NIST Technical Note 1498

Evaluating Positive Pressure Ventilation In Large Structures: School Pressure and Fire Experiments

Stephen Kerber
Daniel Madrzykowski

U.S. Department of Commerce
Building and Fire Research Laboratory
National Institute of Standards
and Technology
Gaithersburg, MD 20899

National Institute of Standards and Technology • U.S. Department of Commerce

NIST Technical Note 1498

Evaluating Positive Pressure Ventilation In Large Structures: School Pressure and Fire Experiments

Stephen Kerber
Daniel Madrzykowski

U.S. Department of Commerce
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

July 2008

Department of Homeland Security
Michael Chertoff, *Secretary*
Federal Emergency Management Association
R. David Paulison, *Administrator*
United States Fire Administration
Gregory B. Cade, *Assistant Administrator*

U.S. Department of Commerce
Carolos M. Gutierrez, *Secretary*
National Institute of Standards and Technology
James M. Turner, *Deputy Director*

Table of Contents

Evaluating Positive Pressure Ventilation In Large Structures: School Pressure and Fire Experiments

Stephen Kerber
Daniel Madrzykowski
Building and Fire Research Laboratory
National Institute of Standards and Technology

Abstract

A series of experiments was run in a masonry educational building examining the ability of fire service Positive Pressure Ventilation (PPV) fans to limit smoke spread or to remove smoke from areas where potential occupants may be located. The PPV fans are able to accomplish this by creating pressures higher than that of the fire to manage where the smoke and hot gases flowed in the building. Preliminary experiments examined the pressure increase created by portable fans and mounted fans in different configurations and locations. The two main fire scenarios included a long hallway with classrooms and a gymnasium. Both scenarios included fires that produced a large amount of smoke and hot gases, and instrumentation was placed to assess tenability criteria and how PPV tactics can either increase or decrease tenability. Measurements included temperature, pressure, thermal imaging and video views.

In the limited series of experiments in the long hallways of this masonry educational building, the use of positive pressure ventilation to increase pressure to reduce temperatures, limit smoke spread and increase visibility was effective. This series of experiments demonstrated that fire service positive pressure ventilation fans can be used successfully in large structures to increase tenability of potential victims and improve conditions for firefighting crews.

Disclaimer

1. Introduction

During the past six years the National Institute of Standards and Technology (NIST) has conducted numerous experiments examining the effectiveness of Positive Pressure Ventilation (PPV) for the fire service. These experimental studies ranged in scale from a single room to a 30-story high-rise office building. The research identified tactical considerations for the most effective use of PPV fans. The results of the studies provide insight to questions such as where to place the fans, how much larger can the fire grow with added oxygen from the fan and what size fans are needed to effectively pressurize a stairwell in a high-rise building [1-6].

This series of experiments provides understanding and insight into how and when; fire service positive pressure ventilation fans be used successfully in large structures. Large structures pose additional challenges to fire fighter and building occupant safety: increased travel distance (exposure time), more complicated egress paths, and potentially larger fires. Large structures include high-rise buildings as well as large volume structures such as warehouses or schools. In all of these structures, PPV has the ability to remove or limit occupant exposure to fire gases, so safe egress can be accomplished. Many fire departments don't have staffing levels that allow them to effect multiple rescues in a highly populated structure. These tactics provide the fire department the ability to remove the hazard from the occupants as opposed to removing the occupants from the hazard which is much more time consuming and labor intensive.

A series of experiments was performed in a retired educational building to examine the ability of PPV fans to limit smoke spread or to remove smoke from desired areas. The two main scenarios included a long hallway with classrooms and a gymnasium. Both scenarios included fires that produce a large amount of smoke and hot gases. Instrumentation was placed to assess tenability criteria and how PPV tactics can either increase or decrease survivability. Measurements included temperature, pressure, thermal imaging and video views.

In Section 1, the components of the experiments will be described including the structure, PPV fans and instrumentation utilized. Then, the pressure experiments in the classroom portion of the building as well as the gymnasium will be presented. Section 3 covers the classroom fire experiments and Section 4 covers the gymnasium fire experiments. Measurement uncertainty is presented in Section 5. That is followed by tactical considerations for the fire service based on the experimental results and overall conclusions. Sections 7 and 8 provide acknowledgments to those which made this work possible and references for this work. Finally, the appendices include detailed pressure and temperature data.

1.1. Structure

The experiments were conducted in a two-story 28 000 m^2 (300 000 ft^2) retired high school in Toledo, OH. The school was originally constructed in 1956 and was added on to substantially until 1988. The structure is oddly shaped with numerous sections and court yards, but overall has the dimensions of 210 m (700 ft) wide by 130 m (425 ft) deep by 9 m (30 ft) tall (Figure 1). The building was constructed of masonry bearing walls and steel column grids. The roof and floor systems were mostly steel deck on steel joists with reinforced concrete. The roof of the gymnasium was insulated lightweight concrete panels over steel joists. Below the roof was a fire resistant drop ceiling with clipped in cementicious tiles.

Due to the complex floor plan, the condition of the structure, and the purpose of the experiments a section of the building was isolated for the experiments. This section was to the right of the front entrance and included long stretches of hallway, numerous classrooms and a large volume gymnasium (Figure 2). The detailed floor plan in Figure 3 shows the section of the building used during the experiments in gray. Temporary partition walls were constructed around the three stairwells in the hallway to eliminate smoke flow to the second floor and to better define the volume of the experimental section. Numerous ventilation points, including windows and doors, existed all the way around the structure, which allowed for many configurations to be examined during the experiments. Exterior views of the experimental section of the school are shown in Figure 4.

Figure 1. Aerial photograph of the high school

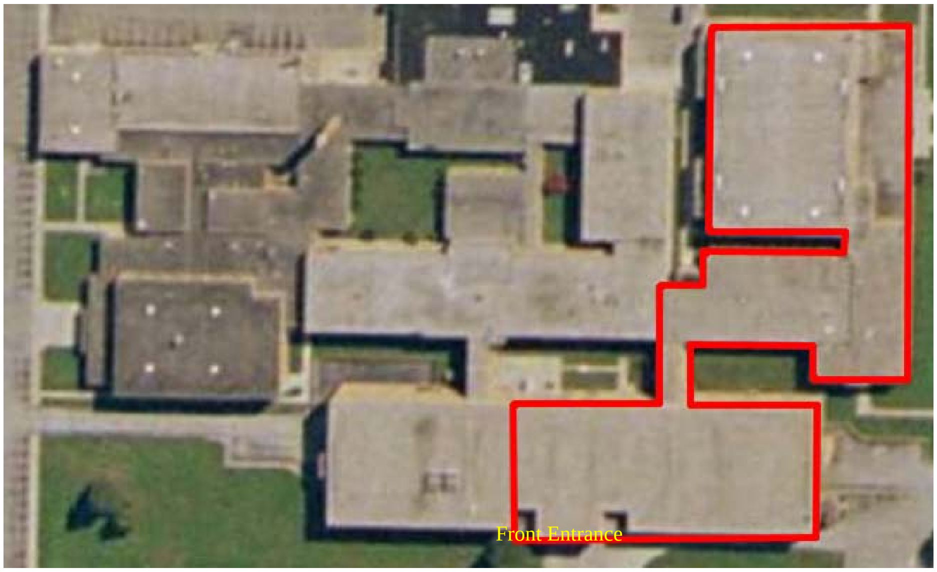

Figure 2. Aerial photograph detailing section used during experiments.

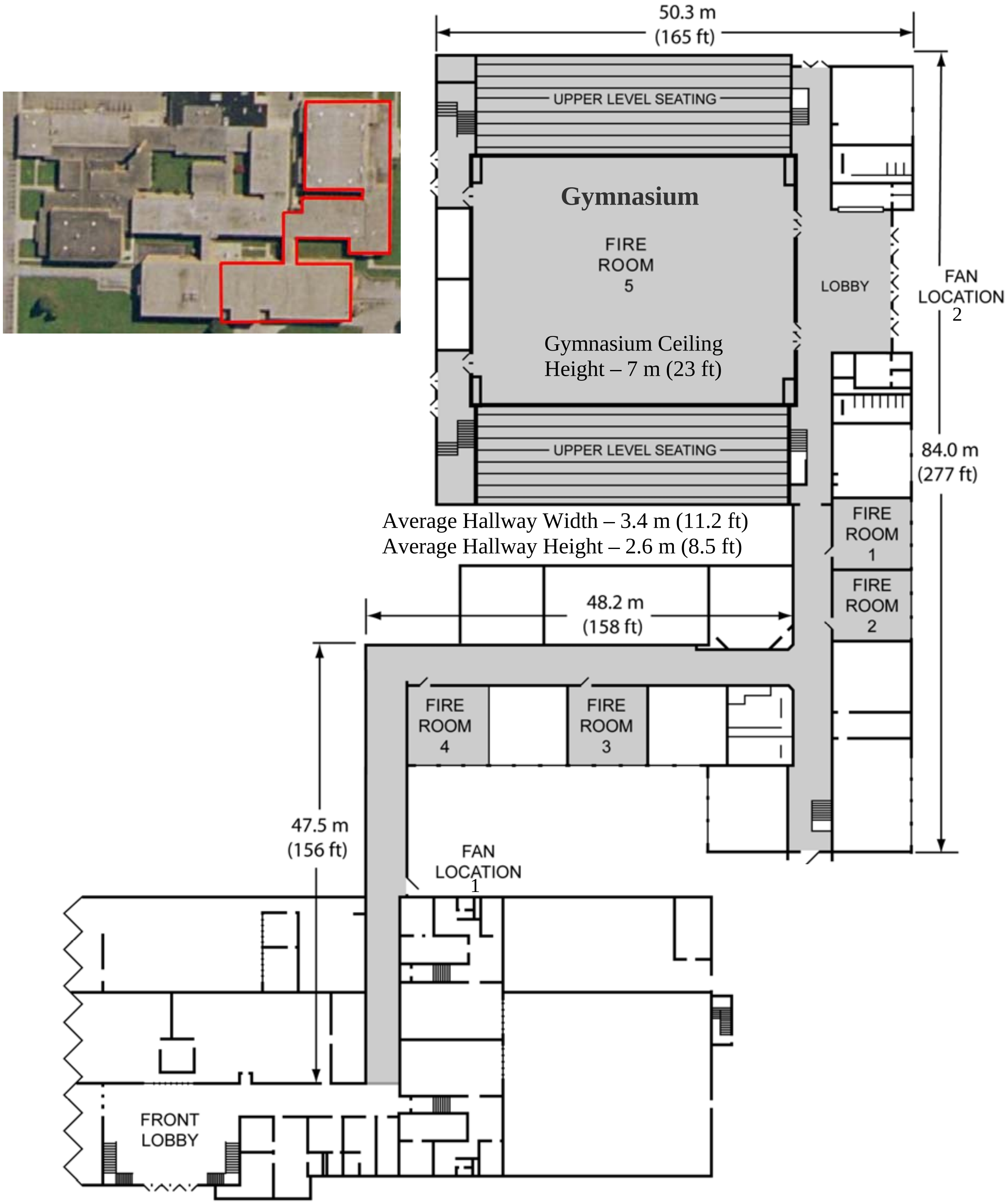

Figure 3. Experimental floor plan and aerial image

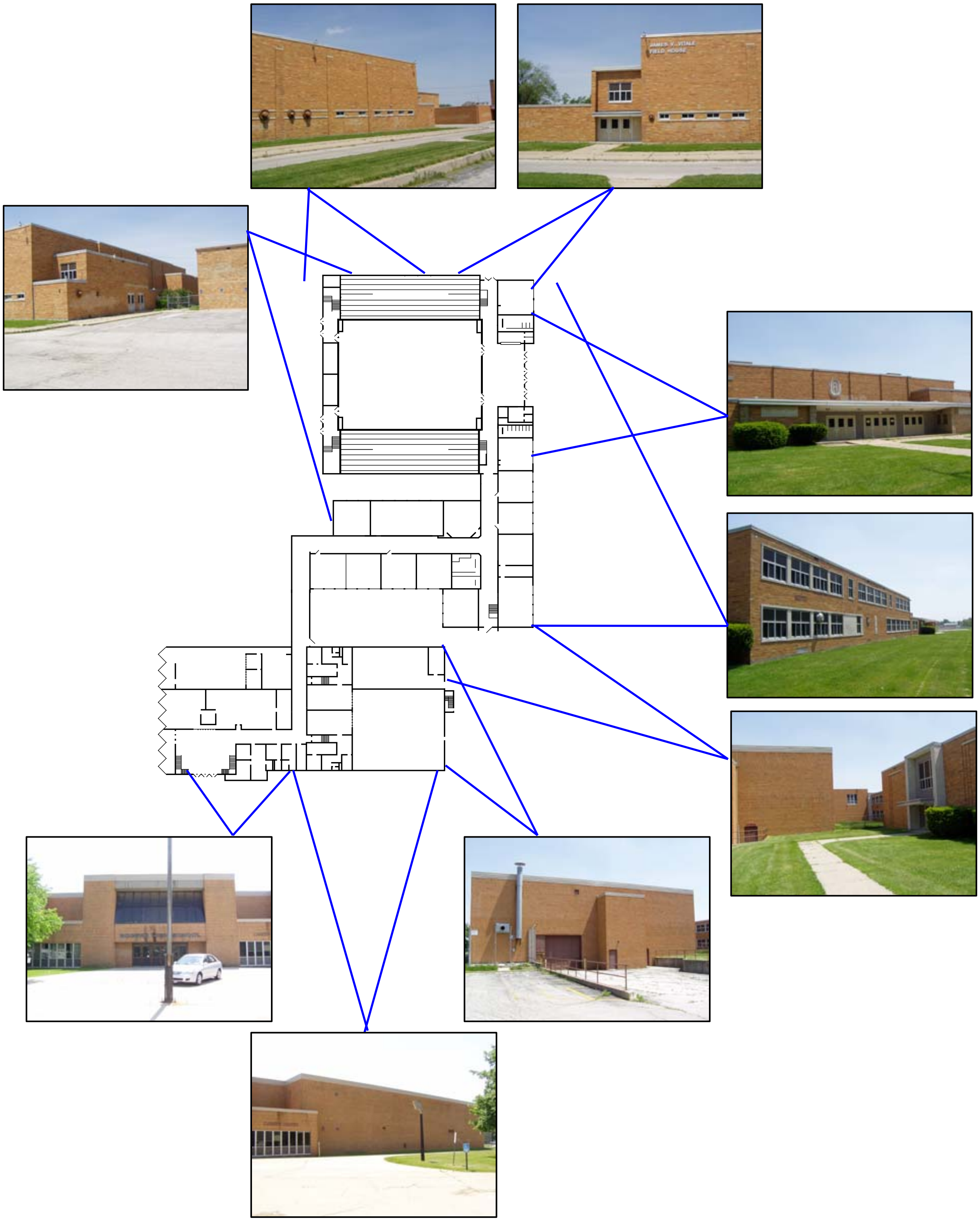

Figure 4. Exterior views of the experimental section

1.2. Fans

Five different types of fans were used during this set of experiments (Table 1). Two different mounted fans and three different portable fans were used in various capacities (Figures 5-9). Each of the fans was used during the pressure experiments as well as the fire experiments. The two main fan locations are labeled in Figure 3, one entering the hallway towards the front of the building and a second into the gymnasium lobby. The portable fans were also moved into the gymnasium lobby to the interior gymnasium doors to directly pressurize the gymnasium. The configuration of the fans was altered and described in the procedure of each experiment. For clarity the fans will be referred to by their identifier throughout the report.

Table 1. Fan details

Identifier	Shroud Size	Motor
MVU	1.2 m (48 in)	Hydraulic (Truck Mounted)
SVU	1.3 m (50 in)	Gasoline (Trailer Mounted)
27	0.7 m (27 in)	Gasoline (9.0 hp)
24	0.6 m (24 in)	Gasoline (6.5 hp)
20	0.5 m (20 in)	Gasoline (4.0 hp)

Figure 5. 27 - 0.7 m (27 in) Fan

Figure 6. 24 - 0.6 m (24 in) Fan

Figure 7. 20 - 0.5 m (20 in) Fan

Figure 8. SVU - 1.3 m (50 in) Fan

Figure 9. MVU - 1.2 m (48 in) Fan

1.3. Instrumentation

The measurements taken during the experiments included differential pressure, gas temperature, video recording and thermal imaging. Differential pressure transducers were located throughout the hallway, 1.2 m (4 ft) above the floor, and in the fire rooms 0.3 m, 1.5 m and 2.1 m (1 ft, 5 ft and 7 ft) above the floor (Figure 10). Transducers were also fixed in two locations on the front and rear walls of the gymnasium. Each location had four transducers positioned vertically at 1.2 m, 3.0 m, 4.9 m and 6.7 m (4 ft, 10 ft, 16 ft and 22 ft) above the floor. A tube was run from the transducers through the wall or door to reference the pressure readings to the outside, or ambient pressure. A floor plan showing each of the pressure measurement locations is in Figure 13.

The thermocouples were bare-bead, Chromel-Alumel (type K), with a 0.5 mm (0.02 in) nominal diameter. Thermocouples were located in the fire rooms and hallways to provide gas temperatures for the conditions that building occupants and fire fighters may encounter and to analyze the effects of ventilation. Each thermocouple location had an array of thermocouples with measurement locations of 0.03 m, 0.2 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m,1.5 m, 1.8 m and 2.1 m (1 in, 0.5 ft, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the ceiling (Figure 11). Thermocouple arrays were also placed in the gymnasium in five locations with measurement locations every 0.3 m (1 ft) from the bottom of the roof deck for the top 1.8 m (6 ft) and then every 0.6 m (2 ft) below that, down to the floor. The top five thermocouples were in the interstitial space between the roof deck and the drop ceiling. A floor plan showing each of the temperature measurement locations is in Figure 14. Detailed experimental uncertainties for each of the measurements are located in Section 5.

Video cameras and thermal imaging cameras were placed inside and outside the building to monitor both smoke and temperature conditions throughout each experiment. As many as ten video camera views and two thermal imaging views were recorded during each test (Figure 12). Camera locations are labeled in Figure 15.

Figure 11. Differential Pressure Transducer

Figure 10. Thermocouple Array with 8 Individual Thermocouples

Figure 12. Thermal Imaging and Video Cameras

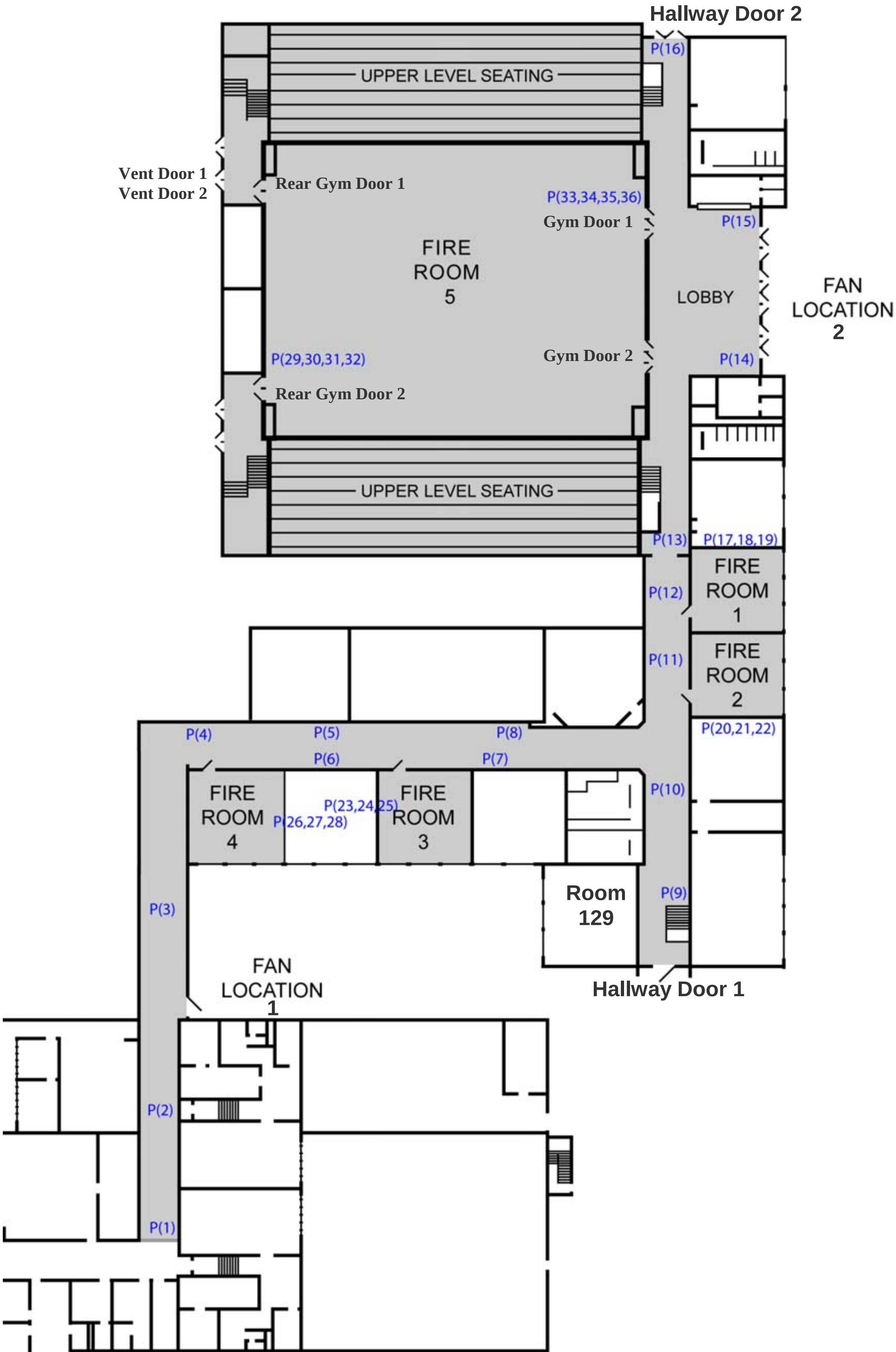

Figure 13. Pressure measurement locations

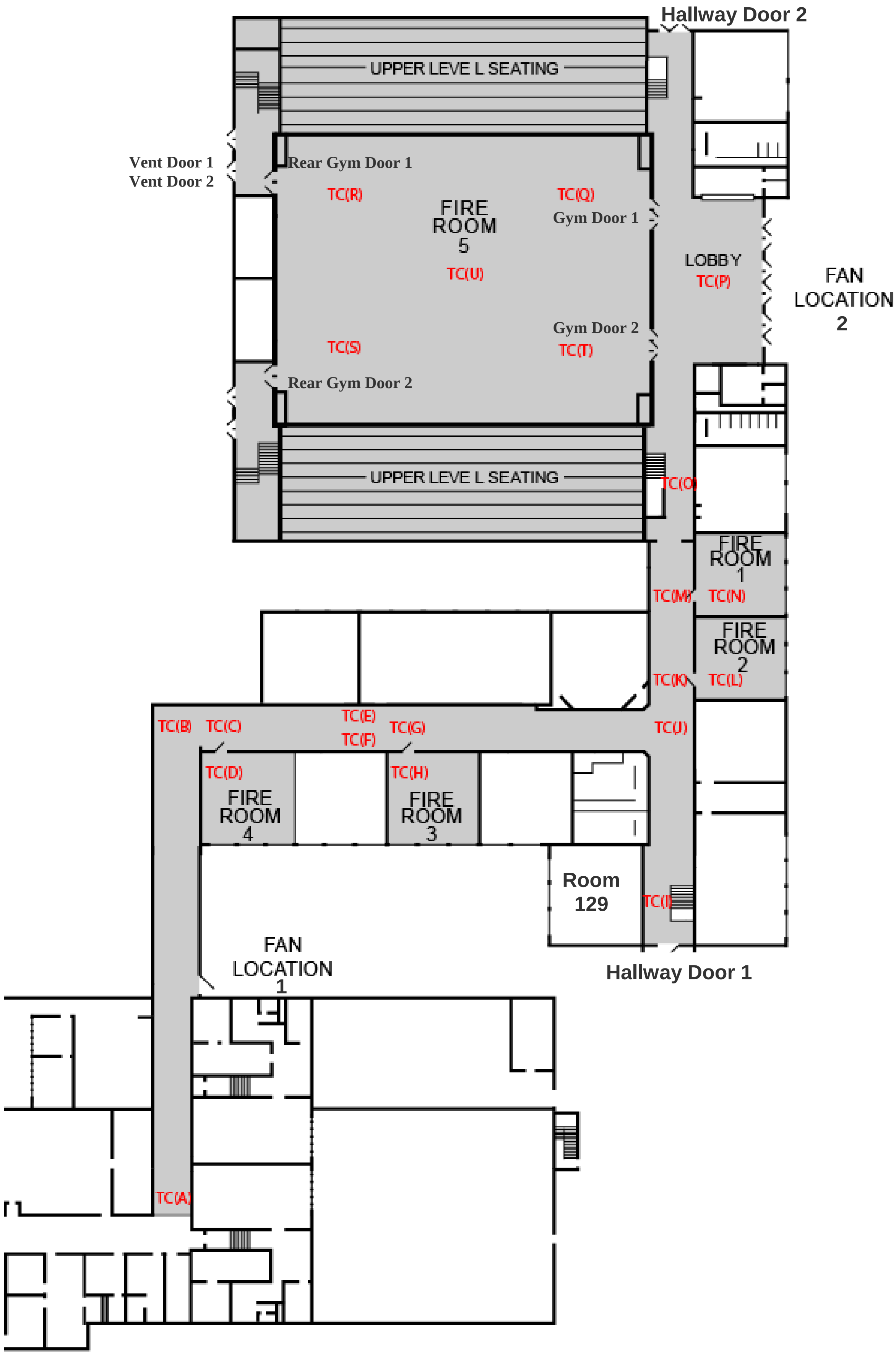

Figure 14. Gas temperature measurement locations

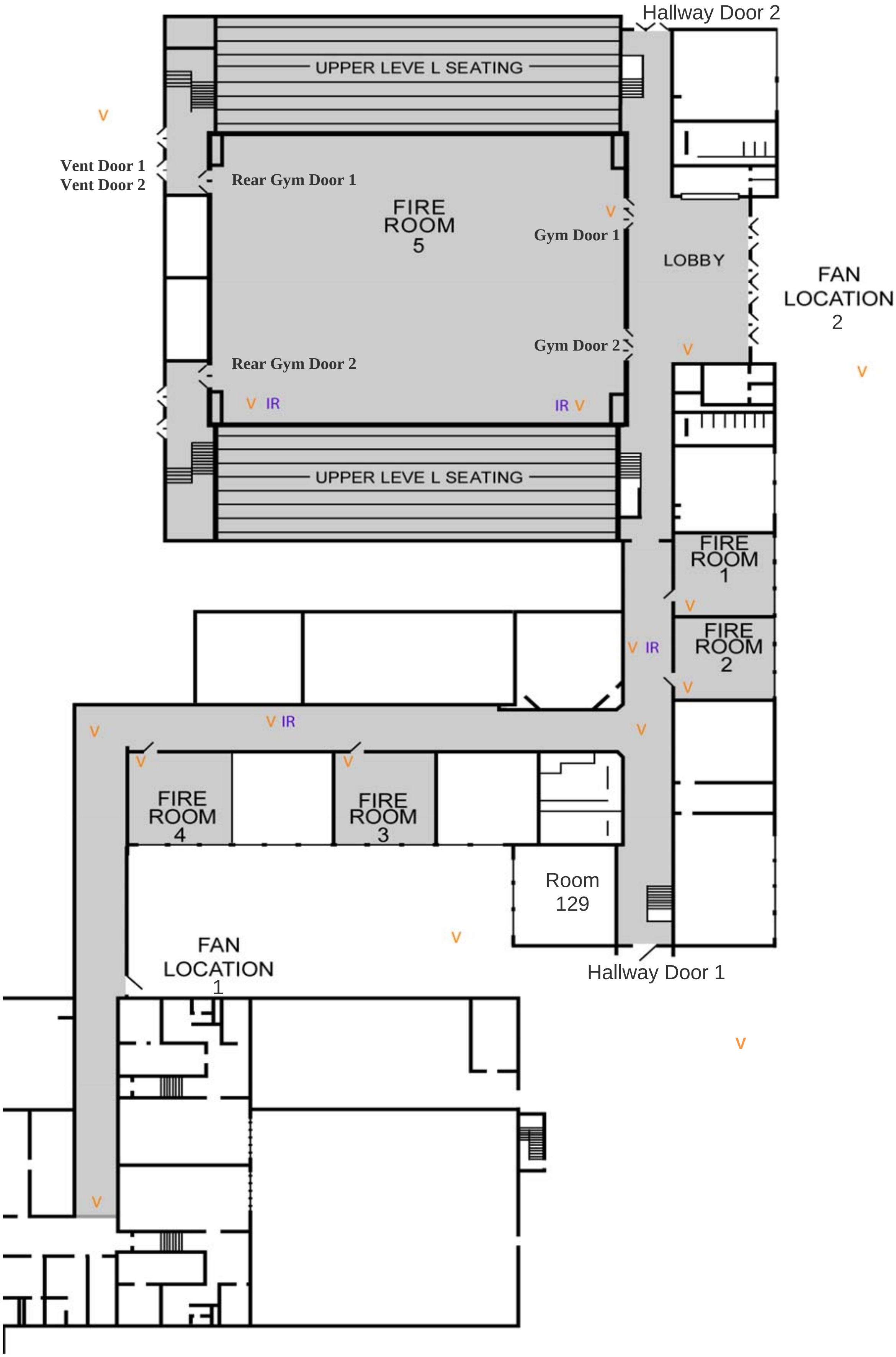

Figure 15. Video camera and thermal imaging camera locations

2. Pressure Experiments

2.1. Experimental Procedure

A series of pressure experiments were conducted prior to the fire experiments in order to examine the effects of the fans on pressurization independent of the fire effects. Different fan configurations were tested at two different door locations (Table 2). The first focused on the long hallways with classrooms while the second focused on the gymnasium. The volume of the school being pressurized was changed by opening and closing the doors to different sections of the hallway and classrooms.

