Analysis of a Near Miss in a Garden Apartment Fire – Georgia 2022

Jason Floyd
Daniel Madrzykowski

Fire Safety Research Institute
UL Research Institutes
Columbia, MD 21045

October 3, 2022

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/RSFD6862

Analysis of a Near Miss in a Garden Apartment Fire – Georgia 2022

Jason Floyd
Daniel Madrzykowski

Fire Safety Research Institute
UL Research Institutes
Columbia, MD 21045

October 3, 2022

UL Research Institutes
Terrence R. Brady, President
Christopher J. Cramer, Chief Research Officer

Fire Safety Research Institute
Steve Kerber, Vice President and Executive Director

Abstract

On February 9, 2022, Cobb County Fire and Emergency Services responded to a fire in a ground floor unit in a garden apartment building. At arrival, the fire was a post-flashover fire in a bedroom. Initial fire control was attempted by an interior fire attack team, which was unable to quickly locate the fire. Exterior suppression through the bedroom window was started prior to discovery of the fire by the interior team. Shortly after fire discovery by the internal team, a mayday was called. Four firefighters from the interior fire attack team received first and second degree burns. This report analyzes photographic, video, and written documentation from the incident to evaluate the timeline of the incident and to assess the fire conditions present. Computer modeling using the Fire Dynamics Simulator (FDS) was performed to provide further insight into the fire conditions and the impact of decisions and actions on the fire ground. Additionally, data from a full-scale fire test of a similar fire in a similar structure was used to provide additional insight.

Four FDS simulations were performed in support of the analysis. These included a simulation of the event as it unfolded and three simulations looking at the impact of alternate tactics, which included: initial exterior attack prior to entry, the use of a smoke curtain to protect the building exit path, and interior-only attack. FDS simulations provided insight on the heat present in the apartment during the fire and the impact of the interior and exterior suppression on conditions inside the apartment. Full-scale test data of a similar fire showed similar behavior to the FDS predictions and gives credence to the FDS results.

Results of the analysis suggest injuries resulted from the length of time the interior attack team was present inside the apartment before actions were taken to reduce the severity of the fire. Six contributing factors were identified including size-up, communication and accountability, delayed exterior attack, lack of entry hall protection, the apartment layout and construction, thermal imager use, and mayday procedures and training. The last contributing factor was a positive contribution that helped avoid more serious injuries.

Based on the contributing factors, five recommendations were made that include improved size-up, exterior fire control to prevent exterior spread, protection of exit pathways, basing fire ground tactics on known information, and recognizing when a change in tactics is needed.

Contents

List of Figures

List of Tables

Acknowledgments

This project was supported through a grant from the Department of Homeland Security (DHS) Federal Emergency Management Agency's (FEMA) Assistance to Firefighters Grant Program, Award EMW-2018-FP-00476.

The authors thank Fire Chief Bill Johnson and Cobb County Fire and Emergency Services for their willingness to share the experience from their incident with others in the fire service so that the safety and effectiveness of the fire service can improve. This analysis was possible based on the excellent documentation of the incident by the Fire Investigation Team including Brian Beaty, Lee Maness, Leon Reese, and Brian Torpy, and the collaboration of the After Action Review Team led by Deputy Chief Kevin Gross. The authors would also like to thank Paul Davis Restoration for proving the Matterport 3D scans of the fire scene.

List of Abbreviations

AART	After Action Review Team
ALS	Advanced life support
AOIC	Acting officer in charge
ARFF	Aircraft Rescue and Firefighting
CMU	Concrete masonry unit
FDS	Fire Dynamics Simulator
FSRI	Fire Safety Research Institute
HAZMAT	Hazardous
HDPE	High density polyethylene
LDPE	Low density polyethylene
NFIRS	National Fire Incident Reporting System
NIST	National Institute of Standards and Technology
PET	Polyethylene terephthalate
PPE	Personal protective equipment
SCBA	Self-contained breathing apparatus
TIC	Thermal imaging camera
TPP	Thermal protective performance

1 Introduction

On February 9, 2022, Cobb County Fire and Emergency Services responded to a fire in a ground floor unit in a garden apartment building in Marietta, Ga. Three firefighters received first and second degree burns while attempting an interior attack on the fire.

This report details an analysis, conducted by the Fire Safety Research Institute (FSRI) at UL Research Institutes, of the fire conditions the interior attack team experienced during the fire event. The report begins with a summary of the resources available to Cobb County, the fire incident, and the response by Cobb County Fire and Emergency Services. This is followed by an examination of photographic and video evidence during and after the fire provided by the Cobb County After Action Review Team (AART). Finally, computer modeling of the fire incident is performed to provide insights into the conditions experienced by the interior attack team during the fire incident.

After discussions with the AART, additional simulations were developed to examine different tactical approaches to the fire including: exterior fire control as the initial action, effective interior fire suppression, and the use of a smoke control curtain. The review of the results of the four fire simulations combined with the incident data led to the development of several key recommendations to improve firefighting effectiveness and improve the safety for civilians and firefighters in fire incidents like this.

2 Fire Department Overview

Cobb County Fire and Emergency Services has approximately 750 members and 29 fire stations. The stations house 66 apparatus as shown in Table 2.1. Cobb County Fire and Emergency Services protects more than 760,000 residents located over a land area of approximately 340 square miles.

Table 2.1: Cobb County Fire and Emergency Services Apparatus

Apparatus Type	Quantity
Engines	29
Trucks	8
Advanced Life Support (ALS) Rescues	8
Battalion Chiefs Cars	5
Air Trucks	3
Hazmat Trucks	2
Heavy Squads	2
Jet Boats	2
Aircraft Rescue and Firefighting (ARFF) Trucks	2
Medical Operations Vehicle	1
Collapse Trench Rescue Truck	1
Mobile Command Truck	1

2.1 Training and Experience

Every Cobb County firefighter completes a 32 week recruit school. Recruit school is composed of 12 weeks of firefighting training and 20 weeks of training related to emergency medicine service. Field personnel are required to complete 228 hours of in-service training each year. This consists of 192 hours of company training, 12 hours of driver or officer training depending on rank, 18 hours of training at an approved facility (live fire training structure, drill tower, etc.) and 6 hours of hazardous materials (HAZMAT) training.

2.2 Responding Equipment and Personnel

The following apparatus and personnel were dispatched from Cobb County Fire and Emergency Services:

Engine 19 (E19)
Lieutenant (E19 Lt)
Engineer (E19 Eng)
Firefighter (E19 FF)

Truck 19 (T19)
Engineer (T19 Eng 1 AOIC)
Engineer (T19 Eng 2 Tractor Driver)
Firefighter (T19 FF 1)
Firefighter (T19 FF 2 Tiller Driver)

Engine 3 (E3)
Lieutenant (E3 Lt)
Engineer (E3 Eng)
Firefighter (E3 FF)

Engine 4 (E4)
Engineer (E4 Eng)
Firefighter (E4 FF 1)
Firefighter (E4 FF 2)

Engine 5 (E5)
Lieutenant (E5 Lt)
Engineer (E5 Eng)
Firefighter (E5 FF)

Truck 4 (T4)
Lieutenant (T4 Lt)
Engineer (T4 Eng)
Firefighter (T4 FF 1)
Firefighter (T4 FF 2)

Engine 55 (E55)
Automatic aid from Marietta Fire Department
Officer, 2 firefighters

Squad 55 (S55)
Automatic aid from Marietta Fire Department
Officer, 2 firefighters

Rescue 5 (R5)
Officer, Driver

Battalion 2 (Batt 2)
Officer, Driver

3 Incident Overview

3.1 Weather

Conditions measured at Fulton County Airport (approximately 10 miles from the fire) in the early morning hours of February 9, 2022, were clear skies, a temperature of 28 °F, 90 % humidity, and SSW winds of 0 to 3 MPH. There had been no precipitation for the prior four days.

3.2 Building Construction

The fire occurred in a garden style apartment building built on the side of a hill that slopes down away from the road and parking in front of the building. Side A of the building is two stories with a crawlspace (Figure 3.1). Side C is three stories on a slab (Figure 3.2). The facade of Side A is brick for the first floor and vinyl siding for the second floor. The building consists of four stacks of apartments with adjacent pairs of stacks sharing a common enclosed entry hallway. The entrance to the apartments is from the common hallway. The hallway has two unenclosed stairs at the front and rear of the building that connect the floors.

Figure 3.1: Front view of apartment building.

The unit with the fire was a 980 ft^2, two-bedroom, two-bathroom unit (Figure 3.3). The fire was in bedroom 1 next to the living room. The unit had an 8 ft ceiling height. The main door measured

Figure 3.2: Rear view of apartment building.

36 in $\times$ 80 in, the interior doors were 30 in $\times$ 80 in, the bedroom windows were 36 in $\times$ 72 in centered over the height of the room, and the door from the living room to the patio was 72 in $\times$ 80 in Interior walls were gypsum board on 2×4 wood studs. The ceiling was gypsum board below 2×10 wood joists topped with plywood that was topped by concrete which served as the floor of the unit above. The subfloor of the fire apartment was plywood on 2×10 wood joists. Below the subfloor was a crawlspace with concrete masonry unit (CMU) exterior walls, CMU pillars supporting the floor above, and a dirt floor (Figure 3.4).

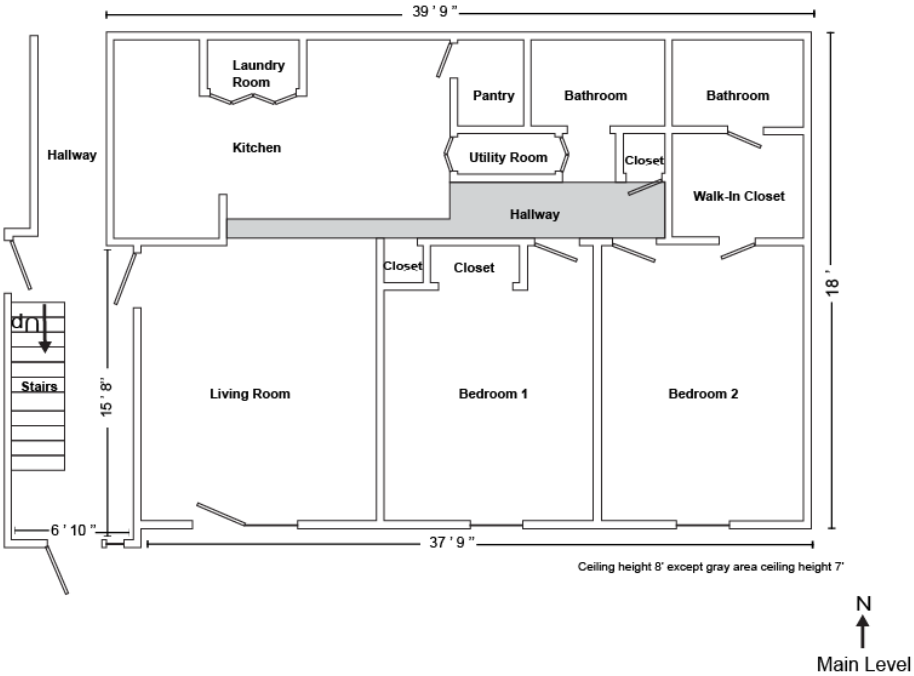


Figure 3.3: Plan view of Fire Apartment. Ceilings were 8 ft tall with the exception of the gray area where the ceiling height was 7 ft.

Figure 3.4: Crawlspace view from access scuttle.

3.3 Personal Protective Equipment

All of the interior firefighters wore their full personal protective equipment (PPE) ensemble including: coat, pants, hood, structural firefighting gloves, boots, helmets, and self-contained breathing apparatus (SCBA). The coat and pants met NFPA 1971 [1] requirements and were less than 10 years old. The thermal protective performance (TPP) rating of the gear was 43.

3.4 Timeline

An approximate timeline was developed to summarize the incident based on helmet and dash camera videos provided by Cobb County Fire and Emergency Services. This timeline served as the basis for this analysis. Times are minutes:seconds with the start time (0:00) taken as the arrival of E19.

- **-04:00**

  Dispatch.

- **00:00**

  Radio announcement that E19 is on scene and that there is fire showing from the Side A window.

- **02:12**

  E19 and T19 interior attack team, Fire Attack 1, (E19 FF, T19 FF 1, and T19 Eng 1 AOIC) briefly opens the door to check conditions inside the apartment (hook and look).

- **02:51**

  Fire Attack 1 enters the apartment.

- **04:30**

  Nozzle becomes entangled in baby furnishings in the living room.

- **04:38**

  Interior water flow into the living room.

- **05:44**

  Interior water flow into kitchen.

- **06:20**

  Report of failed flashlight.

- **07:05**

  Report of no heat seen on thermal imaging camera (TIC) and unclear where the fire blowing out of the window is located.

- **07:43**

  Call to back out to regroup team.

- **08:19**

  Interior water spray into apartment entry doorway from hall.

- **08:48**

  Re-enter apartment.

- **09:18**

  Multiple periods of interior water flow into kitchen over the next 1.5 min.

- **09:43**

  Fire Attack 1 verbalizes that conditions are hotter than normal and discuss backing out.

- **11:01**

  Fire Attack 2 begins exterior fire control once the primary water supply to E19 was secured. Multiple periods of water application to the building facade and into the bedroom from two locations until 14:35.

- **11:23**

  Fire in bedroom located and water applied by the interior nozzle firefighter. Other Fire Attack 1 team members located in flow path between the bedroom and the apartment entry doorway.

- **11:31**

  Mayday call.

- **13:04**

  E5 Rescue team entry into apartment via entry door to the apartment and the living room patio door.

- **13:35**

  Fire Attack 1 emerges from the living room patio door.

3.5 Narrative

At 05:25 AM on February 9, 2022, Company 19 was dispatched to a fire in an apartment complex. Dispatch reported multiple callers had reported a fire and that all occupants should be out. Dispatch reported that the tenant stated his couch was on fire. The first equipment to arrive on scene at 05:29 AM were T19 and E19. E19 reports fire showing from the Side A bedroom window. T19 and E19 were assigned to attack (Fire Attack 1). E55 immediately followed with E3 and E5 arriving over the next few minutes. E55 locates a hydrant and supplies E19. Once tank water was available, Fire Attack 1 entered the apartment via the entry hallway at approximately 05:32 AM.

E55 ran a second line to the exterior of building for Fire Attack 2, but did not begin exterior suppression, as the water supply to Engine 19 was not secured at that point in time.

Fire Attack 1 entered the apartment building via the open front door. Then they entered the fire apartment from the entry hallway and left the door open. Entry into the apartment was led by the E19 FF on the nozzle, followed by the T19 FF1 and T19 Eng 1 AOIC. The AOIC had a thermal imager. Fire Attack 1 encountered difficulties locating the fire inside the apartment with comments on audio suggesting it was expected to be seen quickly after entering the apartment via the entry hallway. The conditions in the apartment were hotter and had less visibility than expected. Approximately 90 seconds after entry, the hoseline was hung up, possibly on a bassinet or baby walker in the living room. Water, using a fog pattern, was applied into the living room in an attempt to reduce heat. Water was also flowed into the kitchen which the attack team perceived as a source of heat as the team observed heat to the left after entering.

After being in the apartment for almost 5 min without locating the fire, a call was made to back out to regroup. The call to regroup was driven by a lack of visibility which led to a lack of accountability. The AOIC noted that the thermal imager was not providing him with any information that could be used to navigate the apartment. While backing out of the apartment, the AOIC became aware that another member of T19, T19 FF 2 Tiller Driver, had gone upstairs and was not the FF on the nozzle. After backing out, the Fire Attack 1 team applied water from the apartment door, re-entered the apartment, and again flowed water into the kitchen.

At some point the team again became separated with the nozzle firefighter moving down the hallway while the other team members appeared to remain near the junction of the living room and kitchen. Team members complained of heat and a call was again made to back out. At this time, approximately 05:40 AM, the team member with the nozzle located the fire and applied water. The other team members were attempting to find their way out and communicate this with the nozzle firefighter. Disoriented, unable to locate the exit, and feeling pain, Fire Attack 1 called a mayday at approximately 05:41 AM. Approximately 90 s after the mayday, a rescue team from E5 entered the apartment, and at 05:43 AM Fire Attack 1 exited the building with the assistance of T19.

Just prior to the discovery of the fire by Fire Attack 1, Fire Attack 2 began applying water from the exterior of the building using a solid stream. The initial water flow was from a position slightly to the living room side of the bedroom window. The exterior suppression alternated between

application of water through the window and application of water to the facade. After 20 s of exterior suppression, the hose was repositioned to be directly in front of the window. At that time flames no longer continuously extend from the bedroom window. Fire Attack 2 then resumed water flow into the window and onto the facade for 30 s with a brief pause during the mayday call. At that time the fire was significantly suppressed. Over the next few minutes water flow into to bedroom and onto facade continued as brief periods of application followed by brief pauses.

Following the rescue, Fire Attack 1 was provided medical treatment. The fire entered an overhaul state and lack of spread into the upper units, crawlspace, and attic space was verified.

3.6 Injuries

Four members of Cobb County Fire and Emergency Services received medical treatment for burns.

1. T19 FF received first degree burns to the back and arms, second degree burns to hands.
2. T19 Eng 1 AOIC received a second degree burn to the right wrist.
3. E19 FF received first degree burns to the left arm.
4. E19 LT (initial IC) received minor facial burns.

4 Analysis

Analysis of the event began with a review of forensic artifacts provided by Cobb County Fire and Emergency Services. The artifacts are summarized in the next section. Following the review of provided data, computer modeling of the event was performed in order to establish a more quantitative assessment of fire conditions during the event. Experimental data from full scale fire testing was also used to provide insights on fire conditions and to provide credence to the computer modeling results.

4.1 Summary of Provided Forensic Documentation

The following list describes the forensic information provided by Cobb County Fire and Emergency Services:

- A pdf file containing a floor plan of the apartment with dimensions.
- A pair of audio files from the 911 system. One file is a condensed audio file of the entire event, and the second file is an uncondensed audio starting from the mayday and ending with the canceling of the mayday after Fire Attack 1 was brought out of the apartment.
- A series of video and audio files containing post-event interviews of fire department members present during the fire event.
- A collection of 263 digital photographs taken after the fire event. Photos are exterior views of the building, and interior views of the entry hallway, the fire apartment, and the apartment above the fire apartment.
- An email from the homeowner listing fuels present in the fire bedroom.
- A Matterport weblink containing a 3D virtual walk through of the post-fire condition of the fire apartment.
- A collection of 110 digital photographs showing the post-fire condition of the turnout gear worn by Fire Attack 1.
- Helmet camera videos from the nozzle firefighter for Fire Attack 1 and from a member of Fire Attack 2.
- A dash camera video from an apparatus located 150 ft from the fire apartment.
- A collection of three National Fire Incident Reporting System (NFIRS) incident reports for the fire event.

- A collection of video files from a TIC carried by the Fire Attack 1 AOIC.
- A collection of written narratives of the fire event.

4.2 Review of Video Footage

This section summarizes observations made by examination of videos taken by helmet and dashboard cameras during the event. The TIC video was reviewed; however, nothing of note was discernible in the video files.

4.2.1 Observations on Fire Size

Figure 4.1 shows a helmet camera video frame recorded shortly before Fire Attack 1 entered the apartment. The bedroom window appears to be fully broken out, the bedroom has flashed over, flames extend up to the bottom the second floor window, and there is heavy black smoke. Strong bidirectional flow can be seen in the bedroom window, indicating the window is the a primary source of air feeding the fire. These are indications of a ventilation-limited fire.

With the front door to the apartment closed and assuming the fire had burned long enough to deplete the available oxygen in the apartment, the window would represent the primary source of ventilation for the fire. Small amounts of air would be entering from leakage flows. Given an opening area A in m^2 and an opening height H in m, the maximum expected heat release rate supported by the air flow through the opening ($\dot{Q}_{max}$ in kW) is given by Equation 4.1 [2]. The bedroom window was 36 in (0.91 m) $\times$ 72 in (1.83 m), which would give a maximum potential heat release rate of approximately 3,400 kW or 3.4 MW. Fully developed fires can consume between 50 % to 90 % of the oxygen entering through a vent [3]. This inefficiency results from some of the oxygen entering the vent being immediately entrained into the exiting gasses before it has time to contribute to the fire in the room. This gives an estimate of a 1.7 to 3.1 MW fire.

$$\dot{Q}_{max} = 1500 \times A \times \sqrt{H} \tag{4.1}$$

Figure 4.1: Exterior view of bedroom window prior to entry into the apartment. Image is a frame from a helmet camera video.

Figure 4.2 shows a view of the fire from a dashboard camera. Two points in time are shown. The top is the fire size prior to entry into the apartment and is at a similar time to that shown in Figure 4.1. The bottom is the fire size just before the exterior attack started. The flame length outside the window has increased from the base of the second floor window to impinging upon the eaves of the roof. This is an 80 % increase of the flame length measuring from the floor of the first floor bedroom. The flame length of a fire scales with the fire size to the four-fifths power [4], which means this increase in flame length means a doubling of the fire size. This increase in fire size is a direct result of opening the door to the apartment which effectively doubled the amount of available ventilation to the fire. From entry into the apartment until sustained flaming was seen at the roof took 2.5 min after entry into the apartment. The image also shows the flow in the bedroom window was largely unidirectional, meaning the primary source of air for the fire was now the open apartment door. A contributing factor, as noted in the next section, was the failure of part of the floor from the fire room into the crawl space below. Failure, however, likely contributed significantly less ventilation than the open apartment door given the limited size of flow paths from the outside into the crawl space.

