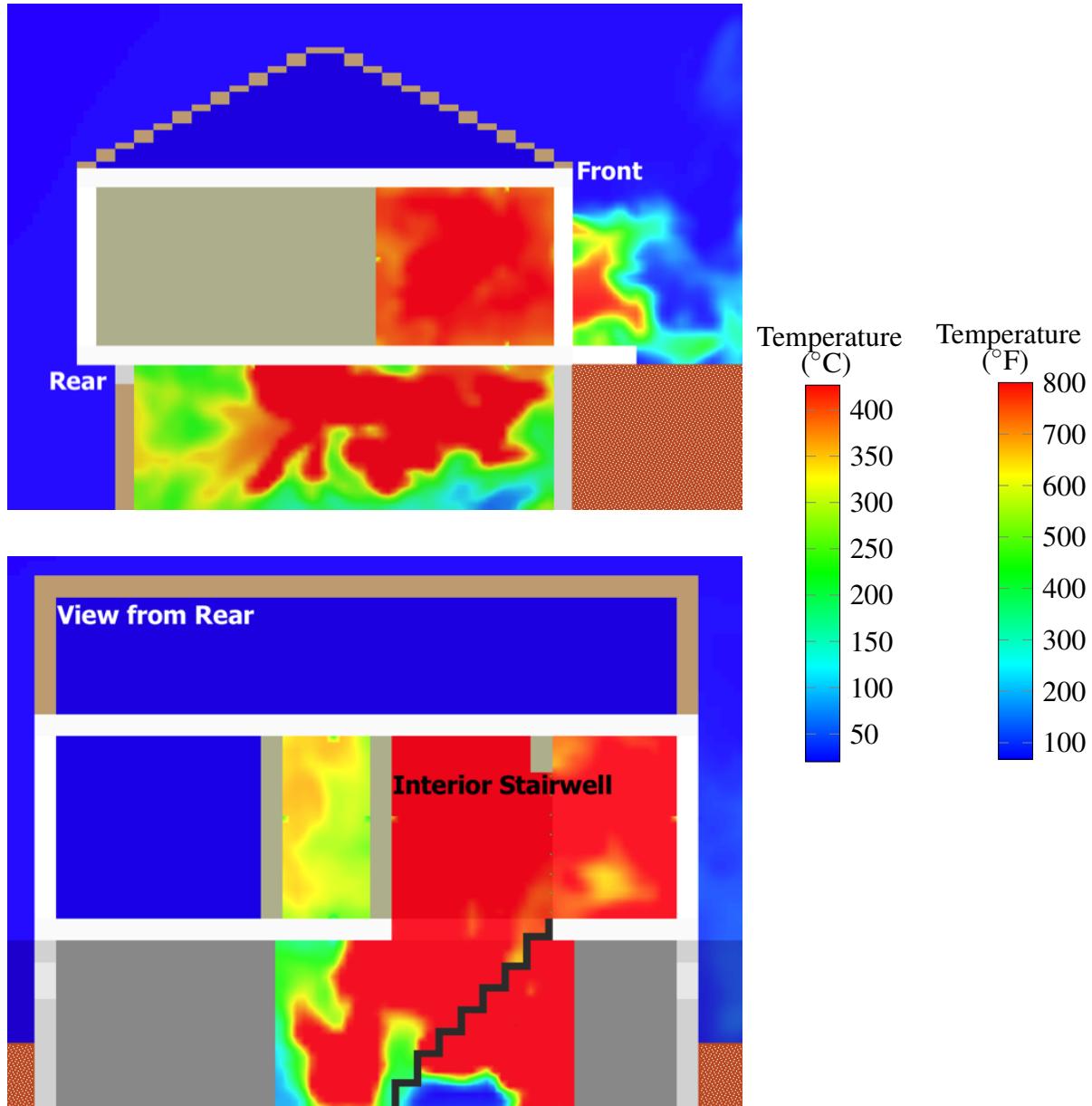


Figure 5.8: Interior temperature contours as firefighters made entry to the structure (21:14:42). The top snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the front door. The bottom snapshot shows temperatures on the first floor and basement on the plane that runs through the center of the interior stairwell doorway.