Table 2. Experimental Overview

Experiment	Fan(s)	Fan Location	Fan Configuration
P1	2 – 27’s	1	V-Shape, Setback 1.2 m (4 ft), 80°
P2	1 - 24	1	Setback and angles varied as noted in Table 4.
P3	SVU	1	Setback 3.7 m (12 ft), 100°
P4	MVU	1	Setback 6.6 m (21.5 ft), 90°
P5	MVU	2	Setback 6.6 m (21.5 ft), 90°
P6	SVU	2	Setback 3.7 m (12 ft), 100°
P7	1 - 24	2	Setback 1.8 m (6 ft)
P8	1 – 24, 1 - 20	2	Setback and angles varied as noted in Table 10
P9	2 – 27’s	2	Setback 1.2 m (4 ft), 80°

Notes: Setback is the distance from the threshold of the door to the face of the fan. Angles measured from 90° meaning completely vertical. Angles less than 90°, the fan was tilted back and angles greater than 90° the fan was tilted forward. 20/24/27 fans operated at “full throttle” setting. SVU/MVU rpm’s noted in tables.

2.2. Timelines

The timelines of the experimental configuration changes are shown in Tables 3 through 11. Figures 13 through 15 can be referenced for room and door locations.

Table 3. Experiment P1

Time (s)	Event
0	Background
220	2 – 27 Fans On (V-shape)
525	Fire Room 1 Open
796	Fire Room 1 Closed
855	Fire Room 2 Open
976	Fire Room 2 Closed
1079	Hallway Door 1 Open
1225	Hallway Door 1 Closed
1430	Gym Door 2 Open
1595	Gym Door 2 Closed
1687	Fan Location 2 Door Open
1826	Fan Location 2 Door Closed
1945	Hallway Door 2 Open
2060	Hallway Door 2 Closed
2160	End of Test

Table 4. Experiment P2

Time (s)	Event
0	Background
156	24 Fan On (10’6”, 80°)
540	Fan Off
685	24 Fan On (10’6”, 75°)
810	Fan Off
1064	Fan On (6’, 80°)
1293	Fire Room 1 Open
1491	Fire Room 1 Closed
1548	Room 129 Open
1680	Room 129 Closed
1694	Hallway Door 1 Open
1762	Hallway Door 1 Closed
1834	Gym Door 2 Open
1959	Gym Door 2 Closed
2023	Hallway Door 2 Open
2090	Hallway Door 2 Closed
2160	End of Test

Table 5. Experiment P3

Time (s)	Event
0	Background
200	SVU (12’, 100°) 4000rpm
300	Door Open
816	2000rpm
972	4000rpm
1184	Fire Room 1 Open
1325	Fire Room 1 Closed
1446	Hallway Door 1 Open
1578	Hallway Door 1 Closed
1668	Gym Door 2 Open
1786	Gym Door 2 Closed
1837	Hallway Door 2 Open
1964	Hallway Door 2 Closed
2039	Fire Room 4 Open
2102	Fire Room 1 Open
2250	Fire Room 1 Closed
2285	Fire Room 4 Closed
2330	End of Test

Table 6. Experiment P4

Time (s)	Event
0	Background
74	MVU idle 1000rpm
185	3000rpm
273	4000rpm
538	Fire Room 1 Open
651	Fire Room 1 Closed
701	Hallway Door 1 Open
799	Hallway Door 1 Closed
870	Gym Door 2 Open
998	Gym Door 2 Closed
1076	Hallway Door 2 Open
1177	Hallway Door 2 Closed
1255	Fire Room 4 Open
1379	Fire Room 1 Open
1444	Fire Room 1 Closed
1487	Fire Room 4 Closed
1505	End of Test

Table 7. Experiment P5

Time	Event
(s)	
0	Background
164	MVU On 2000rpm
241	Gym Doors 1 and 2 Open
303	3000rpm
423	4000rpm
540	Rear Gym Doors Open
610	Vent Door 1 Open
732	Vent Door 2 Open
860	End of Test

Table 8. Experiment P6

Time	Event
(s)	
0	Background
95	SVU On 4000rpm
190	Gym Doors 1 and 2 Open
322	Rear Gym Doors Open
389	Vent Door 1 Open
460	Vent Door 2 Open
580	End of test

Table 9. Experiment P7

Time	Event
(s)	
0	Background
84	24 Fan On (Fan Loc 2)
179	Gym Door 1 Open
307	Rear Gym Doors Open
374	Vent Door 1 Open
465	Vent Door 2 Open
525	End of Test

Table 10. Experiment P8

Time	Event
(s)	
0	Background
72	24 Fan On (Gym Door 1)
150	Rear Gym Doors Open
218	Vent Door 1 Open
320	Vent Door 2 Open
455	Fan Off
520	20 Fan On (Gym Door 2)
604	Gym Door 1 Open
620	24 Fan On (Gym Door 1)
740	End of test

Table 11. Experiment P9

Time	Event
(s)	
0	Background
66	27 Fan On (Gym Door 1)
203	Rear Gym Doors Open
275	Vent Door 1 Open
436	Vent Door 2 Open
524	Vent Doors Closed
614	2-27's (Gym doors 1 and 2)
749	Rear Gym Doors Open
822	Vent Door 1 Open
892	Vent Door 2 Open
1000	End of Test

2.3. Results

The pressure measurement locations are shown in Figure 13. The experiments with the fans at Fan Location 1 focus on the hallway pressures from differential pressure gauges P(1) through P(16). The experiments with the fans at Fan Location 2 incorporate the pressures in the gymnasium lobby, P(13) through P(16), and in the gymnasium, P(29) through P(36), which were all located 1.2 m (4 ft) above the floor. The passageway between gauges P(12) and P(13) was closed for the experiments at Fan Location 2. Pressures at each gauge location were recorded during the configuration changes and are graphed versus time in Appendix A (Page 189). The pressures were averaged over the time of each configuration, and the background ambient pressure was subtracted from the average differential pressure to obtain the pressure increase above ambient at each location. These pressures were then averaged over the entire volume pressurized to provide the average hallway pressure increase and average gymnasium pressure increase. Tables 12 through 20 show the average pressure increase in the hallway or the gymnasium for each experiment. This average was achieved by averaging the pressure at each probe in the volume impacted by the fan over the duration of each configuration and then averaging all of those numbers together.

The experimental volume of the hallway for experiments P1 through P4 was approximately 1800 m^3. The volume of the gymnasium was approximately 9630 m^3 (Figure 16). The volume of the gymnasium lobby when the doorway between pressure transducer P(12) and P(13) was closed during experiments P5 through P9 was approximately 680 m^3. The volume between the rear gym doors and the vent doors was approximately 360 m^3. Each of the ventilation doors measured 0.9 m (3 ft) wide by 2.1 m (6.9 ft) tall. The windows in the fire rooms measured 2.2 m (7.3 ft) wide by 0.85 m (2.8 ft) tall.

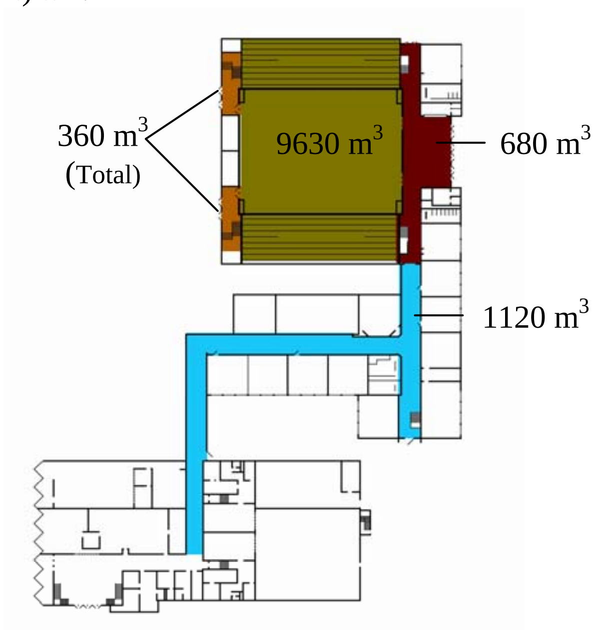

Figure 16. Experimental Volume

Experiment P1

Experiment P1 utilized two 0.7 m (27 in) fans configured in a V-shape to increase the pressure. The fans were setback 1.2 m (4 ft) from the doorway angled back 10º from vertical. The fans were symmetrically placed on either side of the center of the doorway, creating the V-shape. The distance between the fans, measured center to center, was 0.8 m (30 in). The outside temperature at the start of the experiment was 33.1 °C (91.6 °F) and the relative humidity was 44 %. The fans increased the hallway pressure 6.4 Pa to 8.9 Pa above ambient. When doors were opened and the fan flow was vented to the outside, either directly through a doorway or through open windows in the fire rooms, the pressure dropped but was still 1.9 Pa to 5.0 Pa above ambient. When the gym door was opened, increasing the volume but not venting to the outside, the pressure was 5.0 Pa above ambient.

Table 12. Hallway Pressure Increase from 2 - 27 Fans

Event	Average Hallway Pressure (Pa)
2 – 27 Fans On (V)	8.3 (± 0.8)
Fire Room 1 Open	3.2 (± 0.3)
Fire Room 1 Closed	6.4 (± 0.6)
Fire Room 2 Open	3.4 (± 0.3)
Fire Room 2 Closed	7.3 (± 0.7)
Hallway Door 1 Open	1.9 (± 0.2)
Hallway Door 1 Closed	7.8 (± 0.8)
Gym Door 2 Open	5.7 (± 0.6)
Gym Door 2 Closed	8.5 (± 0.9)
Fan Location 2 Door	3.4 (± 0.3)
Fan Location 2 Door	8.9 (± 0.9)
Hallway Door 2 Open	5.0 (± 0.5)
Hallway Door 2 Closed	7.7 (± 0.8)
End of test	

Experiment P2

The increased pressures in Experiment P2 were created by a 0.6 m (24 in) fan. The fan was positioned three different ways as described in Table 4. The position that was used for the configuration changes was setback 1.8 m (6 ft), because it yielded the highest hallway pressure increase. With all of the possible ventilation points closed the fan increased the hallway pressure 6.0 Pa to 7.6 Pa above ambient. When a ventilation point was opened the pressure decreased to between 1.1 Pa and 3.1 Pa above ambient.

Table 13. Hallway Pressure Increase from a 24 Fan

Event	Average Hallway Pressure (Pa)
24 Fan On (10’6”, 80°)	4.9 (± 0.5)
24 Fan On (10’6”, 75°)	4.3 (± 0.4)
Fan On (6’, 80°)	6.2 (± 0.6)
Fire Room 1 Open	3.1 (± 0.3)
Fire Room 1 Closed	7.6 (± 0.8)
Hallway Door 1 Open	1.2 (± 0.1)
Hallway Door 1 Closed	6.1 (± 0.6)
Gym Door 2 Open	2.3 (± 0.2)
Gym Door 2 Closed	6.0 (± 0.6)
Hallway Door 2 Open	1.1 (± 0.1)
Hallway Door 2 Closed	7.5 (± 0.8)
End of test	

Experiment P3

The trailer mounted fan in experiment P3 was positioned 3.7 m (12 ft) from the doorway and tilted 10º forward from vertical. With all of the possible ventilation points closed the fan increased the hallway pressure 9.9 Pa to 16.1 Pa above ambient. When a ventilation point was opened the pressure decreased to between 5.9 Pa and 9.1 Pa above ambient. Two ventilation points were opened toward the end of the experiment and the pressure decreased to 5.1 Pa above ambient.

Table 14. Hallway Pressure Increase from the SVU

Event	Average Hallway Pressure (Pa)
SVU (12’,100°)	16.1 (± 1.6)
Fire Room 1 Open	8.2 (± 0.8)
Fire Room 1 Closed	13.2 (± 1.3)
Hallway Door 1 Open	5.9 (± 0.6)
Hallway Door 1 Closed	10.7 (± 1.1)
Gym Door 2 Open	7.6 (± 0.8)
Gym Door 2 Closed	9.9 (± 1.0)
Hallway Door 2 Open	9.1 (± 0.9)
Hallway Door 2 Closed	13.4 (± 1.3)
Fire Room 4 Open	8.5 (± 0.9)
Fire Room 1 Open	5.1 (± 0.5)
Fire Room 1 Closed	8.8 (± 0.9)
Fire Room 4 Closed	10.6 (± 1.1)
End of test	

Experiment P4

The increased pressures in experiment P4 were created by a truck mounted fan positioned 6.6 m (21.5 ft) from the doorway and the shroud was aligned vertically. The mount for this fan was not able to tilt forward from vertical so the fan was placed further from the doorway to allow its flow to completely cover the doorway. The fan increased the hallway pressure 19.1 Pa to 22.7 Pa above ambient. When doors were opened and the fan flow was vented to the outside, either directly through a doorway or through open windows in the fire rooms, the pressure dropped but was still 13.2 Pa to 17.0 Pa above ambient. Two ventilation points were opened toward the end of the experiment and the pressure decreased to 11.3 Pa above ambient.

Table 15. Hallway Pressure Increase from the MVU

Event	Average Hallway Pressure (Pa)
MVU 4000 rpm	22.7 (± 2.3)
Fire Room 1 Open	14.7 (± 1.5)
Fire Room 1 Closed	20.9 (± 2.1)
Hallway Door 1 Open	13.2 (± 1.3)
Hallway Door 1 Closed	21.7 (± 2.2)
Gym Door 2 Open	17.0 (± 1.7)
Gym Door 2 Closed	19.3 (± 1.9)
Hallway Door 2 Open	13.2 (± 1.3)
Hallway Door 2 Closed	22.6 (± 2.3)
Fire Room 4 Open	15.5 (± 1.6)
Fire Room 1 Open	11.3 (± 1.1)
Fire Room 1 Closed	16.2 (± 1.6)
Fire Room 4 Closed	20.5 (± 2.1)
End of test	

Experiment P5

Experiment P5 was the first of the experiments at Fan Location 2 and the doorway to the hallway section of the building was closed. This experiment also utilized a truck mounted fan positioned 6.6 m (21.5 ft) from the doorway and aligned vertically. The fan was able to pressurize the gymnasium lobby and gymnasium when turned on and the average pressure in the gymnasium increased to 82.8 Pa above ambient. When the rear doors from the gymnasium to the stairwells were opened the volume increased but the flow was not vented to the outside and the pressure was 80.6 Pa above ambient. After the vent doors were opened the flow was able to flow to the exterior of the building and the pressure decreased to 44.8 Pa with one door opened and down to 23.6 Pa with two doors opened to the exterior.

Table 16. Gymnasium Pressure Increase from the MVU

Event	Average Gymnasium Pressure (Pa)
MVU 4000 rpm	82.8 (± 8.3)
Rear Gym Doors Open	80.6 (± 8.1)
Vent Door 1 Open	44.8 (± 4.5)
Vent Door 2 Open	23.6 (± 2.4)
End of test	

Experiment P6

The volumes pressurized for experiment P6 were the same as experiment P5. The fan used for this experiment was the trailer mounted fan positioned 3.7 m (12 ft) from the doorway and tilted 10 degrees forward from vertical. The fan increased the pressure in the lobby and the gymnasium to 75.9 Pa and the slightly larger volume with the rear gym doors open to 74.1 Pa above ambient. After one ventilation door was opened the pressure decreased to 42.2 Pa. The second ventilation door was opened and the pressure was 24.2 Pa above ambient.

Table 17. Gymnasium Pressure Increase from the SVU

Event	Average Gymnasium Pressure (Pa)
SVU On 4000rpm	75.9 (± 7.6)
Rear Gym Doors Open	74.1 (± 7.4)
Vent Door 1 Open	42.2 (± 4.2)
Vent Door 2 Open	24.2 (± 2.4)
End of test	

Experiment P7

Experiment P7 utilized a 0.6 m (24 in) portable fan to pressurize the lobby and gymnasium to 15.5 Pa. The volume was increased when the rear gym doors were opened and the pressure increase decreased to 13.8 Pa above ambient. As the ventilation doors were opened the gymnasium's average pressure dropped to 1.8 Pa and to 0 Pa with both doors open.

Table 18. Gymnasium Pressure Increase from a 24 Fan

Event	Average Gymnasium Pressure (Pa)
24 Fan On (Fan Loc 2)	15.5 (± 1.6)
Rear Gym Doors Open	13.8 (± 1.4)
Vent Door 1 Open	1.8 (± 0.2)
Vent Door 2 Open	0.0 (± 0.0)
End of test	

Experiment P8

Experiment P8 utilized the same fan as experiment P7 but moved it inside to gym door 1 with the same setback and angle as experiment P7. This eliminated the additional volume of the lobby. This allowed the gymnasium pressure to be increased to 21.5 Pa above ambient. After the rear gym doors were opened the pressure decreased to 20.7 Pa. The pressure still dropped significantly when the fan was ventilated to the outside. With one ventilation door opened the pressure dropped to 4.1 Pa and to 3.8 Pa with two doors opened.

The experiment was continued by utilizing a 0.5 m (20 in) portable fan at gym door 2. This smaller fan created pressures of 12.6 Pa with all of the other doors closed. That pressure dropped significantly to 4.2 Pa when gym door 1 was opened. Finally both fans were turned on at their respective doors and the pressure increased to 24.6 Pa.

Table 19. Gymnasium Pressure Increase from the 20 and 24 Fans

Event	Average Gymnasium Pressure (Pa)
24 Fan On (Gym Door 1)	21.5 (± 2.2)
Rear Gym Doors Open	20.7 (± 2.1)
Vent Door 1 Open	4.1 (± 0.4)
Vent Door 2 Open	3.8 (± 0.4)
20 Fan On (Gym Door 2)	12.6 (± 1.3)
Gym Door 1 Open	4.2 (± 0.4)
24 Fan On (Gym Door 1)	24.6 (± 2.5)
End of test	

Experiment P9

Experiment P9 also utilized portable fans. A 0.7 m (27 in) fan was setback 1.2 m (4 ft) and tilted back to 80°. During the fire experiments this setback was discovered to be a little too close to the doorway as smoke was flowing out of the top of the doorway. Optimally for this door height (2.2 m) the fan should be placed approximately 1.8 m (6 ft) in order to more effectively pressurize the gymnasium. Even with the less than optimal positioning the fan increased gymnasium pressures to 17.1 Pa with all doors closed and 16.0 Pa with the rear gym doors open. With the vent doors opened to the exterior the pressures dropped significantly to an average of 6.6 Pa and 3.4 Pa above ambient.

The experiment was continued by utilizing a second 0.7 m (27 in) portable fan at gym door 2. This additional fan created pressures of 20.0 Pa with all of the other doors closed. The pressure decreased slightly with the rear gym doors opened to 18.5 Pa. That pressure then dropped to 9.0 Pa when vent door 1 was opened. Both vent doors opened decreased the pressure to 5.4 Pa above ambient.

Table 20. Gymnasium Pressure Increase from the 27 Fans

Event	Average Gymnasium Pressure (Pa)
27 Fan On (Gym Door 1)	17.1 (± 1.7)
Rear Gym Doors Open	16.0 (± 1.6)
Vent Door 1 Open	6.6 (± 0.7)
Vent Door 2 Open	3.4 (± 0.3)
2-27's (Gym doors 1 and 2)	20.0 (± 2.0)
Rear Gym Doors Open	18.5 (± 1.9)
Vent Door 1 Open	9.0 (± 0.9)
Vent Door 2 Open	5.4 (± 0.5)
End of test	

2.4. Discussion

On average, the portable fans (20, 24 or 27) pressurized the 1800 m^3 hallway 7 Pa. This pressure decreased to 2 Pa with a ventilation point open. The mounted fans (SVU or MVU) pressurized the hallway to an average of 17 Pa above ambient. After a ventilation door or window was opened that pressure decreased to an average of 10 Pa.

The portable fans were able to pressurize the gymnasium an average of 20 Pa above ambient. This pressure decreased to 5 Pa when the gymnasium was vented. The mounted fans pressurized the gymnasium to 80 Pa above ambient. This pressure decreased to approximately 40 Pa with one vent door open and to 20 Pa with two vent doors opened.

There is a small benefit when additional portable fans are used in addition to the first unit. The second fan added to pressurize the gymnasium only increased the pressure 15 %. The portable fan should be positioned at a doorway as close to the area needed to be pressurized in order to increase effectiveness.

This data will be revisited after the results of the classroom and gymnasium fire experiments in sections 3 and 4.

3. Classroom Fire Experiments

Six fire experiments were conducted in four classrooms, Fire Rooms 1 through 4, along the hallway shown in Figure 3. Four different fan configurations were utilized during the experiments with three different types of fans (Table 21). Four of the experiments used mounted fans while two used portable fans. The fans were all positioned at Fan Location 1 and were started after ventilation took place. Two different ventilation locations were used. The fire room window was used as an ideal ventilation location, as it is close to the seat of the fire. Hallway Door 1 was used as a non-ideal ventilation location as it is remote from the fire and the potential to spread hot gases after ventilation was greater.

3.1. Experimental Procedure

Each experiment began with all of the ventilation points, doors and windows closed, with the exception of the door from the fire room to the hallway. The fuel package was ignited and the fire was allowed to grow for a minimum of six min. This was approximately the time when the fire reached its peak and became ventilation limited. Using the interior cameras and thermocouples it was determined when the smoke layer had lowered to the floor in the hallway and tenability would be compromised. At this time the structure was ventilated, either the fire room window or the doorway remote from the fire rooms. The fire was naturally ventilated for two min prior to turning the fans on and forcing the ventilation. Different fan configurations were observed and recorded, and then the fire was suppressed.

Table 21. Classroom Fire Experimental Overview

Experiment	Fire Location	Fan(s)	Fan Location	Fan Configuration
CF1	Fire Room 1	MVU	1	Setback 6.6 m (21.5 ft), 90°
CF2	Fire Room 1	MVU	1	Setback 6.6 m (21.5 ft), 90°
CF3	Fire Room 2	2 – 27’s	1	V-Shape, Setback 1.2 m (4 ft), 80°
CF4	Fire Room 4	1 - 27	1	Setback 1.2 m (4 ft), 80°
CF5	Fire Room 3	SVU	1	Setback 3.7 m (12 ft), 100°
CF6	Fire Room 2	MVU	1	Setback 6.6 m (21.5 ft), 90°

3.2. Fuel Load

The fuel load for the classroom fire experiments consisted of three components. The main component was the wood pallets. The wood pallets were stacked flat as shown in figures 17 and 18. The second component was excelsior or shredded wood to allow the electric match ignition to catch the pallets on fire. Each experiment utilized 8 kg of excelsior layered between the pallets as seen in figures 17 and 18. The final component was polyurethane foam mats. The foam mats measured 1.5 m x 0.6 m x 0.05 m (4.8 ft x 2 ft x 0.2 ft) and weighed 9.0 kg. The foam mats had a vinyl covering and were backed with particle board. The mats were added to experiments CF3 through CF6 to increase the smoke production of the fuel load. Each fuel package was positioned in the center of the room and was ignited remotely with electric matches positioned at either side of the pallets at the open ends (figure 18). As a first order estimate, each stack of 6 pallets, without mats, produced a heat release rate of 2.5 MW and a stack of 10 pallets produced 3.5 MW. This was calculated using the correlation from Babrauskas [7] and is consistent with the author’s heat release rate experiments in [3].

Table 28. Classroom Fire Fuel Loads

Experiment	Pallets	Stacks	Foam Mats	Total Pallet Weight (kg)
CF1	6	1	0	89.8 (± 0.5)
CF2	20	2	0	360.4 (± 1.8)
CF3	12	2	6	224 (± 1.1)
CF4	12	2	6	225.6 (± 1.1)
CF5	12	2	6	213.2 (± 1.1)
CF6	12	2	6	215.8 (± 1.1)

Figure 17. One stack of 6 pallets

Figure 18. Two stacks of 6 pallets with 6 foam mats

3.3. Timelines

The timelines of the experimental configuration changes are shown in Tables 22 through 27. Figures 13 through 15 can be referenced for room and door locations.

Table 22. Experiment CF1

Time (s)	Event
0	Ignition
480	FR 1 Window Open
600	MVU On
930	Sprinkler On
960	MVU Off
1200	End Test

Table 23. Experiment CF2

Time (s)	Event
0	Ignition
480	FR 1 Window Open
600	MVU On
840	MVU Off
1020	MVU On
2280	End of Test

Table 24. Experiment CF3

Time (s)	Event
0	Ignition
380	Hallway Door 1 Open
490	2 -27 in. Fans On
640	2 -27 in. Fans Off
650	Hallway Door 1Closed
710	FR 2 Window Open
800	1 27 in. Fan On
850	2 – 27 in. Fans On
1150	Water Applied
1260	End of Test

Table 25. Experiment CF4

Time (s)	Event
0	Ignition
360	Hallway Door 1 Open
480	27 in. Fan On
570	27 in. Fan Off/Door Closed
635	FR 4 Window Open
770	27 in. Fan On
1080	Water Applied
1470	End of Test

Table 26. Experiment CF5

Time (s)	Event
0	Ignition
360	Hallway Door 1 Open
500	SVU On
500	Long Ramp Up
690	SVU Off/Door Closed
750	SVU On
1080	SVU Off
1108	Water On
1240	End of Test

Table 27. Experiment CF6

Time (s)	Event
0	Ignition
360	Hallway Door 1 Open
480	MVU On
615	MVU Off/Door Closed
700	FR 2 Window Open
760	MVU On
1045	2nd Floor Stairs Open
1180	End of Test

3.4. Results

The pressure, temperature and video recordings were analyzed to determine the impact of the various ventilation tactics on the conditions inside the school. Graphs displaying the pressure during the experiment at every measurement point are located in Appendix B (Page 202). Temperature plots versus time are in Appendix C (Page 216). All of these graphs have lines showing the events and when they occurred during the experiment.

3.4.1. Pressure

The pressure in any structure during a fire is very important as it dictates the flow of smoke and heat throughout the structure. The fire creates its own pressure, and smoke and hot gases flow away from the fire to the lower pressure, which in this scenario is the hallways of the school outside of the fire room. The purpose of the positive pressure ventilation fan is to create pressures higher than that of the fire to manage where the smoke and hot gases flow.

The pressure transducers in the fire rooms were located at 0.3 m, 1.2 m and 2.1 m (1 ft, 4 ft and 7 ft) above the floor. The doorway to the fire room was left open for each experiment so the pressure increased in the fire room prior to fan activation were in the upper gas layer at the 2.1 m (7 ft) pressure transducer. Table 29 shows the peak pressure in the fire room, before natural or positive pressure ventilation was applied, ranged from 12 Pa to 18 Pa. This table also shows the pressure drop that occurred in the fire room after natural ventilation took place. The opening of the window dropped pressure at the 2.1 m (7 ft) an average of 4 Pa.

Table 29. Peak Fire Room Pressures

Experiment	Peak Fire Room Pressure Before Ventilation (Pa)	Pressure After Fire Room Window was Ventilated with no Fans (Pa)
CF1	13 (± 1.3)	12 to 8 (± 1.2)
CF2	14 (± 1.4)	14 to 11 (± 1.4)
CF3	18 (± 1.8)	15 to 12 (± 1.5)
CF4	14 (± 1.4)	16 to 10 (± 1.6)
CF5	17 (± 1.7)	NA
CF6	12 (± 1.2)	NA

The key to controlling the fire flow with fans was to create a pressure with the fan(s) that is greater than that of the fire. There was always a ventilation location open when the fans were activated. Hallway Door 1 was opened or the fire room window was opened, and in most of the experiments both configurations were used. The average pressure increases in the hallway created by the fans in the vicinity of the fire rooms during each of the experiments are in Table 30.

In most of the experiments, the pressure increase created by the fans exceeded the peak pressure created by the fire. During CF3 the peak pressure created by the fire was 18 Pa while the two portable fans created an average pressure in the hallway of 16 Pa. This may have allowed a little bit of smoke and heat to flow into the hallway if the fire room was not ventilated but the fire room pressure was 12 Pa when vented which the two portable fans would have been able to overcome. The single portable fan would have a more difficult time forcing the flow back through the fire room as it was able to create a pressure of 8 Pa with the window opened but the fire was creating a pressure of 10 Pa at its peak after ventilation. Once the fire decayed, the single fan would have been able to reverse the flow back through the fire room. The larger mounted fans created pressures in the hallway that exceed those created by the fire, even at its peak. In CF5, both the hallway door and the fire room window were open and the SVU was able to keep pressures in the hallway above that of the fire.

Table 30. Average Hallway Pressures

Experiment	Average Hallway Pressure in the Vicinity of the Fire Room with Fans Operating (Pa)	
	Ventilated out Fire Room Window	Ventilated out Hallway Door
CF1	18 (± 1.8)	NA
CF2	21 (± 2.1)	NA
CF3	16 (± 1.6)	12 (± 1.2)
CF4	8 (± 0.8)	6 (± 0.6)
CF5	35 (± 3.5)	25 (± 2.5) [Both open]
CF6	32 (± 3.2)	28 (± 2.8)

The fans also created higher pressures in the fire room while the fans were operating. This increased pressure combined with the pressure created with the fire allowed for faster venting to atmospheric pressure outside. The mounted fans created fire room pressures of 21 Pa to 42 Pa (Table 31). These values may be underestimated because the mounted fans were blowing out and lifting ceiling tiles and in turn losing some flow to the large volume open above the ceiling tiles. A single portable fan increased the pressure to 16 Pa and the two-fan configuration increased the average pressure to 24 Pa. When Hallway Door 1 was used for ventilation the fire room pressure was 5 Pa to 15 Pa higher. This pressure when above the hallway pressure allowed for flow out of the fire room and towards the ventilation door. The fire room pressures with the fans operating were also higher for the fire rooms closer to the fans as would be expected.

Table 31. Average Fire Room Pressures at 2.1 m

Experiment	Average Fire Room Pressure at 2.1 m with Fans Operating (Pa)	
	Ventilated out Fire Room Window	Ventilated out Hallway Door
CF1	21 (± 2.1)	NA
CF2	31 (± 3.1)	NA
CF3	24 (± 2.4)	29 (± 2.9)
CF4	16 (± 1.6)	21 (± 2.1)
CF5	42 (± 4.2)	40 (± 4.0) [Both open]
CF6	33 (± 3.3)	48 (± 4.8)

While the pressure at the top of the fire room was greatest because of the thermal gradient, the fans created increased pressures throughout the fire room. Table 32 shows the pressure gradient at all three levels in the fire room. Prior to fan activation the pressures measured at the middle and bottom pressure transducers were ambient.