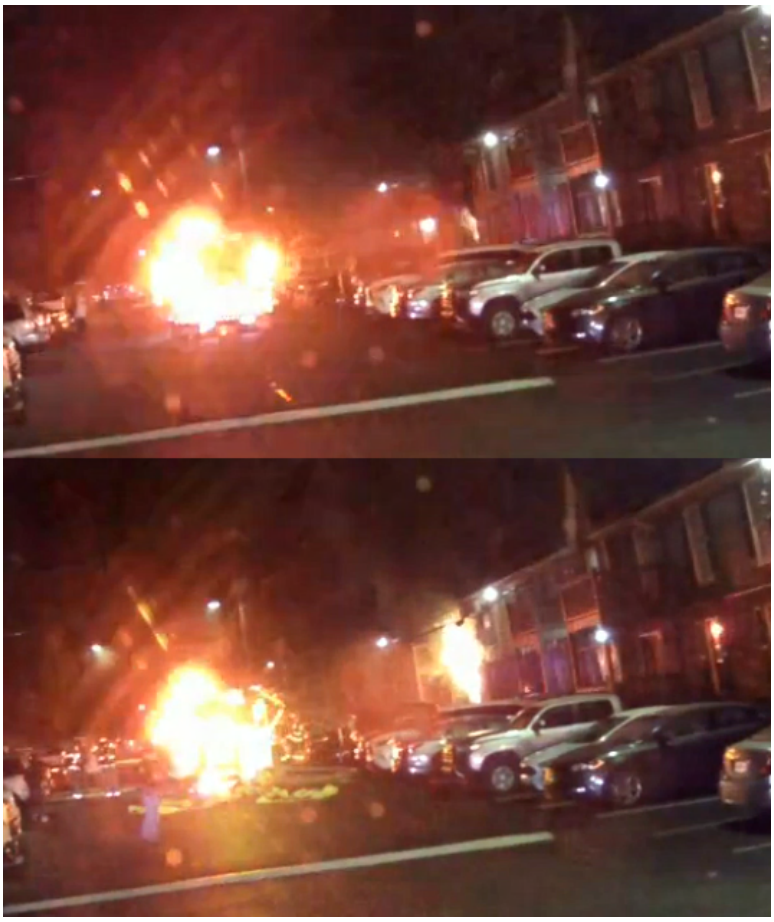


Figure 4.2: The top photo shows the fire size in the bedroom prior to entry into the apartment. The bottom photo shows the fire size prior to the start of exterior attack.

4.2.2 Observations on Interior Attack

Figure 4.3 is an exterior view of building showing the entry hallway exterior door and the fire apartment window just prior to Fire Attack 1 entering the building. The flame lengths from the bedroom window are unchanged from those seen at arrival in Figure 4.1. No significant loss of visibility is seen in the entry hallway.

Figure 4.4 shows conditions in the entry hallway as Fire Attack 1 was laying out the hoseline preparing to enter the apartment. The view is from a helmet video camera looking from just inside the entrance to the entry hallway toward the fire apartment. A smoke layer can be seen along the ceiling down the tops of the apartment doors. Smoke can be seen leaking out from the top and upper sides of fire apartment door. This leakage flow would have been stronger prior to window breakage.

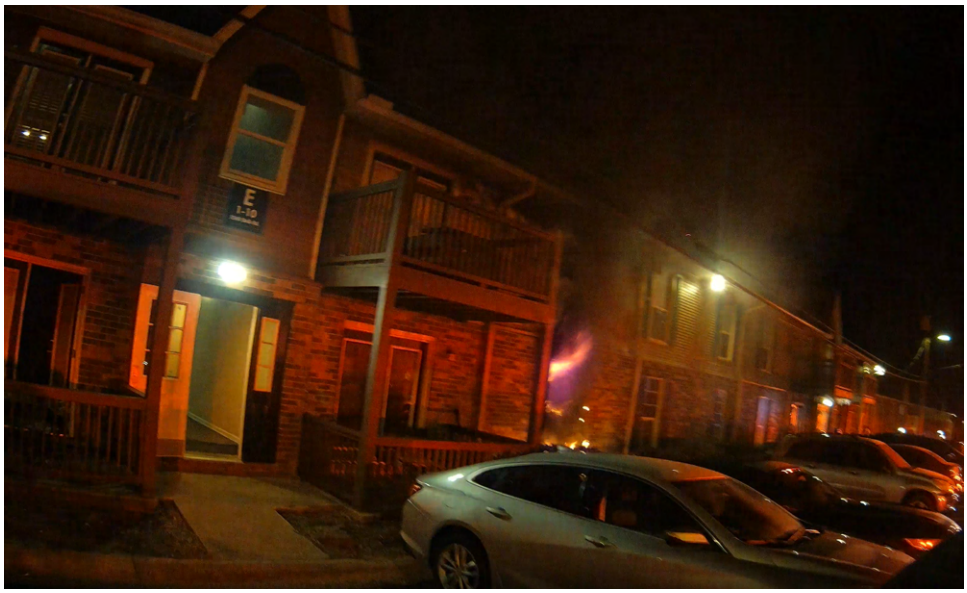


Figure 4.3: View of the conditions prior to entry into the apartment building from the nozzle FF helmet camera video.

Figure 4.4: Conditions in entry hallway prior to entry into the apartment taken from the nozzle FF helmet camera video.

Figure 4.5 is a view looking at the apartment door as it was briefly opened to check the conditions inside (hook and look) prior to making entry. Immediately, thick smoke began to fill the entry hallway and nothing could be seen inside the apartment.

Figure 4.6 is a view inside the apartment looking from somewhere near the entrance door toward the patio door. This image is a few seconds after entry. The glow seen in the image was from the lights on the trucks outside the apartment. The next time anything can be discerned, other than lights worn by Fire Attack 1, in the helmet camera video was when the fire in the bedroom was finally discovered 8.5 min after entry.

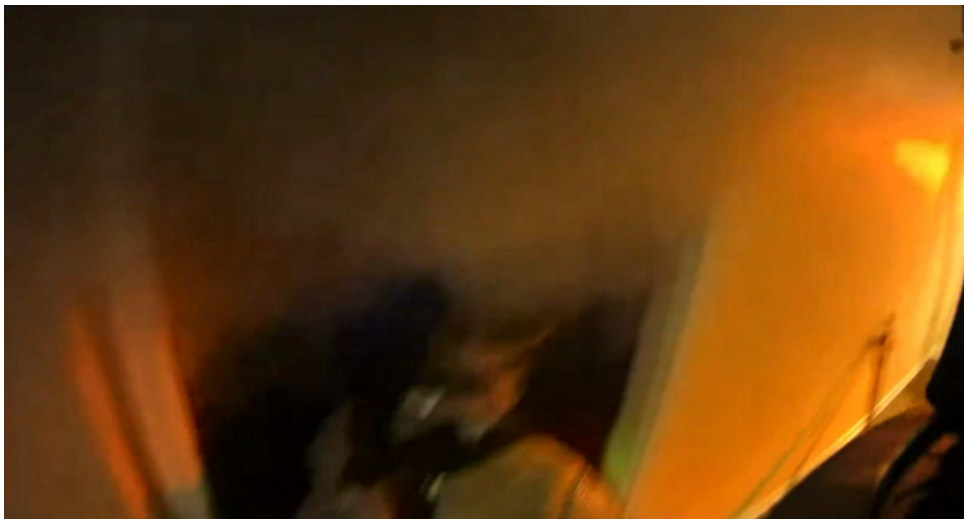


Figure 4.5: View of the apartment doorway as it is first being opened.

Figure 4.6: View from inside of the apartment living room looking toward the patio door.

Figure 4.7 is a view looking in from the door of the fire bedroom just after discovery of the fire by Fire Attack 1. This is approximately 20 s after the start of water flow from the exterior by Fire Attack 2. As detailed in the next section, exterior suppression quickly knocked down the fire, which would have led to improving the visibility in the bedroom. Immediately after discovery, a brief period of interior water flow on the fire began. Interior suppression stopped as a result of the mayday call initiated by the officer of Fire Attack 1, who was located near the entry door to the apartment.

The next point where anything is discernible in the interior video is after the rescue team had entered the apartment. With the entrance door open, the patio door open, and the fire largely suppressed by the exterior attack, the visibility would have rapidly improved in the living room.

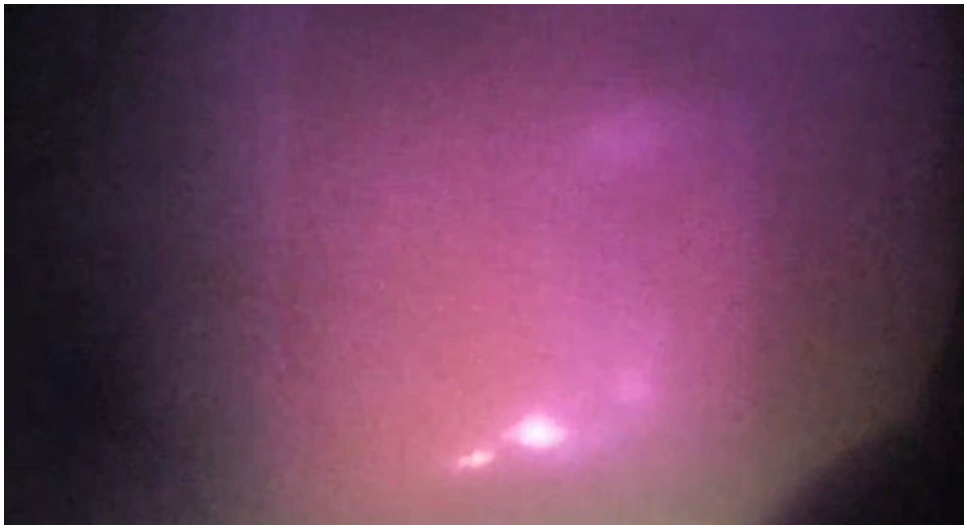


Figure 4.7: View of fire bedroom after discovery of fire by Fire Attack 1.

4.2.3 Observations on Exterior Fire Control

Figure 4.8 is a view looking at the fire bedroom window just as the exterior water flow by Fire Attack 2 was starting. This was approximately 30 s prior to the mayday. At this point in time flames fill the windows with the flame height reaching the eaves of the building. The initial water application was a few second burst consisting of approximately 1 s onto the shrubs and the remaining flow into the room, mostly directed upwards into the window.

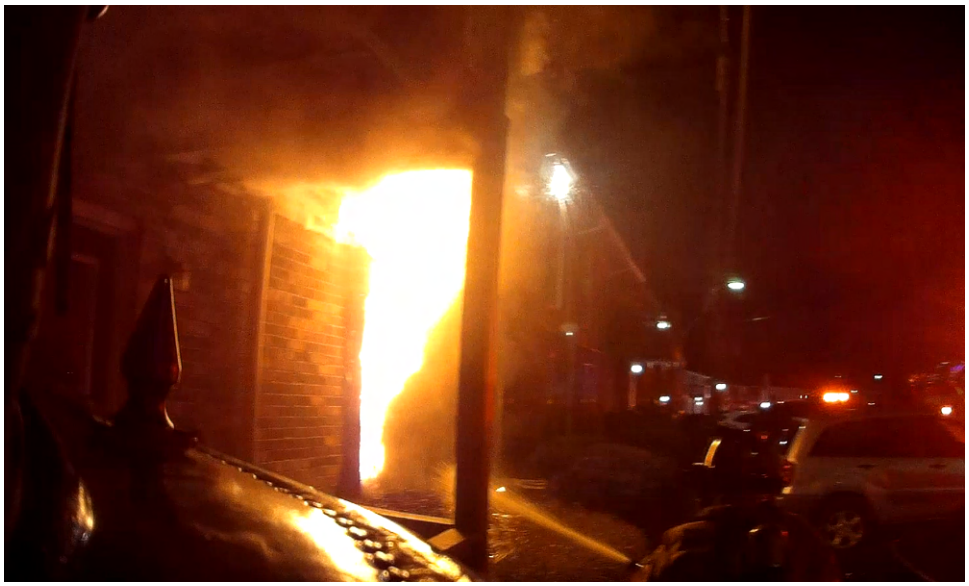


Figure 4.8: Exterior view of fire bedroom at the start of the exterior attack.

Figure 4.9 is a view looking at the fire bedroom window just after the initial application of water into the room. This was followed by a couple seconds of applying water to the facade. After the

initial brief application of water into the bedroom, the fire was significantly knocked down. Flame heights leaving the window were reduced to the state prior to entry into the apartment.

Figure 4.9: Exterior view of fire bedroom after initial application of water into the room.

Figure 4.10 is a view looking at the fire bedroom window just after the second application of water into the room. Following the 2 s of water application onto the facade, the exterior suppression alternated between the room and the facade for approximately 4 s. Immediately at the end of this second period of applying water into the bedroom, no flames were visible exiting the window. Glow from combustion inside the room can be seen through the smoke and water vapor. Following this, there was a brief pause as the fire hose was repositioned to be directly in line with the window.

Figure 4.10: Exterior view of fire bedroom after the second application of water into the room.

Figure 4.11 is a view looking at the fire bedroom window just after the hose was relocated and just before the resumption of water flow. Flames slightly extend out from the window. This was a significant reduction in fire intensity compared to the fire size at arrival. This time corresponds to the time the fire was discovered by Fire Attack 1. After repositioning, there was a period of water application into the bedroom that lasted until the mayday call was made 7 s later. This period of time overlaps the time period when Fire Attack 1 was suppressing the fire from the hallway.

Figure 4.11: Exterior view of fire bedroom after relocation of the fire hose.

Figure 4.12 is a view looking at the fire bedroom window 2 s after the mayday call was made. The exterior suppression paused for a brief period (12 s) immediately after the mayday call. No significant fire is seen in the helmet camera video at this time. Following the pause, when the exterior suppression resumed it first focused on the building facade and eaves. This was followed by another brief pause as the hose was repositioned as close to the window as possible given the shrubs outside the building. The next period or water application was a 10 s long period directly into the bedroom window.

Figure 4.13 is a view looking at the fire bedroom window 93 s after the mayday call was made. This was after the 10 s period of water application directly into the bedroom window. There is still no sign of fire and the intensity of the outflow is reduced from that seen in Figure 4.12. During this pause Fire Attack 2 moved towards the patio door to support the rescue effort. Approximately 90 s passed before there was another brief application of water to the facade, eaves, and into the bedroom before the end of the provided video footage. Total flow from the exterior was under 100 gallons of water, which was less than 15 % of the water carried by E19.

Figure 4.12: Exterior view of fire bedroom 2 s after mayday. Exterior attack paused for 12 s after the mayday call.

Figure 4.13: Exterior view of fire bedroom 93 s after mayday.

4.3 Review of Post-Fire Photography

This section summarizes observations made by examination of post-fire photography.

4.3.1 Post-Fire Condition of Fire Attack 1 Turnout Gear

Post-fire photographs were taken of the turnout gear worn by Fire Attack 1. The photos show significant soot deposition on clothing and equipment. Photos of nylon webbing do not show any thermal damage to the webbing. Photos of the SCBA harnesses, face pieces, regulators, and gauges show only soot deposition. No indications of thermal damage are seen.

4.3.2 Post-Fire Condition of the Fire Apartment

The images in this subsection were captured from a Matterport 3D scan of the fire scene. Matterport is a commercial service that creates virtual 3D models by stitching together sets of images taken from a rotating camera placed at various locations within a structure. In some images in this section, white circles can be seen on the floor. These circles represent locations where the Matterport scanner was placed.

Figure 4.14 shows a view of the first floor entry hallway. Soot deposition is seen on the walls and ceilings with a heavier band of deposition seen on the upper 2 to 2.5 ft of the wall. No signs of thermal damage are seen in the entry hallway.

Figure 4.14: Photograph of the entry hallway taken near the building entrance looking at the door to the fire apartment.

Figure 4.15 shows a view of the entrance to the fire apartment. Significant soot deposition is seen on the door frame from the middle hinge upwards. The degree of deposition on the hinge side of the door jamb is similar to the deposition on the living room wall. The deposition on the jamb is heavier than that seen on the entry hallway wall just above the door. This suggests much of the deposition on the door jamb was the result of leakage flow around the door and not deposition that occurred after Fire Attack 1 entered the apartment. No visible signs of thermal damage are seen on the door jamb or on the hinge side of the door leaning against the wall in the image.

Figure 4.15: Photograph of apartment entrance door taken from the entry hallway looking into the fire apartment.

Figure 4.16 shows a view of the living room. Significant soot deposition is seen from ceiling to within 1.5 ft of the floor. This is indicative of the zero visibility conditions that Fire Attack 1 encountered after entering the apartment. Thermal damage can be seen on the plastic blinds on the patio door over the same height as the wall soot deposition. The blinds are not fully melted indicating temperatures somewhat below the melting point. Plastic blinds are typically a vinyl thermoplastic (which melts upon exposure to heat) with melting points ranging between 200 and 500 °F. Thermal damage is not seen on the sofa, the TV, the TV stand, or the baby chair and bassinet. Some of the plastic materials in those items are likely thermoset materials (which char upon exposure to heat) that generally require temperatures over 600 °F before significant damage occurs.

Figure 4.16: Photograph of the living room taken from just inside the apartment door and looking at the patio door.

It is likely that either the baby chair or the bassinet was the object the fire hose hung up on shortly after entry.

The bedroom with the fire is on the other side of the wall with the baby chair and bassinet. The wall does not show burn through on the living room side. There is a hole visible above the baby chair; however, the edges look like a puncture rather than fallout of gypsum wall board due to heating suggesting this occurred during overhaul.

Figure 4.17 shows the dining area. Similar soot deposition patterns are seen here as were seen in the living room. The edges of the folding doors to the utility closet show little to no soot deposition indicating these doors were not open during the fire. The soot deposition in laundry nook and on the interior side of the door to the laundry nook suggest these doors were open during the fire. The various items seen in the dining area have a range of soot deposition from heavy soot deposition to minor soot deposition. This suggests some of these items were moved during post-fire activities. The light switch cover plate is melted over the upper half of the plate. Plastic outlet cover plates are typically nylon. Nylon is a thermoplastic where the melting point depends upon the specific polymer chemistry used and the types and quantities of additives combined with the polymers. Generally nylon will have a melting point in the range of 375 to 575 °F [5] with softening occurring at lower temperatures.

Figure 4.17: Photograph of the dining area taken from the archway to the kitchen.

Figure 4.18 shows a view of the counter dividing the kitchen from the living room. The image shows a soffit at the top. The air handler for the apartment is located in the utility closet and the duct serving the living room and kitchen runs in a gypsum board box below the ceiling forming the top of the soffit separating the areas. The counter top contains a number of plastic bottles and the wall has two plastic wall plates. On the kitchen side of the counter, the wall plate and the plastic bottles are melted. On the living room side, the wall plate and plastic bottles do not show any signs of softening or melting. This is likely a result of the ceiling jet formed by hot gases leaving the fire bedroom and entering the hallway being trapped by the soffit separating the kitchen and the living room. The jet would not have been able to spill into the living room until it encountered the wall seen in photo, which would have caused the jet to turn down. Only the wall plate and plastic bottles on the kitchen side of the soffit would have been within the turned-down portion of the ceiling jet. Plastics used for drinking containers are typically low or high density polyethylene (LDPE or HDPE) or polyethylene terephthalate (PET or polyester). LDPE plastics generally melt in the lower end of the temperature range given for nylon, and HDPE melts in the upper end. PET plastics melt in the middle to upper end of the range for nylon [5].

Figure 4.18: Photograph of the counter between the living room and kitchen taken from the kitchen looking into the living room.

Figure 4.19 shows a view of the range, sink, and kitchen cabinets. Outlet covers near the sink are partially melted. The outlet cover left of the stove does not show any damage. This outlet is more sheltered as it is tucked deep under a corner cabinet and is in the shadow of the refrigerator. No evidence of charring is seen on the cabinets. For shorter term exposures (minutes), wood products do not begin significant degradation until temperatures of approximately 400 °F [6]. This suggests temperatures in the kitchen were hot enough to soften and melt thermoplastics but not significantly in excess of 400 °F.

Figure 4.19: Photograph of the kitchen stove and cabinets.

Figure 4.20 shows a view down the hallway. The view is from the kitchen end of the hallway looking toward the doors to the two bedrooms. The studs in the foreground on the left border the utility closet. No charring is evident, but there is soot deposition indicating some drywall likely failed during the fire. The studs in the foreground on the right are the back wall of the closet in the fire bedroom. Lesser amount of soot deposition are seen, likely a result of the closet front wall and door providing an extra level of protection. Charring of studs, joists, and door jambs is only seen at the end of hallway in vicinity of the door to the fire bedroom.

Figure 4.20: Photograph looking down the hallway from the kitchen.

Figure 4.21 shows the bathroom across the hallway from the fire bedroom. Significant soot deposition is seen on the walls indicating the door to the bathroom was open during the fire. Discoloration and the beginning of charring is seen on the ceiling joists and subfloor above the bathroom. The bath towels above the toilet show some discoloration.

Figure 4.21: Photograph of the hallway bathroom taken from its door.

Figure 4.22 shows the master bedroom. Significant soot deposition is seen to within a couple of feet of the floor. The subfloor and ceiling joists above the bedroom show soot deposition but no indications that significant pyrolysis had begun. Along the wall connecting to the fire bedroom, significant charring of the studs is only seen on the studs behind the mirror on top of the dresser. This suggests much of the wall board failure occurred late during the fire or during suppression and overhaul.

Figure 4.22: Photograph of the master bedroom taken from just inside the doorway to the bedroom.

Figure 4.23 shows the interior of the fire bedroom. All bedroom contents have been reduced to ash and non-combustible remnants. The ceiling shows significant charring of the joists and the wood subfloor. Studs near the window and a few studs along the side walls show charring. Portions of the room floor in front of the window have collapsed into the crawlspace below the room. The severe damage in this room and the relative lack of damage outside this room indicate the fire was largely contained to bedroom other than a small region in the hallway outside the bedroom door where some charring of joists and studs is seen.

Figure 4.23: Photograph of the fire bedroom looking from the door towards the window.

Figure 4.24 shows the floor of the fire bedroom. Three bays between floor joists are open to the crawlspace beneath the bedroom. The open area is approximately 3 ft wide measured along the wall with the window, and 5 ft long measured away from the window. The exposed tops of the floor joists show char depths that appear to be less than 0.5 in Charring rates for southern pine, the likely wood used, are 0.6 to 0.7 mm/min [7] suggesting the floor failure was late in the fire and likely close to the start of suppression. While the opening area in the floor is substantial, the crawlspace itself has limited ventilation. The primary opening into the crawl space is an expanded metal mesh covered scuttle in the exterior wall of the building, which is approximately 2 ft $\times$ 2 ft. Any air flow into the bedroom would be limited by the area of the openings in the expanded metal mesh (approximately 50 % of the total opening size) rather than the floor opening area.