5.3 Tactical Considerations

In this fire incident, the initial failure of the basement windows with strong incident winds on the rear side of the structure coincided with a rapid change in the thermal conditions in the interior stairwell and first floor after the front door to the structure was opened. The open front door resulted in the establishment of a flow path within the interior stairwell from the high pressure side of the structure to the low pressure side with highly hazardous conditions.

The interior stairwell acted as a chimney for hot gases in the basement to flow towards regions of lower pressure and vent openings located on the front side of the structure. Firefighters should avoid placing themselves within a flow path where elevated temperatures and flow velocities can present hazardous conditions and increase the rate of heat transfer to the firefighter via convection. A 360° scene size-up by arriving firefighters can help determine the location of the fire and identify potential flow paths within a structure. Door control can also be used to avoid creating inlet and outlet vents that could result in the establishment of a flow path.

First suppression efforts should take place at the same level as the fire (i.e. fight basement fires from the basement level) with the wind at the back of firefighters. Ongoing research by NIST, Underwriters Laboratories (UL), and others has demonstrated that applying water from the exterior into the fire area of a structure (prior to the start of interior operations) can significantly improve the safety of firefighters by reducing the thermal hazard from the fire and reducing the potential for developing high velocity hot gas flows within the structure [17, 18].

There have been many previous fire incidents [28–42] in which changes in the flow paths are thought to have had an adverse impact on firefighter and occupant safety. Table 5.1 lists the NIOSH investigation reports from the past 15 years in which it could be determined that a flow path played a role in the related incident. This table lists the NIOSH report number, the outcome, and a brief description of the flow path details.

Based on a review of these incidents, it is clear that fires with rapidly developing or changing ventilation may lead to flow paths that are a significant hazard to the fire service during a response. The development of (or changes to) a flow path could be caused by the failure of a component of the structure, such as a door, window, or portion of a ceiling, wall or floor. Environmental conditions such as wind can generate hazardous thermal conditions within a flow path. Uncoordinated ventilation procedures can also be the cause of increased thermal hazards within a flow path.

Table 5.1: Flow path related LODD/LODI incidents.

NIOSH Report No.	No. of LODDs/LODIs	Flow Path Details
99-F01 [28]	3 LODDs	From apartment into hallway on 10th floor of high-rise apartment building
99-F21 [29]	2 LODDs 2 LODIs	Basement to 1st floor
F2000-04 [30]	3 LODDs 3 civilian deaths	1st floor to 2nd floor
F2000-16 [31]	1 LODD 1 LODI 1 civilian death	2nd floor hallway through 2nd floor apartment
F2000-23 [32]	1 LODD 2 LODIs	From ground level to 1st floor then to 2nd floor, flow exited through ceiling
F2000-43 [33]	1 serious LODI 2 other LODIs	1st floor to 2nd floor
F2004-02 [34]	1 LODD	1st floor to basement
F2005-02 [35]	1 LODD 4 LODIs	Rear to front of the building
F2005-04 [36]	1 LODD 9 LODIs	Basement to 1st floor
F2007-09 [37]	1 LODD 2 LODIs	3 story training burn - flow through all levels
F2007-35 [38]	4 LODIs	1st floor to 2nd floor
F2009-11 [39]	2 LODDs	Rear to front of the building
F2011-13 [40]	2 LODDs	Lower level up stairs and through entry door and garage
F2011-31 [41]	1 LODD	Fire extended from lower level apartment
F2012-28 [42]	1 LODD 1 LODI	Attic fire extended into closed porch and then into 2nd floor

Section 6

Summary

Fire Dynamics Simulator was used to provide insight into the fire dynamics of a fire that occurred within a single-story, single-family residential structure in Riverdale Heights, MD, that resulted in the serious injury of two firefighters. The fuel, fire size, and fire growth rate that were used in the FDS simulation were estimated by taking into account all of the available information including the post incident report from Prince George's Country Fire/EMS [10], post-incident pictures, and relevant literature. This resulted in a maximum specified source fire of approximately 8.5 MW in the basement. Based on the limited ventilation conditions in the basement, the FDS simulation results indicated that before the front door was opened, there was combustion occurring outside the structure at the rear basement windows which had failed prior to fire department arrival. Once the front door was opened, there was sufficient oxygen for combustion to occur within the structure, with intermittent flaming combustion on the first floor.