Table 32. Average Fire Room Pressures at All Levels

Experiment	Average Fire Room Pressure with Fans Operating and Fire Room Window Ventilated (Pa)		
	Top (2.1 m)	Middle (1.2 m)	Bottom (0.3 m)
CF1	21 (± 2.1)	18 (± 1.8)	13 (± 1.3)
CF2	31 (± 3.1)	21 (± 2.1)	16 (± 1.6)
CF3	24 (± 2.4)	21 (± 2.1)	15 (± 1.5)
CF4	16 (± 1.6)	12 (± 2.1)	7 (± 0.7)
CF5	42 (± 4.2)	32 (± 3.2)	28 (± 2.8)
CF6	33 (± 3.3)	25 (± 2.5)	23 (± 2.3)

Table 33 shows the fire room pressures at 2.1 m with fans operating when the fuel load had burned down to a flaming pile of debris. The pressure increase due to the fire was minimal and the fan contribution to the total pressure with the fire room window ventilated was emphasized. During overhaul these are the pressures that could be expected in the fire room which are 5 Pa to 10 Pa less than those during the fire attack stage of the fires.

Table 33. Average Fire Room Pressures at 2.1 m During Decay

Experiment	Average Fire Room Pressure at 2.1 m with Fans Operating in the Decay Stage Just Prior to Suppression (Pa)
CF1	15 (± 1.5)
CF2	23 (± 2.3)
CF3	18 (± 1.8)
CF4	10 (± 1.0)
CF5	32 (± 3.2)
CF6	28 (± 2.8)

3.4.2. Temperature

Limiting the spread of hot gases and minimizing the temperature in a structure allows for increased survivability for potential victims as well as increased safety of firefighters. Temperature measurements taken throughout the structure allowed for the analysis of occupant conditions and potential fire and smoke spread. Research by Montgomery [8] in 1975 indicated that in humid air, rapid skin burns would occur at 100 °C (212 °F), and 150 °C (302 °F) was the exposure temperature at which escape was not likely. In 1947, Moritz [8] conducted experiments on large animals and found that 100 °C (212 °F) represented the threshold for local burning and hyperemia (general burning). The occupant tenability criteria of 150 °C (302 °F) will be used throughout this analysis.

Fire fighters operating in structures are also susceptible to harm from exposure to elevated temperatures. Fire fighter protective clothing standards such as NFPA 1971 require that protective clothing withstand exposure to 260 °C (500 °F) for five min without substantial damage [9]. While the turnout gear has to withstand this temperature to become certified the fire fighter inside the turnout gear may not survive or may sustain injury from this exposure.

In a building with long hallways, the potential for exposure to higher temperature is increased remote from the seat of the fire due to lack of compartmentation. Proper ventilation techniques are a tactic through which the fire service can limit or control these temperature exposures both to occupants as well as themselves, while operating to search for the occupants and extinguish the fire. The impact of several ventilation techniques on temperature was analyzed. The effects of natural ventilation and positive pressure ventilation using the fire room window as well as the hallway door as ventilation points is described for each experiment.

Table 34 shows the average ceiling temperature change of the two closest thermocouple arrays to the fire room 90 s after ventilation for each experiment. The thermocouple array in the fire room and right outside the fire room doorway were not included. This is an area of the hallway with the potential for highest temperature exposure for both occupants as well as firefighters that are not intimate with the fire itself. The temperatures in the fire rooms exceeded the tenability thresholds for both occupants and fire fighters. Due to the large volume of the hallways the temperature outside of the fire room, below 1.2 m (4 ft) above the floor never exceeded 100 ^{o}C (212 ^{o}F).

The natural ventilation did not have a large impact on the ceiling temperatures in the hallway adjacent to the fire room. In each case there was little change to the temperature. There was either a slight decrease in temperature, because of heat escaping or slight increase in temperature because of increased fire size due to the introduction of oxygen as airflow was provided to the fire.

The PPV ventilated scenarios decreased the ceiling temperature in every experiment regardless of ventilation location. Ventilating the fire room window usually had a greater benefit by lowering temperatures, but even when ventilated remote to the fire the hallway temperatures either decreased or remained the same. The mounted fans had the maximum impact but even the single portable fan reduced temperatures.

Table 34. Impact of Ventilation on the Average Fire Room Temperatures at 2.1 m (Uncertainty 15%)

Experiment	Average Hallway Temperature Change in the Vicinity of the Fire Room 90 s After Ventilation (^oC)			
	Naturally Ventilated out Fire Room Window	Naturally Ventilated out Hallway Door	PPV Ventilated out Fire Room Window	PPV Ventilated out Hallway Door
CF1	- 25	NA	- 110	NA
CF2	+ 5	NA	- 200	NA
CF3	+ 10	- 25	- 138	0
CF4	+ 50	+ 25	- 88	- 5
CF5	NA	+ 20	- 140	- 180
CF6	- 10	- 5	- 135	- 43

Figures 19 through 28 show the impact of positive pressure ventilation on the hallway ceiling temperatures, in Celsius, at each measurement location. The red number (upper number) is the temperature prior to ventilation and the blue number (lower number) is the temperature within 90 s following ventilation. During experiments CF3 through CF6, the hallway door was opened and then closed, and the fire room window was used as the ventilation point for the PPV, so there are two figures for each of those experiments. Temperatures were greatly reduced in the hallway leading up to the fire room, especially with the larger fans. Lower temperatures and less hot gases are safer for fire fighters advancing to the seat of the fire. Ventilating the hallway door remote from the fire room did not pull hot gases into the hallway or push hot gases down the hallways, creating problems that would not already be there with natural ventilation. In most cases the temperatures were decreased greatly. In experiment CF4, the downstream temperature did increase, but it remained below the tenability threshold before and after ventilation. The increased pressure from the mounted fans was able to limit the flow of fire gases into the hallway as well as ventilate the gases that were already in the hallway. The portable fans were able to accomplish this when the window to the fire room was ventilated, but not when just the hallway door was opened.

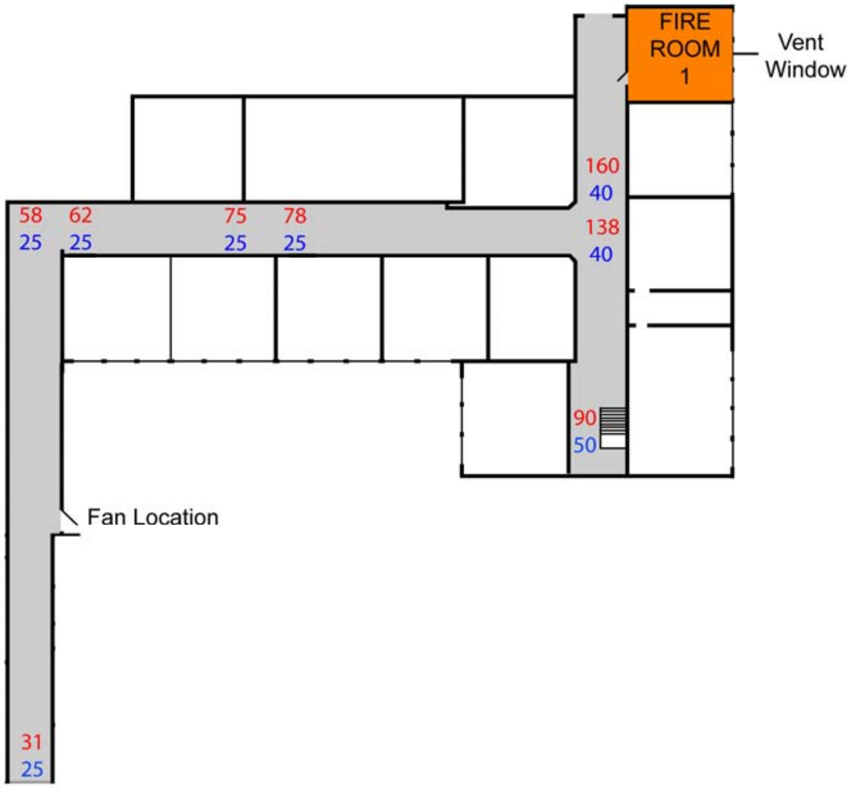

Figure 19. Experiment CF1 temperature change after PPV through window

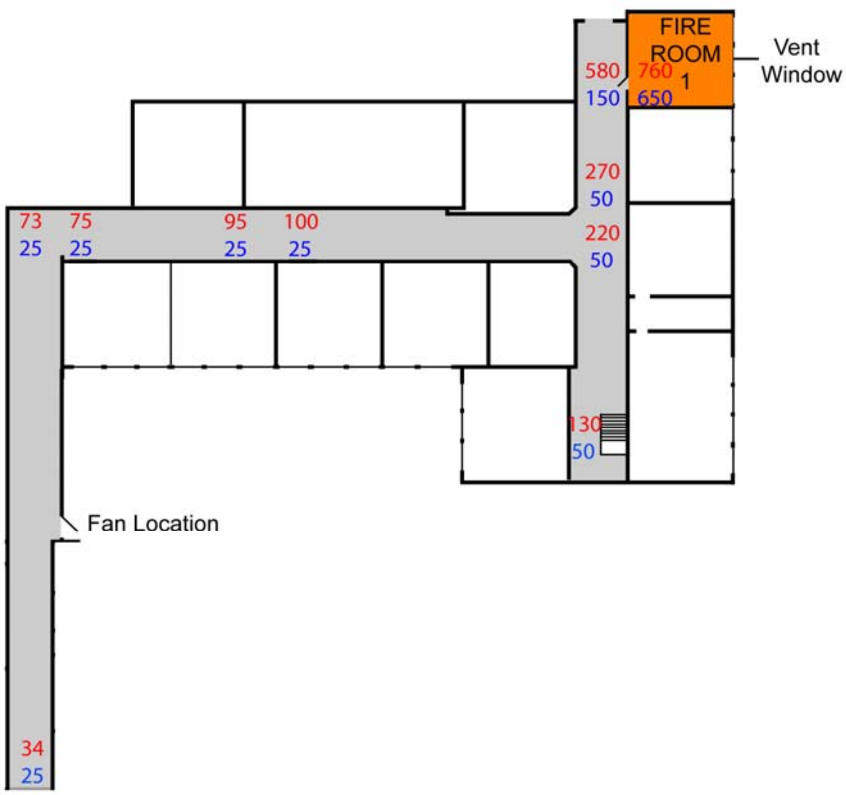

Figure 20. Experiment CF2 temperature change after PPV through window

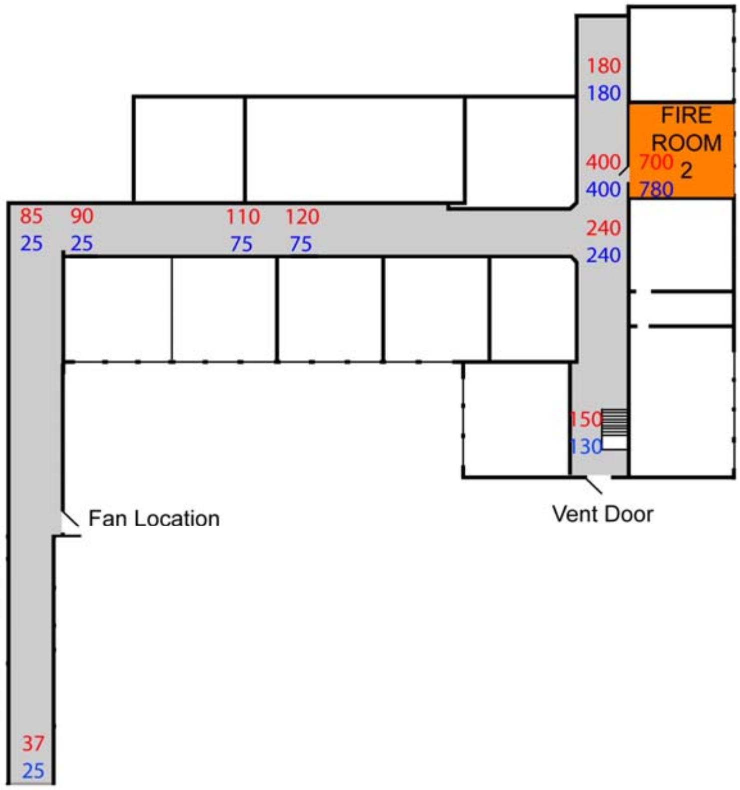

Figure 21. Experiment CF3 temperature change after PPV through doorway

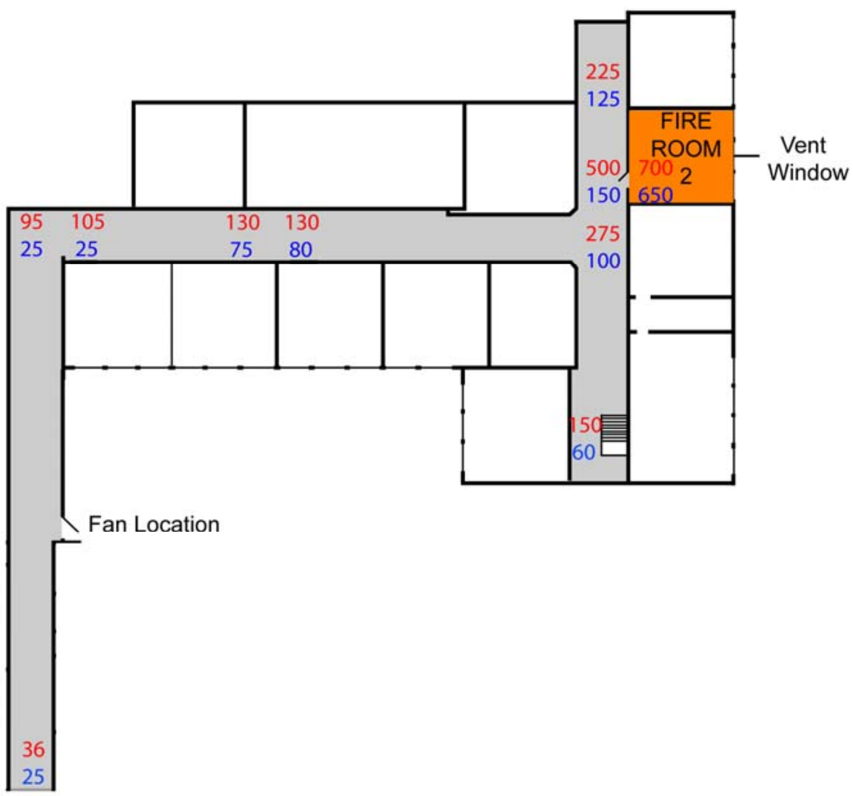

Figure 22. Experiment CF3 temperature change after PPV through window

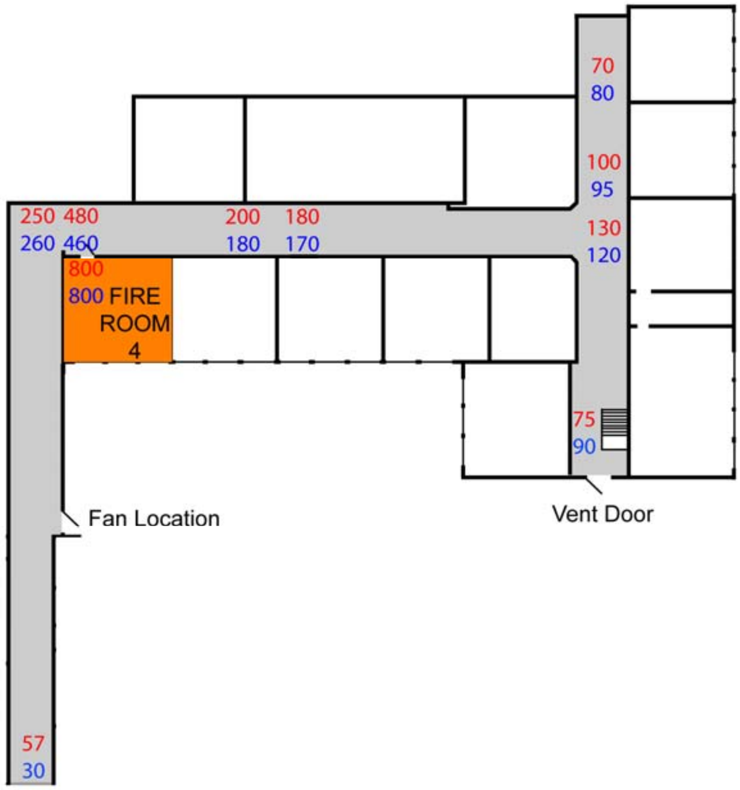

Figure 23. Experiment CF4 temperature change after PPV through doorway

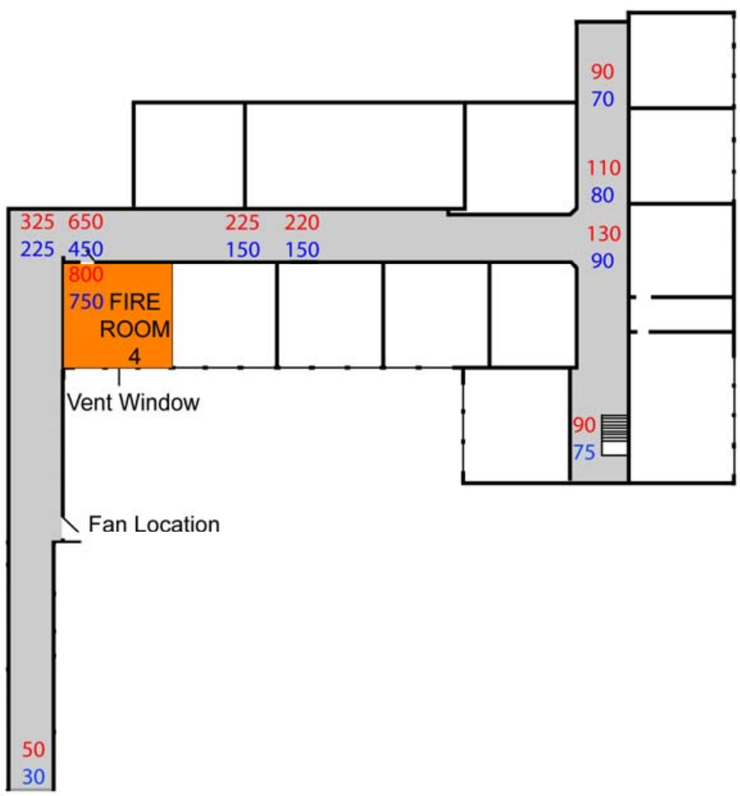

Figure 24. Experiment CF4 temperature change after PPV through window

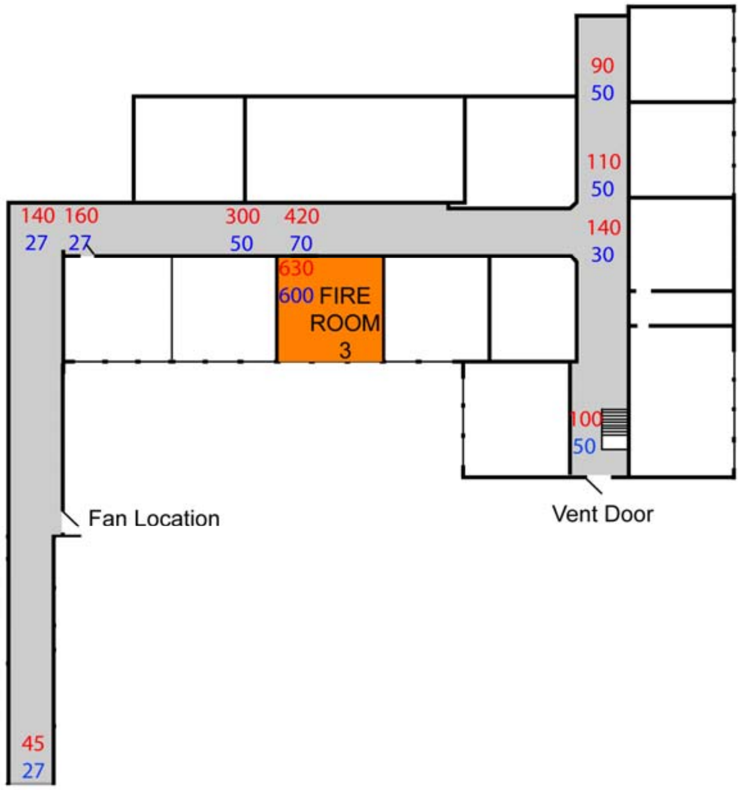

Figure 25. Experiment CF5 temperature change after PPV through doorway

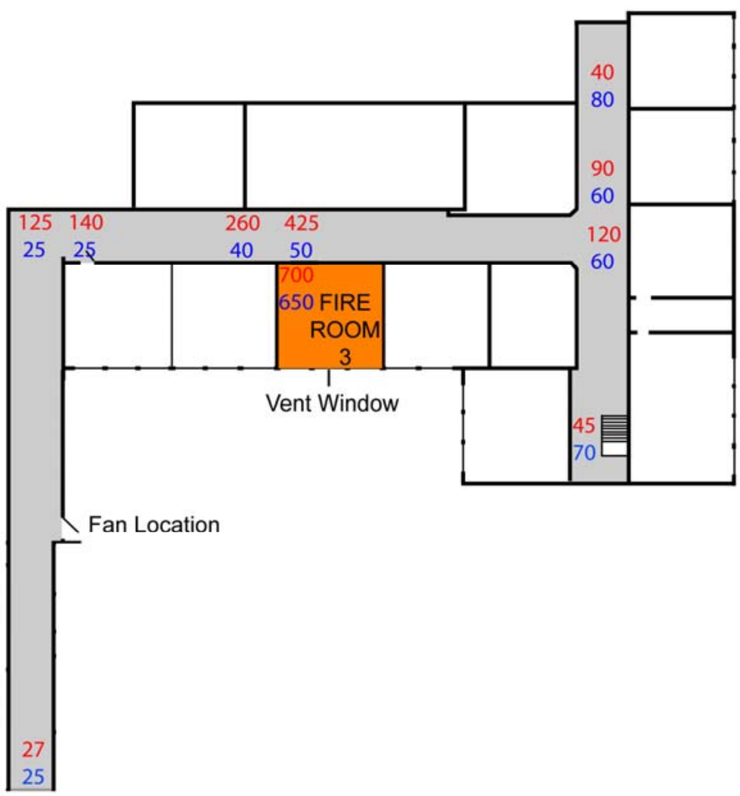

Figure 26. Experiment CF5 temperature change after PPV through window

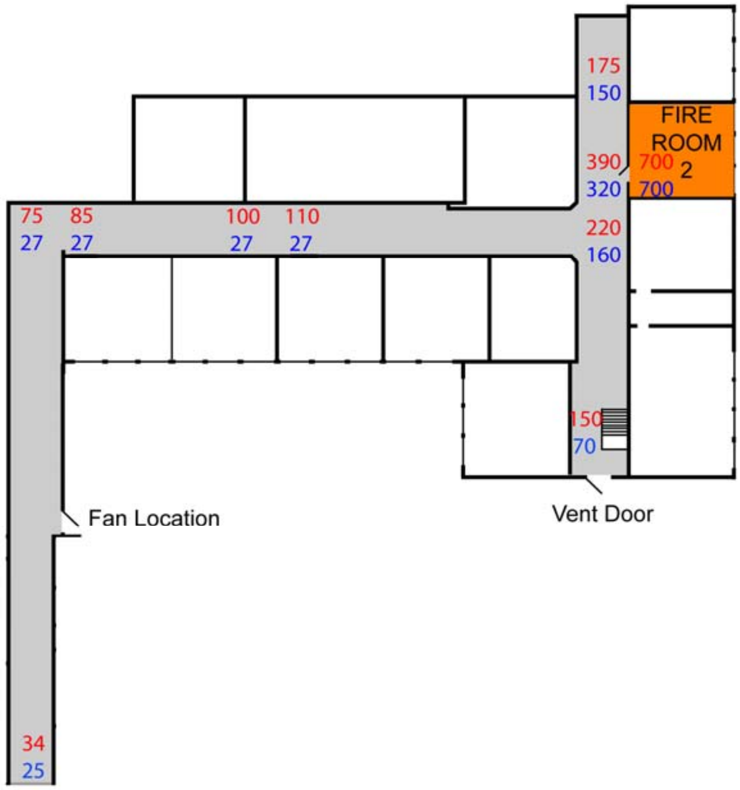

Figure 27. Experiment CF6 temperature change after PPV through doorway

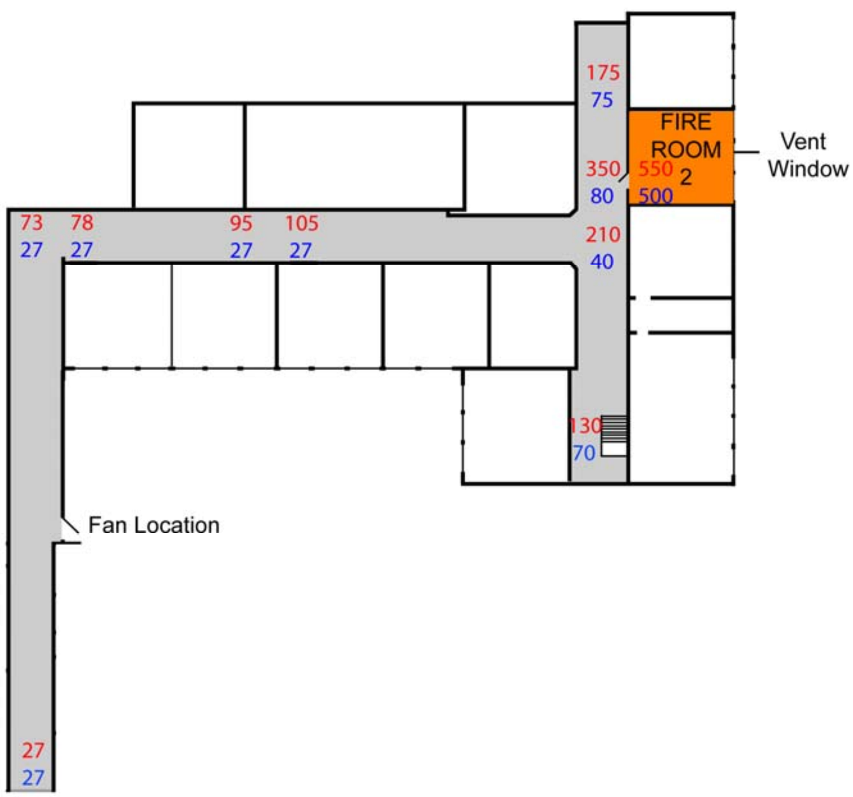

Figure 28. Experiment CF6 temperature change after PPV through window

3.4.3. Smoke/Visibility Observations

In each of the experiments, the smoke layer descended to the floor. The concentrations of toxic gases in the smoke were not measured, however a tenability assessment could be made based on visibility. Occupants exposed to reduced visibility from smoke may become disoriented, lost or slow down which all increase their exposure to toxic gases and reduce their chances of getting out of the structure safely. Fire fighters while breathing air from self contained breathing apparatus will not be affected by the toxicity of the smoke but their effectiveness and safety are greatly affected by visibility. Searches for both occupants and the seat of the fire can be slowed greatly, especially when long complex hallways are involved.

Each experiment was recorded with eight cameras located inside the structure, six visual and two thermal imaging. These views combined with the data facilitated the event changes and allowed the smoke and heat movement to be analyzed. Figure 29 shows the camera locations for the classroom fires and their labels, which are used in the timeline images at the end of this section. Images were captured every two min and at times when an important event occurred such as the activation of a fan or opening of a ventilation point. All times referenced during the experiments are after ignition.

The temperature displayed in the top right view of the thermal imaging images is the average surface temperature of the object or objects within the crosshairs in the center of the image. The camera has a fixed emissivity of 0.95 [10], which is representative of many surfaces found in the field of view of the thermal imaging camera. This temperature is not the gas temperature.

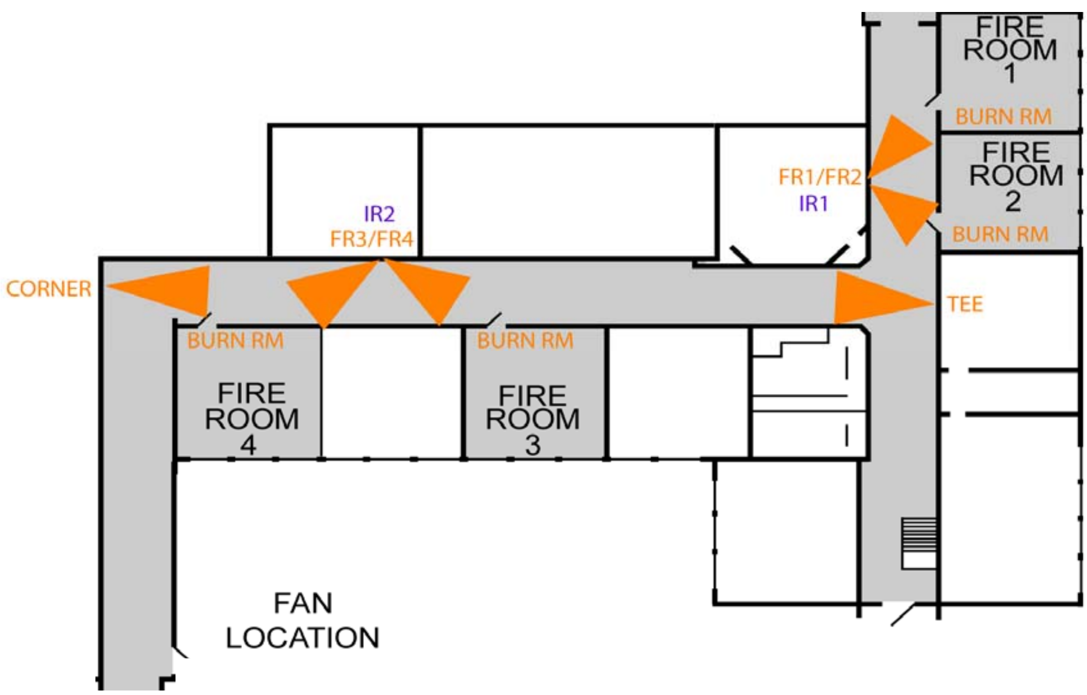

Figure 29. Video view labels and directions.

Experiment CF1 (Figures 30 – 37)

The stack of six pallets and excelsior were ignited and flames reached the ceiling within 2 min. Light gray smoke reached the “corner” adjacent to Fire Room 4 by 6 min. At 8 min, the fire room window was opened and the smoke layer reached the floor in the hallway adjacent to the fire room. The natural ventilation of the fire room reduced the visibility of the hallway between 8 min and 10 min. At 10 min the MVU was activated, and by 11 min the smoke was forced back to the “Tee”. The flow of hot gas out of the fire room visible with the thermal imaging camera was completely stopped. At 12 min there was no smoke visible in the hallway.