The floor to the right shows the remnants of coil springs and dimensional lumber consistent with stated room contents of a mattress and box spring on the floor. Thin metal strapping is seen in the left side of the image and is likely the remnants of other furniture present in the room.

Figure 4.24: Photograph of the floor of the fire bedroom taken from in front of the bedroom closet.

Figure 4.25 shows the ceiling of the fire bedroom. All of the ceiling joists and the sub floor above show significant charring. The joist bays in line with the window are missing portions of the subfloor, exposing the poured concrete layer above the subfloor. In the second from the left joist bay with missing subfloor, a piece of the concrete has broken off exposing the carpet padding above it. The carpet padding shows only minor discoloration, indicating it was not exposed to high temperatures for very long. Given that the missing subfloor above is in front of the window, this may have been a result of suppression activities where the hose stream removed heavily charred sub floor and thermal stresses from rapid cooling cracked the concrete enough to result in a piece falling out either during suppression or during overhaul. Had the concrete fallen out when there was still significant fire in the bedroom, the carpet pad would have quickly ignited and spread fire into the apartment above. Other than at the top of the window, little to no charring is seen on wood structure below the ceiling joists.

Figure 4.25: Photograph of the fire bedroom ceiling looking up from in front of the closet.

Figure 4.26 is a view looking from the bedroom, through the closet, and into the hallway. Charred remnants of the closet door can be seen attached to the jamb. Significant charring is seen at the top of the closet door jamb, and some charring is seen at the ceiling inside the closet and on the closet face of one stud at the hallway. Small amounts of charring are seen on one stud at the living room wall. At the hallway ceiling between the bedroom closet and the utility closet, minor charring is seen in some of the members forming the gypsum board box around the HVAC ducts. This indicates some of the gypsum board in this area failed prior to suppression.

Figure 4.26: Photograph of the fire bedroom closet looking from the fire bedroom into the closet.

The review of the post-fire photographs shows the fire was contained to the bedroom of origin. Other than in the hallway immediately outside the fire bedroom, there are no signs of significant thermal damage beyond the melting and softening of thermoplastics. This suggests that thermal conditions throughout the apartment away from the fire bedroom were generally in the range of 200 to 600 °F. As previously stated, temperatures above 200 °F are needed to soften and melt thermoplastics. Charring of hard thermoset plastics, which was not seen in the photographs, generally requires temperatures over 600 °F.

4.4 Modeling of the Fire Event

To aid in understanding the thermal conditions present inside the apartment, modeling of the fire event was performed using Fire Dynamics Simulator (FDS). FDS is a computational fluid dynamics (CFD) model developed in an multi-national effort led by the National Institute of Standards and Technology (NIST). FDS was developed specifically for the purpose of modeling fires in the built environment [8, 9]. FDS has a companion tool called Smokeview to aid in the visualization of FDS results [10, 11]. Both FDS and Smokeview have undergone significant verification and validation [12–14] and are developed under a modern software quality assurance process [15].

Four FDS simulations were performed. The first examined the fire incident as it happened. Additional scenarios were modeled based on three other tactical approaches.

1. The first simulation used the actual event timeline for entering the apartment, fire growth post-entry, suppression from the interior and exterior, and decay of the fire. The timeline was developed from the various helmet and dash camera videos of the event.

2. The second simulation examined the tactic of suppressing the fire from the exterior prior to entering the apartment. In this simulation, exterior suppression started at the time Fire Attack 1 entered the apartment in the real event timeline. Entry was delayed for 2 min to give time for the exterior attack to suppress the fire. The sequence of exterior attack and fire decay followed the first simulation sequence but was time-shifted to occur when entry was made in the actual event timeline.

3. The third simulation examined the tactic of protecting the building exit by placing a smoke curtain in the apartment door. The post-entry fire growth was reduced as a result of the reduced ventilation due to the smoke curtain. The timing of suppression and fire decay from the first simulation was kept.

4. The fourth simulation examined the tactic of only having interior suppression. In this simulation at the point in time when interior suppression began, the timing of water application from the exterior suppression and resulting fire decay was used. This simulation assumed the mayday did not occur. This simulation had no exterior suppression.

4.4.1 Development of the FDS Model

As a CFD model, FDS requires a detailed specification of the fire event. This includes the structure of the building, thermophysical properties of the materials of construction, the heat release rate of the fire, and the flow of water from hoses.

The geometry of the structure should include all relevant free air volumes where smoke and heat from the fire can vent. Because the fire did not break through into the upper apartment or adjacent apartments on the same floor, those apartments do not need to be included in the model. The windows and patio door for the apartment serve as leakage locations for smoke, and ultimately the fire bedroom window broke out and the patio door was opened. Capturing the flows due to the broken window and open patio door require modeling a small region of the outdoors adjacent to the facade of the building. The apartment door into the entry hallway also serves as a path for smoke leakage, and that door was opened during the fire. The two floors of the entry hallway are connected by open staircases and the building entrance door was open to the outside. Therefore, the entry hallway and a small region outside the entry hallway door should be included in the model. The floor in the fire bedroom had partial failure into the crawlspace. Since the crawlspace has vent openings to the outside, those openings will allow for air flow into the crawlspace and up into the bedroom once the floor fails. Therefore, the crawlspace should also be included in the model.

The apartment floor plan shown in Figure 3.3 and various post-fire photos were used to develop the FDS geometry model. The model included the fire apartment, the upper two levels of the

entry hallway, and the building facade, plus a small region of the outdoors sufficient to resolve flow through the broken window, patio door, and the building entrance door. Figure 4.27 shows multiple views of the FDS geometry model using the Smokeview visualization tool. The model was meshed with 4 in grid cells. This grid size provides seven grid cells across the width of interior doors, which is a reasonable number of cells to capture fire-driven flow through a doorway.

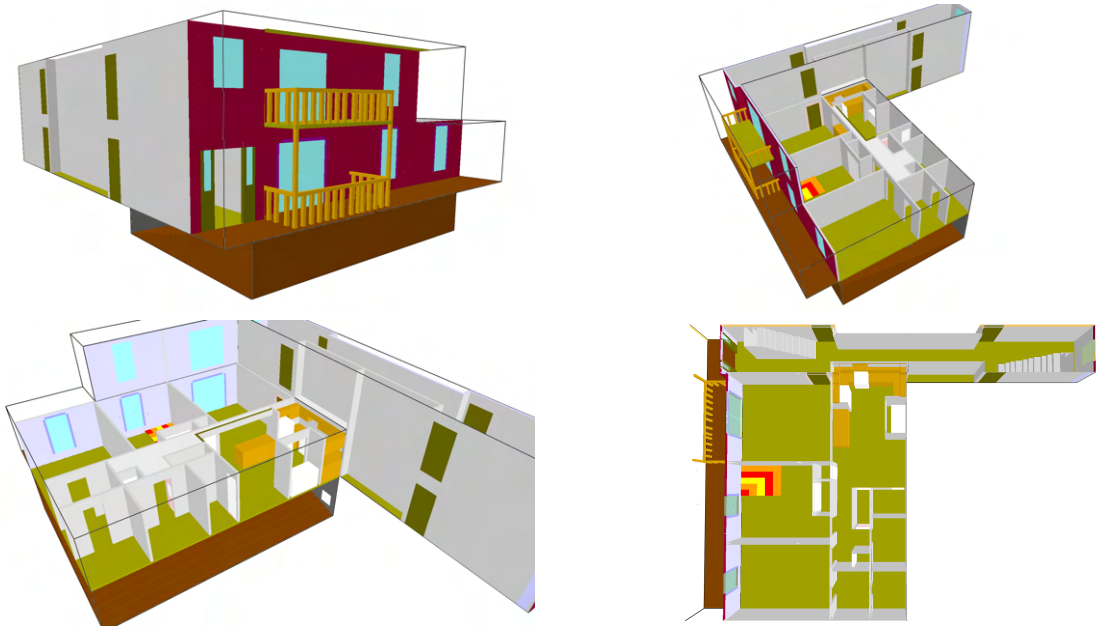


Figure 4.27: Views of the FDS geometry model. Top left: View of front corner of building showing the facade, entry hallway side wall, and crawlspace, Top right: View of opposite front corner of the fire apartment from above showing the interior of the apartment. The red/orange/yellow area is the fire source. Bottom left: View of rear corner of fire apartment from above. The pink shaded region on the door to the air handler is defined as a 50 % open louvered vent in the model. Bottom right: Top view of the geometry with the second floor and fire apartment HVAC duct enclosure removed.

Based on the post-fire photos and event videos, the building entrance door, both bedroom doors, the laundry nook door, and the master suite interior doors were open in the model. All other interior doors were closed. For the louvered doors to the water heater and air handler, a set of louvers was defined for the upper and lower halves of the doors. All other interior doors had a leakage path defined at the base of the door. Defining leakage paths for enclosed volumes connected to the fire apartment is needed to avoid anomalous pressure solutions in the closed volumes due to pressure work. Heat conducted through the doors and walls into a sealed space will raise the pressure in the space. In ordinary construction this pressure is relieved by leakage around doors, windows, and other small gaps. The apartment door to the entry hallway, the patio door, and the two bedroom windows also had leakage paths defined. Five leakage paths were defined for each item: a leakage path along the top of the opening and a pair of leakages paths to either side. These leakage paths relieve the pressure buildup due to the fire growth. Having two leakage paths along the sides allows for bi-directional leakage flow to develop.

The fire bedroom window was defined to break when the temperature at the mid-height of the window reached 752 °F (400 °C). Window breakage due to fire is a complex phenomenon that depends on the air tightness of the building, the type of glass used in the window, and pre-fire stress on the glass due to the window frame. The exact time of window breakage is not a critical factor in this analysis other than having the window broken out prior to the arrival of E19.

The apartment door, a portion of the fire bedroom subfloor, and the patio door were assigned timers that were programmed to remove the corresponding solid obstructions at specific times in the simulation representing entry of Fire Attack 1 into the apartment, failure of the subfloor, and entry of the rescue team after the mayday.

The fire and suppression timelines are discussed as in sections for the first, second, and fourth simulations. The third simulation used the first simulation timeline.

Interior walls were defined as two, 0.5 in layers of gypsum separated by a 3.5 in air gap. Exterior walls were defined as 0.5 in of gypsum, 3.5 in of fiber glass insulation, 0.75 in of wood, and 3 in of brick. Windows were defined as 0.125 in of glass. The fire apartment floor was defined as 0.75 in of wood. The fire apartment ceiling was defined as 0.5 in of gypsum, 10 in air gap, 0.75 in of wood, and 1.5 in of concrete. Interior doors were defined as two layers of 0.125 in wood separated by a 1 in air gap. The exterior and main apartment doors were defined as 1 in thick wood.

4.4.2 Modeling of Event Timeline

Discussion of Model Inputs

Timing in the FDS model for the event was tied to the entry of Fire Attack 1 into the apartment. NFIRS reports indicate 4 min from alarm until the arrival of E19. It was just under 3 min from arrival of E19 until the entry of Fire Attack 1. There would be additional time from the ignition of the fire and its discovery plus time for the 911 call center to receive the call and gather the necessary information. Based on this it was assumed that entry took place 20 min after the start of the fire.

It is unknown at what point in time the wood floor in the bedroom failed; however, floor joist char depth in Figure 4.24 suggests this occurred late in the fire. It was observed to be failed during the overhaul of the fire. In the simulation, it was assumed the floor failed at the same time Fire Attack 1 entered the apartment, or 20 min after the start of the fire.

The bedroom fire was defined with two growth phases and four decay phases. The first growth phase was assumed to be a medium-growth fire where the growth ceases at 2.5 MW after 474 s. This was based on the ventilation limit for the open bedroom window and scoping calculations with FDS that looked at the exterior flame height. The fire was defined to occur over an area representing the queen-sized bed in the room. The fire was defined to spread over the surface as it grew to 2.5 MW. This fire size was maintained until 20 min when Fire Attack 1 entered

the apartment. Over the next 2.5 min the fire size was increased by a factor of 1.7 (from 2.5 to 4.25 MW). This size was based on the visual observations of the flame length increase after the apartment door was opened. This fire size was maintained until the start of the exterior attack. The fire was then decreased in four steps as the various periods of water application to the bedroom occurred: a reduction in fire size of 30 % of the peak fire size (down to 2.975 MW), a second reduction to 40 % of the peak fire size (1.7 MW), a reduction down to 10 % of the peak fire size (425 kW), and a final reduction to 0 kW. The timing of these steps are discussed in the event timeline at the end of this subsection.

For water-based suppression, FDS has an input specification developed for standard sprinklers and water mist systems. This set of input specification includes spray angle, orientation, flow rate, and droplet size. Simulation input parameters were defined to represent the exterior and interior hose streams.

The exterior suppression was made with a straight stream directed upward through the bedroom window. As discussed in Section 4.2.3, the exterior suppression took place from two locations outside the window. Each location was implemented in the FDS model using two spray nozzles. For each location, one spray nozzle was used to represent the solid stream, and a second spray nozzle was used to represent the break-up of the solid stream where it impacted the ceiling of the bedroom. The exterior location spray nozzles were defined as flowing 150 gpm with a 2° cone angle and a volume mean diameter of 1.7 mm [16]. The droplets from the two exterior locations were killed after 0.55 s, which is approximately the time for water to travel from the nozzle to its impingement point on the ceiling inside the bedroom. Each exterior spray nozzle was paired with an interior spray nozzle at the location where the solid stream impinged on the ceiling. For the interior spray nozzles, the same flow rate was used but the droplets were defined with a smaller volume mean diameter of 1 mm to reflect breakup of the solid stream into smaller droplets after impact. Each interior spray nozzle had a cone angle of 120° centered along the mirror reflection angle of the solid stream.

During the interior attack water was sprayed in the living room, the kitchen, and the bedroom. Audio from the Fire Attack 1 helmet camera indicates multiple periods of water flow in the living and kitchen prior to discovery of the fire in the bedroom. Since the fire was not in the living room or kitchen, water spray in these locations would only have the effect of cooling the gas. Two locations were selected as representative of the water spray in the kitchen and living room. One was just inside the apartment doorway pointed toward the wall between the living room and the fire bedroom, and the other was in the archway from the living room pointed into the kitchen. The water spray into the bedroom is briefly visible on the helmet camera video and shows the nozzle was located near the doorway and sprayed toward the bedroom window. The video indicates a fog pattern was used. Each interior spray nozzle location used the same input parameters to define the spray. These were a 150 gpm flow rate, a cone angle estimated from the video as 20°, and a median droplet diameter of 0.5 mm [16].

Figure 4.28 shows the FDS model implementation of the five locations. The five images show the five spray locations and the resulting droplet patterns.

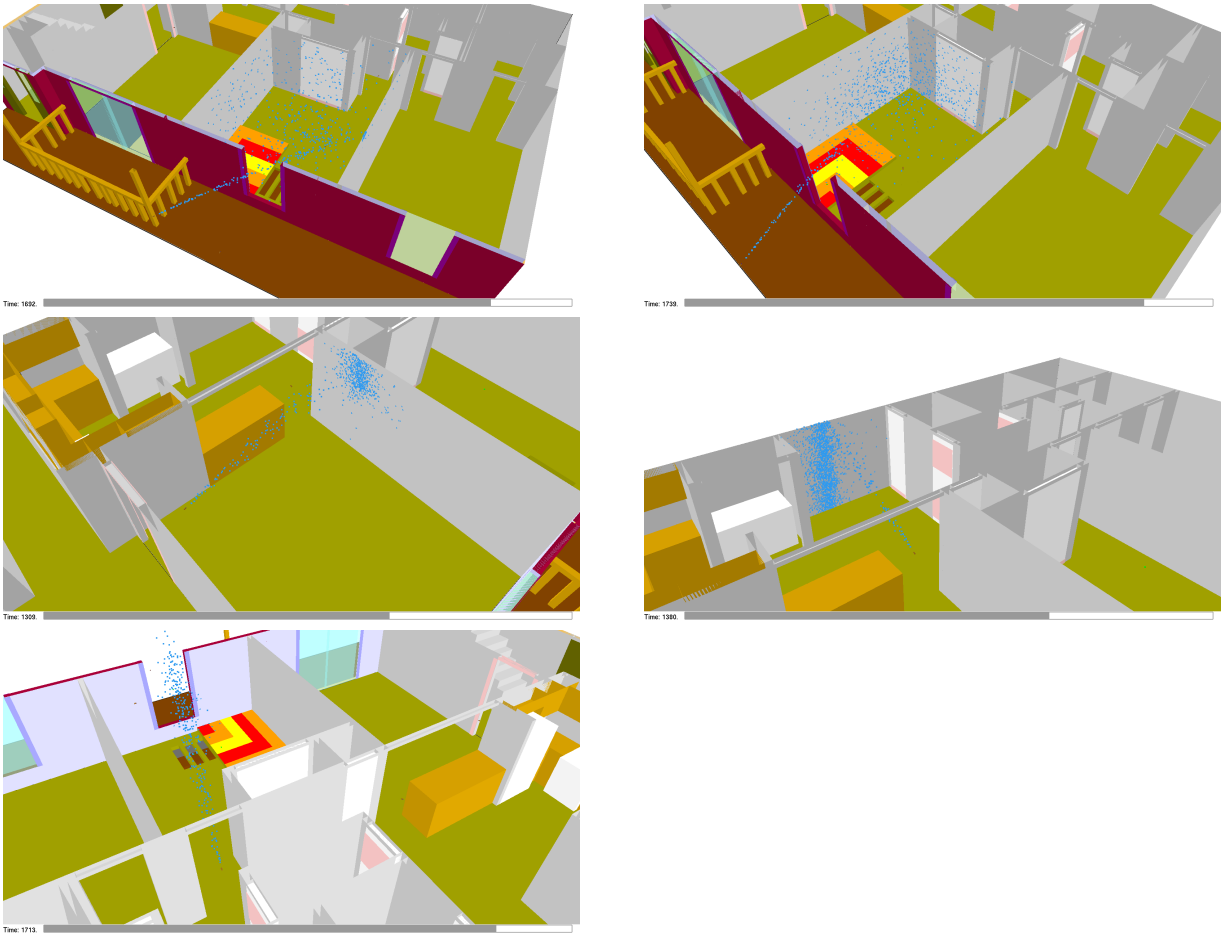


Figure 4.28: FDS representation of the five hose stream locations included in the simulations. Top left is the initial exterior attack location. Top right is the second exterior attack location. Middle left is the interior attack living room location. Middle right is the interior attack kitchen location. Bottom is the interior attack bedroom location.

The overall timeline of events is as follows (time in seconds is model time, time in mm:ss is event time following the timeline in Section 3.4 where 0:00 is the arrival of E19):

- **0 s (-17:09)**
  Start of first fire growth period. Building entrance door, laundry door, bedroom doors, and master suite doors are open.
- **474 s (-9:15)**
  Fire plateaus at 2.5 MW.
- **1,200 s (2:51)**
  Apartment door opens, bedroom subfloor fails, start of 2 min fire growth period from 2.5 MW to 4.25 MW.

- **1,307 s (4:38)**
  4 s application of water into the living room.
- **1,350 s (5:21)**
  Fire plateaus at 4 MW.
- **1,373 s (5:44)**
  8 s application of water into the kitchen.
- **1,528 s (8:19)**
  13 s application of water into the living room.
- **1,587 s (9:18)**
  9 s application of water into the kitchen.
- **1,602 s (9:33)**
  6 s application of water into the kitchen.
- **1,612 s (9:43)**
  Fire Attack 1 verbalizes that conditions are hotter than normal and discussed backing out.
- **1,676 s (10:47)**
  5 s application of water into the kitchen.
- **1,690 s (11:01)**
  2 s application of water into the bedroom from the first exterior attack location and beginning of decrease of fire size from 4 MW to 3 MW.
- **1,692 s (11:03)**
  End of decrease of fire size from 4 MW to 3 MW.
- **1,694 s (11:05)**
  4 s application of water into the bedroom from the first exterior attack location and beginning of decrease of fire size from 3 MW to 1.7 MW
- **1,701 s (11:12)**
  2 s application of water into the bedroom from the first exterior attack location.
- **1,705 s (11:16)**
  2 s application of water into the bedroom from the first exterior attack location.
- **1,707 s (11:18)**
  End of decrease of fire size from 3 MW to 1.7 MW
- **1,713 s (11:24)**
  8 s application of water into the bedroom from the second exterior attack location and decrease of fire size from 1.7 MW to 400 kW.
- **1,720 s (11:31)**
  Mayday call.

- **1,735 s (11:46)**
  5 s application of water into the bedroom from the second exterior attack location and beginning of decrease of fire size from 400 kW to 0 kW.
- **1,801 s (12:52)**
  10 s application of water into the bedroom from the second exterior attack location.
- **1,811 s (13:03)**
  10 s application of water into the bedroom from the second exterior attack location.
- **1,813 s (13:04)**
  Patio door is opened.
- **1,904 s (14:35)**
  6 s application of water into the bedroom from the second exterior attack location.
- **2,000 s (16:11)**
  Simulation ends.

Discussion of Model Results

Figure 4.29 shows FDS predicted temperatures 6 ft above the floor when the bedroom window broke. At this point in time temperatures in the kitchen were 220 to 260 °F, and temperatures in the living room and master bedroom were under 200 °F.

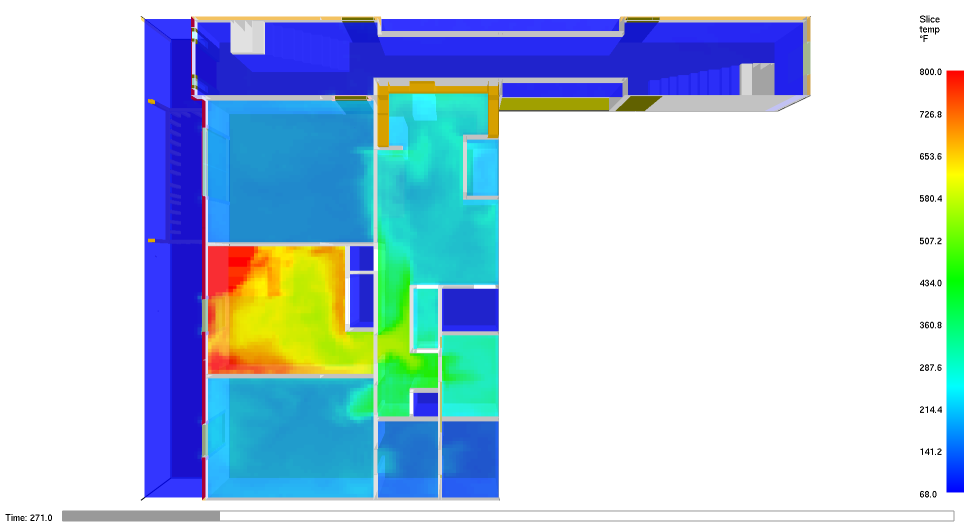


Figure 4.29: Temperatures at breakout of the bedroom window. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.30 shows FDS predicted temperatures in a grid plane down the center of the hallway to the bedrooms 4 min prior to entry. The color scale is set such that colors yellow or warmer indicate temperatures where softening and melting of typical drinking container plastics would be expected.