The fire originated in the basement, and the interior stairwell acted as a chimney for hot gases in the basement to flow towards regions of lower pressure through the open front door of the structure. After the front door was opened, a flow path was established between the basement and the front side of the structure (the front door). The opening of the front door resulted in a rapid change in the conditions within the flow path. In the interior stairwell, the flow velocities were greater than 9 m/s (20 mph) and the temperature of the gases was estimated to be in excess of 400 °C (750 °F), which puts fully protected firefighters at risk for burn injuries.

Two firefighters were located in the flow path between the basement and the doors on the front side of the structure. One firefighter was able to break a window to escape the hazardous conditions and after a call for assistance, the second firefighter was removed from the structure and immediate medical treatment was provided. The two firefighters were transported to the local medical center where they were treated for their injuries. Five other firefighters were injured on-scene and transported to the hospital for treatment.

Section 7

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Appendix A

Dimensioned Drawings

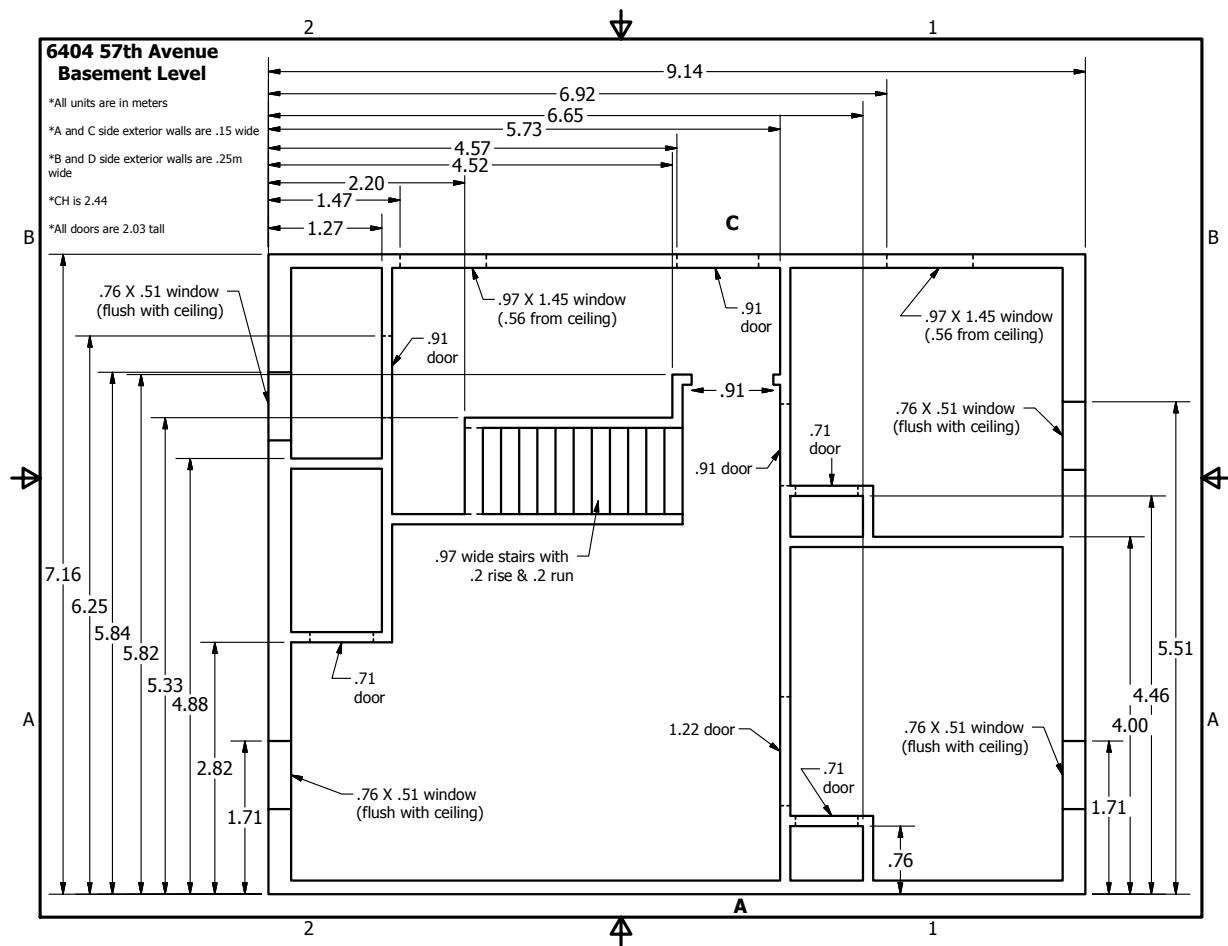


Figure A.1: Dimensioned drawing of the basement. The measurements are accurate to within 15 cm (6 in).