Experiment CF2 (Figures 38 – 49)

This experiment was in Fire Room 1, the same fire room as experiment CF1. A larger fuel load was used to generate more smoke and heat. At 2 min there was a smoke layer developing at approximately 1.5 m (5 ft) above the floor in the fire room and hallway adjacent to the fire room. Smoke had reached the “Tee” but had not traveled down the hallway towards Fire Rooms 3 and 4. At approximately 8 min the fire room window was ventilated and at that time there was no visibility in the fire room, and visibility was limited throughout the hallway with large amounts of heat entering the hallway and flowing toward the fan location. At 10 min the natural ventilation had not improved the visibility in the hallway but had reduced some of the heat flow into the hallway as displayed by the thermal imaging cameras. At 11 min the MVU had been running for 1 min and the smoke and heat was forced back past Fire Room 3 near the “Tee”. At this time the heat flow from the fire room to the hallway was stopped suggesting the pressure in the hallway from the fan is greater than that in the fire room. At 12 min the smoke was cleared back past the “Tee” and the smoke was thinned near the fire room but still present. By 14 min there was no smoke in the hallway and the fire was free burning with a large amount of pallets remaining.

The images at 16 min show the conditions when the fan was turned off to show natural ventilation again. The flow of smoke and hot gases returned to the hallway and the heat displayed by the thermal imaging cameras greatly increased. At 18 min the MVU was back on for 1 min and the flow was reversed, stopping the heat flow into the hallway and thinning the smoke. By 19 min the hallway is free of smoke again.

Experiment CF3 (Figures 50 – 62)

Experiment CF3 was the first experiment where the foam mats were added to thicken the smoke. There was also a video malfunction that was corrected by 4 min, so the 4 min images are the first ones displayed. By 4 min the smoke layer was developed and smoke has reached the open fan location doorway. At 8 min the hallway door had been open for 100 s naturally ventilating and the visibility throughout the entire hallway worsened. The fire became ventilation-limited and the heat entering the hallway was increased. At 10 min the 2- 27 inch portable fans had been operating for 110 s. The visibility was improved beyond the “Corner” up to Fire Room 3. The heat flow into the hallway was not affected by the fans ventilating through the hallway door. By 11 min the fans were turned off for 20 s and the heat flow into the hallway increased.

Just before 12 min the fire room window was ventilated. At 13 min the heat flow into the hallway has increased but the smoke was only increased slightly. The images at 14 min are with one fan running while the images at 15 min are with two fans running. The two fans are able to stop the heat flow into the hallway while the single fan had little impact. By 16 min the visibility in the portion of the hallway up to the “Tee” was improved. At 18 min there was visibility up to the fire room. It took until 22 min from ignition for all of the smoke to be evacuated out of the hallway.

Experiment CF4 (Figures 63 – 75)

This experiment utilized the same fuel load as experiment CF3 and a single portable fan for ventilation. This experiment was conducted in Fire Room 4 which is the room closest to the fan location and prior to the hallway door ventilation point. The smoke and heat flow into the hallway increased up to 6 min at which time Hallway Door 1 was opened for natural ventilation. A light diffuser melted and fell onto the "Corner" camera blocking its view for the remainder of the experiment. After the hallway door was opened for 2 min the fire remained ventilation limited, the visibility decreased. The images at 9 min show no improvement with 1 min of fan flow.

The fan was turned off and the fire room window was opened prior to the 11 min images. Opening the window allows the fire to increase and in turn increase the heat flow into the hallway. At 14 min, the single portable fan was operating for 70 s with little to no improvement to hallway visibility or heat flow. By 20 min, heat flow into the hallway was reduced and visibility had returned to the hallway up to and surrounding the fire room.

Experiment CF5 (Figures 76 – 87)

This experiment had similar fire growth as the two previous experiments, reaching a ventilation limited condition by 4 min. This experiment was located in Fire Room 3 which also allowed it to be ventilated past, with Hallway Door 1 open. At 6 min visibility is poor in most of the hallway. The hallway door was opened for natural ventilation and two min later, at 8 min, visibility had worsened and the heat flow into the hallway remained the same. By 10 min the SVU has been running at full speed for 40 s and heat flow into the hallway was stopped and the visibility was returned in the hallway up to the fire room. Beyond the fire room visibility remained poor. At 11 min after ignition, the fire room was flashed over with ghosting flames filling the room. Visibility returned to most of the hallway and the glow of fire could easily be seen in the fire room from the hallway. The SVU was turned off at 11 min and 30 seconds and in the 12 min images, the heat flowed back into the hallway and some flames can be seen extending into the hallway. Once the SVU was turned back on, the flow was forced out of the fire room window.

Experiment CF6 (Figures 88 – 100)

Experiment CF2 moved back to Fire Room 2. The IR2 view was not available for this experiment. The fire was allowed to develop for the first 6 min without a change to ventilation and the smoke layer dropped close to the floor in most of the hallway. At 8 min Hallway Door 1 had been open for 2 min and conditions did not change much in the hallway. At 9 min, the MVU was running for 1 min and the smoke was forced back toward the hallway door ventilation point. The "Corner" and most of the hallway up to the "Tee" was free of smoke. By 10 min, the hallway was free of smoke up to the fire room and a little residual smoke was in the hallway beyond the fire room. Fifteen seconds later the MVU was turned off, the hallway ventilation door was closed, and the smoke was allowed to flow back into the hallway. At 12 min, the fire room window was open for 20 s and the smoke continued to fill the hallway. At 12 min and 40 s, the MVU was turned back on and the flow was reversed back through the fire room. By 16 min, the hallway was free of smoke.