The FDS predicted conditions reflect the damage patterns seen in Figure 4.18. Hot outflow from the top of the bedroom doorway moved down the hall into the kitchen. The ceiling jet from the hallway was trapped by the soffit, and a downward jet formed at the wall at the end of the counter.

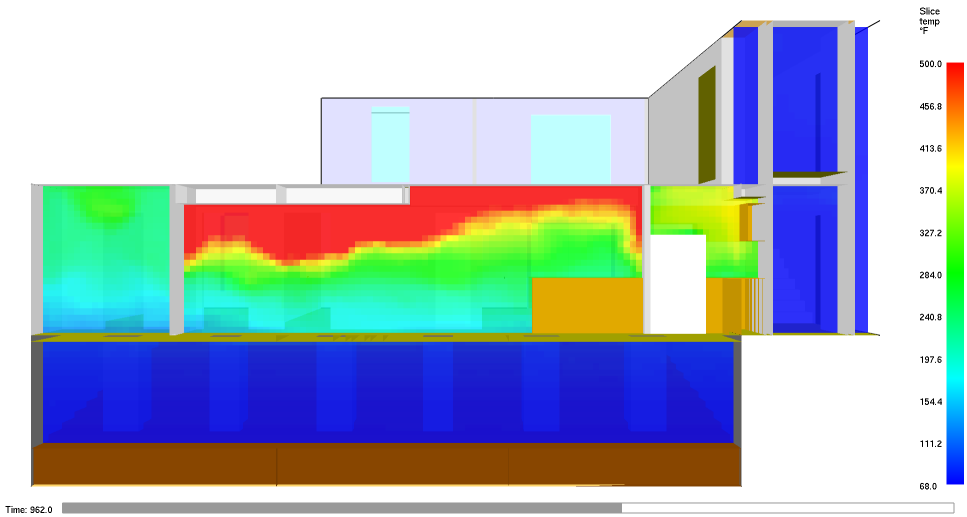


Figure 4.30: Ceiling jet temperatures along the hallway ceiling at 960 s or -4:00. Rear portion of apartment is clipped from view.

Figure 4.31 shows the visibility inside the apartment 6 ft (top), 4 ft (middle), and 2 ft (bottom) above the floor. The visibility is shown at the entry of Fire Attack 1 (left) and at the end of the second fire growth period (right). At entry, visibility was zero everywhere in the apartment where doors are open except for small portions of the bedroom due to air entering through the broken window. Visibility in the living room and kitchen remained near zero as the fire grew.

Figure 4.32 shows FDS predicted temperatures 6 ft above the floor at 1,200 s (2:51) or at entry of Fire Attack 1. Bedroom temperatures were over 800 °F as expected with a post-flashover fire. Temperatures in the living room ranged from 300 to 330 °F, temperatures in the kitchen ranged from 350 to 420 °F which was consistent with damage to thermoplastic materials, and the master bedroom ranges from 300 to 330 °F which was consistent with the lack of significant thermal damage in the room.

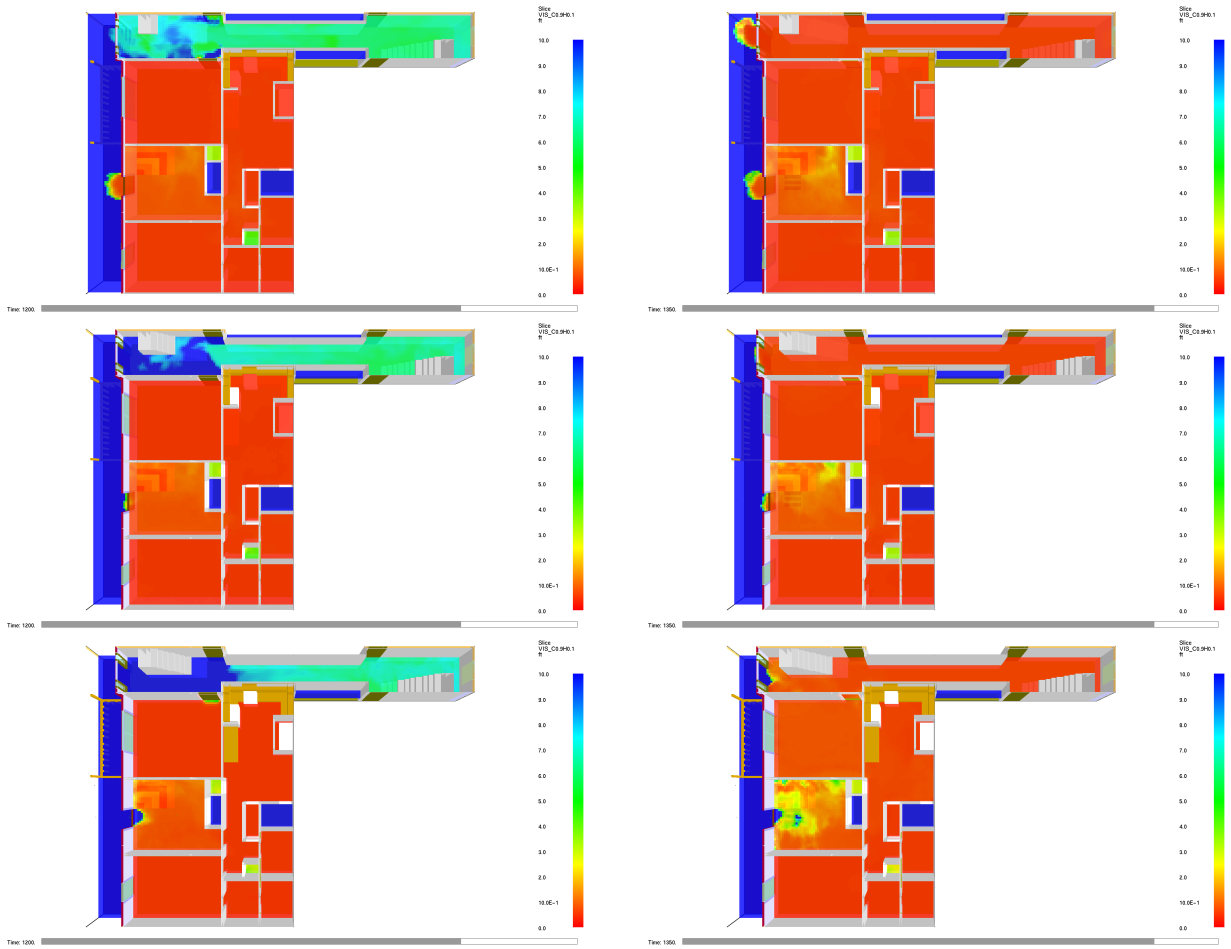


Figure 4.31: Visibility 6 ft, 4 ft, and 2 ft above the floor at entry of Fire Attack 1 and at the end of the second fire growth period. Left is at entry of Fire Attack 1, and right is at the end of the second fire-growth period. Top to bottom is 6 ft, 4 ft, and 2 ft above the floor.

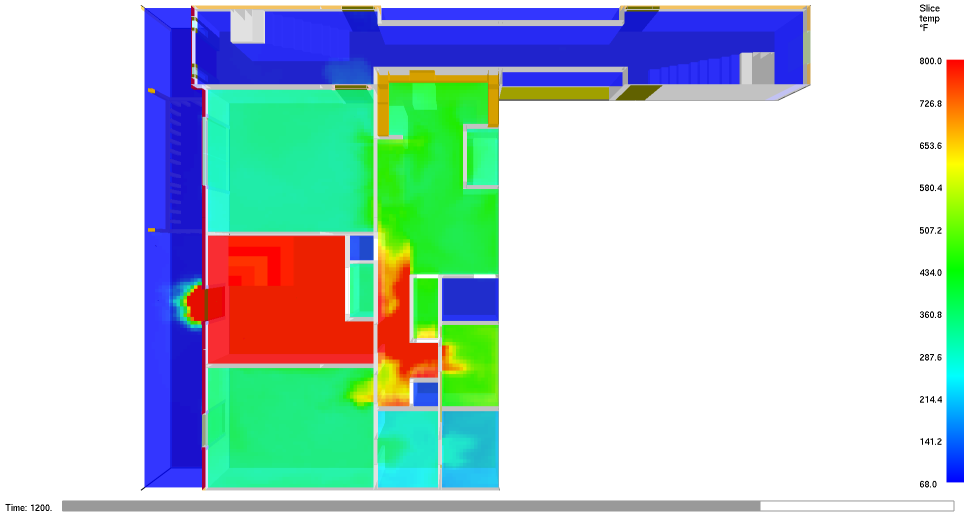


Figure 4.32: Temperatures 6 ft at entry of Fire Attack 1. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.33 shows FDS predicted temperatures 6 ft above the floor at 1,350 s (5:31) or at the end of the second fire growth period. Temperatures in the living room ranged from 330 to 370 °F, temperatures in the kitchen ranged from 400 to 500 °F, and the master bedroom ranged from 330 to 400 °F. Conditions have worsened throughout the apartment and the heat flux seen by Fire Attack 1 in the living room has increased by 13 %.

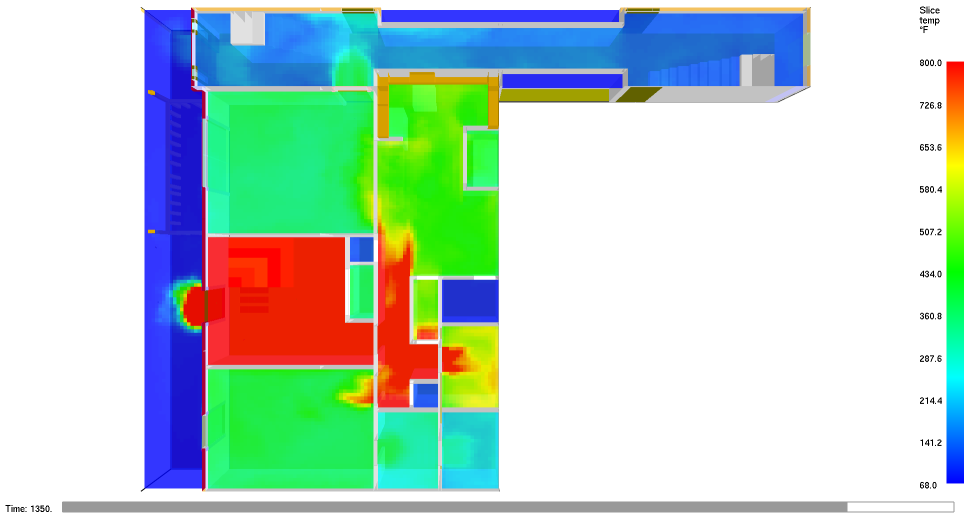


Figure 4.33: Temperatures at 6 ft at end of second fire-growth period. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.34 shows FDS predicted temperatures 6 ft above the floor at 1,500 s or 5 min after the entry of Fire Attack 1. Temperatures in the living room ranged from 340 to 410 °F, temperatures in the kitchen ranged from 450 to 550 °F, and the master bedroom ranged from 360 to 425 °F. Conditions have continued to worsen throughout the apartment, and the heat flux seen by Fire Attack 1 has increased another 5 %.

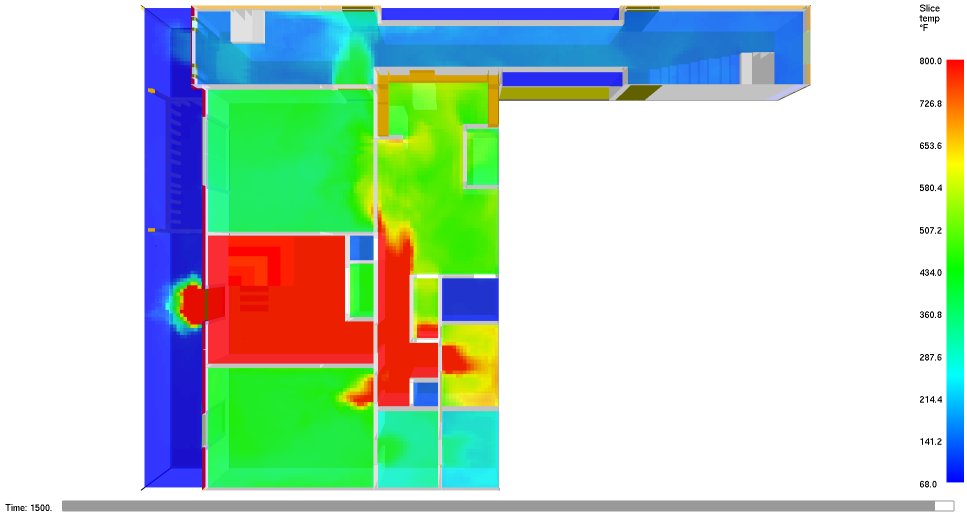


Figure 4.34: Temperatures 6 ft, 5 min after the entry of Fire Attack 1. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

The next set of figures look at temperatures 4 ft above the floor. In each pair of figures, the first figure is just before the start of the first application of water from each hose location, and the second figure is at the end of the first application of water from that location. The 4 ft elevation was selected to allow visualization of the droplets from the hose. At each location the hose nozzle was placed 3 ft above the floor; therefore, the first few feet of spray is hidden below the temperature slice.

Figure 4.35 shows the conditions 4 ft above the floor before and during the first application of water in the living room at 1,307 s. Prior to water spray ,temperatures ranged from 270 to 320 °F. After water spray, temperatures were 210 to 280 °F. One minute later there was a brief period of water spray into the kitchen (see Figure 4.36). In that brief period of time since water spray in the living room, temperatures in the living room and kitchen rebounded to be slightly higher than prior to the living room spray. After water spray in the kitchen, temperatures near the spray dropped over 100 °F.

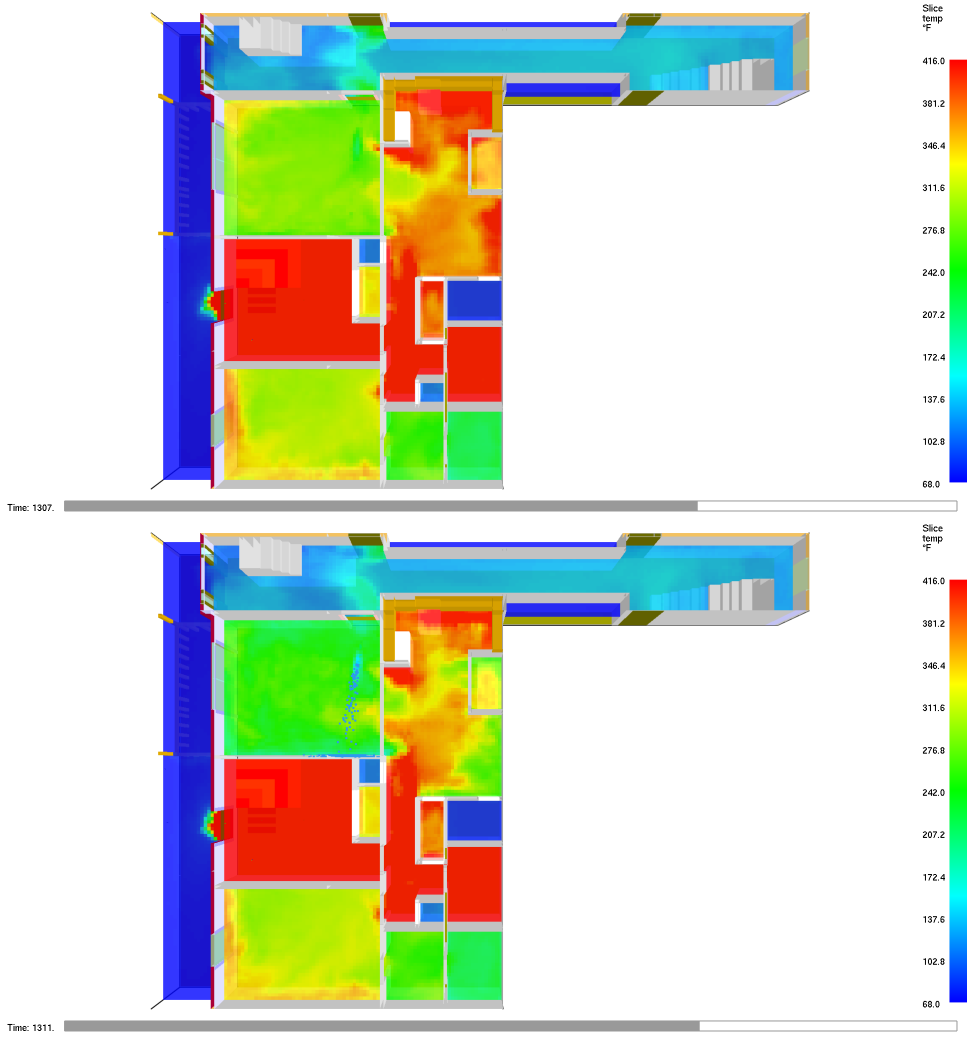


Figure 4.35: Temperature 4 ft above the floor before and at the end of the first application of water in the living room. Top is immediately prior to the start of water spray at 1,307 s (4:38), and bottom is just before the end of the water spray at 1,311 s (4:42). Blue dots are drops from the hose stream.

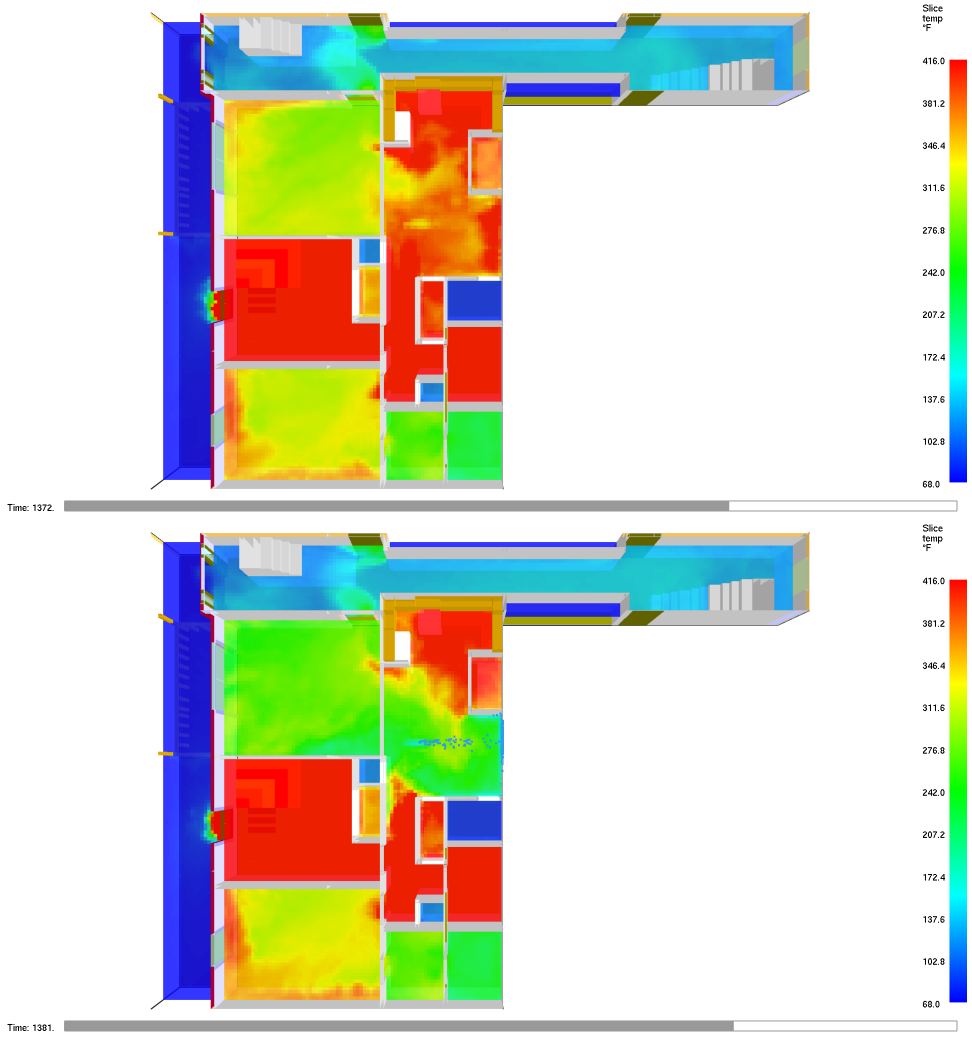


Figure 4.36: Temperature 4 ft above the floor before and at the end of the first application of water in the kitchen. Top is immediately prior to the start of water spray at 1,373 s (5:44), and bottom is just before the end of the water spray at 1,381 s (5:52). Blue dots are drops from the hose stream.

Figure 4.37 shows before and at the end of the first application of water from the first exterior attack location at 1,690 s (11:01), 2 ft and 4 ft above the floor.

At 4 ft, temperatures in the bedroom and the hallway in the outflow from the bedroom exceeded 800 °F prior to the attack. In the hallway, temperatures outside the master bedroom were near 550 °F, and temperatures from the kitchen until the bedroom were 390 to 470 °F. At the end of the exterior attack from the first location, temperatures in the bedroom dropped significantly with most of the bedroom at 400 to 500 °F. Temperatures in the hallway were 500 to 540 °F at the bedroom doorway and near 390 °F in the remainder of the hallway. During this exterior attack, the nozzle for Fire Attack 1 was near the entrance to the master bedroom. The fire was discovered by Fire Attack 1 just after this initial exterior attack, and in post-fire interviews it was stated the nozzle was at the master bedroom before discovering the fire.