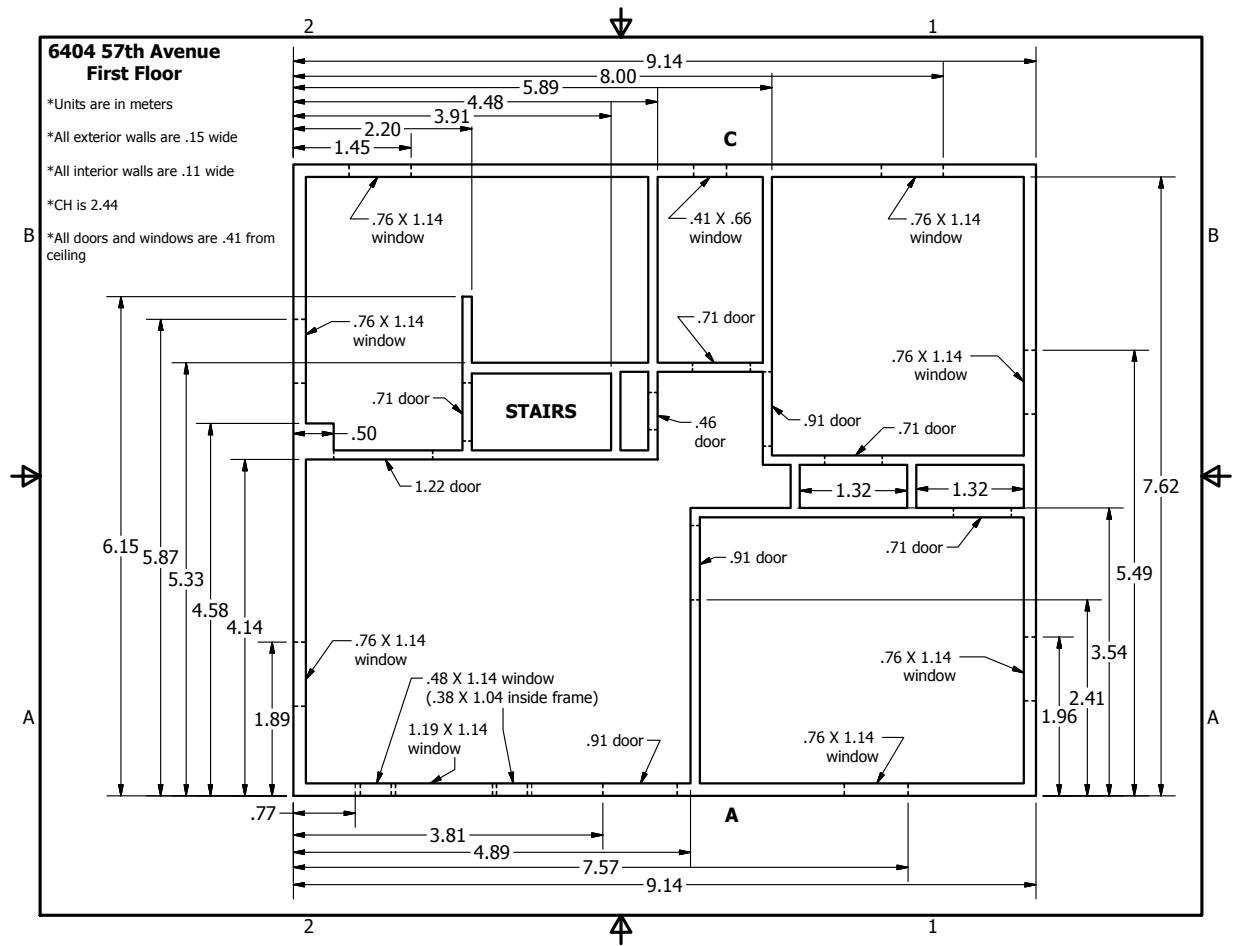


Figure A.2: Dimensioned drawing of the first floor. The measurements are accurate to within 15 cm (6 in).