Experiment CF1 Video Images

Figure 30. Experiment CF1 video images captured at 0 min

Figure 31. Experiment CF1 video images captured at 2 min

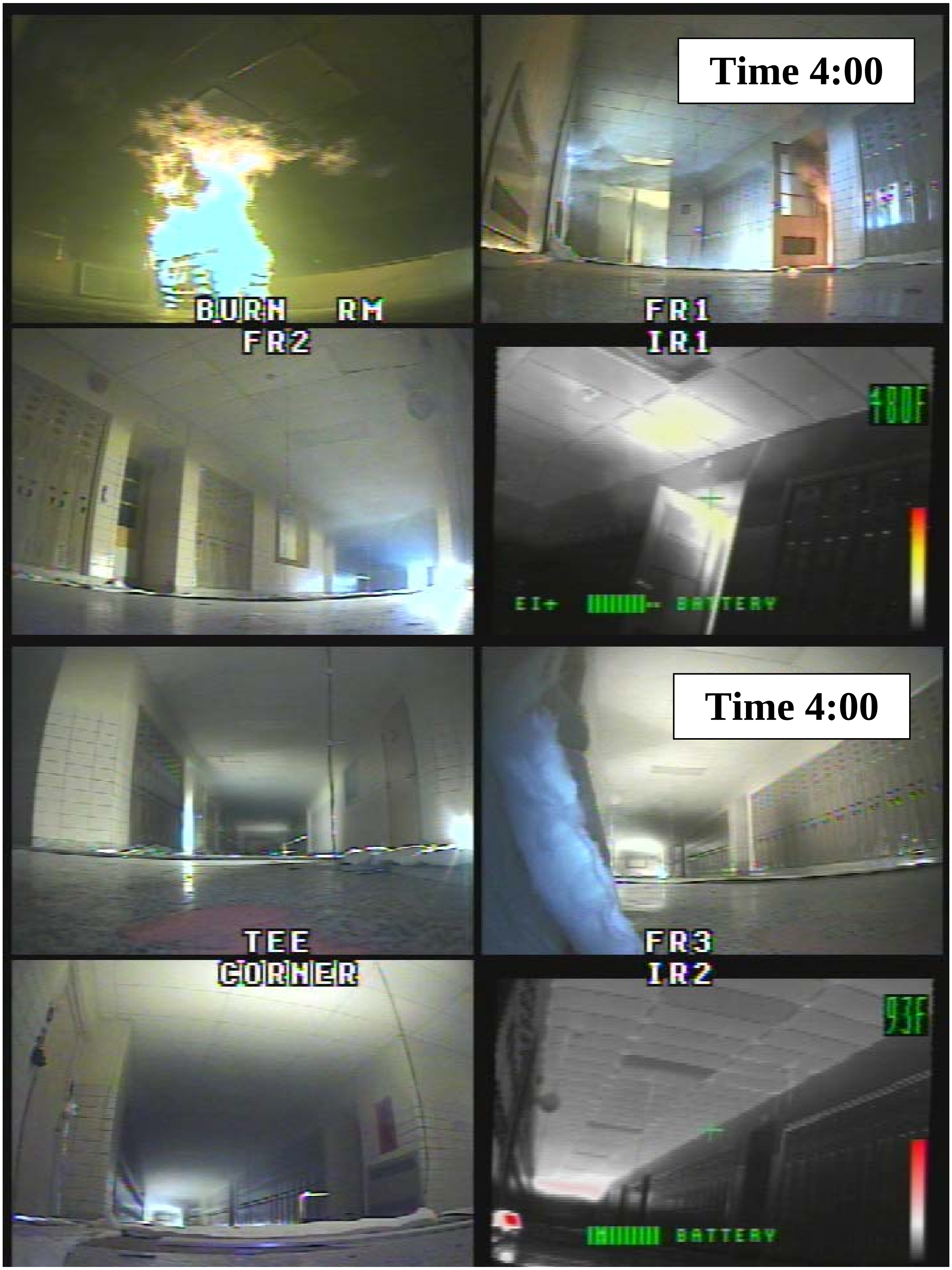

Figure 32. Experiment CF1 video images captured at 4 min

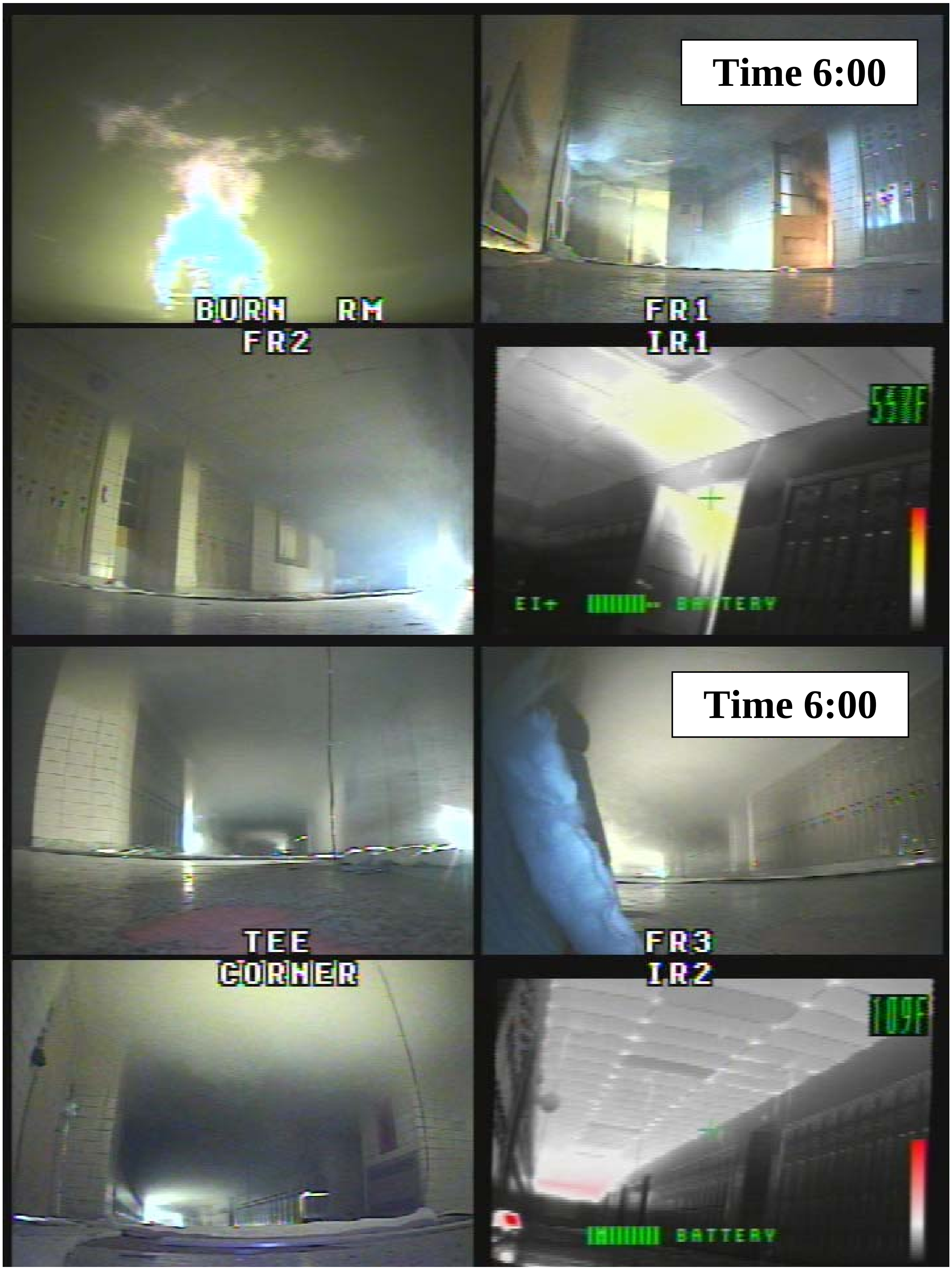

Figure 33. Experiment CF1 video images captured at 6 min

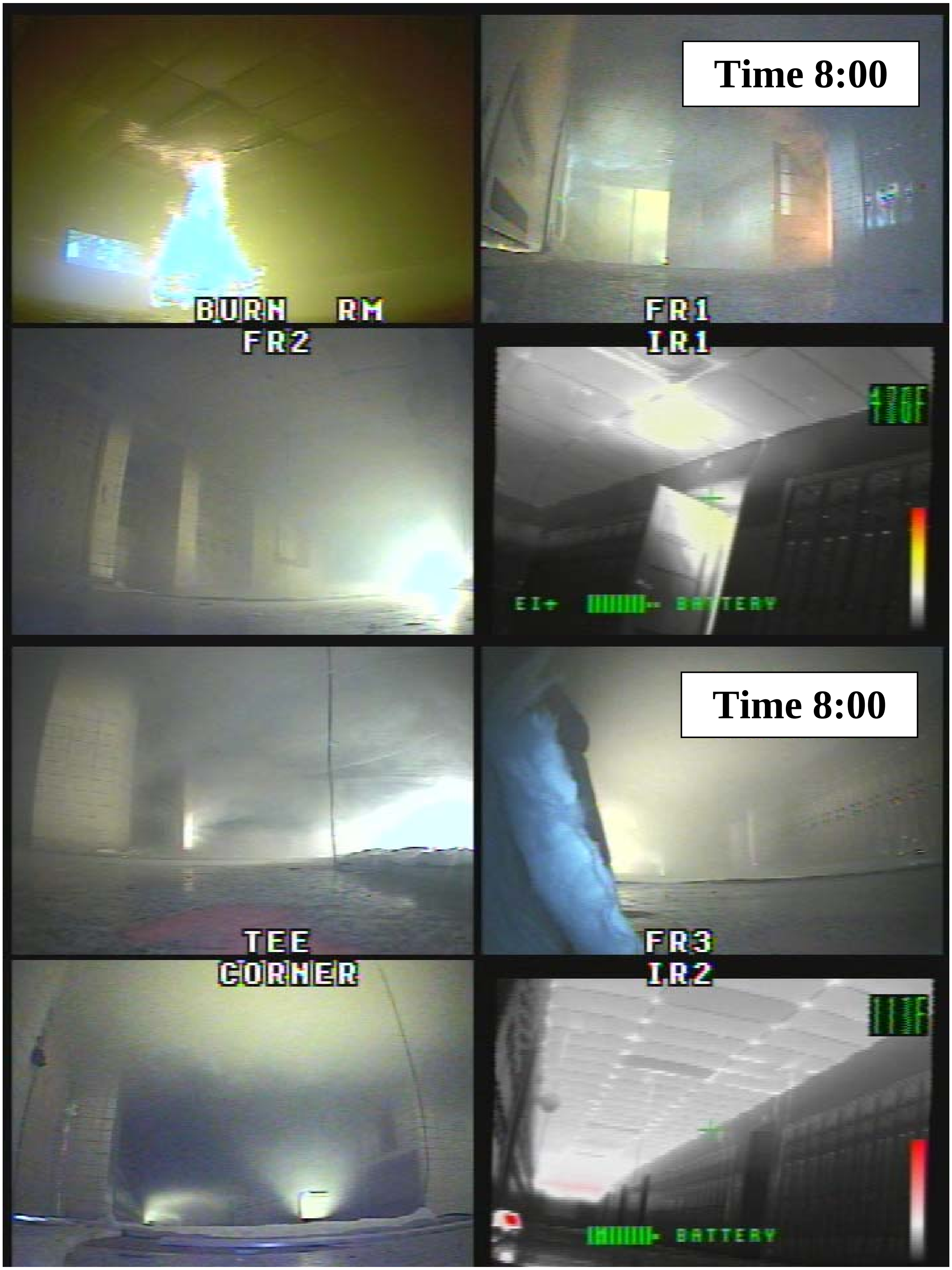

Figure 34. Experiment CF1 video images captured at 8 min

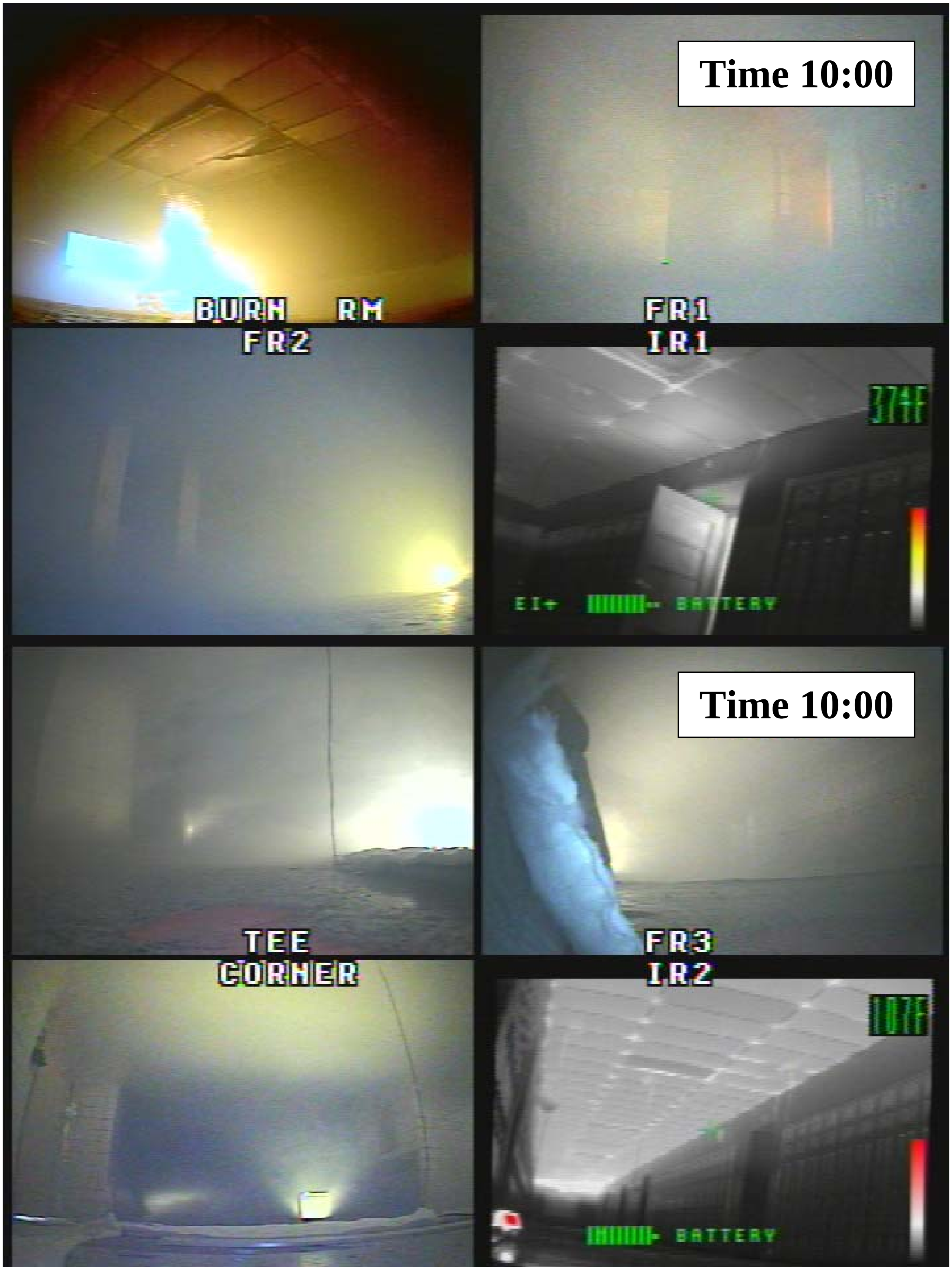

Figure 35. Experiment CF1 video images captured at 10 min

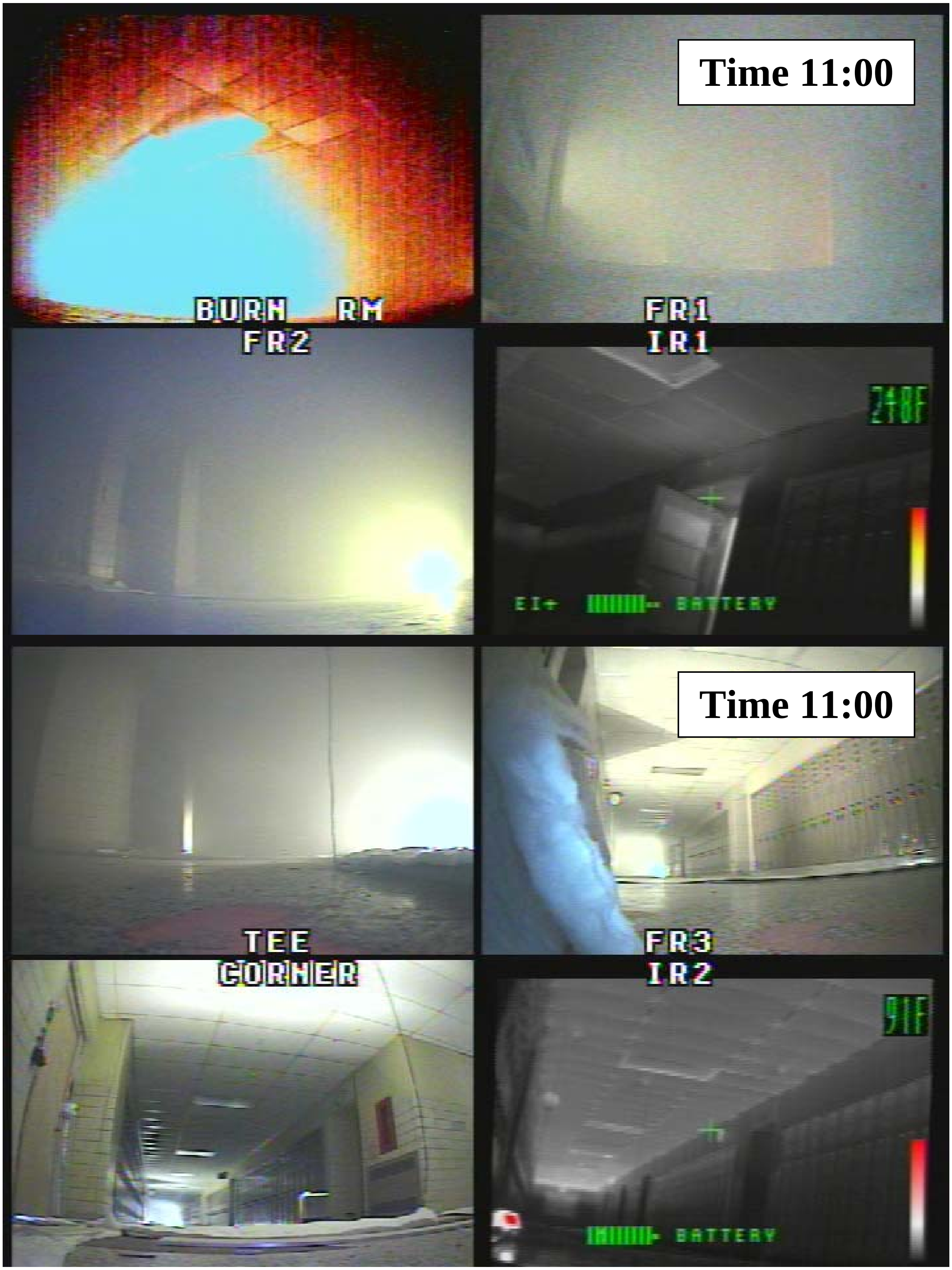

Figure 36. Experiment CF1 video images captured at 11 min

Figure 37. Experiment CF1 video images captured at 12 min

Experiment CF2 Video Images

Figure 38. Experiment CF2 video images captured at 0 min

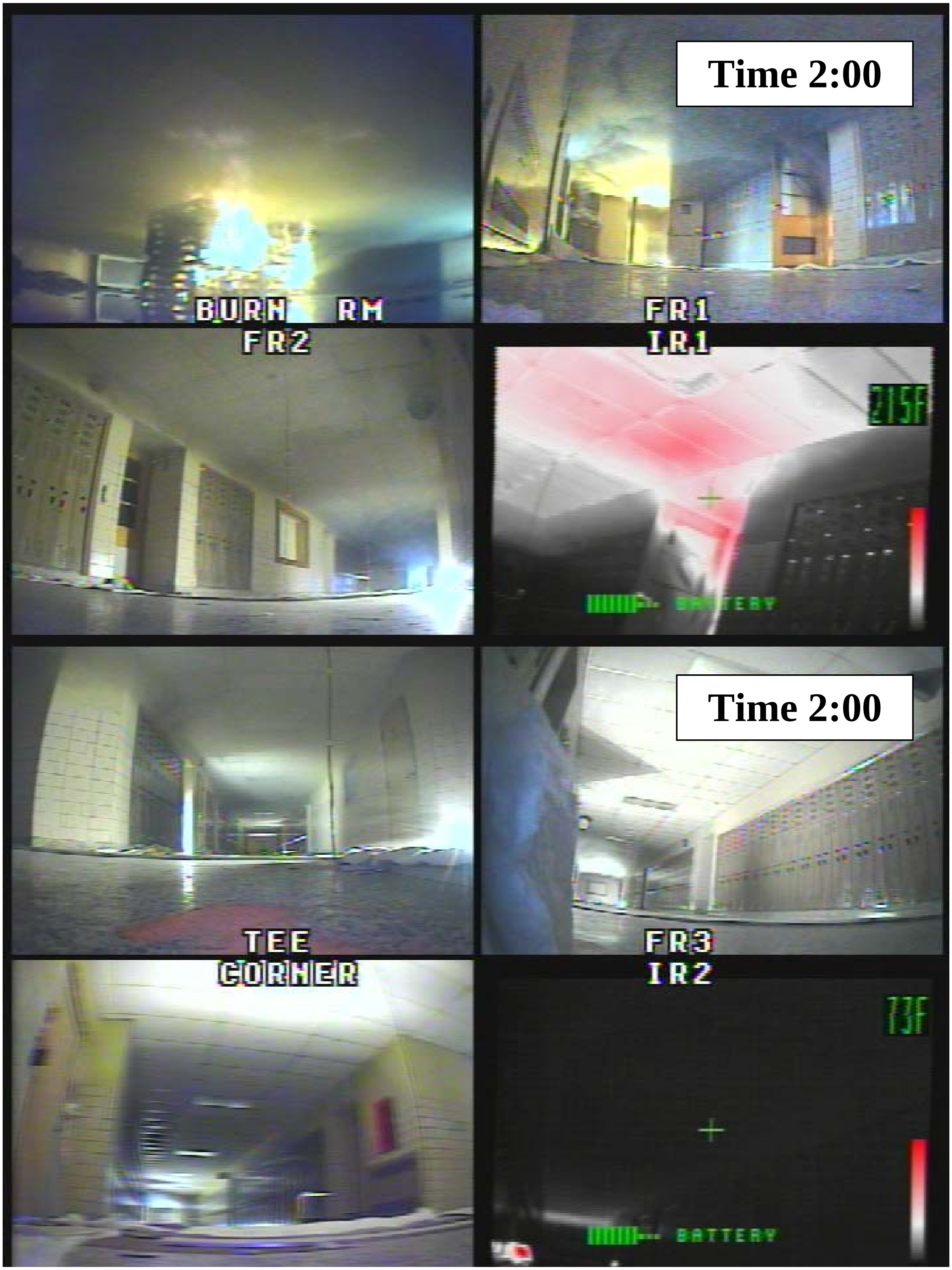

Figure 39. Experiment CF2 video images captured at 2 min

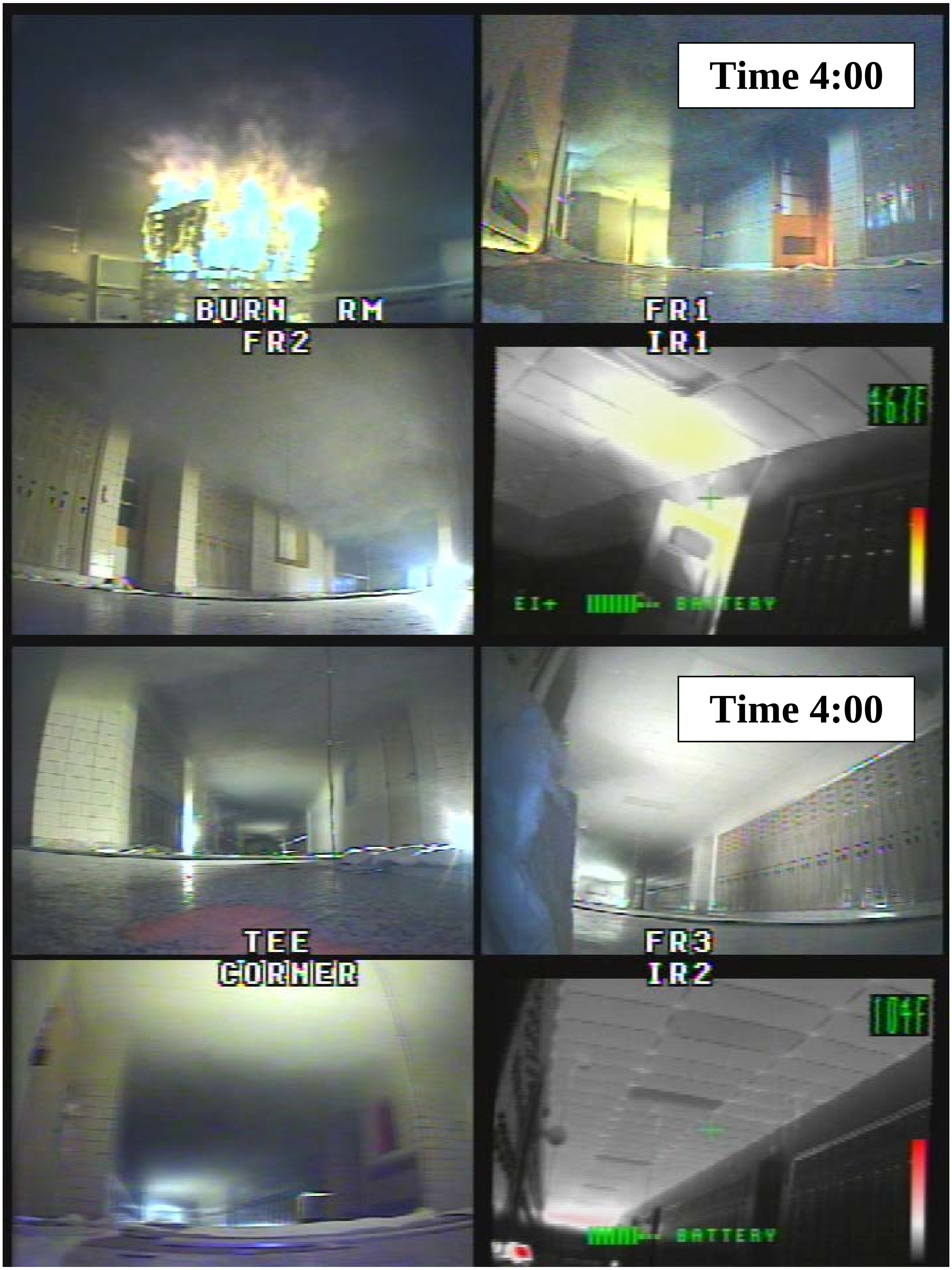

Figure 40. Experiment CF2 video images captured at 4 min

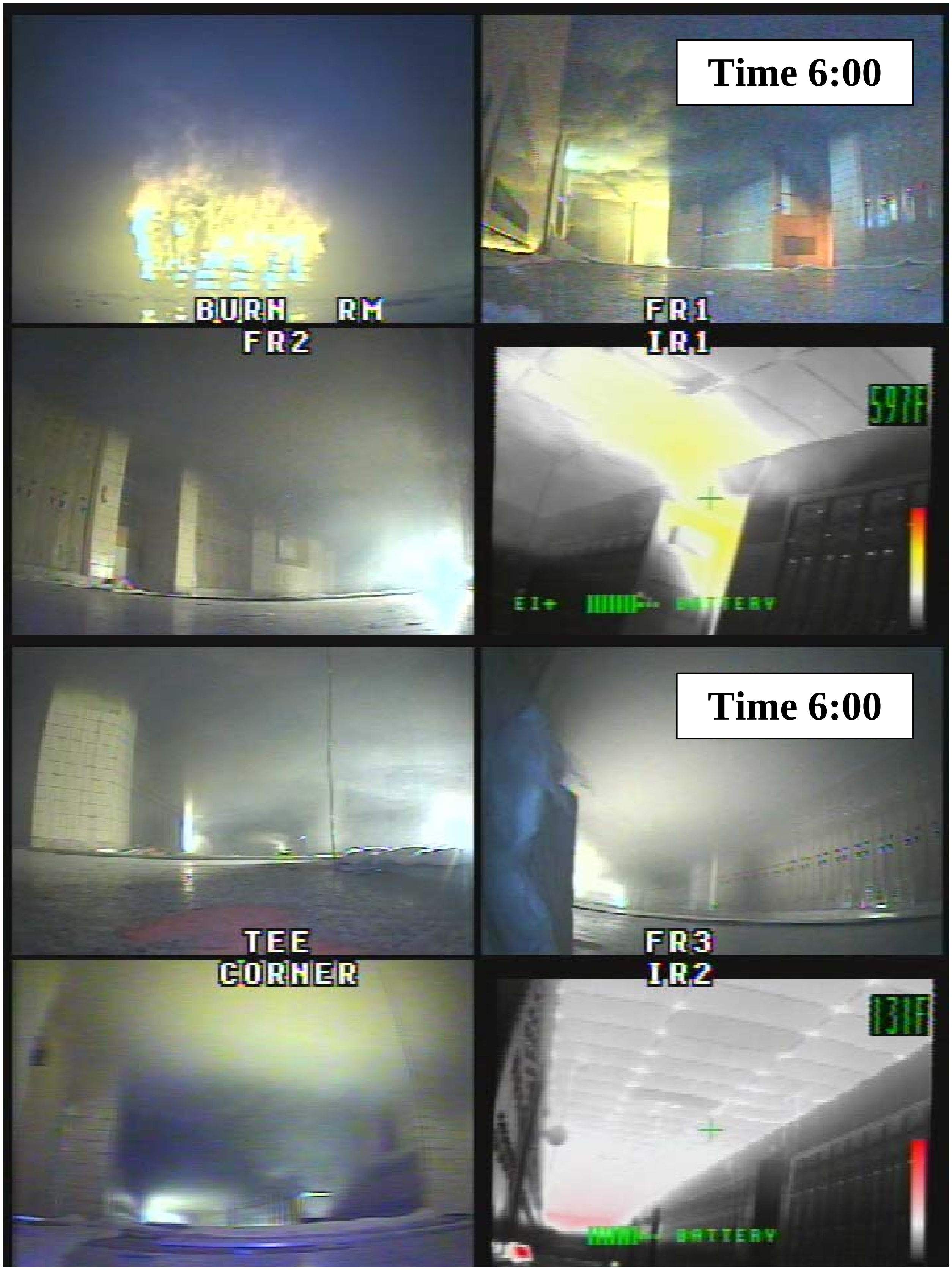

Figure 41. Experiment CF2 video images captured at 6 min