At 2 ft, temperatures in the bedroom exceeded 800 °F prior to the attack. Hallway temperatures just outside the fire bedroom were 350 to 400 °F. Temperatures outside the master bedroom were near 290 °F, and temperatures from the kitchen until the bedroom were near 290 °F. At the end of the exterior attack from the first location, temperatures in the bedroom dropped significantly with most of the bedroom now at 400 to 500 °F. Temperatures in the hallway were 400 °F at the bedroom doorway and near 290 °F in the remainder of the hallway.

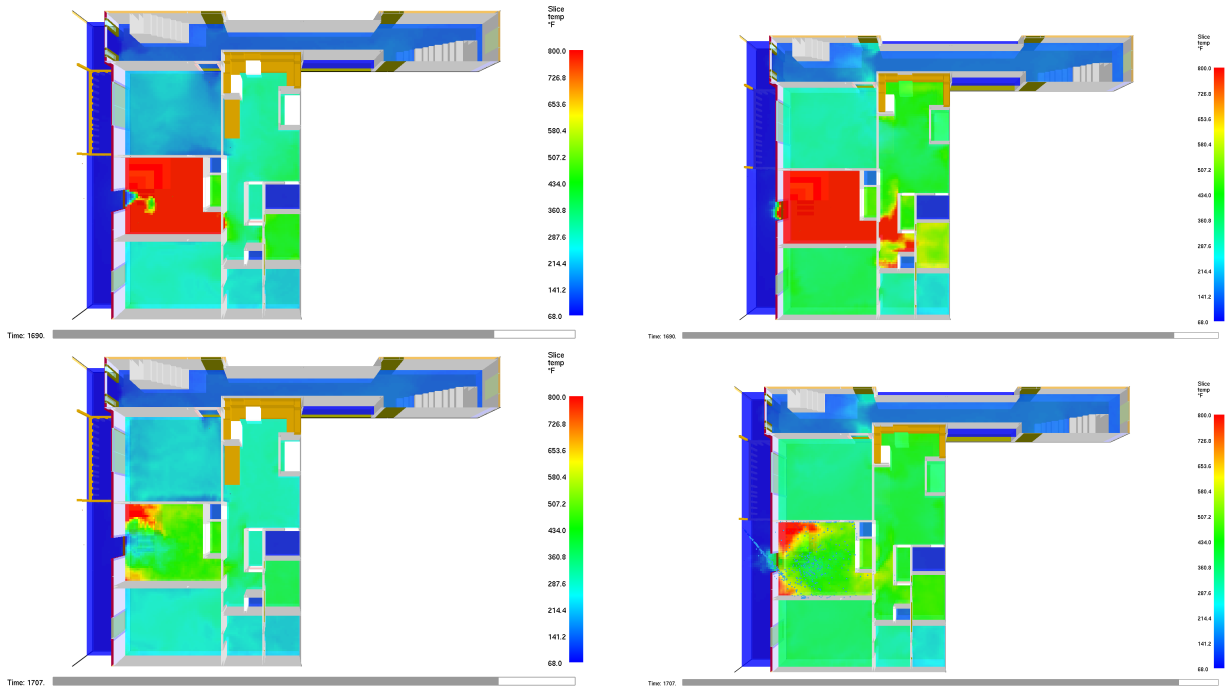


Figure 4.37: Temperature 2 ft (left) and 4 ft (right) above the floor before and at the end of the first application of water from the first exterior location. Top is immediately prior to the start of water spray at 1,690 s (11:01), and bottom is just before the end of the water spray from the first exterior location at 1,707 s (11:18). Blue dots are drops from the hose stream.

The start of water spray from the interior and from the second exterior attack location were near simultaneous. Figure 4.38 shows before the start of water spray at 1,712 s (11:23) and at the end of the interior attack, 2 ft and 4 ft above the floor.

At 4 ft above the floor, temperatures in the bedroom largely rebounded back to near 800 °F, though the layer in the room had not fully recovered in the region along the initial path of the exterior spray. Temperatures in the hallway outside the master bedroom and between the bedroom and the kitchen were near 400 °F. In the image with water spray, the solid line of droplets along the centerline of window were from the exterior hose stream. These droplets impacted the ceiling and were thrown about the room. The larger diameter, less dense column of spray outside the window was from the interior attack. Following the combined attack, temperatures were again significantly reduced.

At 2 ft above the floor, temperatures in the bedroom only partially rebounded back to near 800 °F. Temperatures in the hallway outside the master bedroom and between the bedroom and the kitchen were still near 290 °F. Following the combined attack, temperatures were again slightly reduced at 2 ft.

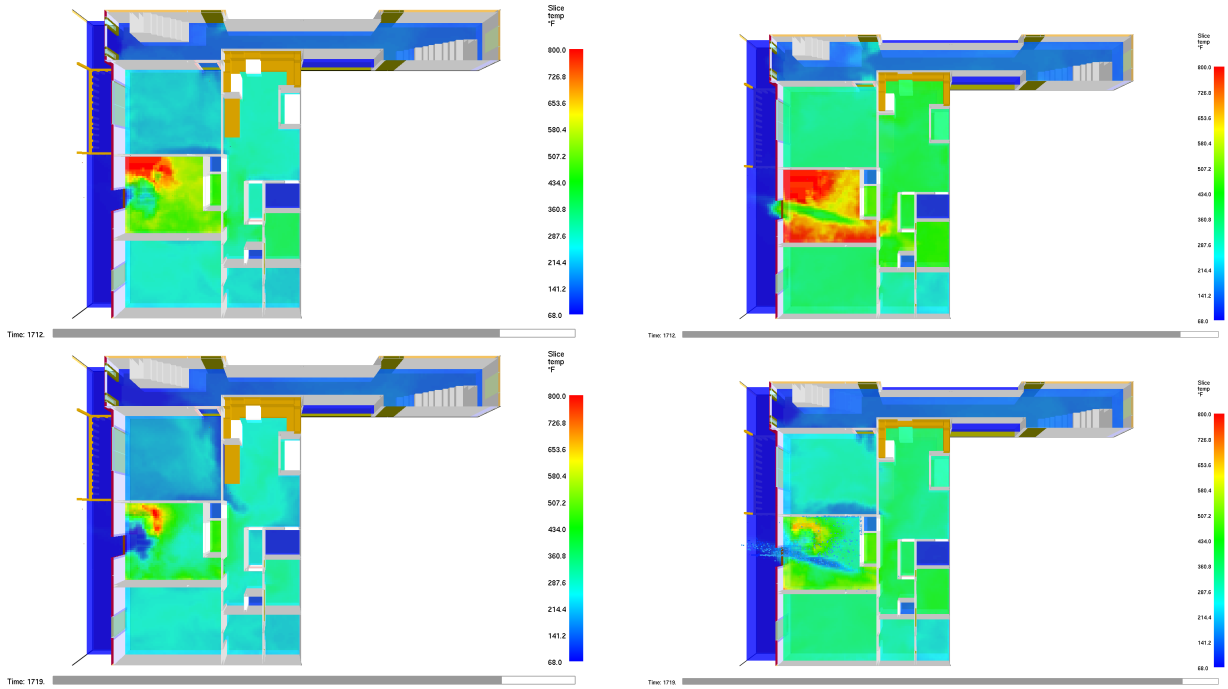


Figure 4.38: Temperature 2 ft (left) and 4 ft (right) above the floor before and at the end of the first application of water from the second exterior location and the interior. Top is immediately prior to the start of water spray at 1,712 s (11:23), and bottom is just before the end of the water spray from the interior location at 1,719 s (11:30). Blue dots are drops from the hose stream.

Figure 4.39 shows conditions for three time points after the mayday call at 2 ft and 4 ft above the floor. The first time point was 45 s after the mayday call or halfway between the call and when the rescue team enters the apartment. The second time point is just before the patio door was opened. During the time period between these images, Fire Attack 1 was likely in the vicinity of

the archway between the kitchen and the living room. At 45 s after the mayday, temperatures were near 300 °F 4 ft above the floor and were near 200 °F 2 ft above the floor. By the time the patio door was opened, temperatures dropped another 50 °F 4 ft above the floor and remained steady at 2 ft above the floor. For the final time point, 1 min after opening the patio door, temperatures were 100 °F at 2 ft and 170 °F at 4 ft. These much lower temperatures than before opening the door meant that protective gear was no longer soaking in significant additional heat. However, the heat absorbed by the PPE had not yet been dissipated.

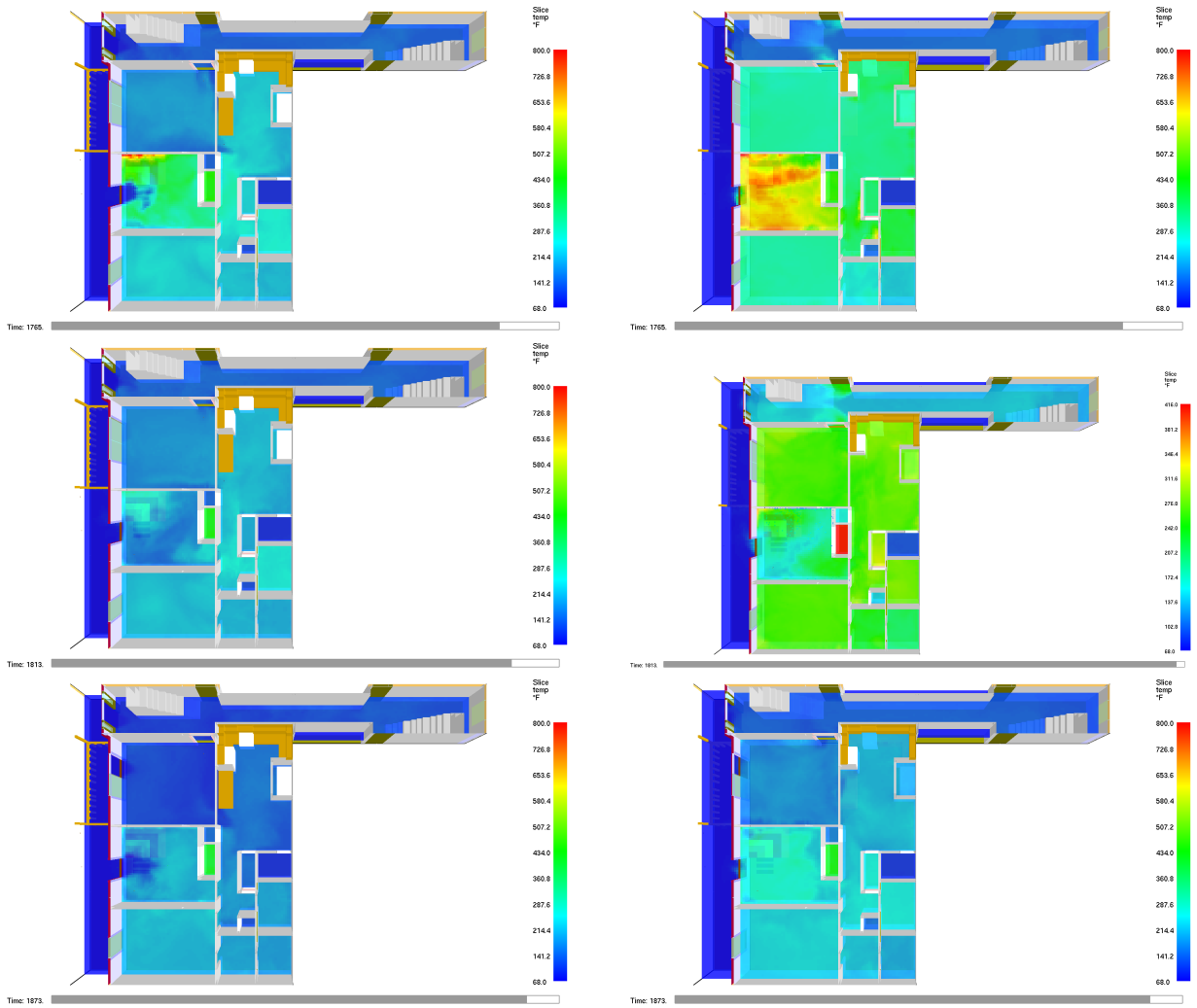


Figure 4.39: Temperature 2 ft (left) and 4 ft (right) above the floor 45 s after the mayday call (12:16), just before the patio door was opened by the rescue team at 1,813 s (13:04), and one minute after opening the patio door at 1,873 s (14:04). Top is 45 s after the mayday call (50 % of the time between the mayday call and the opening of the patio door), middle is just before the opening of the patio door, and bottom is 1 min after the opening of the patio door.

Figure 4.40 through Figure 4.42 respectively show water vapor volume fractions 3 ft and 6 ft above the floor for before and at the end of the first water spray in the kitchen, before and at the end of water spray from the first exterior attack location, and before and at the end of the interior attack

and the first water spray from the second exterior attack location. Before and after the kitchen water spray, water vapor mass fractions were near 10 %. While Figure 4.36 shows some cooling from the water spray in the kitchen, the actual amount of water vapor produced had not noticeably increased the water vapor present. Prior to the first exterior attack, water vapor amounts were similar. After the first exterior attack, water vapor in the bedroom had increased to 20 to 45 %. This was not unexpected as both gas and wall temperatures were 800 °F or more in the bedroom prior to the attack. Water vapor outside the master bedroom was under 15 %. In the hallway leading to the kitchen, water vapor peaked near 20 %.

The saturation condition for 20 % water vapor is 140 °F. Given the gas temperatures present in the hallway, kitchen, and living room were over 250 °F at this time, water vapor in the hallway would not have condensed out in the gas phase or onto walls. However, there was some potential that water vapor could have condensed onto exposed skin if any gaps in protection from turnout gear had been present. By the end of the interior attack, water vapor in the hallway ranged from 10 to 15 % with saturation temperatures from 110 to 130 °F. The potential for any significant surface condensation would be low by this point in time. Water vapor has approximately twice the specific heat of air, meaning it can transfer more heat for a given temperature difference than air; however, half of the 20 % water vapor in the hallway was due to combustion products where it was accompanied by carbon dioxide, which has a lower specific heat than air. All combined, any increase in the specific heat of gas in the hallway from the presence of water vapor from suppression was limited to 10 to 20 % above air. Taken all together, these observations mean that water vapor production from suppression would not have meaningfully increased the heat loading of the PPE.

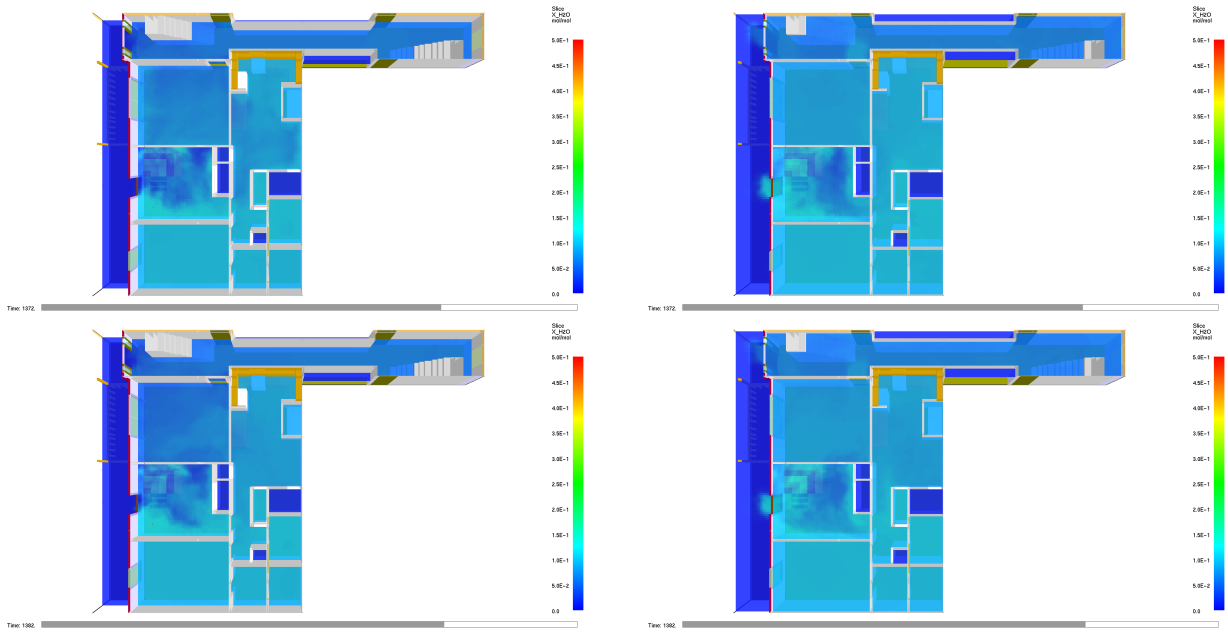


Figure 4.40: Water vapor volume fraction 3 ft and 6 ft above the floor before and at the end of the first water application in the kitchen. Left is 3 ft above the floor, and right is 6 ft above the floor. Top is prior to the first water spray in kitchen, and bottom is at the end at the first water spray in the kitchen.

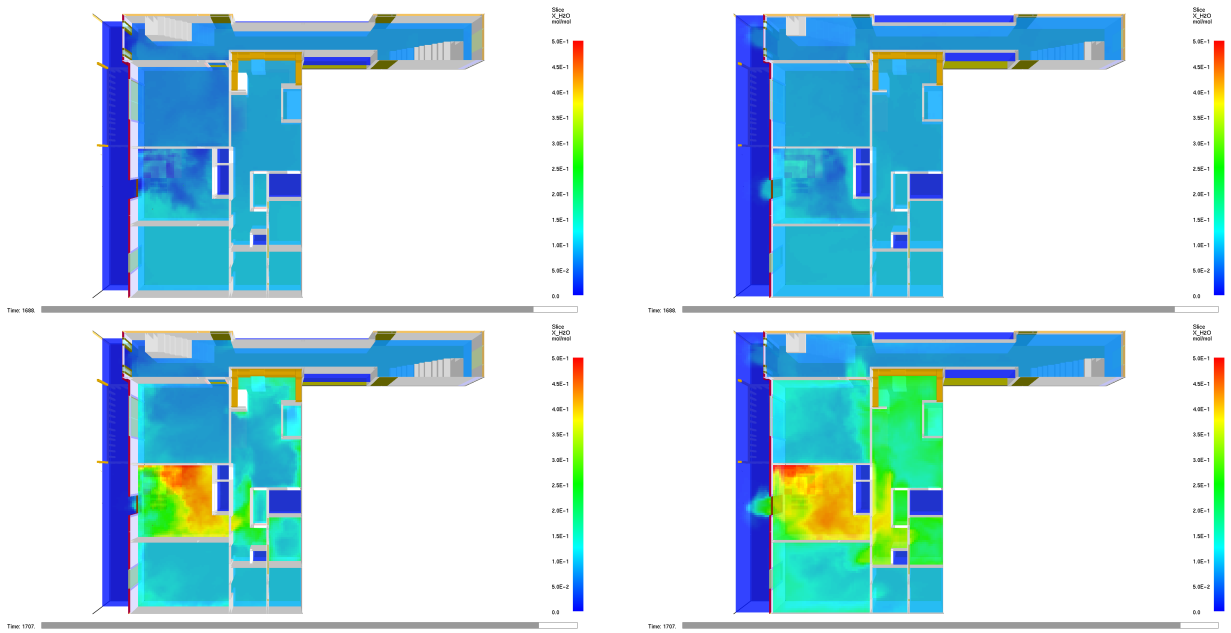


Figure 4.41: Water vapor volume fraction 3 ft and 6 ft above the floor before and at the end of the first water application in the kitchen. Left is 3 ft above the floor, and right is 6 ft above the floor. Top is prior to the first water spray in kitchen, and bottom is at the end at the first water spray in the kitchen.

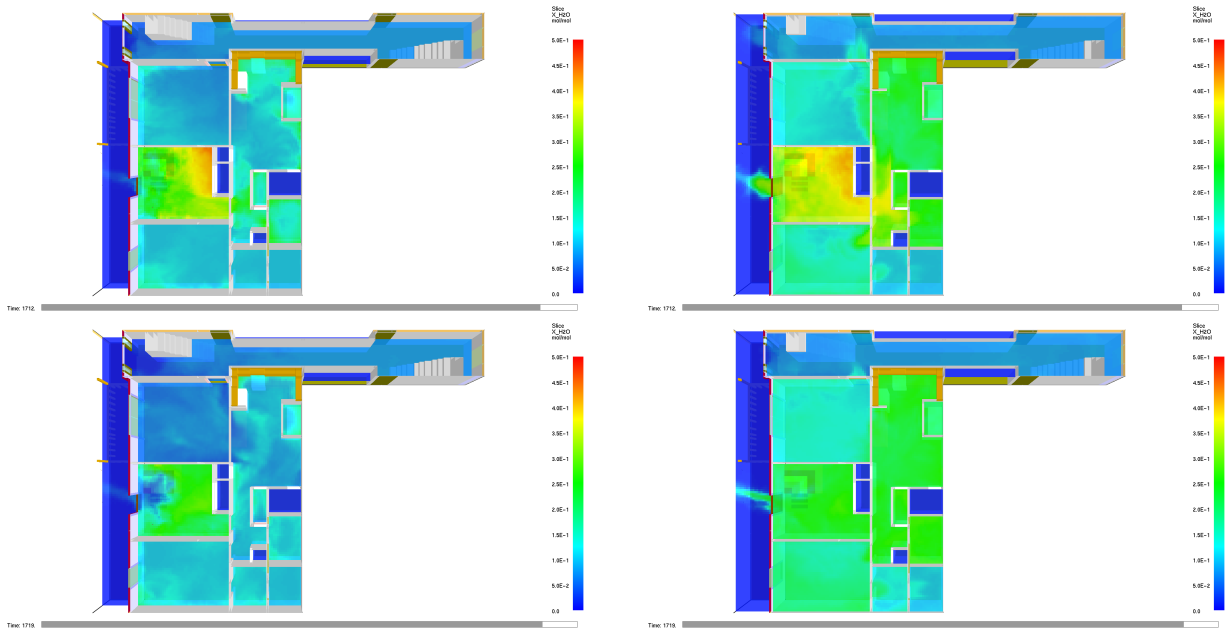


Figure 4.42: Water vapor volume fraction 3 ft and 6 ft above the floor before and at the end of the first water application in the kitchen. Left is 3 ft above the floor, and right is 6 ft above the floor. Top is prior to the first water spray in kitchen, and bottom is at the end at the first water spray in the kitchen.

Skin burns are associated with skin temperatures of 111 °F (44 °C) or higher [17]. From entry into the apartment until the mayday call (8.7 min), Fire Attack 1 was immersed in temperatures exceeding 275 °F. With the fire suppressed at the mayday call, temperatures did begin decreasing in the apartment, but temperatures were still over 250 °F prior to the opening of the patio door 1.5 min after the mayday. As seen in the post-fire photos, the fibers and other materials used in turnout gear will physically survive those exposures. Those materials, however, only delay but do not prevent the wearer from experiencing the elevated temperatures outside the gear. There was over 10 min of exposure time from entry until exit after the mayday. This was a substantial amount of time at those exposures for heat to penetrate the gear. The timeline in Section 3.4 shows that the team was already beginning to feel the heat through the protective gear prior to the the exterior suppression. Since the exterior attack was using a solid stream in through the open window, it wasn't entraining large amounts of air in through the bedroom window. Strong outflow from the window continued to occur during the exterior attack. Water vapor flow from the bedroom into the apartment at the onset of the exterior attack may have briefly accelerated heat transfer; however, as noted, the crew was already commenting about being hot prior to the mayday call. Once the sensation of pain begins, burns quickly follow unless the source of heat is removed. In this case the source of heat was the temperature inside the apartment and the heat stored in the turnout gear. With conditions of low visibility and the disorientation experienced by the team, they were unable to quickly remove themselves from the source of heat. If there were no exterior attack, that might have slightly delayed the onset of injury and the mayday call (seconds at most). However, once the interior attack began, similar water vapor conditions would have been present in the apartment plus a longer duration of exposure. See Section 4.4.5 for the conditions resulting from an interior attack.

4.4.3 Modeling of an Initial Exterior Attack Timeline

Discussion of Model Inputs

This model used the same geometry and fire growth timeline as the prior subsection with a different suppression and fire decay timeline. In this model the exterior attack began at the time Fire Attack 1 entered the apartment in the actual event model. In this simulation, Fire Attack 1 does not enter the apartment until 2 min of exterior suppression had occurred (1,320 s). The same relative timing for the exterior attack was used along with the same relative decrease in fire size; however, since this model started suppression prior to opening the apartment door the initial fire size at suppression was 2.5 MW rather than 4.25 MW which made the reduction values 1.75 MW, 1 MW, 250 kW, and 0 kW. No interior attack was performed since the fire was suppressed prior to entry. The timeline was as follows (time in seconds is model time, time in mm:ss is event time following the timeline in Section 3.4 where 0:00 is the arrival of E19):

- **0 s (-17:09)**
  Start of first fire growth period. Building entrance door, laundry door, bedroom doors, and master suite doors are open.

- **474 s (-9:15)**
  Fire plateaus at 2.5 MW.
- **1,200 s (2:51)**
  Bedroom subfloor fails, 2 s application of water into the bedroom from the first exterior attack location and decrease of fire size from 2.5 MW to 1.75 MW.
- **1,202 s (2:53)**
  End of decrease of fire size from 2.5 MW to 1.75 MW.
- **1,204 s (2:55)**
  4 s application of water into the bedroom from the first exterior attack location and beginning of decrease of fire size from 1.75 MW to 1 MW
- **1,211 s (3:02)**
  2 s application of water into the bedroom from the first exterior attack location.
- **1,215 s (3:05)**
  2 s application of water into the bedroom from the first exterior attack location.
- **1,217 s (3:08)**
  End of decrease of fire size from 1.75 MW to 1 MW
- **1,223 s (3:14)**
  8 s application of water into the bedroom from the second exterior attack location and decrease of fire size from 1 MW to 250 kW.
- **1,245 s (3:36)**
  5 s application of water into the bedroom from the second exterior attack location and beginning of decrease of fire size from 250 kW to 0 kW.
- **1,311 s (4:42)**
  10 s application of water into the bedroom from the second exterior attack location.
- **1,320 s (4:51)**
  Apartment door is opened.
- **1,321 s (6:31)**
  Fire size has decreased to 0 kW.
- **1,414 s (6:25)**
  6 s application of water into the bedroom from the second exterior attack location.
- **2,000 s (16:11)**
  Simulation ends.

Discussion of Model Results

Figure 4.43 shows FDS predicted temperatures at 6 ft above the floor for the initial exterior attack timeline at 1,200 s or at the start of the initial exterior attack. Up to this time, these results were the same as the original fire event. Bedroom temperatures were over 800 °F as expected with a post-flashover fire. Temperatures in the living room ranged from 300 to 330 °F, temperatures in the kitchen ranged from 350 to 420 °F which was consistent with damage to thermoplastic materials, and the master bedroom ranged from 300 to 330 °F which was consistent with the lack of significant thermal damage in the room.

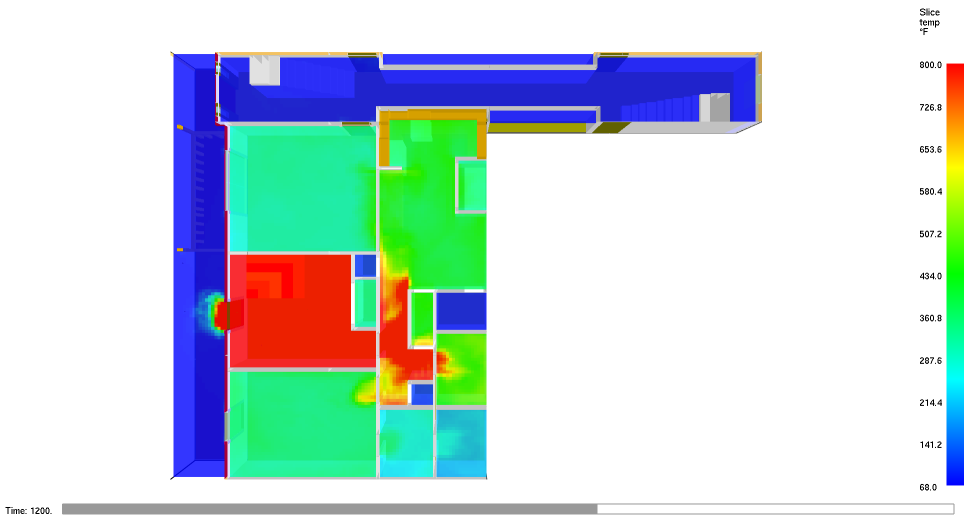


Figure 4.43: Temperatures at 6 ft at the start of suppression in the alternate timeline. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.44 shows the temperatures 6 ft above the floor at 2 min after the start of the initial exterior attack. In this scenario, this was the time that Fire Attack 1 was assumed to enter the apartment. Bedroom temperatures were now under 200 °F. The temperature range in the living room and master bedroom had dropped by approximately 100 °F. The temperature range in the kitchen had dropped by approximately 150 °F. Compared to the conditions at 1,200 s, the heat flux seen by Fire Attack 1 upon entry was reduced by one-third and would continue to decrease over time.

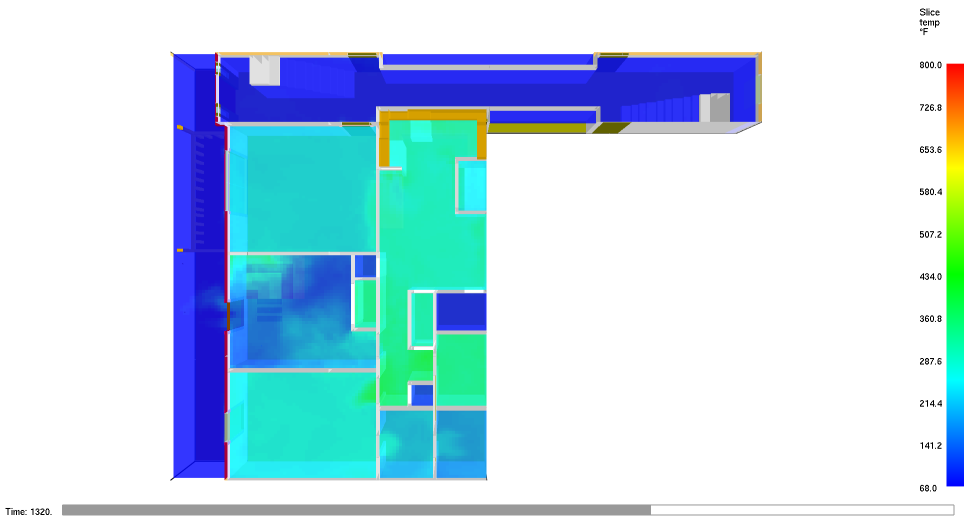


Figure 4.44: Temperatures at 6 ft at entry of Fire Attack 1 in the alternate timeline. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.45 shows the temperatures 6 ft above the floor at 2 min after the entry of Fire Attack 1. Temperatures in the living room, kitchen, and master bedroom had continued to drop. The heat flux seen by Fire Attack 1 would continue to decrease over time. The bedroom temperature showed a slight increase. In the prior image, suppression was ongoing and this acted to cool the gases in the fire room. Post suppression, while the fire was out, hot gases from the hallway flowed into the bedroom and out the window. Additionally, some surfaces in the room were still at an elevated temperature. Without the active cooling from the water spray, temperatures rebounded slightly but over time will cool as stored heat in the apartment vented through the open window and open apartment door.

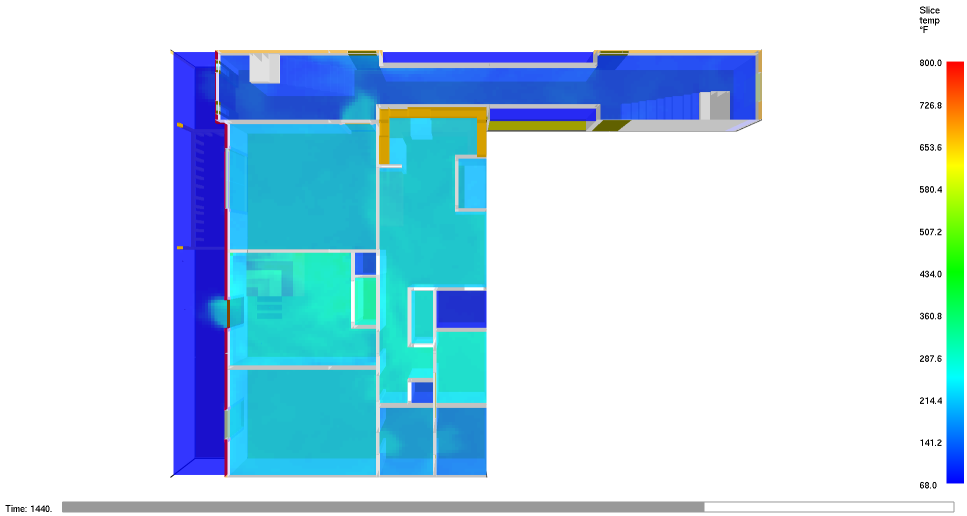


Figure 4.45: Temperatures at 6 ft, 2 min after entry of Fire Attack 1 in the alternate timeline. The geometry is clipped at a height of 7 ft in order to remove the HVAC duct cover.

Figure 4.46 shows the visibility inside the apartment 6 ft (left side) and 4 ft (right side) above the floor. The top row shows visibility at the start of the exterior attack. There was zero visibility in the apartment. When Fire Attack 1 entered 2 min later (middle row), the bedroom visibility had improved significantly but the remainder of the apartment still had zero visibility. Two min after entry (bottom row), the visibility in the bedroom had continued to improve and at 4 ft above the floor most of the bedroom had visibility in excess of 10 ft. In the kitchen and living room, visibility was near 1 ft at both 4 ft and 6 ft above the floor. While this was still very poor visibility, it was not zero visibility and ease of movement would be improved. Visibility continued to improve over time. At 1,800 s, 10 min after the start of suppression, the living room and kitchen visibility had improved to 1.5 ft. With the fire suppressed, active ventilation efforts and/or opening the patio door would have hastened the clearing of smoke from the apartment.

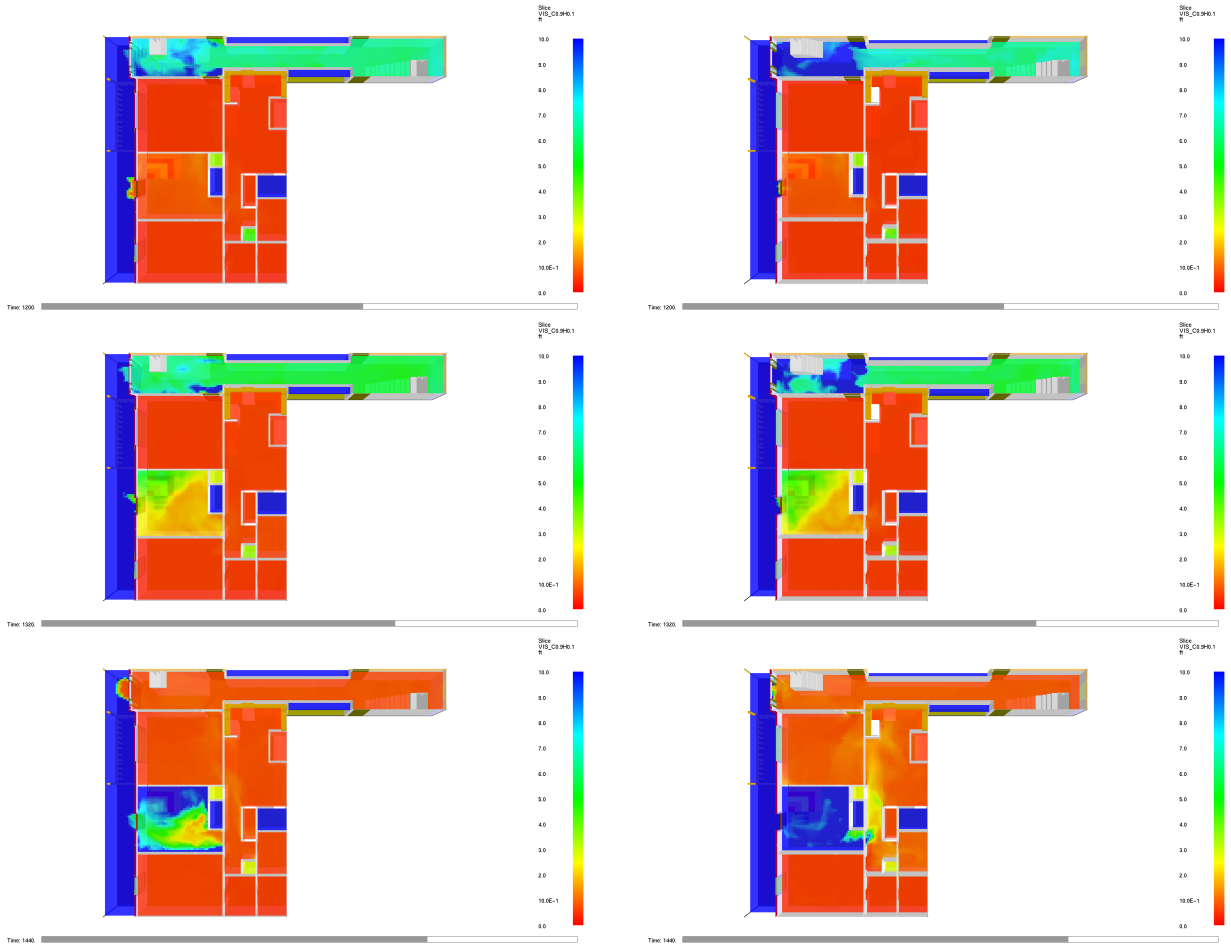


Figure 4.46: Visibility at 6 ft and 4 ft above the floor during and after the exterior attack. Left is 6 ft above the floor, and right is 4 ft above the floor. Top to bottom is at the start of the exterior attack, at entry by Fire Attack 1, and 2 min after entry of Fire Attack 1.

Initial exterior attack would have avoided the large increase in fire size associated with the additional ventilation flow path from opening the apartment door before the fire was suppressed. Early exterior attack would also have resulted in rapidly improving conditions inside the apartment. The heat flux firefighters would experience would have been greatly reduced. It is likely the contin-

ued reduction in interior temperatures would have prevented burn injury. The improved visibility would have allowed for a more rapid and effective search of the apartment and faster determination that no fire existed other than the already suppressed bedroom fire.

4.4.4 Modeling of a Smoke Curtain

Discussion of Model Inputs

This simulation was a repeat of the first model (actual fire event timeline) with the assumption that as the interior attack team entered the apartment they placed a smoke curtain in the doorway. It was assumed that a 5 s period existed after opening the door before the smoke curtain was installed. Once installed, it was assumed that the curtain had a gap at the bottom to allow for passing a hoseline and that the curtain had small gaps, 0.25 in, around the sides and tops (a smoke curtain does not form an airtight seal). In FDS this was implemented by removing the doorway obstruction at 1,200 s, and then at 1,205 s adding back in part of the doorway to represent the smoke curtain. The gap at the bottom was represented by a single cell high gap at the floor. The leakage around the top and sides were represented by having a single grid cell missing at the top corners of the door and on each side at the mid height of the door. A view of the door with the curtain installed is shown in Figure 4.47. Since the smoke curtain blocks much of the doorway flow area, the post-entry fire growth was reduced from a peak of 4,250 kW (increase of 1,750 kW post-entry) to a peak of 2,926 kW (increase of 426 kW post-entry). The suppression timeline was not changed.

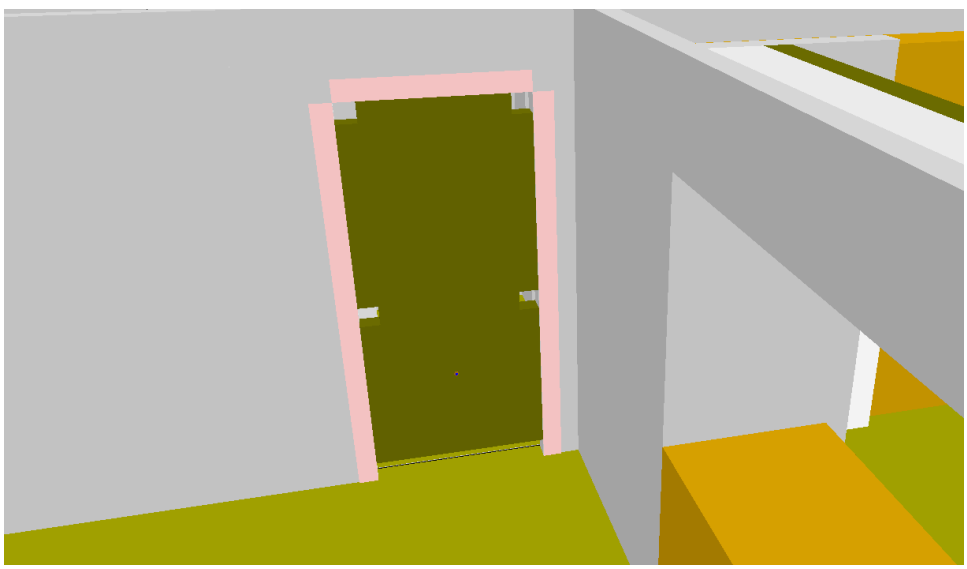


Figure 4.47: FDS representation of a smoke curtain in the apartment doorway.

Discussion of Model Results

Figure 4.48 shows visibility and temperature in the entry hallway 2 min after the entry of Fire Attack 1 into the apartment. With a smoke curtain, visibility did not quickly go to zero in the entry hallway. Additionally, temperatures remained near ambient throughout the entry hallway versus exceeding 150 °F without a smoke curtain. The use of a smoke curtain preserved the entry hallway as a potential path for rescuing occupants in other apartments.

Figure 4.49 shows the temperatures 6 ft above the floor at 2.5 min and 5 min after the entry of Fire Attack 1. Temperatures in the living room were approximately 300 °F. Temperatures in the kitchen were 400 to 450 °F. These temperatures were 70 to 100 °F lower than those seen in Figures 4.33 and 4.34. This was a direct impact of the reduction in flow area with the smoke curtain resulting in less fire growth post entry. This decrease in temperature would significantly reduce the thermal exposure seen by Fire Attack 1 while they were in the living room and kitchen.

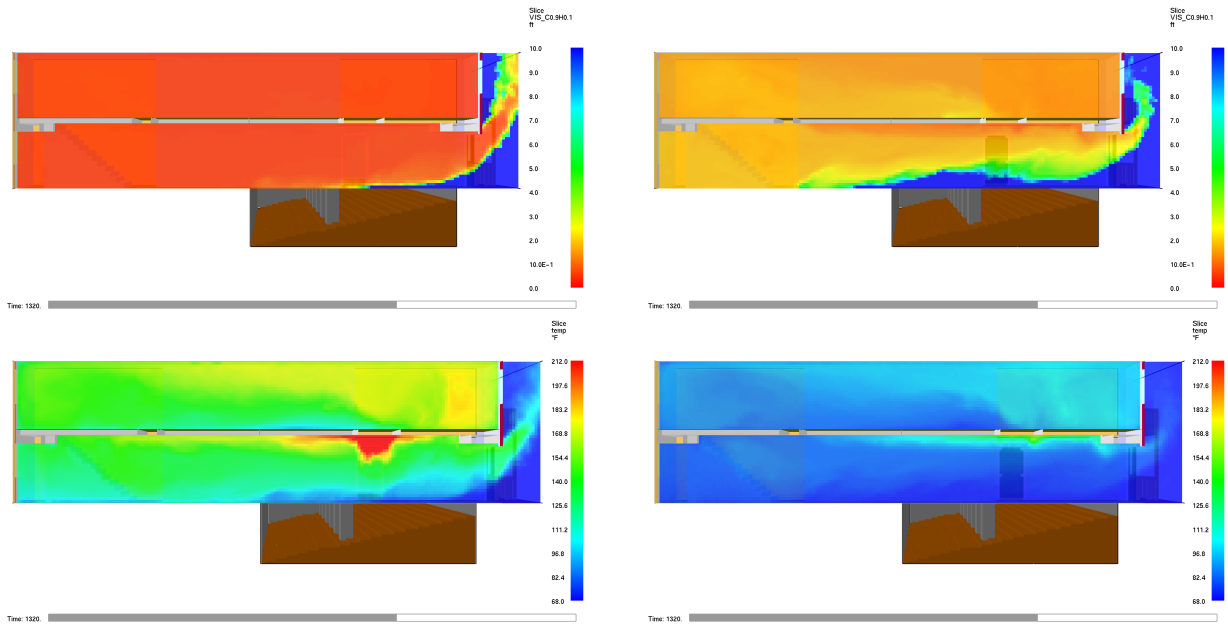


Figure 4.48: Visibility and temperature in the entry hallway 2 min after entry of Fire Attack 1. Left is with no smoke curtain, right is with a smoke curtain. Top is visibility, and bottom is temperature.