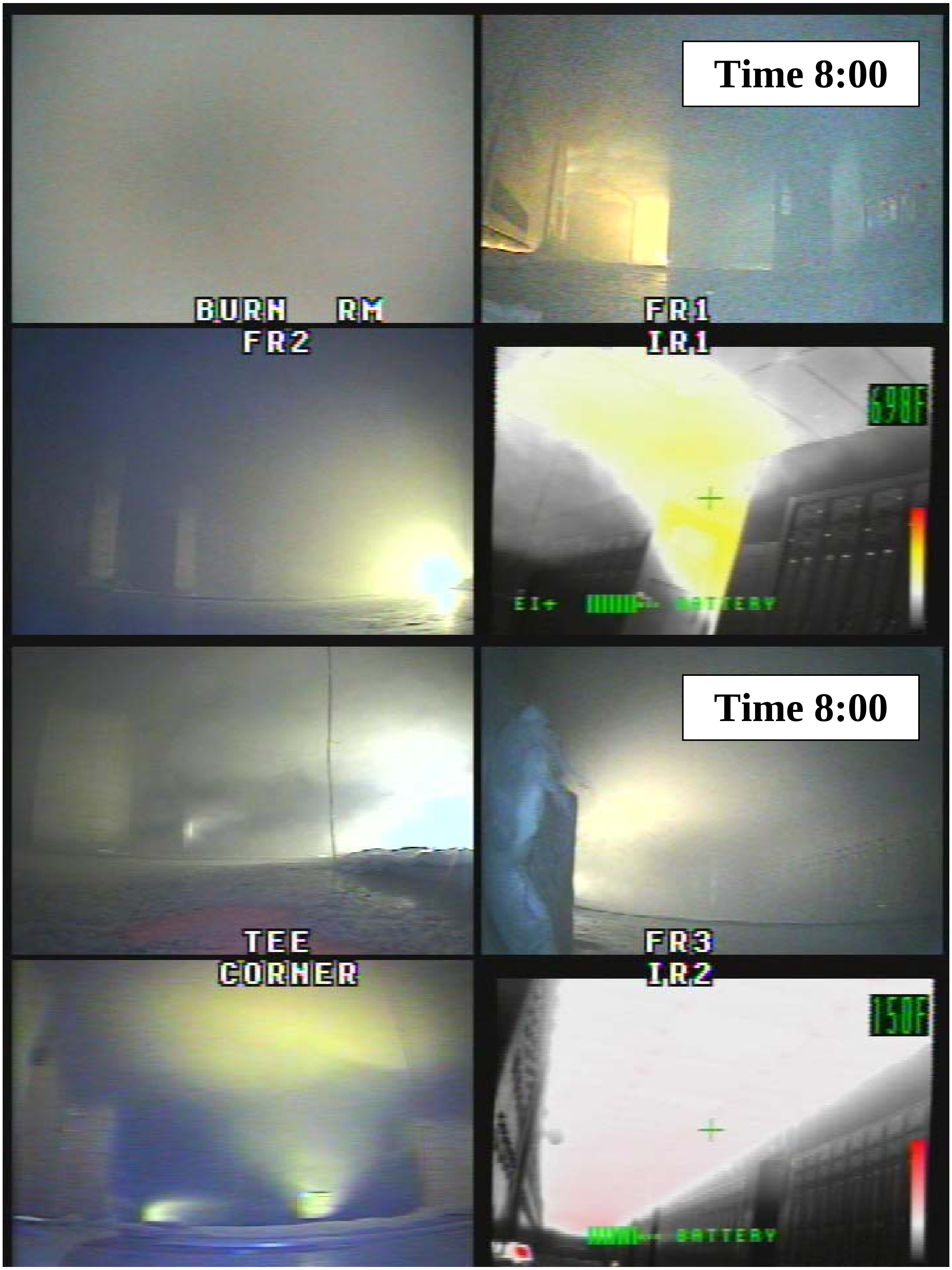

Figure 42. Experiment CF2 video images captured at 8 min

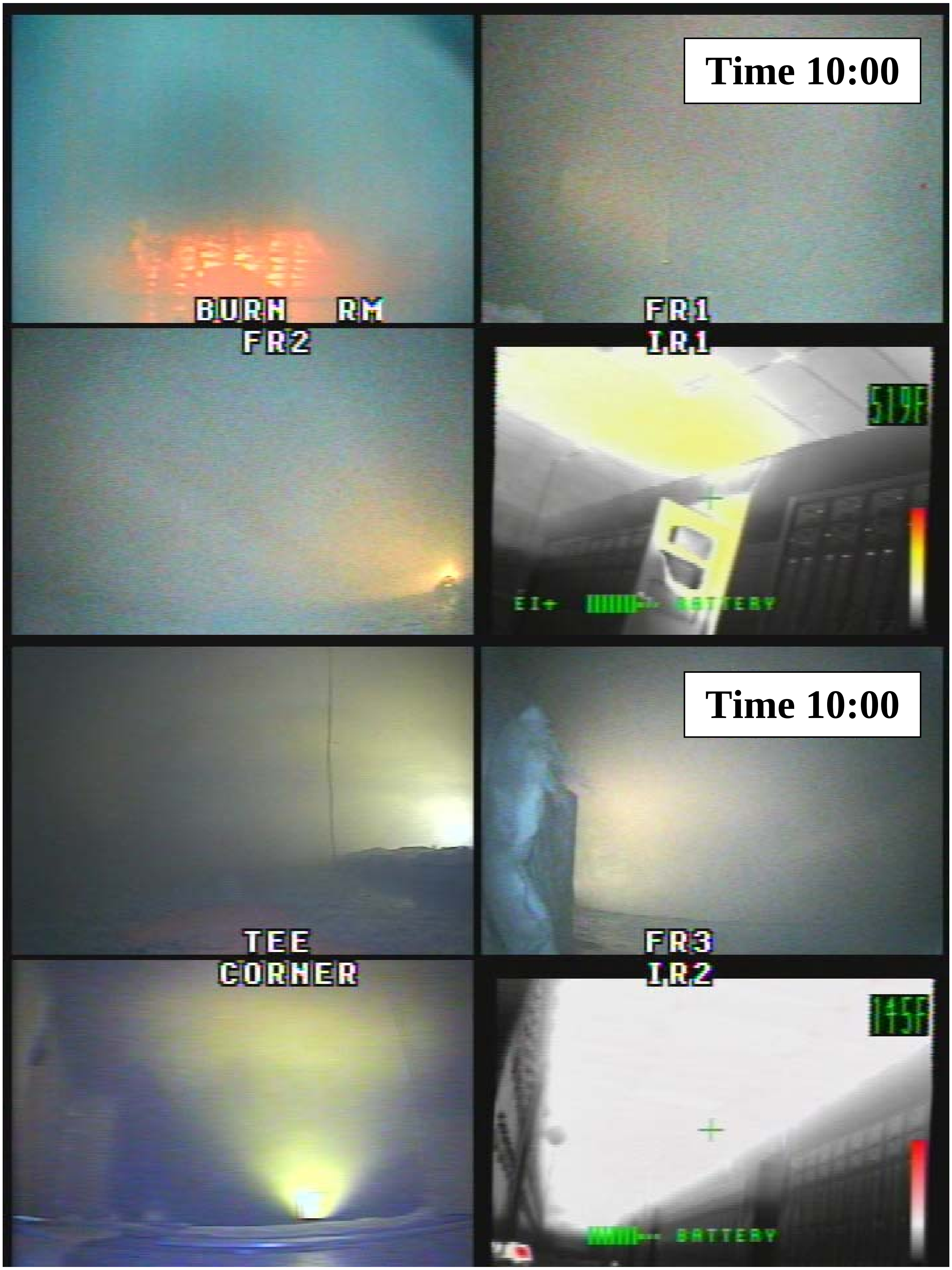

Figure 43. Experiment CF2 video images captured at 10 min

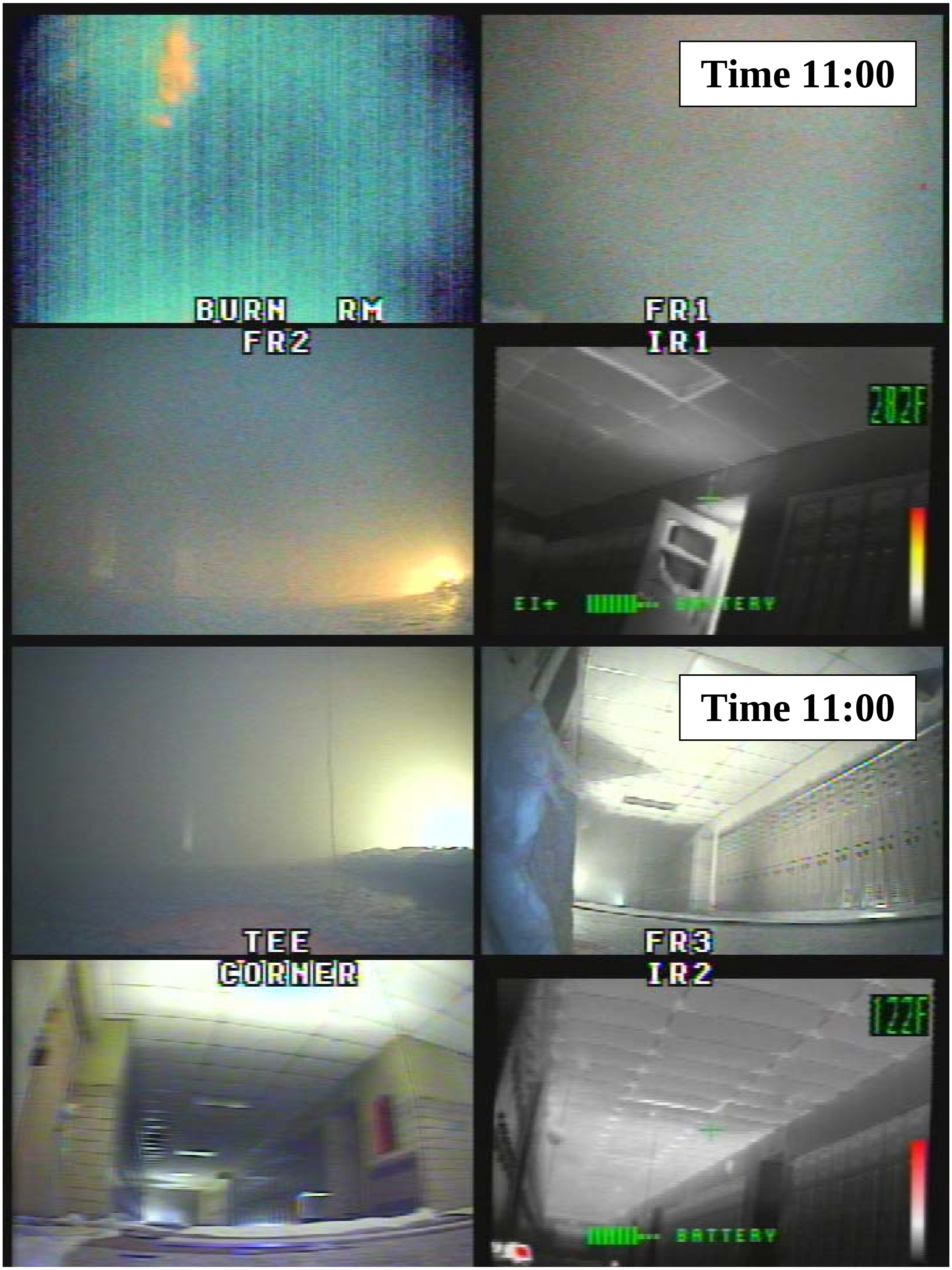

Figure 44. Experiment CF2 video images captured at 11 min

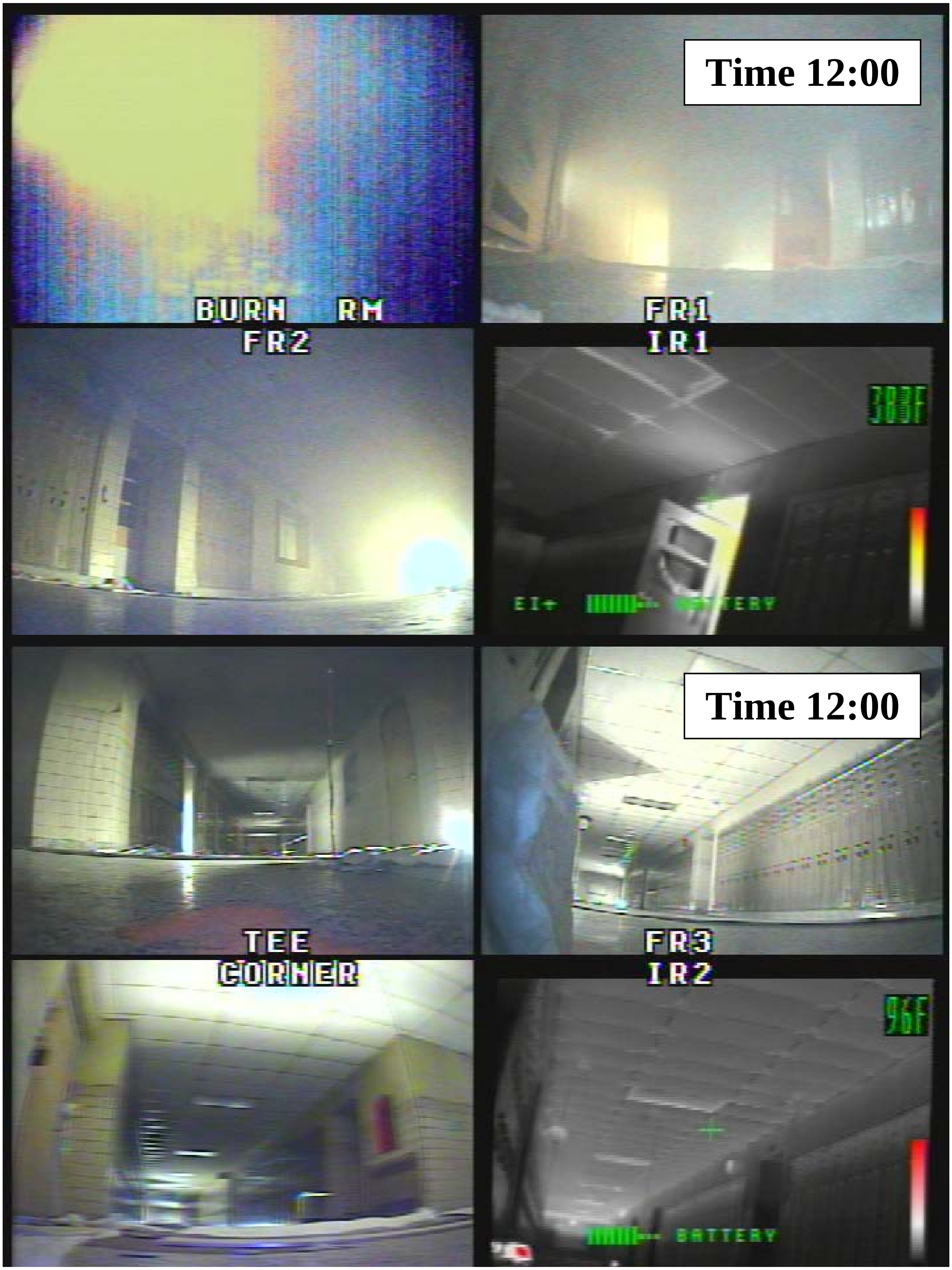

Figure 45. Experiment CF2 video images captured at 12 min

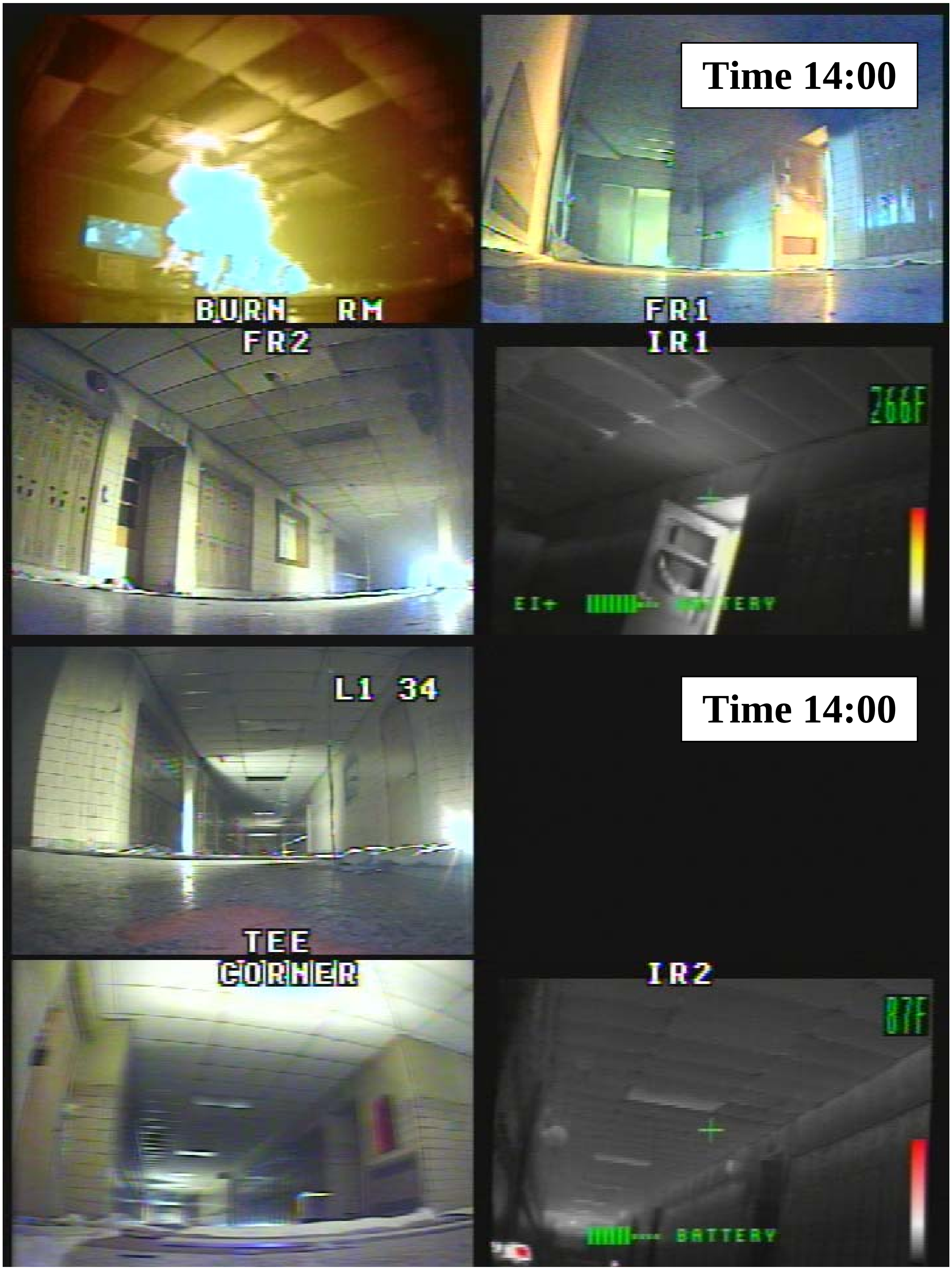

Figure 46. Experiment CF2 video images captured at 14 min

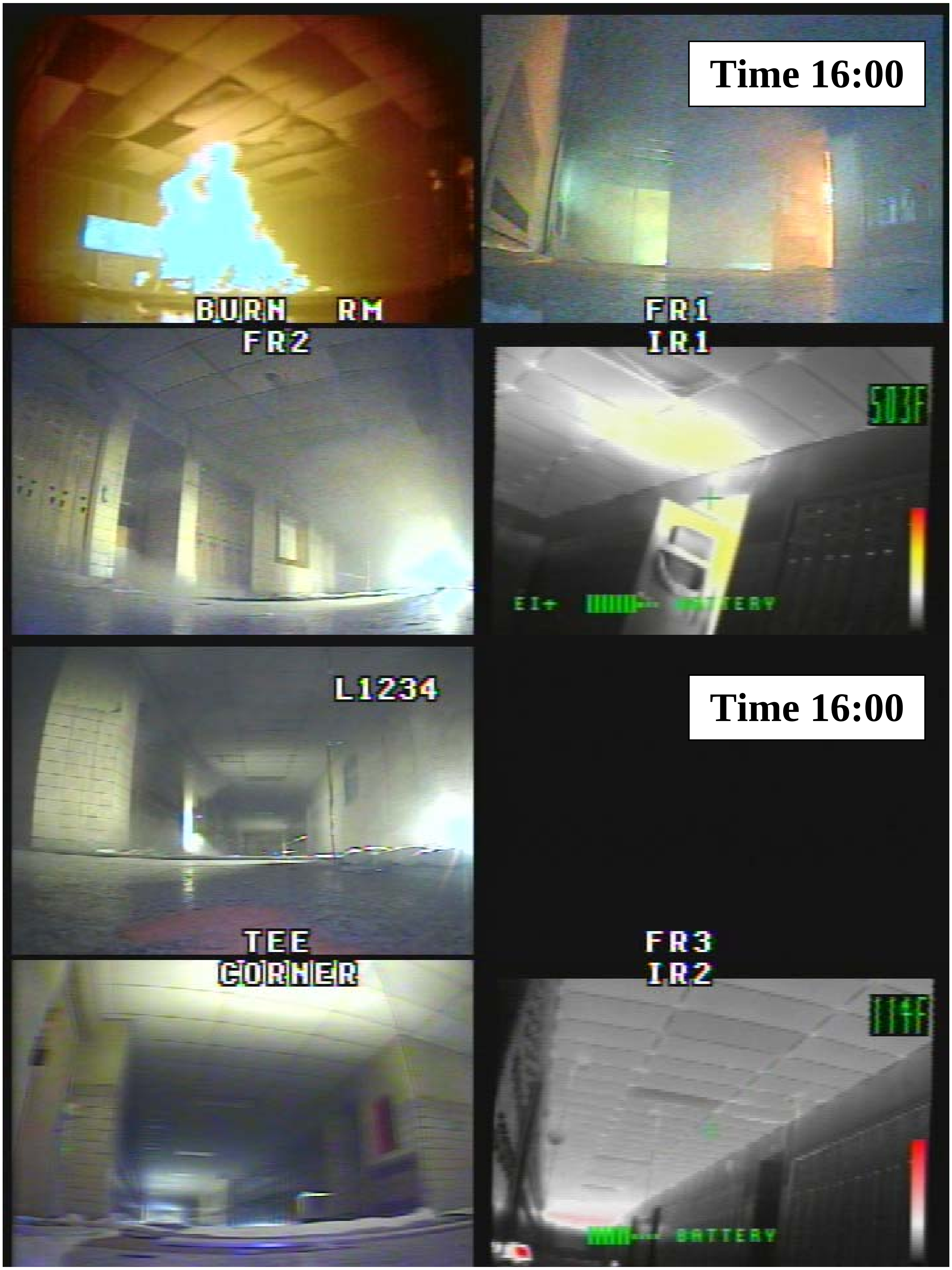

Figure 47. Experiment CF2 video images captured at 16 min

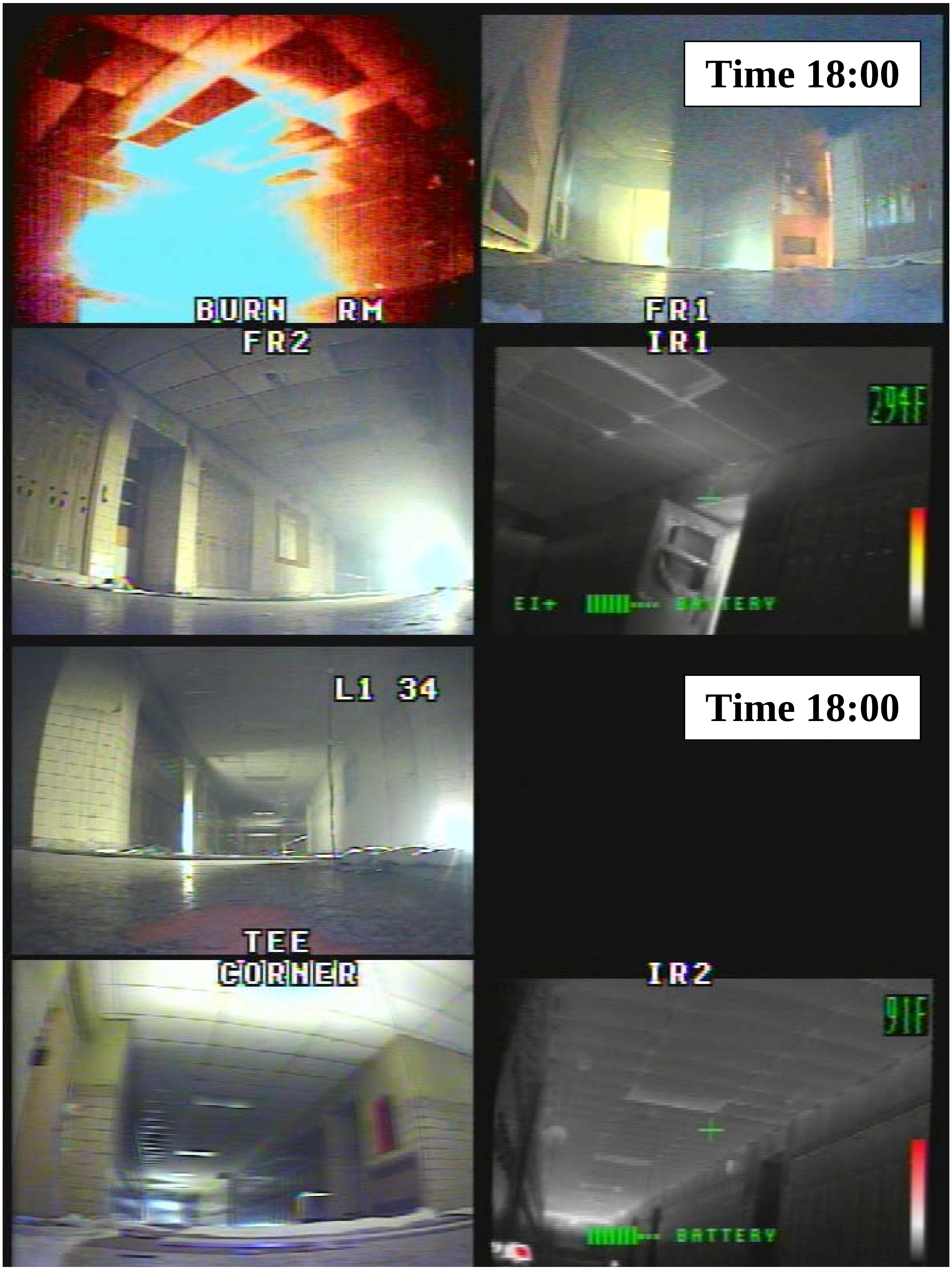

Figure 48. Experiment CF2 video images captured at 18 min

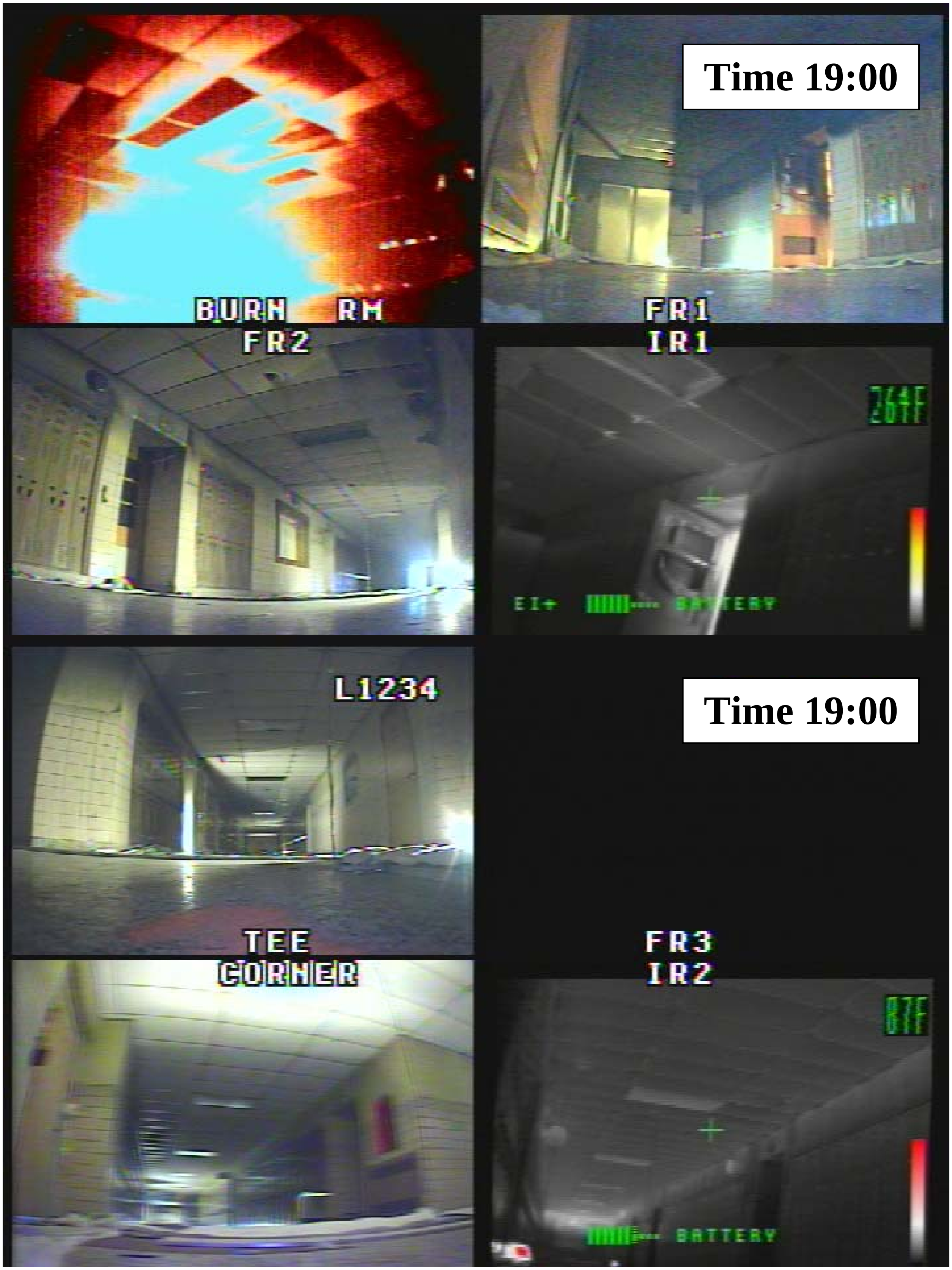

Figure 49. Experiment CF2 video images captured at 19 min

Experiment CF3 Video Images

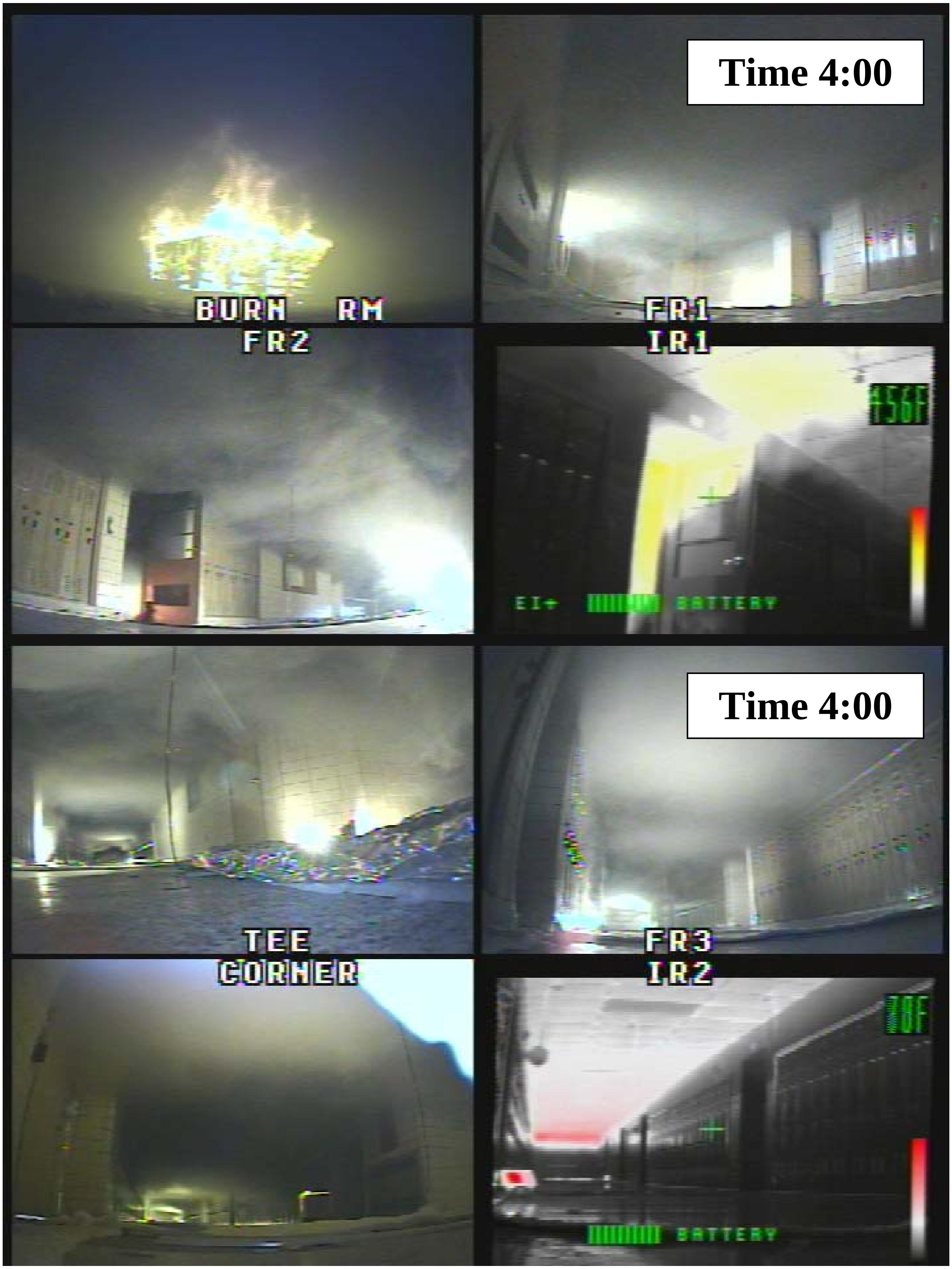

Figure 50. Experiment CF3 video images captured at 4 min

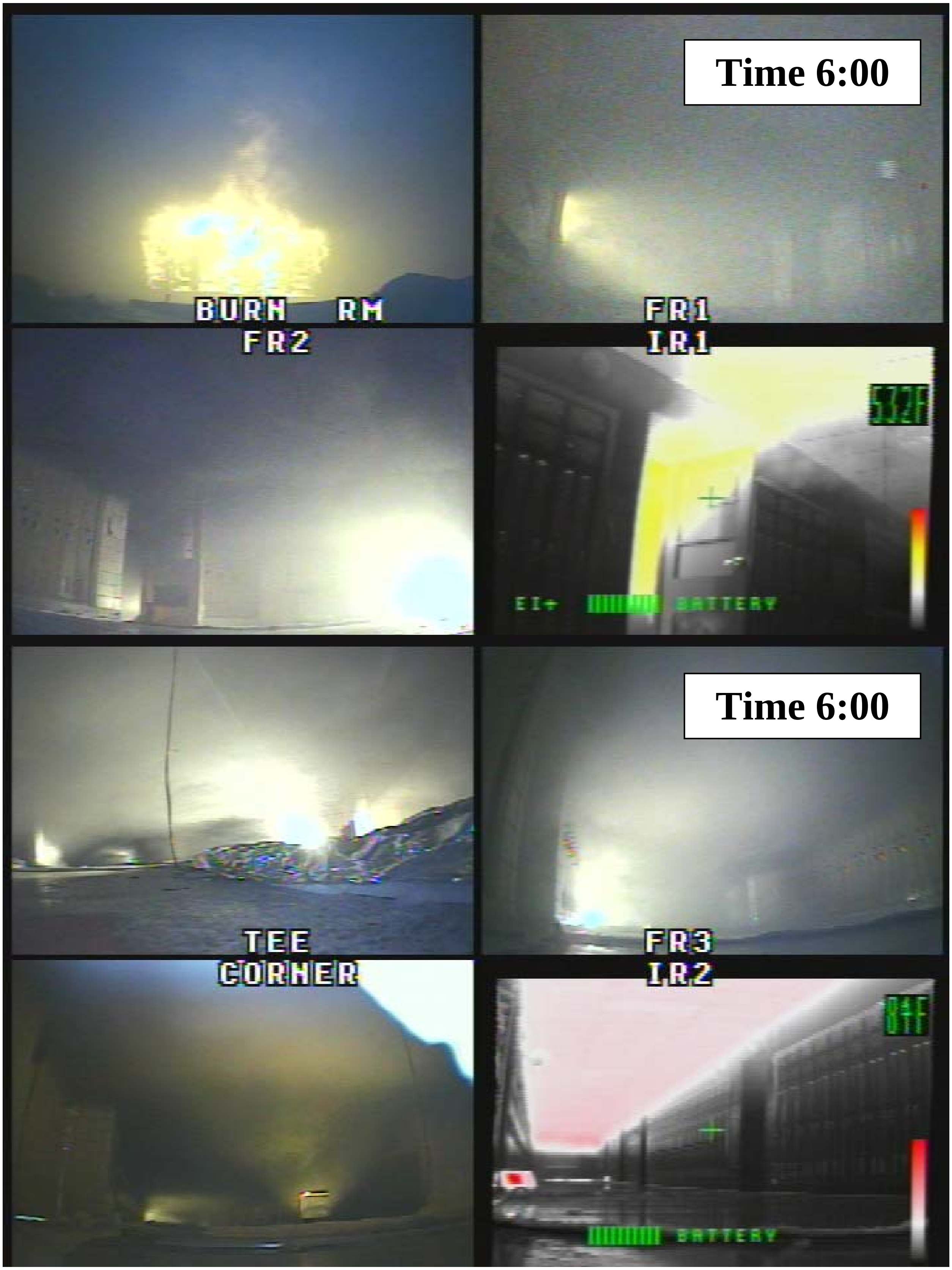

Figure 51. Experiment CF3 video images captured at 6 min