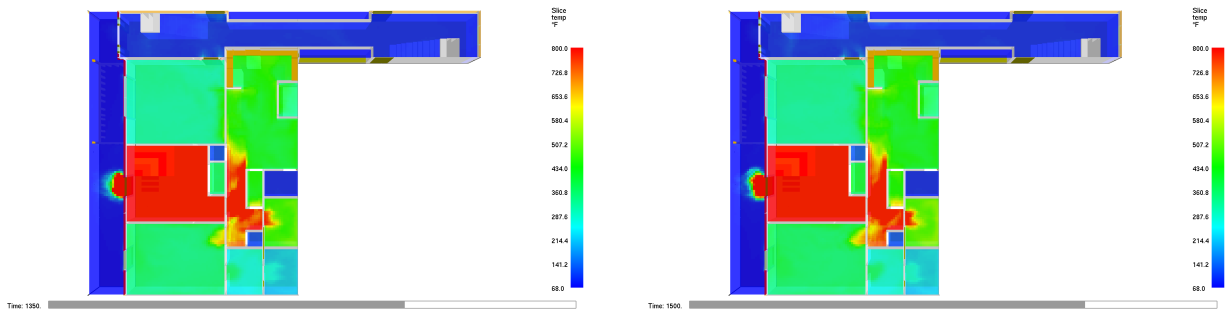


Figure 4.49: Temperatures at 6 ft above the floor at 2.5 min (left) and 5 min (right) after of Fire Attack 1.

4.4.5 Modeling of an Interior Attack Only

Discussion of Model Inputs

This model uses the same geometry and fire growth timeline as the first scenario. In this simulation no exterior suppression occurred. Instead the time sequence of the exterior suppression, both water flow and fire reduction, was applied as the interior attack. The timing was shifted in time to occur at the start of the interior attack. The new timeline is as follows:

- **0 s (-17:09)**
  Start of first fire growth period. Building entrance door, laundry door, bedroom doors, and master suite doors are open.
- **474 s (-9:15)**
  Fire plateaus at 2.5 MW.
- **1,200 s (2:51)**
  Apartment door opens, bedroom subfloor fails, start of 2 min fire growth period from 2.5 MW to 2.926 MW.
- **1,307 s (4:38)**
  4 s application of water into the living room.
- **1,350 s (5:21)**
  Fire plateaus at 2.926 MW.
- **1,373 s (5:44)**
  8 s application of water into the kitchen.
- **1,528 s (8:19)**
  13 s application of water into the living room.
- **1,587 s (9:18)**
  9 s application of water into the kitchen.

- **1,602 s (9:33)**
  6 s application of water into the kitchen.
- **1,676 s (10:47)**
  5 s application of water into the kitchen.
- **1,712 s (11:23)**
  2 s application of water into the bedroom from the interior attack location and beginning of decrease of fire size from 2.926 MW to 2.048 MW.
- **1,714 s (11:25)**
  End of decrease of fire size from 2.926 MW to 2.048 MW.
- **1,716 s (11:27)**
  4 s application of water into the bedroom from the interior attack location and beginning of decrease of fire size from 2.048 MW to 1.170 MW.
- **1,723 s (11:34)**
  2 s application of water into the bedroom from the interior attack location.
- **1,727 s (11:38)**
  2 s application of water into the bedroom from the interior attack location.
- **1,729 s (11:40)**
  End of decrease of fire size from 2.048 MW to 1.170 MW.
- **1,735 s (11:46)**
  8 s application of water into the bedroom from the interior attack location and decrease of fire size from 1.170 MW to 293 kW.
- **1,757 s (12:08)**
  5 s application of water into the bedroom from the interior attack location and beginning of decrease of fire size from 293 kW to 0 kW.
- **1,823 s (13:14)**
  10 s application of water into the bedroom from the interior attack location.
- **1,833 s (13:24)**
  Fire size has decreased to 0 kW.
- **1,926 s (14:57)**
  6 s application of water into the bedroom from the interior attack location.
- **2,000 s (16:11)**
  Simulation ends.

Discussion of Model Results

Figure 4.50 shows water vapor concentrations 3 ft and 6 ft above the floor just prior to and just after the first application of water into the bedroom. Figure 4.51 shows temperature 3 ft and 6 ft above the floor just prior to and just after the first application of water into the bedroom. Conditions before and after the first water spray were similar to those seen in Figure 4.37 and Figure 4.41. There was an increase in the water vapor concentrations seen in the hallway and kitchen area just after the first application of water. Temperatures did not see a significant change. This was followed by a decrease in temperature as the fire was extinguished and stored heat vented out of the open window and apartment door. The interior-only attack conditions were the same as for the exterior attack in the actual event timeline. The only change was a slight delay to the start of decreasing temperatures since the interior attack started after the exterior attack did in the actual incident.

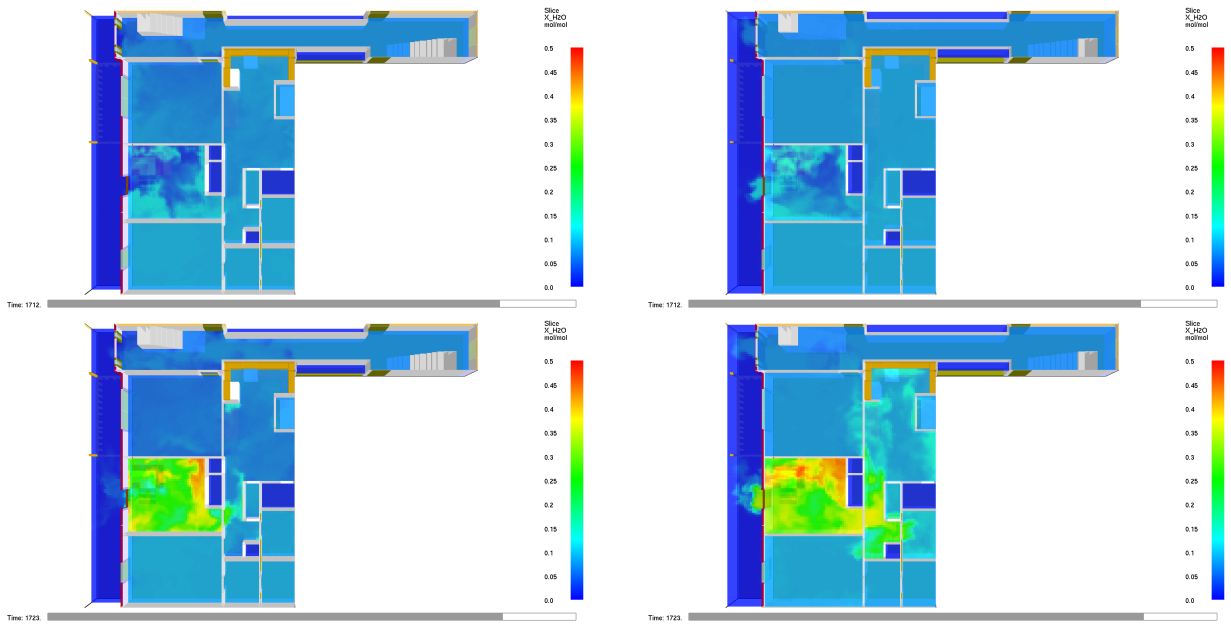


Figure 4.50: Water vapor concentration 3 ft and 6 ft above the floor just prior to (1,712 s or 11:23) and just after (1,723 s or 11:34) the first water application in the bedroom. Left is 3 ft, and right is 6 ft. Top is prior to water flow, and bottom is after water flow.

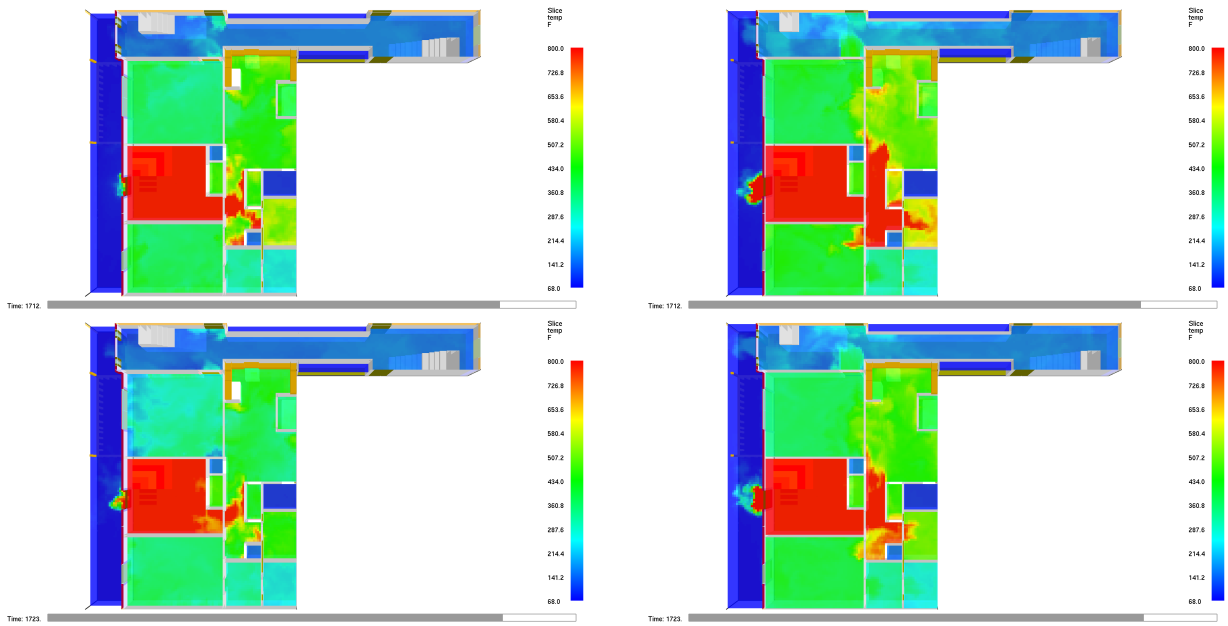
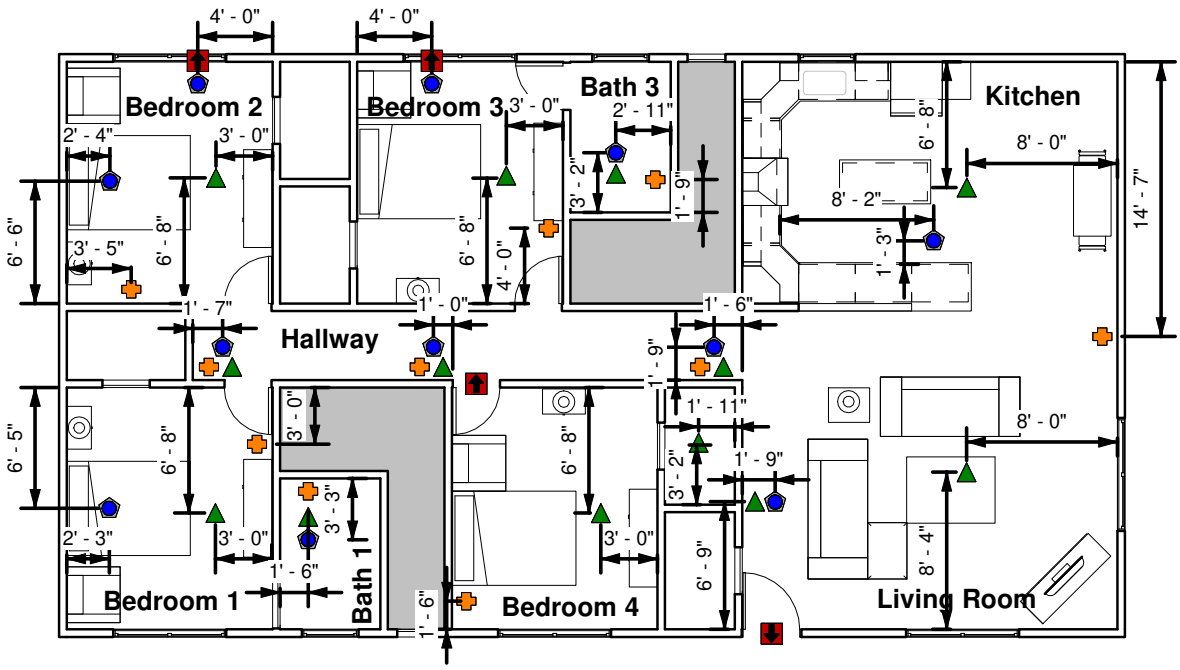


Figure 4.51: Temperature 4 ft and 6 ft above the floor just prior to (,1712 s or 11:23) and just after (1,723 s or 11:34) the first water application in the bedroom. Left is 4 ft, and right is 6 ft. Top is prior to water flow, and bottom is after water flow.

4.5 Data from Relevant Testing

The FSRI recently completed a study examining the impact of suppression and search tactics on the exposure that occupants requiring rescue would receive [18–20]. As part of the study, a series of 21 fire experiments were performed in a purpose-built, single-level ranch home with approximately 1,600 ft^2 of interior floor area. The structure contained four bedrooms, two bathrooms, a kitchen, and a living room, and included a typical residential HVAC system. The home was carpeted and furnished with typical interior furnishings. Testing varied fire location, ventilation tactics, suppression tactics, and search tactics. The home was instrumented with thermocouples, heat flux gauges, bi-directional probes (velocity), and gas sensors. A layout of the test structure plus instrumentation is shown in Figure 4.52. As seen, the overall layout is similar in arrangement to that of the apartment. Heat flux gauges were mounted in the floor looking upward. Thermocouple locations were an array of eight thermocouples spaced at 1 in below the ceiling then one thermocouple spaced every foot from the ceiling to the floor. Bi-directional probe locations were at five locations starting 4 in above the floor and spaced 18 in apart. Each probe had an accompanying thermocouple.



Icon	Instrumentation	Notes
	Thermocouple Array	
	Gas Velocity	Arrow indicates positive flow direction.
	Pressure Tap	6 in off the wall.
	Heat Flux and Gas Probe	In hallway locations, heat flux was centered in hallway flush with floor and gas probes were 6 in off the wall at 1 ft and 3 ft.

Figure 4.52: Dimensioned instrumentation layout of structure.

Experiment 3 featured a fire that started in bedroom 4 with the doors to bedrooms 2, 3, and 4 open along with the front door. The window panes for bedroom 4 were removed. Post-flashover, at 5 min after ignition, the windows to bedrooms 2 and 3 were removed. As the windows were being removed, suppression was started from the exterior through the bedroom 4 window using a straight stream. This was similar to the this report's fire in terms of fire location (in both cases only the bedroom was involved), ventilation (in both cases the bedroom window was missing and the bedroom door was open with a flow path to other openings to the outside), and attack (both had the initial suppression through the bedroom window using a straight stream). Figure 4.53 shows the fire just prior to the start of suppression. Conditions were very similar to that seen in Figure 4.8.

Figure 4.53: Fire conditions during Experiment 3 just prior to suppression.

Figure 4.54 shows the Experiment 3 temperatures in the bedroom and along the hallway around the time suppression started (309 s). In the bedroom and its doorway there was an immediate drop in temperatures as soon as suppression started. The same was seen at the mid hallway location. At the ends of the hallway there was a brief, few second, spike in the gas temperature followed by a drop in temperature. This echoed the results seen in the FDS simulations where a brief temperature pulse was seen at the start of suppression followed by a cool down. These observations on temperature were also seen in the velocity data shown in Figure 4.55. The velocities in the bedroom door show a brief period, a few seconds, where the velocity signals became very noisy with large spikes up and down. This was followed by a resumption of the pre-suppression velocities. The front door data did not see any change at the start of suppression. The spike 20 s after suppression was an artifact due to having to move the array of probes out of the doorway before the interior fire attack team could enter. Neither the temperature data nor the velocity data indicated any significant change in the severity of exposure in or near the hallway during the exterior attack.

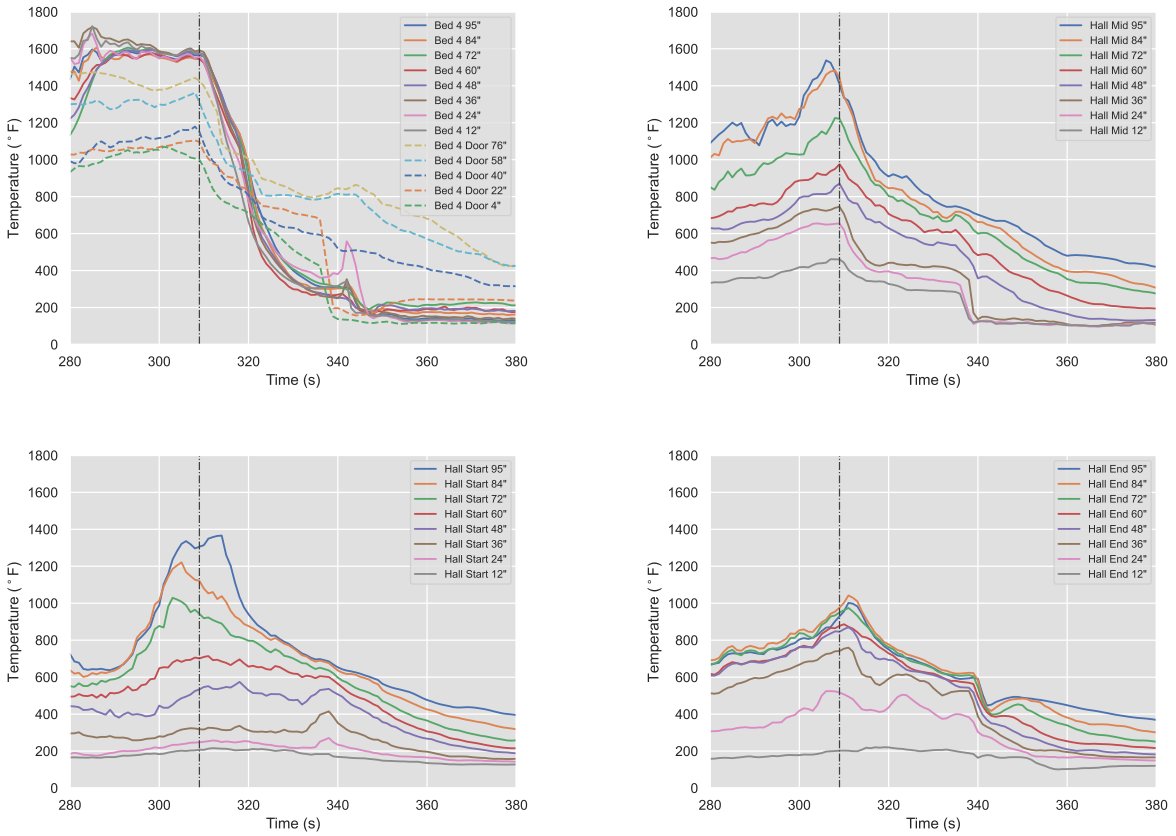


Figure 4.54: Temperatures in the bedroom and hallway during Experiment 3 around the time of suppression. Top left is in the bedroom. Top right is the hallway just outside the bedroom. Bottom left is the hallway end by the front door. Bottom right is the hallway end near bedroom 1. The vertical dot-dash line is the start of suppression at 309 s.

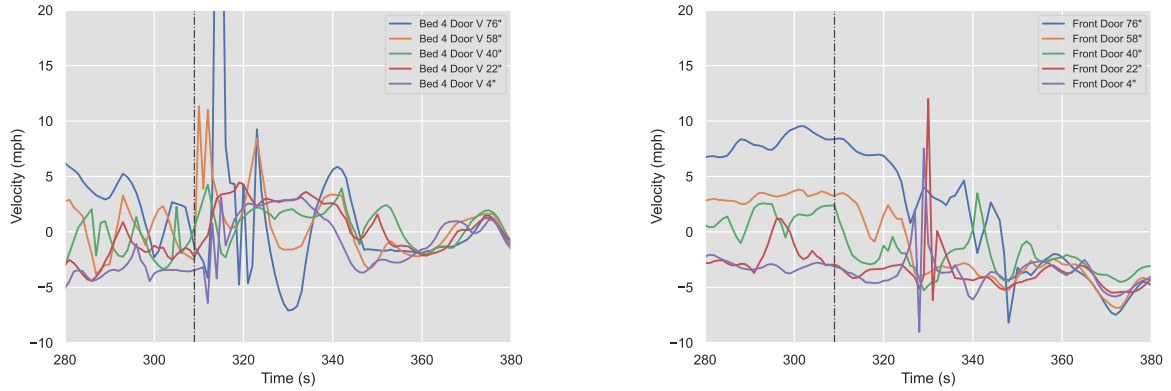


Figure 4.55: Velocities in the bedroom door and front door during Experiment 3 around the time of suppression. Left is bedroom door. Right is front door. The vertical dot-dash line is the start of suppression at 309 s.

Table 4.1 compares experimental temperatures against those of FDS. The table shows temperatures in the bedroom, in the hallway just outside the bedroom, and at the end of the hallway by the entrance door for just before exterior suppression and 30 s after exterior suppression. The table also shows the percentage drop in temperature after suppression. The drop was computed as the relative change in temperature above ambient. The window in the experiment was not as tall as the window in the apartment. As a result it did not provide as effective a vent as the window in the apartment did. As a result somewhat more heat remained in the house leading to higher overall temperatures outside the bedroom prior to suppression. Post suppression similar relative temperature reductions were seen. Large drops in temperature (over 80 %) were seen in the bedroom and just outside the bedroom (40 %). At the entrance doorway end of the hallway conditions did not substantially change. It took more time for changes in the bedroom condition to have appeared over the height of the hallway at this end. This comparison provides credence to the FDS post-suppression simulation results.

Table 4.1: Comparison of Experiment 3 Pre- and Post-Suppression Temperatures with FDS Simulation Results

Bedroom						
Height (ft)	Experiment			FDS		
	Pre	Post	Relative	Pre	Post	Rel
6	1,605	309	-82 %	1,494	324	-79 %
4	1,544	302	-81 %	1,285	280	-79 %
2	1,553	271	-84 %	1,063	208	-82 %
Hallway Outside Bedroom						
Height (ft)	Experiment			FDS		
	Pre	Post	Relative	Pre	Post	Rel
6	865	567	-35 %	1,272	460	-65 %
4	793	491	-39 %	590	354	-41 %
2	468	345	-27 %	275	250	-10 %
End of Hallway by Living Room						
Height (ft)	Experiment			FDS		
	Pre	Post	Relative	Pre	Post	Rel
6	966	617	-37 %	306	309	1 %
4	471	518	10 %	266	293	11 %
2	244	246	1 %	257	234	-10 %

5 Contributing Factors

A review of the incident and the fire department response identified several contributing factors to the outcome of the event.

5.1 Size-Up, Communication, and Accountability

The fire scene at arrival showed a post flashover fire venting out of a window. Between the main building entrance and the window with the fire was a door opening onto a patio. In a typical garden style apartment, a single patio door is usually associated with the living room. Typically, the apartment's front door leads to a living room which is connected to the kitchen. Bedrooms and bathrooms are then located off a hallway moving away from the living room and kitchen area. With the fire seen only in the window and not in the patio door, there should have been the expectation of no fire immediately upon entry. Rather it should have been expected that the fire was in a room whose entrance would be 15 to 20 ft from the apartment door. Helmet camera audio does not indicate significant communication among the attack team members prior to entry outlining a plan of action as to where the fire was believed to be located. Comments made immediately after entry do suggest that at least one member of Fire Attack 1 expected the fire to be in the living room. This in part may have resulted from the 911 call reporting a sofa on fire; however, the fire conditions at arrival did not present as a fire in the living room. The lack of communication among Fire Attack 1 and between the AOIC and IC also led to a lack of accountability as the AOIC was not aware of who was with him in the fire apartment as a result of the crew assignments being split. This impacted the decisions made by the AOIC later in the fire.

5.2 Delayed Exterior Attack

Upon arrival to the fire scene, fire was observed venting out of the bedroom window. The main building entrance was open, and the door to the apartment was closed. At this point in time, the fire size was limited by air entering through the bedroom window and possibly air via the crawlspace (it is unknown if the bedroom one floor failed prior to or after the arrival of E19 and T19). This was a prime opportunity to quickly suppress the fire from the exterior and make entry.

Once the interior attack team opened the apartment door, a new flow path was available consisting of the main building entrance through the apartment door down the hallway into the bedroom. This path doubled the area available for ventilation and provided additional air flow to the fire room. At arrival, flames from the bedroom one window were extending to the sill of the second floor window. The flame height, and therefore the fire size, stayed constant until the apartment door was

opened for the interior attack. Over the next 2.5 minutes, the fire grew until flames were reaching the roof line of the building.

Inside the apartment there was near zero visibility, the fire was not visible from apartment door, and the path to the bedroom was not a straight line from the apartment door. Shortly after entry, the fire hose became entangled on a object in the living room. Had this been the upper floor apartment with hoarder conditions, effective movement towards the bedroom would have been near impossible. The perception of heat from the left, likely a result of the ceiling jet from the bedroom, led to the application of water into the kitchen which was not the seat of the fire. It took more than 8 minutes after entering the apartment to locate the seat of the fire. A time period during which the fire severity had significantly increased along with temperatures inside the apartment. By the time the primary water supply was established and the exterior attack started, the interior attack team was already starting to experience pain from heat that had been absorbed by their turnout gear. Only a few seconds of interior water flow was made into the fire room before the mayday was called.

The exterior attack did not begin until the primary water supply was established at approximately 30 s before the interior team discovered the fire (approximately 7.5 min after the interior attack team entered the apartment). Once started, the exterior attack quickly brought the fire in the bedroom under control with less than 100 gallons of water, which was less than 15 % of the water carried by E19. The first few seconds of water application into the bedroom knocked the fire down to near its size at arrival. Over the next 15 seconds, as water application alternated between the bedroom and the vinyl siding on the building exterior, the fire was further reduced until little to no exterior flaming was evident. After repositioning of the fire hose, the next period of exterior attack brought the fire under control with further water flow essentially suppressing the fire. Had the fire been attacked and brought under control from the exterior before opening the apartment door, visibility and the thermal environment would have improved after entry rather than continuing to degrade. Significantly more interior operational time would have been available prior to loading the turnout gear with heat. The ability to navigate the apartment would have improved with the better visibility.

5.3 Entry Hall of a Garden Apartment

It is important to protect the common entry hall of a multiple dwelling unit from smoke and fire in order to provide a safe egress path for occupants. During this fire, no tactics were used to limit the amount of smoke or heat that flowed from the fire apartment into the entry hall. The build up of smoke and the loss of visibility in the entry hall contributed to disorientation of the interior attack crew.

5.4 Apartment Arrangement and Construction

The floor plan of the apartment did not provide a straight path of travel from the apartment entry door to hallway leading to the bedrooms. The interior attack crew did not expect to have to enter the kitchen in order to access the hallway to the bedrooms. The window to the bedroom was large at 36 in $\times$ 72 in The entry doorway to the apartment was 36 in $\times$ 80 in As a result the window served as an efficient bi-directional vent and provided sufficient airflow to support post-flashover burning in the bedroom. The post-flashover fire lead to a burn-through of the floor in the bedroom as well as the failure of the gypsum board ceiling. Once the gypsum board fell from the ceiling ,this added the wood joists and plywood subfloor of the second floor to the fuel load in the bedroom. It was discovered after the fire that second floor consisted of poured concrete. The concrete absorbed and re-radiated heat, resulting in increased temperatures in the fire apartment.

5.5 Thermal Imager Use

Thermal imagers can be useful on the fire ground; however, as with any tool, the capabilities and limitations of the device need to be understood. Members of Fire Attack 1 stated that they were feeling heat, but temperature readings from the thermal imager indicated the heat level was not high. The AOIC had taken a position near the open entry door to the apartment. It was likely that fresh air mixed with the thick, soot-laden smoke in the view of the thermal imager, resulting in a local temperature reading that was lower and inconsistent with the thermal exposure of Eng 19 FF and T19 FF 1. In this case, the thermal imager may have been of better use if it was moving with the nozzle.

5.6 Mayday Procedures and Training

The decision to call a mayday was a positive action and needs to be recognized as such. Once the mayday call was made, there was an immediate response from personnel outside of the building. Radio traffic was promptly cleared and communication with the Fire Attack 1 established to assess their situation and location. Within 1.5 min of the mayday, E5 had entered the apartment via the door in the living room. Within 2 min of the mayday, E5 had located Fire Attack 1 and brought them out through the patio door. This prompt and efficient response avoided more serious injury.

5.7 Key Recommendations

There were a number of factors that contributed to the severity of this incident. Some of these factors, including the apartment geometry, the fuel load, and the construction materials, were unavoidable. The contributing factors that were identified as avoidable have led to the following recommendations.

Recommendation #1: Size-up should include an assessment of the fire location and the extent of fire spread to determine strategy and tactics.

Discussion: NFPA 1700 *Guide for Structural Fire Fighting* [2] presents strategic considerations for the fire control strategy upon initial arrival:

> **§9.5.2** Initial arrival factors should include considerations of the following:
>
> (7) Fire location, size, extent
> (9) Suspected direction of fire and smoke travel within the structure (flow path)
>
> **§9.7 Assessment of Fire Dynamics to Determine Strategy.** Factors observed from the exterior of the structure should be used for determination of interior conditions.
>
> **§9.7.7 Fire Progression.** Based on the 360-degree survey, identify the fire's suspected direction of travel or potential directions of travel. Consider dynamic events such as changes in ventilation and application of cooling, which may effect the path of travel. What is the current extent of the fire and where is it spreading.
>
> **§9.9.1** The incident commander (IC) should consider the entirety of available information when making a decision with respect to strategy. The IC should continually re-assess the strategy decision based upon changing conditions.

In addition to an assessment of Fire Progression, NFPA 1700 also includes an assessment of Smoke and Fire Conditions (§9.7.1), Fuel Load (§9.7.2), Openings (§9.7.3), Flow Path (§9.7.4), and Fire Control Positioning (§9.7.8). The first responding units conducted a quick size-up, but in the process failed to recognize the distance between the entry door and the room on fire. As a result, the assumption that the fire was in the living room led to confusion and delays in finding and suppressing the fire. Had the size-up yielded recognition of the location of the fire relative to the living room and recognized the potential threat to the second floor apartment, different tactics may have been applied that would have prevented the mayday situation and the burn injuries.

In this incident the continued size-up included the use of a thermal imager. Training in accordance with NFPA 1408, Standard for Training Fire Service Personnel in the Operation, Care, Use and Maintenance of Thermal Imagers, is needed to understand the capabilities and limitations of the device [21]. That knowledge is needed to optimize the use of thermal imager in a fire environment.

Recommendation #2: When the initial size-up reveals fire with the potential to rapidly spread on the exterior of the structure, exterior fire control should be applied to limit fire spread.

Discussion: The fire was post-flashover and extending outside the fire room window upon arrival. This was an indication that the fire was going to extend to the second floor and potentially the attic. In this type of structure, fire extension into the attic usually results in the loss of the building. This is noted in NFPA 1700 *Guide for Structural Fire Fighting* [2] sections on Multifamily Dwelling Units. Exposure protection and early fire knockdown should be a tactical priority because: 1) exterior fire communication can occur through interior ceiling openings, and auto exposure through eaves and soffit vents can result in fire spread to the attic, and 2) common attic areas can facilitate horizontal fire spread [2].

It has been demonstrated through experimental research that exterior wall fires may easily spread to the interior via penetrations such as air vents, electrical receptacles, plumbing penetrations to faucets and drains, and especially windows [22]. Responding firefighters should recognize the potential for rapid development and spread of fire along the exterior of the structure and suppress the exterior fire prior to interior fire control. Kerber and Zevotek recommended initial fire control or simultaneous fire control of the fire on the exterior of a structure in their report on tactical considerations for attic fires and exterior fire spread hazards [22]. That recommendation and the justification behind it also apply to this incident. Depending on the firefighting resources available, two hose lines could be pulled to simultaneously conduct interior and exterior fire control.

Based on data from FSRI's Fire Attack Study, exterior fire control of a post flashover bedroom fire was accomplished with less than 100 gallons of water. Complete suppression with application from either interior or exterior hose streams was accomplished with 120 gallons or less [23]. In the Analysis of the Coordination of Suppression and Ventilation in Single-Family Homes, which consisted of second-floor bedroom fires and first-floor kitchen fires, less than 250 gallons was required to achieve extinguishment in each of the 20 experiments [24]. In a similar study conducted in garden apartments, all of the at grade apartment fires were suppressed with less than 200 gallons of water. For the two experiments where at-grade exterior fire control was used, less than 100 gallons was needed to control the fire prior to interior suppression [25]. This is consistent with water flows used in this incident.

For department's looking to implement or refresh on effective interior and exterior fire control methods, training in appropriate hose stream mechanics can be found at https://fsri.org/programs/hose-stream-mechanics.

Recommendation #3: Protection of exit pathways should be a tactical priority.

Discussion: In NFPA 1700's section on Multi-Unit Residential Buildings, the need to prioritize the protection egress routes and the consideration of flow path management that facilitates evacuation of occupants are presented [2].

In 2019, the FSRI conducted a series of fire experiments in garden apartments. One of the objectives was to examine the best practices for protecting the common egress stairwell. Three tactics were examined: interior attack with door control, positive pressure attack (PPA), and initial ex-

terior fire control. Initial exterior fire control proved to be the most effective in protecting the egress stairwell. As presented in *Analysis of the Coordination of Suppression and Ventilation in Multi-Family Dwellings*, "...the initial water flow reduced temperatures and subsequently pressures through gas contraction. As a result, when the suppression crew immediately moved to the interior to complete extinguishment, the temperatures and velocities of the gases that flowed into stairwell were reduced. This lessened the hazard for potential occupants in the stairwell" [25].

The computational analysis in this report demonstrated that the rapid implementation of a smoke control curtain, similar to door control, would also limit the amount of smoke and heat that would enter the common egress stairway.

In this case with an easily accessible ground level apartment, another approach to protecting the stairs (after the initial fire suppression using exterior fire control) would be entry into the apartment through the patio door. Using the patio door allows the apartment door to the stairwell to remain closed until the heat and smoke hazard from the fire apartment has been eliminated.

Recommendation #4: Use known information to guide fire ground decisions.

Discussion: The fire extending from the interior of the apartment to the exterior of the structure was observed. Therefore, the location of the fire was known and the path to advance a hoseline to the fire on the exterior of the apartment building was known. Prior to entry into the apartment, the path from the front door to the fire was unknown. In this case, acting on the known information would have improved interior conditions, both for firefighting and occupant survival, thereby reducing the risk of the unknown conditions (e.g., unexpected floor plan, lack of visibility, high heat) that were encountered as fire operations moved to the interior. In the course of this analysis, the AOIC mentioned the idea of the tactical pause. If a tactical pause had been taken, just a few seconds to process the information observed during size-up and account for the crew, the effectiveness of both the decisions made and the fire attack would likely have been improved.

Recommendation #5: Prepare for Plan B.

Discussion: NFPA 1700's chapter on Tactical Considerations for Fire Control and Extinguishment states that strategy, tactics, and tasks should be based on an ongoing (exterior and interior) size-up. The chapter also provides that communication and coordination result in fire ground operations that enhance life safety, incident stabilization, and property conservation [2].

In this case, the interior attack crew, after being in the apartment for approximately 5 min, had to back out due to lack of visibility, lack of accountability, and increasing heat conditions. That provided an opportunity for the interior attack crew to communicate the situation to command and request exterior fire control, which would enable them to resume the interior attack.

Incident command also should have noted the passage of time, the growth of the fire, and communicated the situation to the interior attack crew. Once the flames extended to the second floor of the building, incident command initiated exterior fire control tactics via face-to-face communication. While starting exterior fire control was appropriate, clear communication of this should have been made to the interior team.

Communications and the understanding that changes to the tactical approach may needed during a firefight need to be practiced during company drills and multi-company drills if there is an expectation that company officers and incident commanders will be able to effectively perform these tasks on the fire ground.

6 Summary

On February 9, 2022, three Cobb County firefighters were injured while attempting an interior attack on a bedroom fire in a garden apartment. Upon arrival to the fire scene, fire was seen venting with bidirectional flow out a bedroom window with no sign of fire in the other bedroom window or patio door. Fire Attack 1 entered the apartment through the door from the entry hall. Neither door control or a smoke control curtain was used to reduce the flow of heat and smoke into the entry hall. With zero visibility inside the apartment, Fire Attack 1 was unable to quickly locate the fire. With the building entrance door and apartment door open, the resulting flow path allowed the fire to grow significantly in size in the few minutes following entry. Approximately 8 min after entry, the interior crew was being impacted by heat. Seconds later, an exterior application of water started which quickly knocked down the fire. Half a minute later, the interior firefighter with the nozzle discovered the fire and began an interior attack. During this period of water flow, the stored energy in the interior team member's gear continued to impact them. A decision was made to back out of the apartment but with the low visibility the team was unable to find the exit and called a mayday. A rescue was quickly made.

To gain insight on the conditions Fire Attack 1 experienced, a computational fluid dynamics model (FDS) was utilized. The fire timeline with video footage of the event and post-fire photographs were used to define the parameters of the model. An FDS model of the event timeline shows temperatures of 300 to 400 °F in the living and kitchen from entry until the mayday call was made. Video evidence shows a rapid reduction in fire size following the start of exterior fire suppression. In the FDS model results, this exterior application of water caused a brief increase in water vapor concentration inside the apartment. However, this was not accompanied by a significant increase in temperature, and temperatures remained above the saturation condition. Therefore, the spike in water vapor would not have resulted in immediate condensation onto protective clothing as the surface temperature of that clothing would have been above the saturation condition. In other words, the conditions created by the exterior application of water were not likely to cause steam burns.

Based on the FDS modeling results, the primary factor contributing to the burn injuries was the duration of exposure prior to the mayday. An FDS simulation of only an interior attack showed that an interior-only attack timeline would have resulted in the same exposures as the actual event timeline with its exterior attack. Since the fire location was known upon arrival, an immediate exterior attack prior to entry would have significantly improved conditions in the apartment. This was shown in the results of another FDS simulation that assumed an exterior-only attack on the fire prior to entry. In that simulation, temperatures are 100 °F lower upon entry and decreasing. Visibility was also improving, which would allow for a more efficient search effort inside of the apartment.

The FDS simulations and observations during the event showed the entry hallway quickly became smoke-filled once the apartment door was opened and left open. In this specific incident the building occupants had evacuated and fire did not spread outside of the apartment of origin. However,

had this not been the case, the loss of tenability in the entry hallway would have increased and made search and rescue efforts more difficult. An FDS simulation with a smoke curtain in the apartment doorway showed that controlling smoke flow into the entry hallway would have maintained tenable conditions in the hallway and would also have limited the increase in fire size post entry.

Based on the analysis of provided documentation and the FDS simulations, five contributing factors were identified: size-up,communication and accountability, delayed exterior attack, lack of entry hall protection, the apartment layout and construction, and mayday procedures and training. The last contributing factor was a positive contribution that helped avoid more serious injuries. Based on the contributing factors, five recommendations were made that include improved size-up, exterior fire control to prevent exterior spread, protection of exit pathways, basing fire ground tactics on known information, and recognizing when a change in tactics is needed.

References

[1] NFPA 1971. *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*. National Fire Protection Association, Quincy, Massachusetts, 2018.

[2] NFPA 1700. *Guide for Structural Fire Fighting*. National Fire Protection Association, Quincy, Massachusetts, 2021.

[3] William D. Walton, Phillip H Thomas, and Yoshifumi Ohmiya. *SFPE Handbook of Fire Protection Engineering*, chapter Estimating Temperatures in Compartment Fires. Springer, New York, NY, 5th edition, 2016.

[4] G. Heskestad. Luminous Heights of Turbulent Diffusion Flames. *Fire Safety Journal*, 5:103–108, 1983.

[5] Plastic Ranger. Melting points of plastics, the ultimate guide. URL: https://plasticranger.com/melting-point-of-plastics/.

[6] Haruo Kawamoto. Lignin Pyrolysis Reactions. *Journal of Wood Science*, 63:117–132, 2017. doi:10.1007/s10086-016-1606-z.

[7] Robert H. White. Charring Rate of Composite Timber Products. In *Proceedings of the Fourth International Conference on Wood & Fire Safety*. Technical University of Zvolen, Slovakia, 2000.

[8] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. *Fire Dynamics Simulator, User's Guide*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2022. doi:10.6028/NIST.SP.101.

[9] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. *Fire Dynamics Simulator, Technical Reference Guide*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2022. Vol. 1: Mathematical Model; Vol. 2: Verification Guide; Vol. 3: Validation Guide; Vol. 4: Software Quality Assurance. doi:10.6028/NIST.SP.1018.

[10] G.P. Forney. *Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data, Volume I: User's Guide*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, sixth edition, May 2013.

[11] G.P. Forney. *Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data, Volume II: Technical Reference Guide*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, sixth edition, May 2013.

[12] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. *Fire Dynamics Simulator, Technical Reference Guide, Volume 2: Verification*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2022. doi:10.6028/NIST.SP.1018.

[13] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. *Fire Dynamics Simulator, Technical Reference Guide, Volume 3: Validation*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2022. doi:10.6028/NIST.SP.1018.

[14] G.P. Forney. *Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data, Volume III: Verification Guide*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, sixth edition, May 2013.

[15] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. *Fire Dynamics Simulator, Technical Reference Guide, Volume 4: Software Quality Assurance*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2022. doi:10.6028/NIST.SP.1018.

[16] Brian Salyers. *Spray Characteristics from Fire Hose Nozzles*. PhD thesis, University of Maryland, College Park, MD, 2010.

[17] A.N. Takata, Z. Zaneveld, and W. Richter. Laser-induced thermal damage of skin. SAM-TR 77-38, USAF School of Aerospace Medicine, Brooks AFB, Texas, April 1977.

[18] C. Weinschenk, K. Stakes, and A. Quiat. Gas Burner Fires in Ranch Structure with HVAC: Report of Test. UL Fire Safety Research Institute, Columbia, Maryland, December 2021.

[19] C. Weinschenk. Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part I: Bedroom Fires. Technical report, UL Fire Safety Research Institute, Columbia, Maryland, December 2021. doi:10.54206/102376/DPTN2682.

[20] C. Weinschenk and J. Regan. Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part II: Kitchen and Living Room Fires. Technical report, UL Fire Safety Research Institute, Columbia, Maryland, December 2021. doi:10.54206/102376/ZKXW6893.

[21] NFPA 1408. *Standard for Training Fire Service Personnel in the Operation, Care, Use, and Maintenance of Thermal Imagers*. National Fire Protection Association, Quincy, Massachusetts, 2020.

[22] S. Kerber and R. Zevotek. Fire Service Summary Report: Study of Residential Attic Fire Mitigation Tactics and Exterior Fire Spread Hazards on Firefighter Safety. UL Firefighter Safety Research Institute, Columbia, Maryland, November 2014.

[23] R. Zevotek, K. Stakes, and J. Willi. Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Full-Scale Experiments. UL Firefighter Safety Research Institute, Columbia, Maryland, January 2018. doi:10.54206/102376/DNYQ2164.

[24] J. Regan, J. Bryant, and C. Weinschenk. Analysis of the Coordination of Suppression and Ventilation in Single-Family Homes. UL Firefighter Safety Research Institute, Columbia, Maryland, March 2020. doi:/10.54206/102376/SLZH7498.

[25] K. Stakes, J. Bryant, N. Dow, J. Regan, and C. Weinschenk. Analysis of the Coordination of Suppression and Ventilation in Multi-Family Dwellings. UL Firefighter Safety Research Institute, Columbia, Maryland, June 2020. doi:10.54206/102376/YMPJ4047.