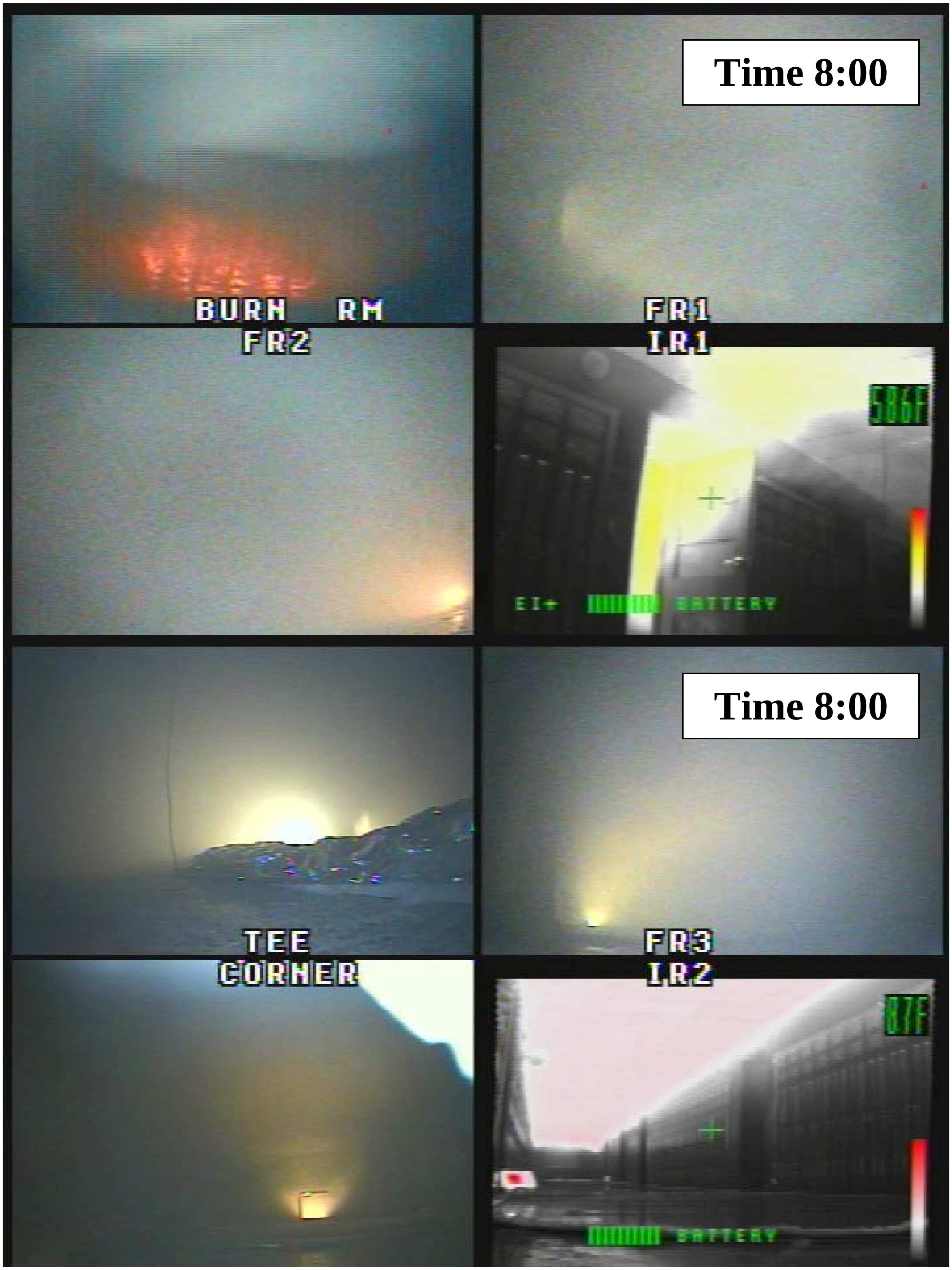

Figure 52. Experiment CF3 video images captured at 8 min

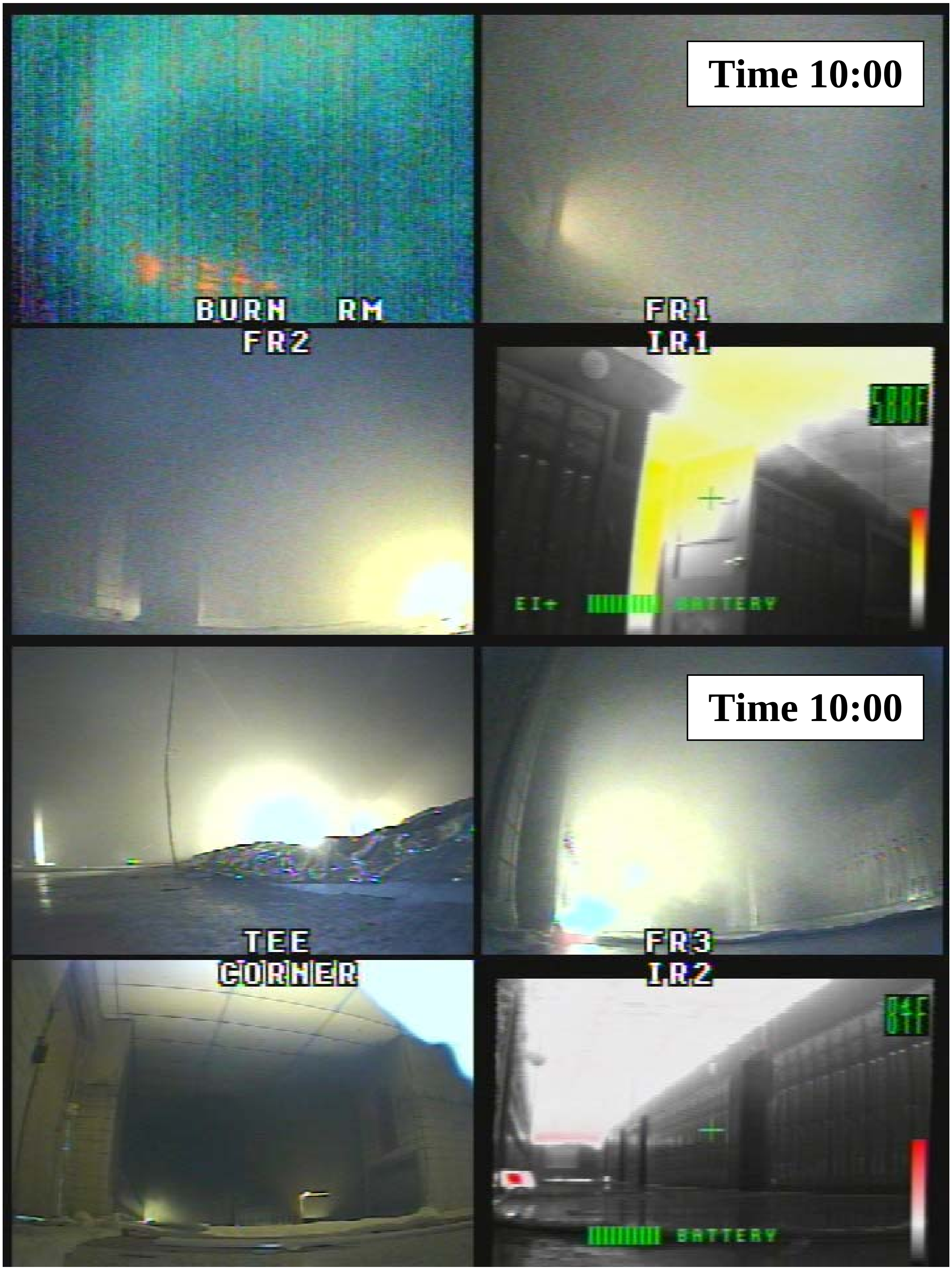

Figure 53. Experiment CF3 video images captured at 10 min

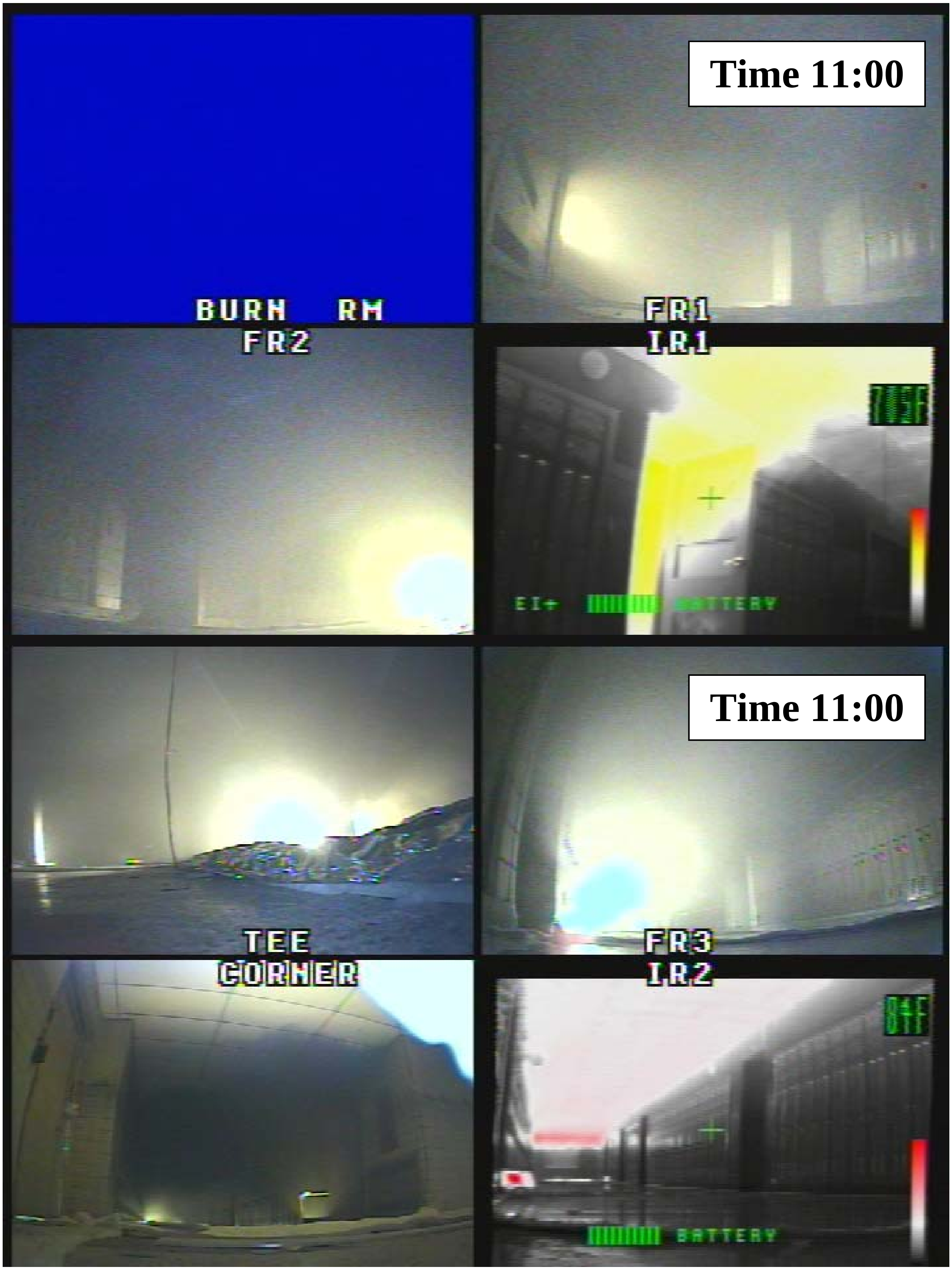

Figure 54. Experiment CF3 video images captured at 11 min

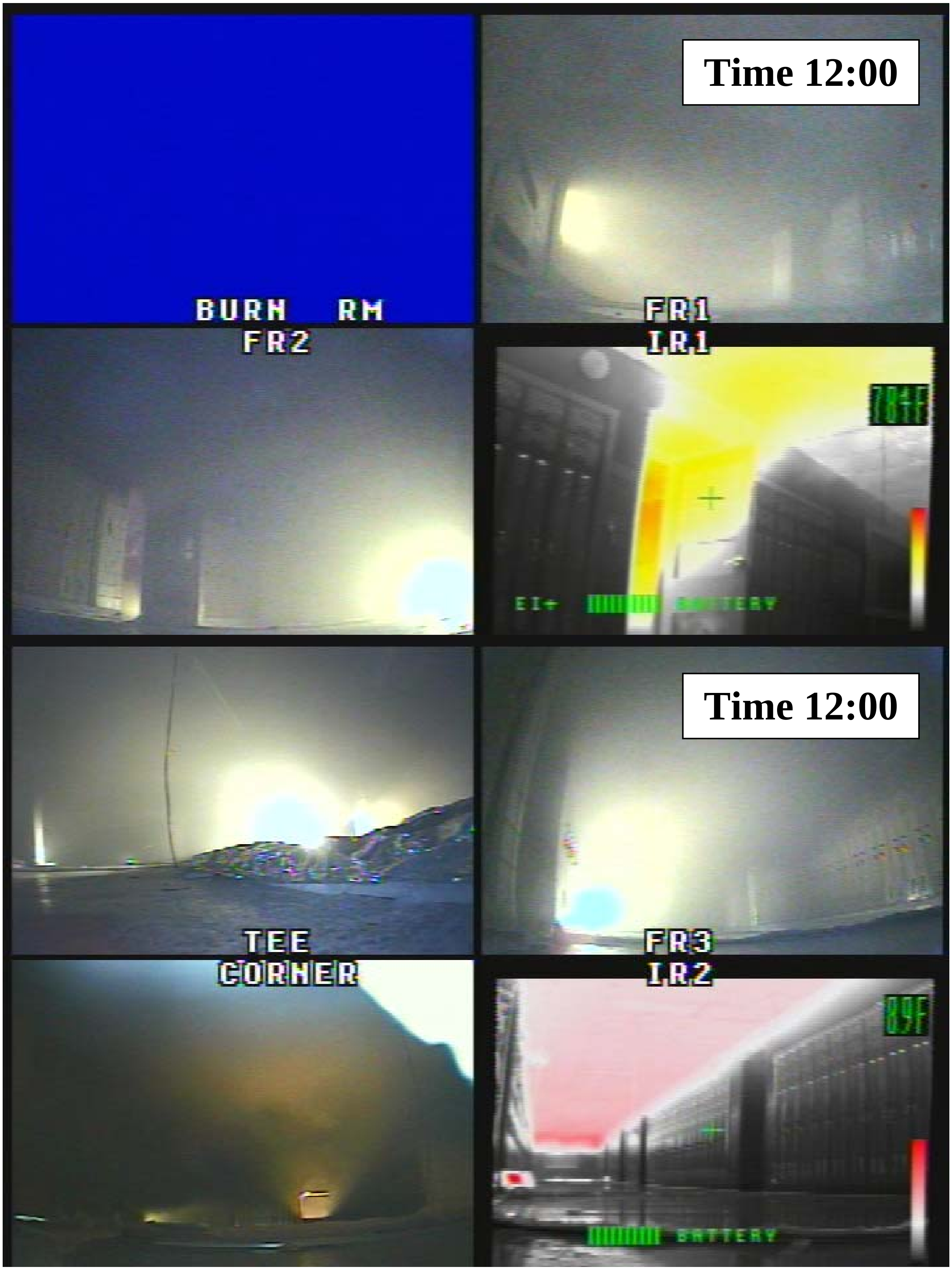

Figure 55. Experiment CF3 video images captured at 12 min

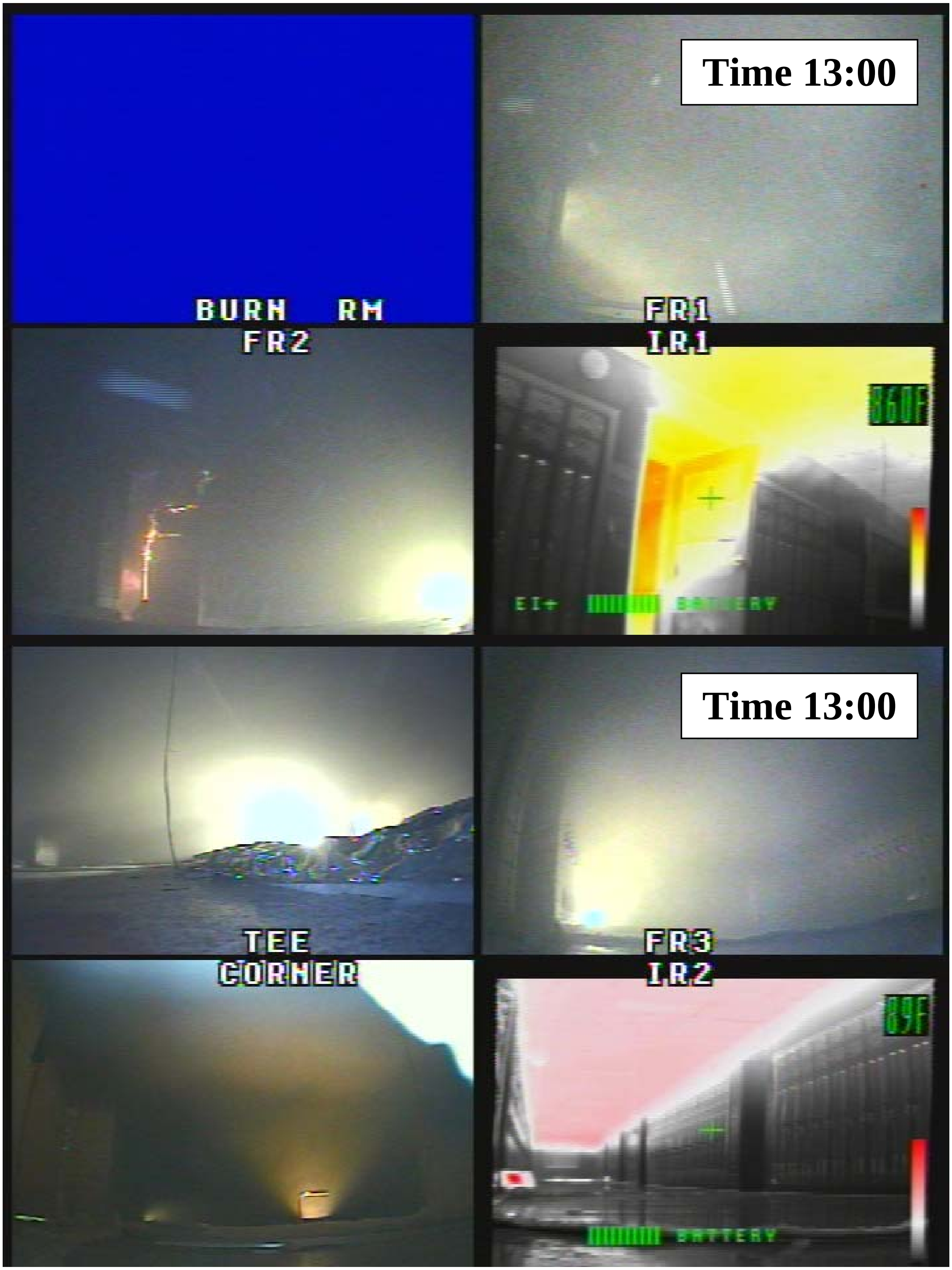

Figure 56. Experiment CF3 video images captured at 13 min

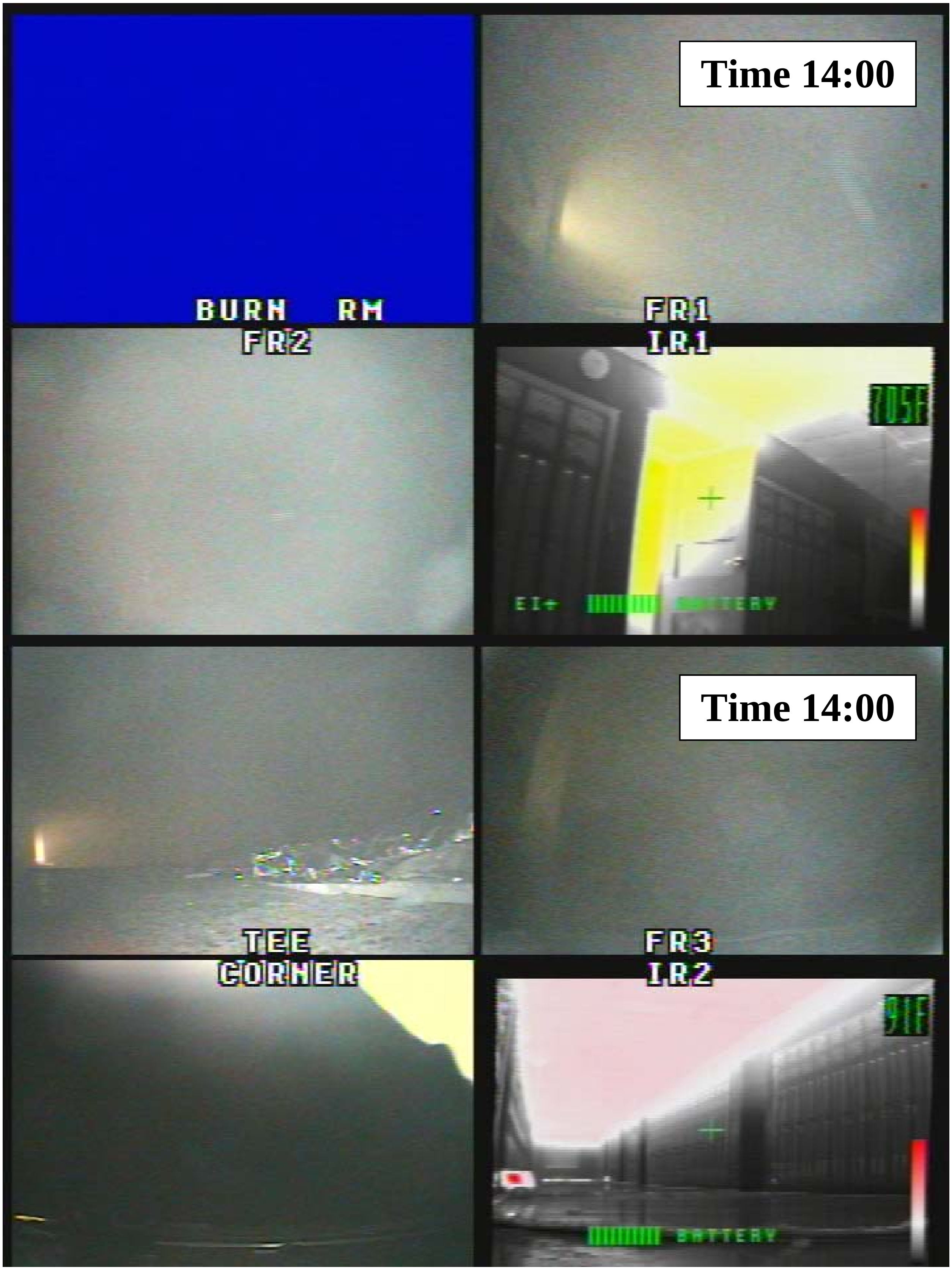

Figure 57. Experiment CF3 video images captured at 14 min

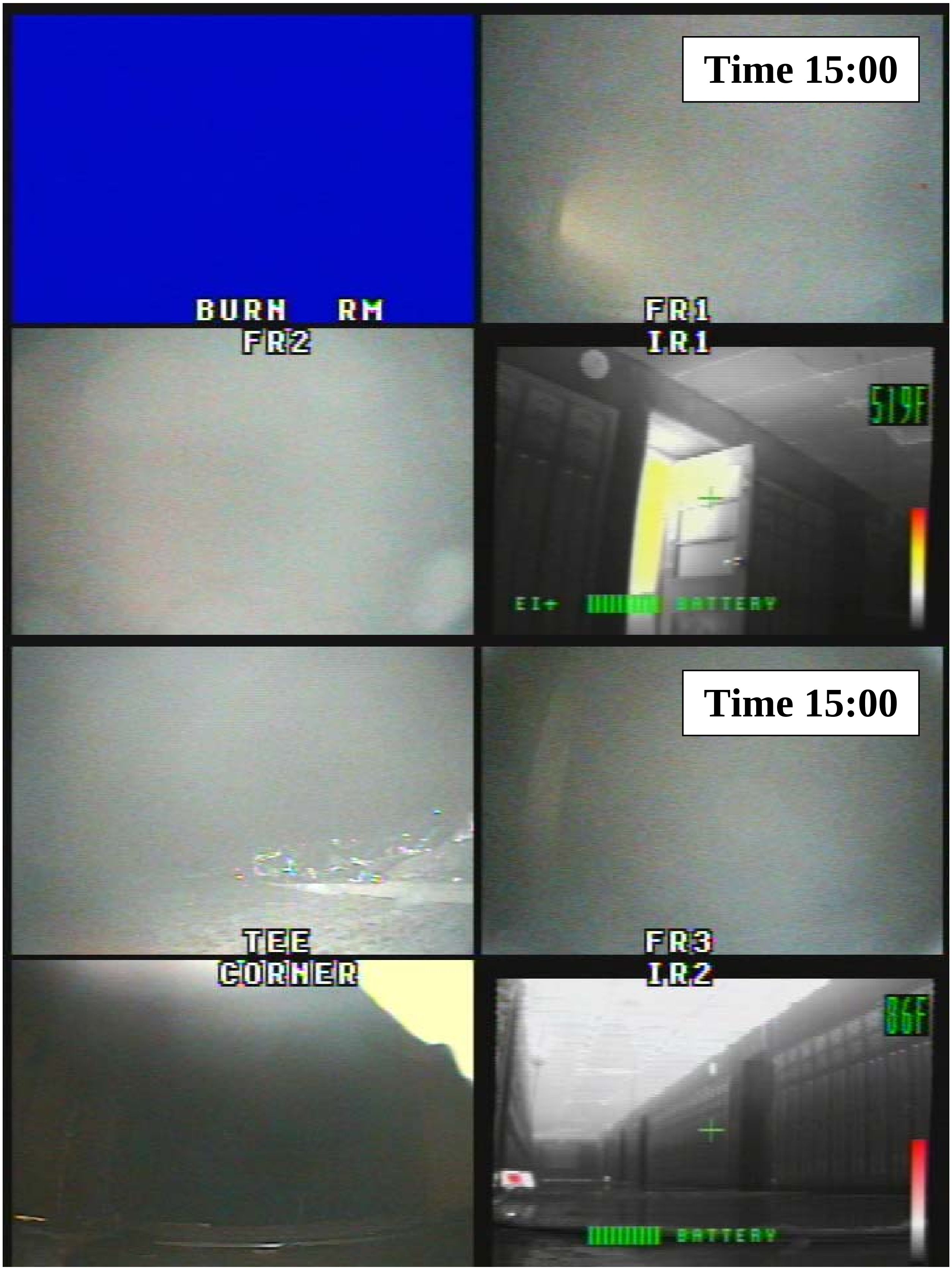

Figure 58. Experiment CF3 video images captured at 15 min

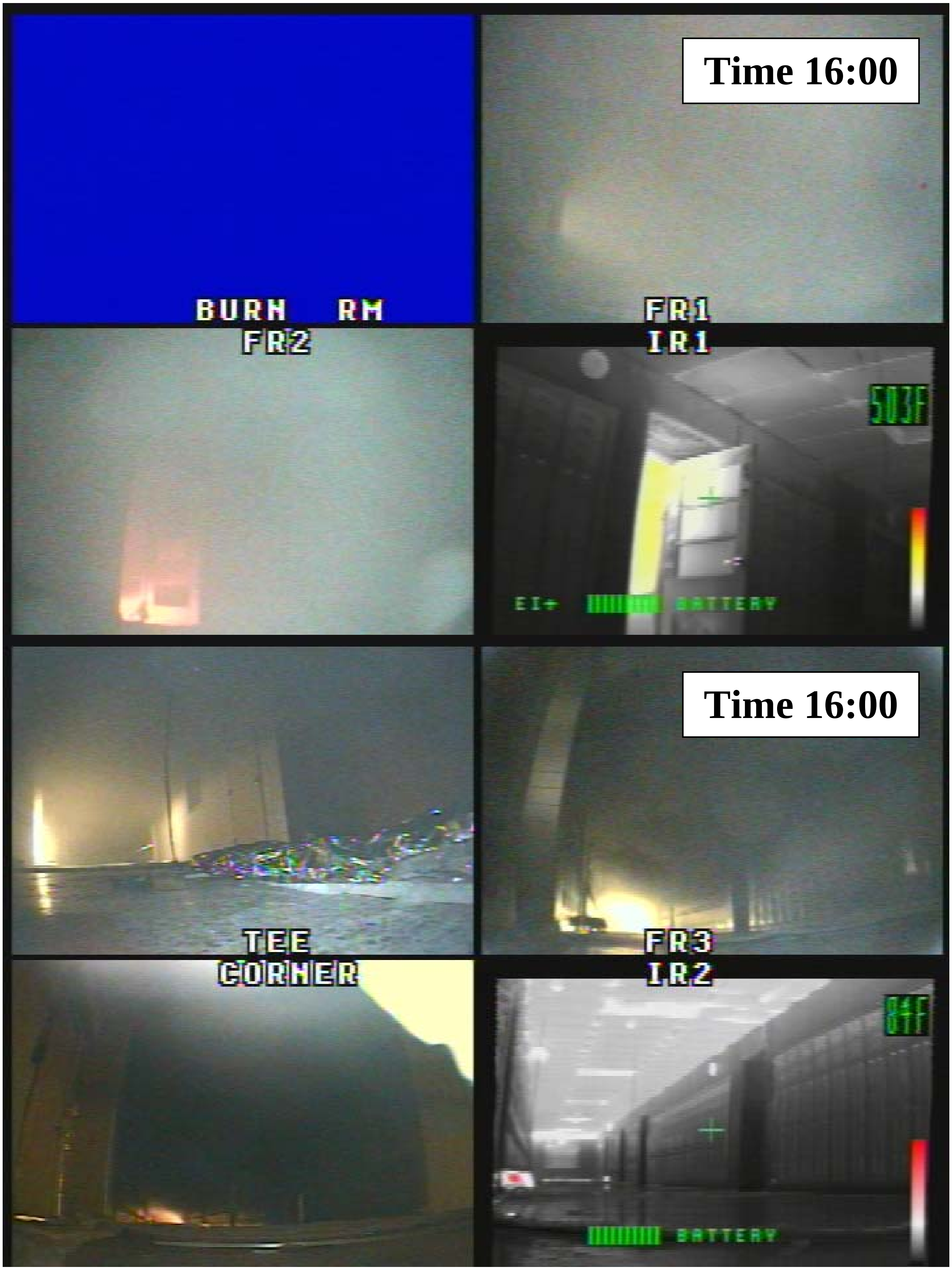

Figure 59. Experiment CF3 video images captured at 16 min

Figure 60. Experiment CF3 video images captured at 18 min

Figure 61. Experiment CF3 video images captured at 20 min

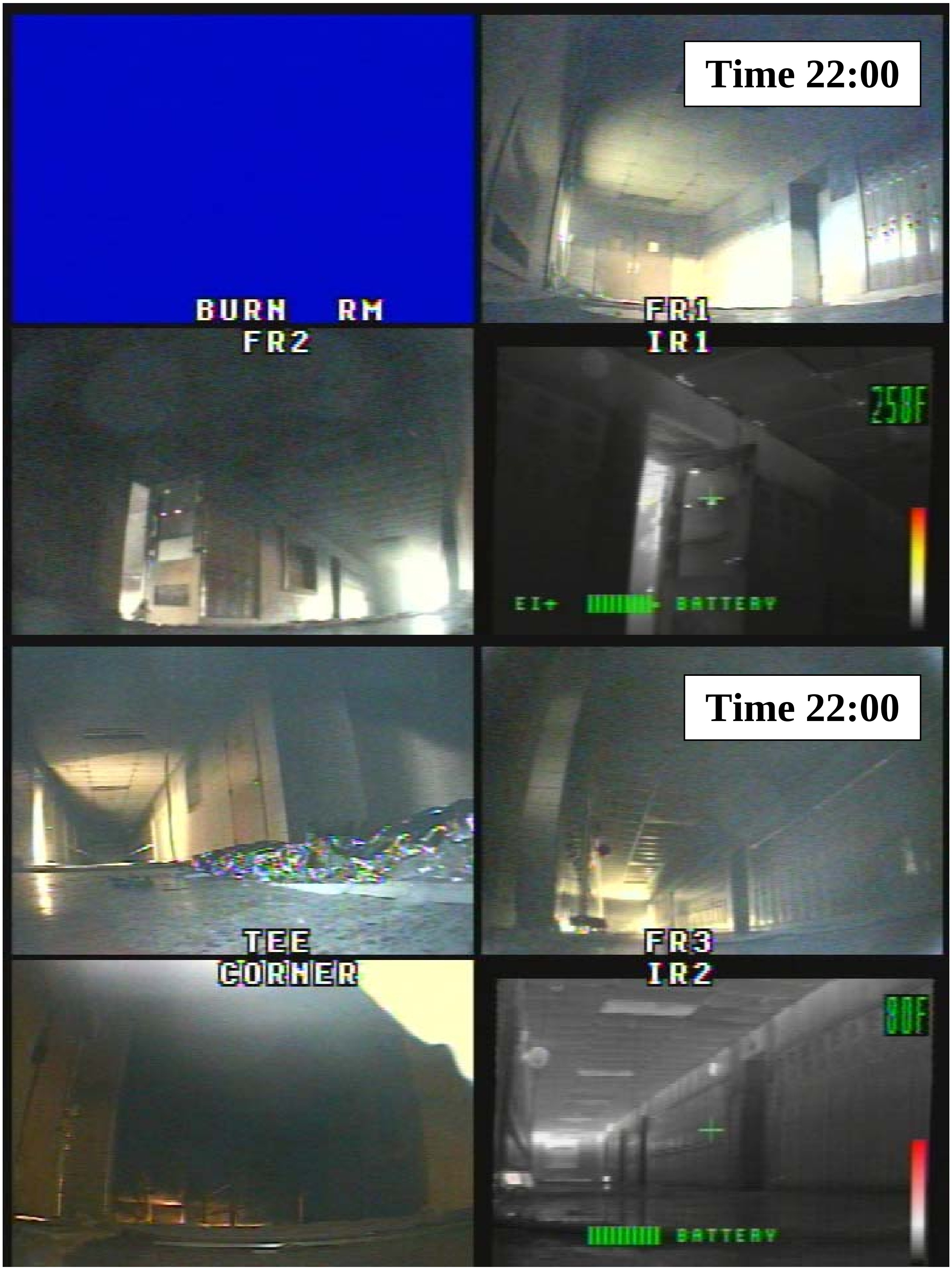

Figure 62. Experiment CF3 video images captured at 22 min

Experiment CF4 Video Images

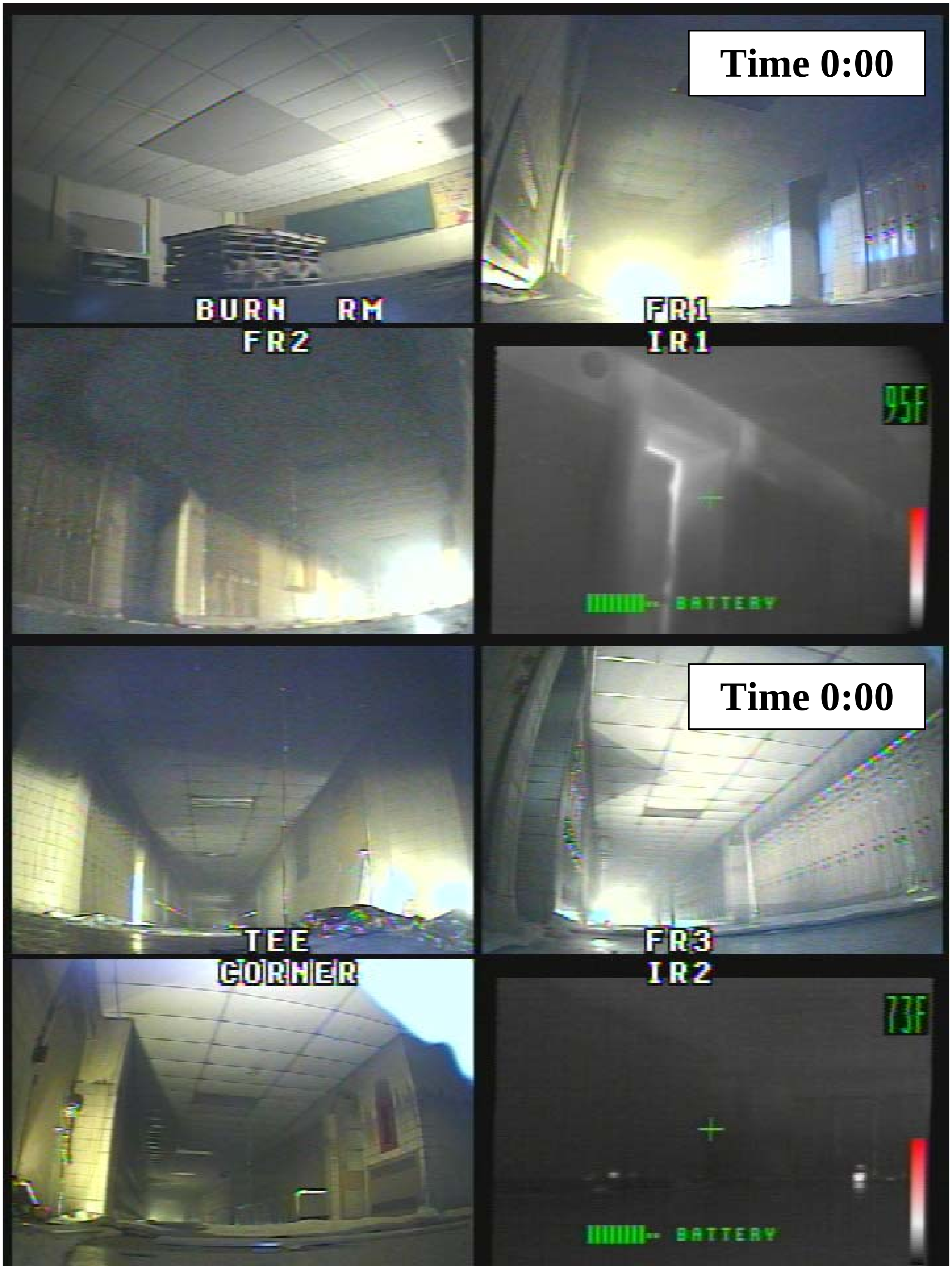

Figure 63. Experiment CF4 video images captured at 0 min

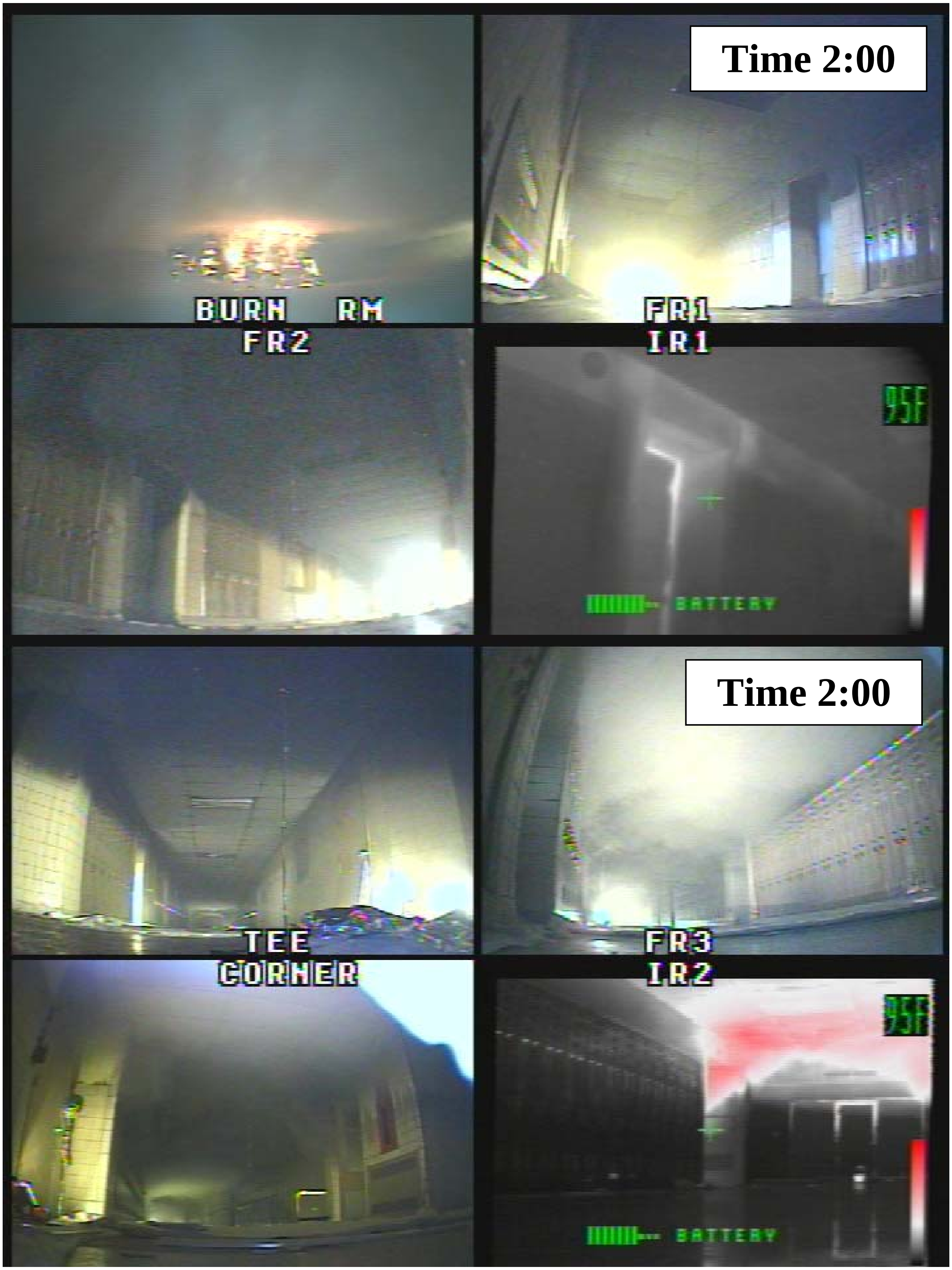

Figure 64. Experiment CF4 video images captured at 0 min

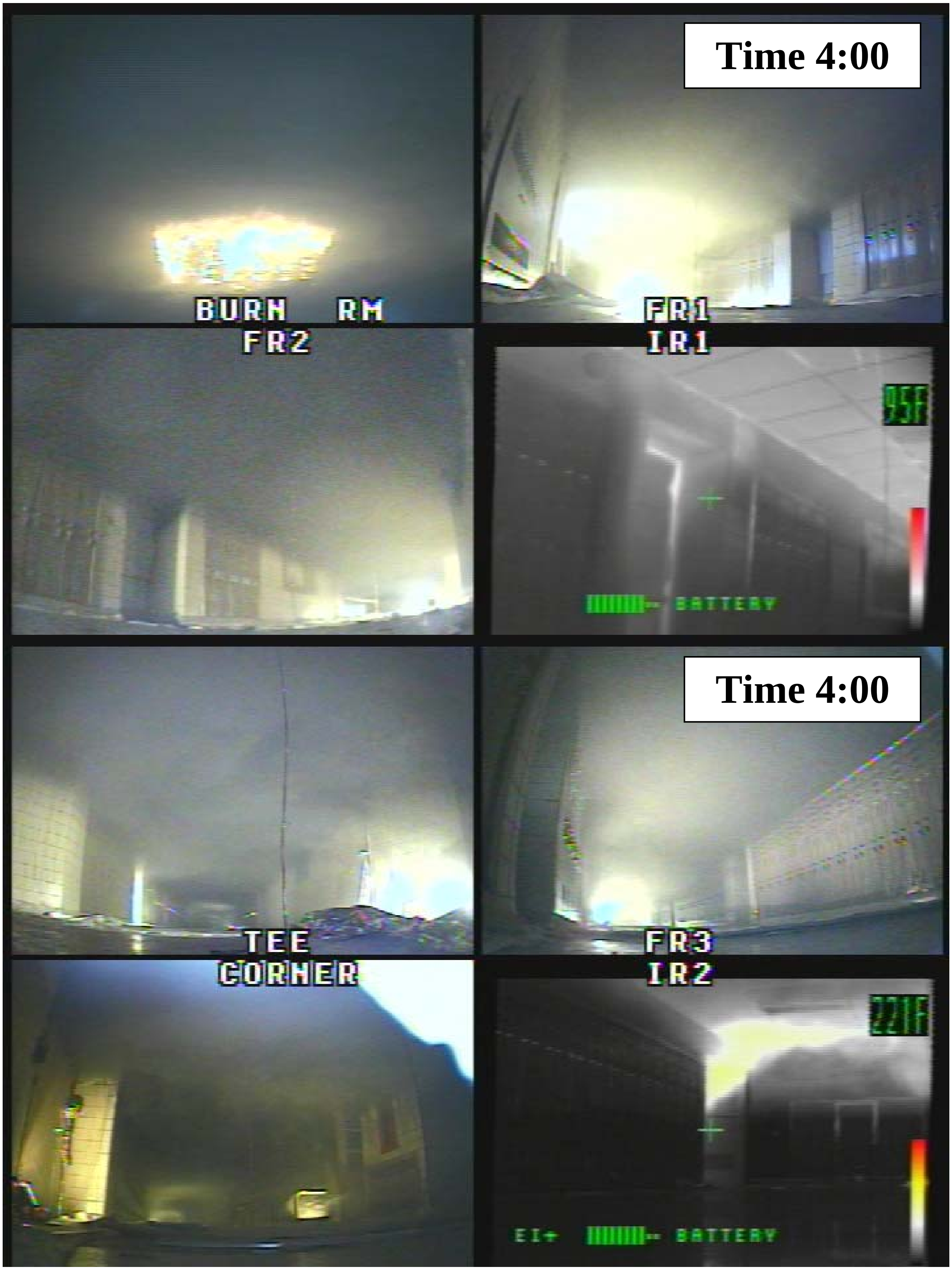

Figure 65. Experiment CF4 video images captured at 4 min

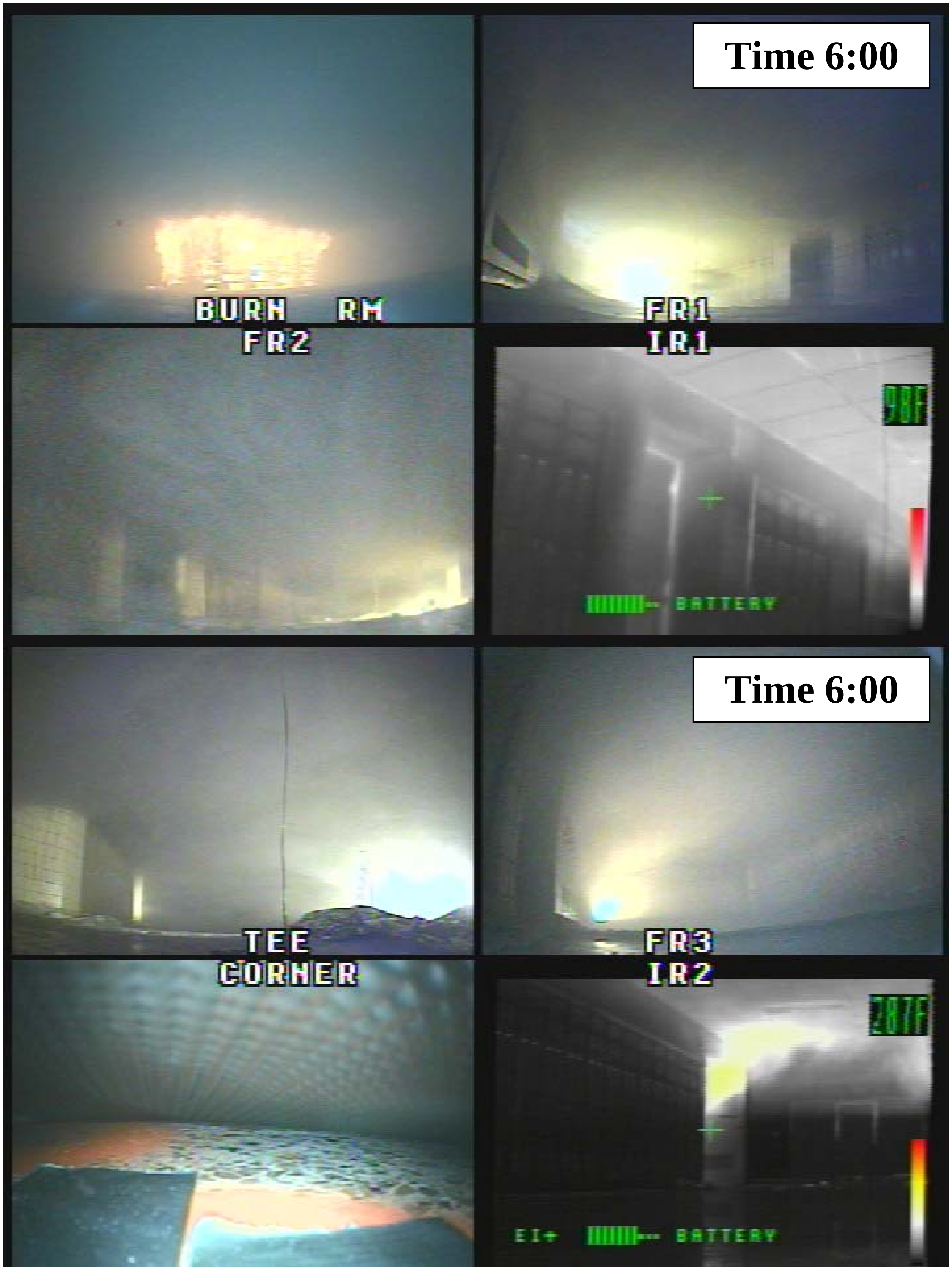

Figure 66. Experiment CF4 video images captured at 6 min

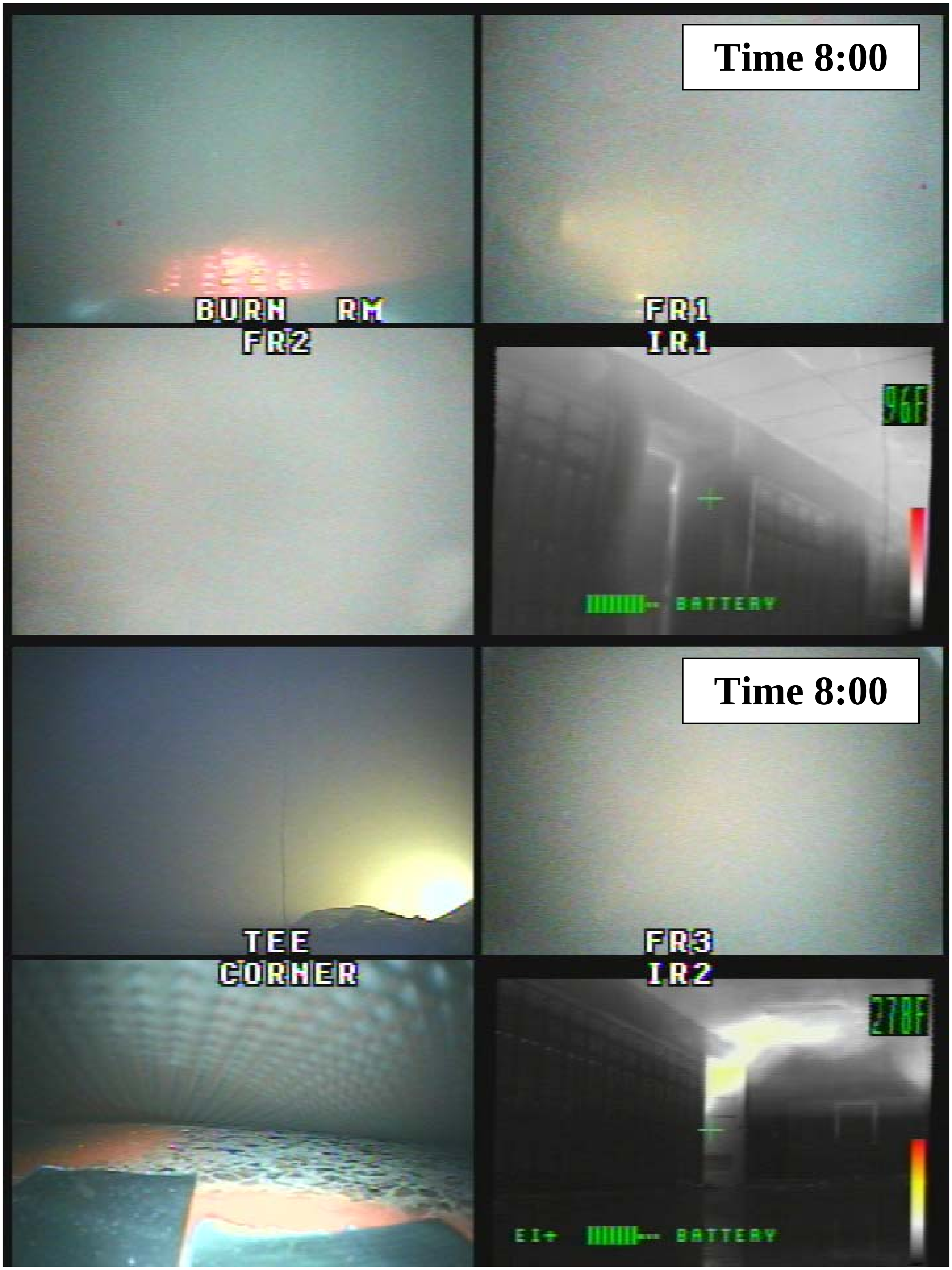

Figure 67. Experiment CF4 video images captured at 8 min

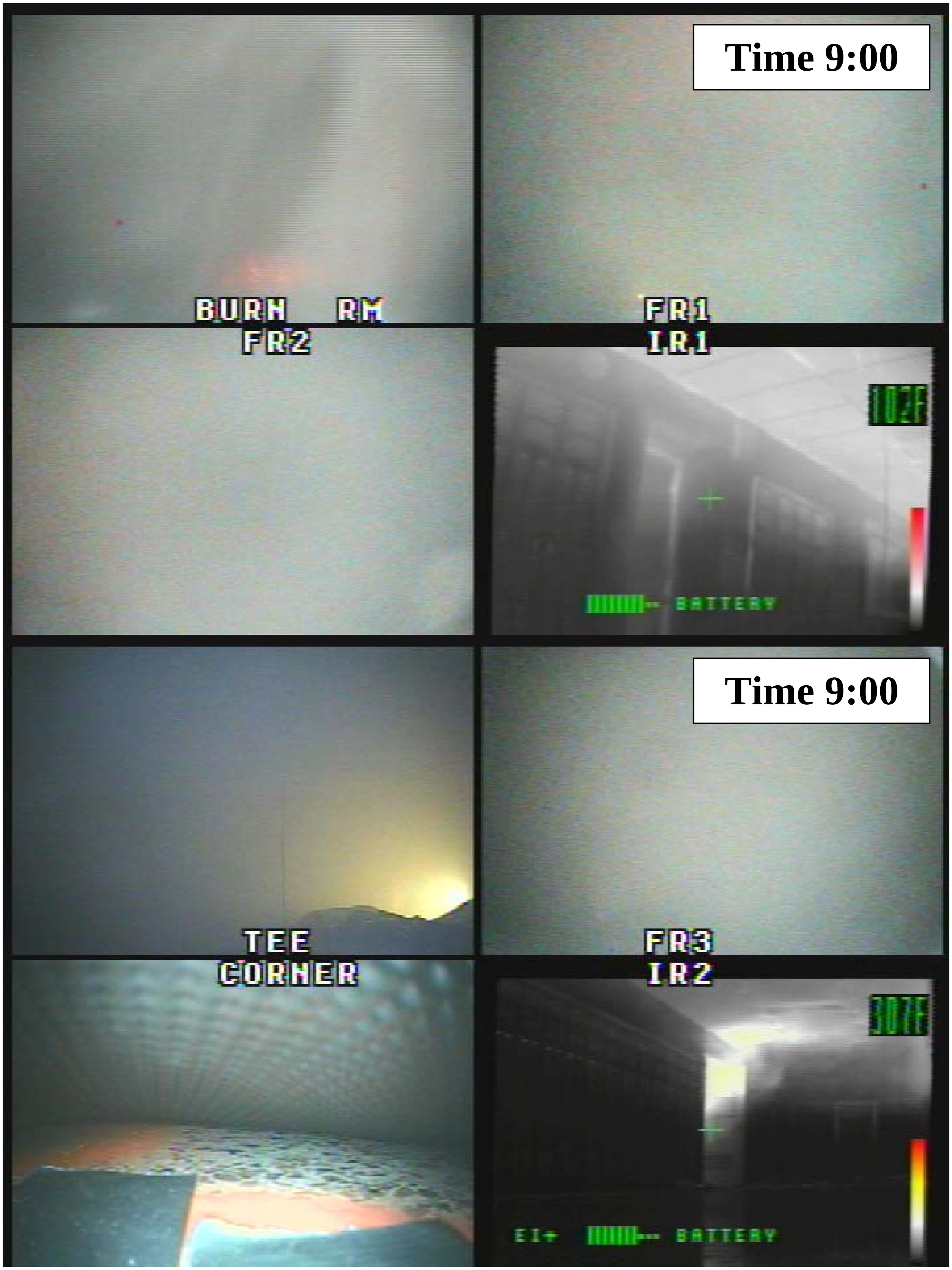

Figure 68. Experiment CF4 video images captured at 9 min

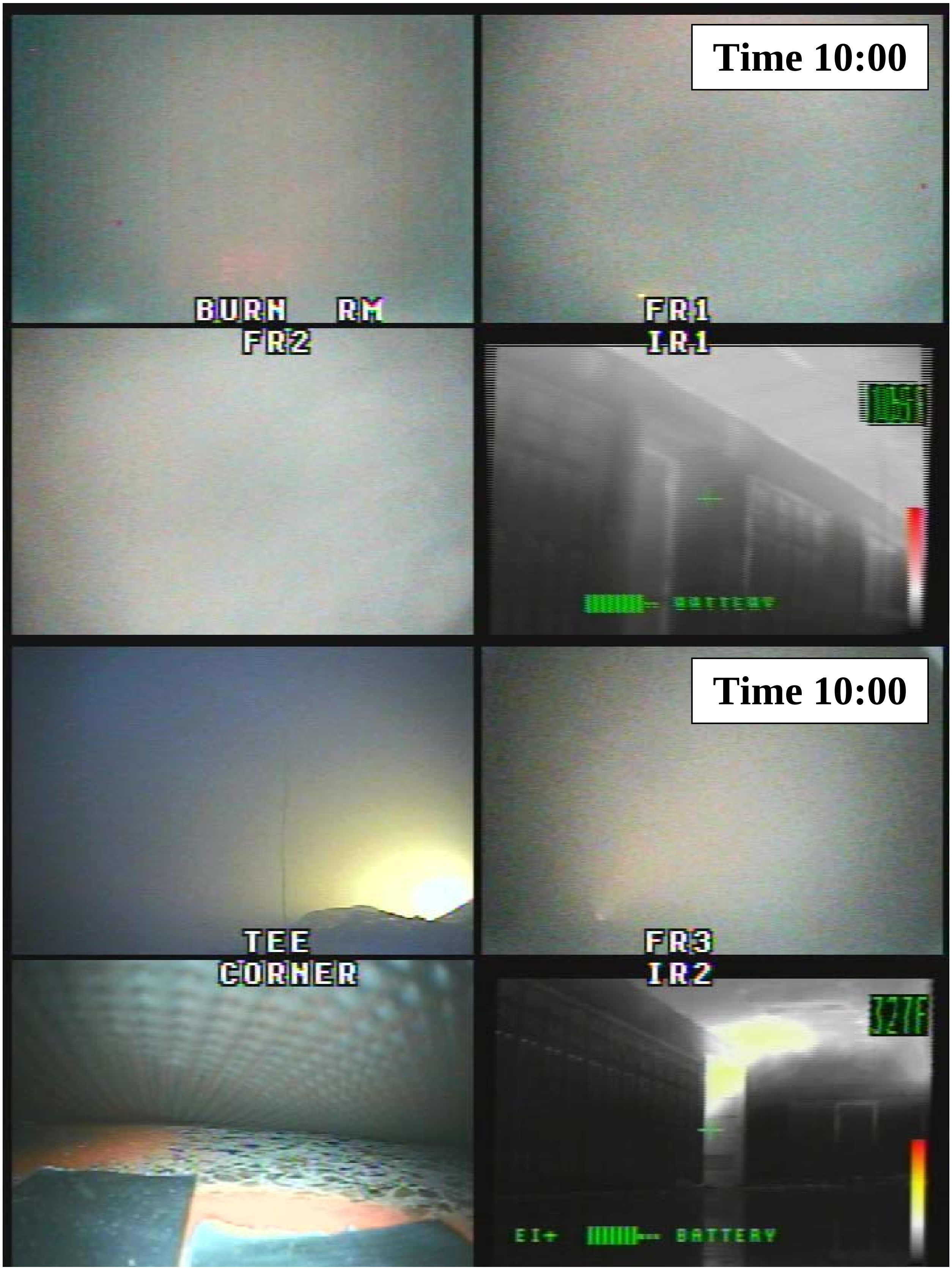

Figure 69. Experiment CF4 video images captured at 10 min

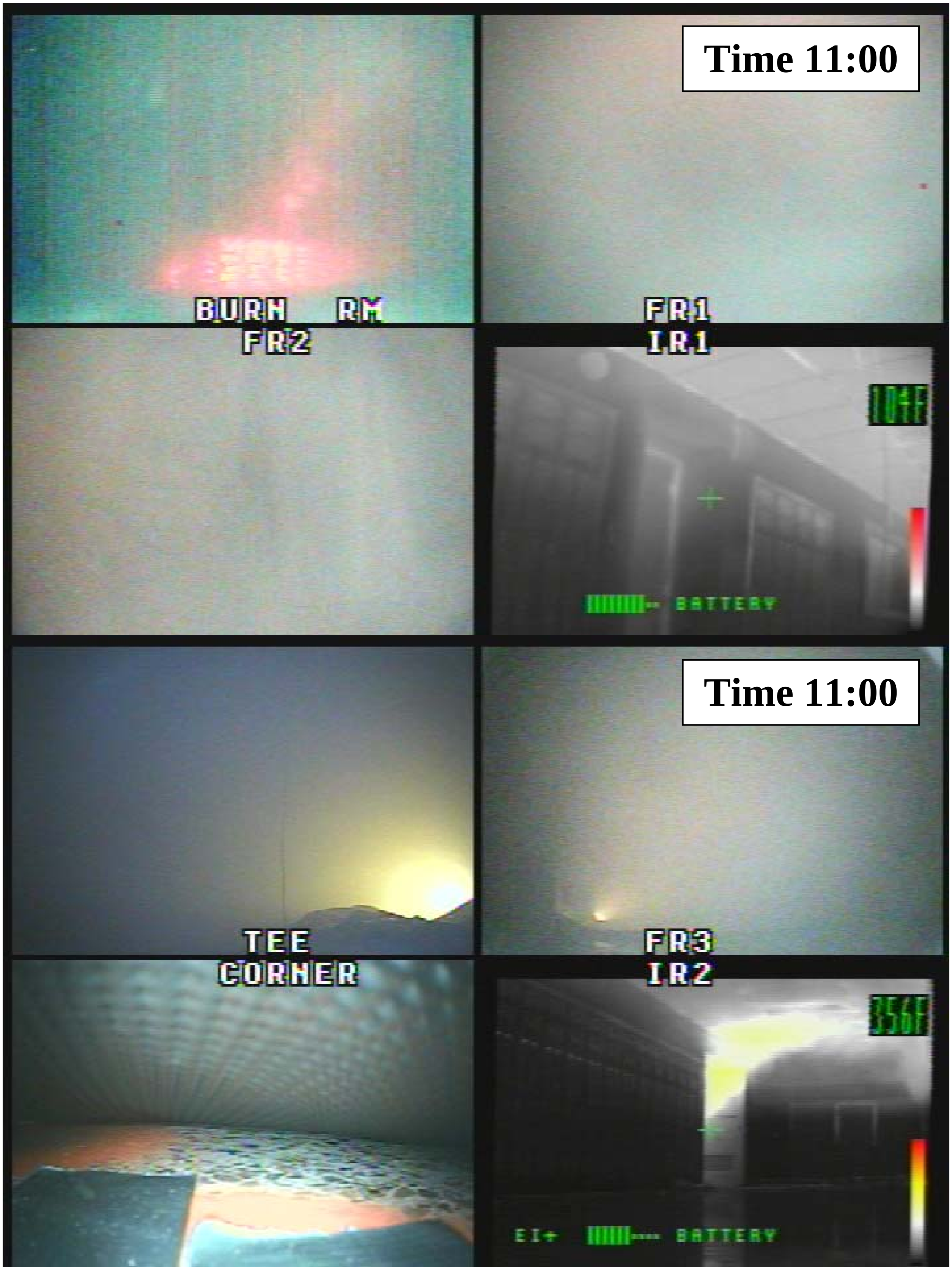

Figure 70. Experiment CF4 video images captured at 11 min

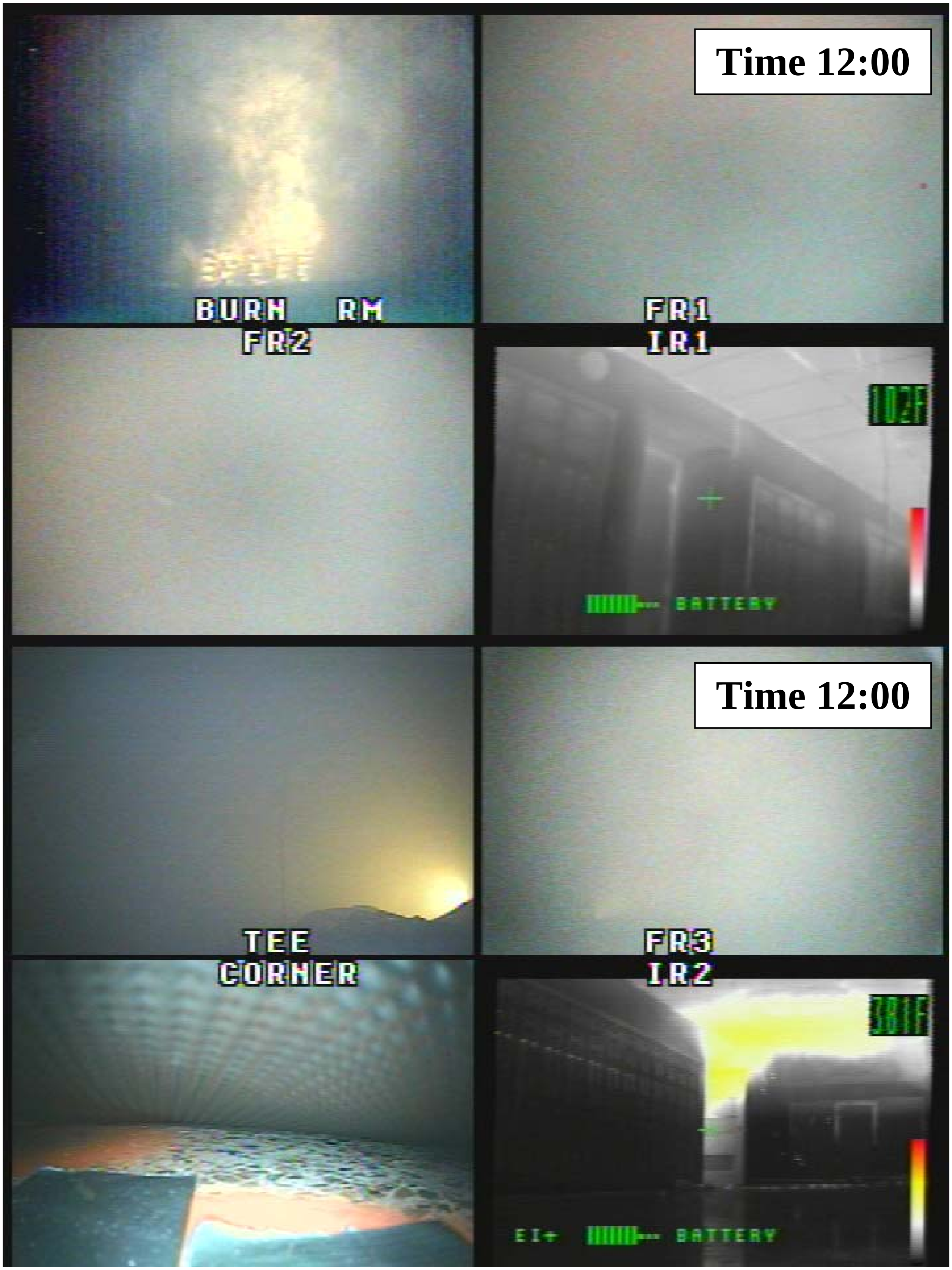

Figure 71. Experiment CF4 video images captured at 12 min

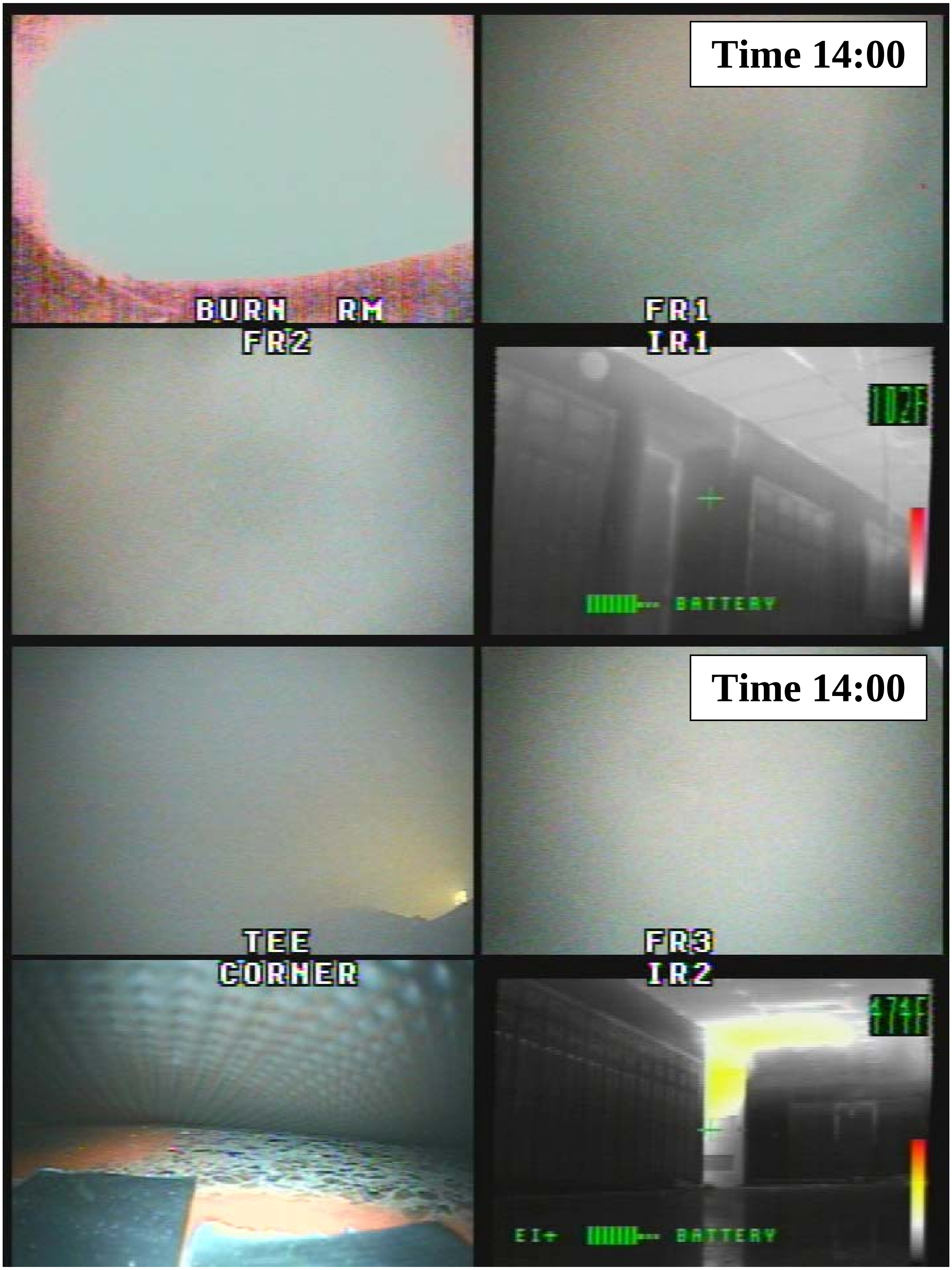

Figure 72. Experiment CF4 video images captured at 14 min

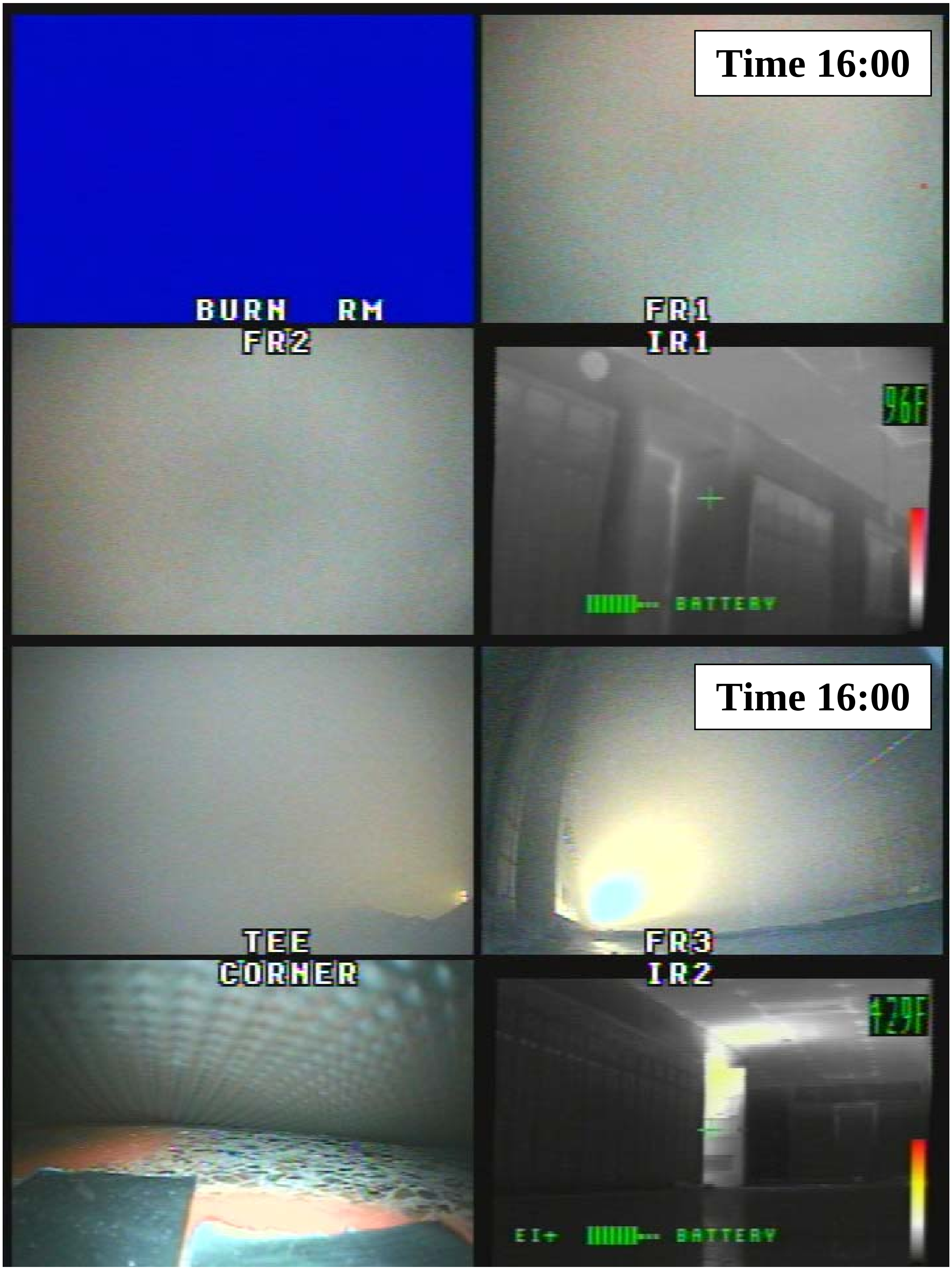

Figure 73. Experiment CF4 video images captured at 16 min

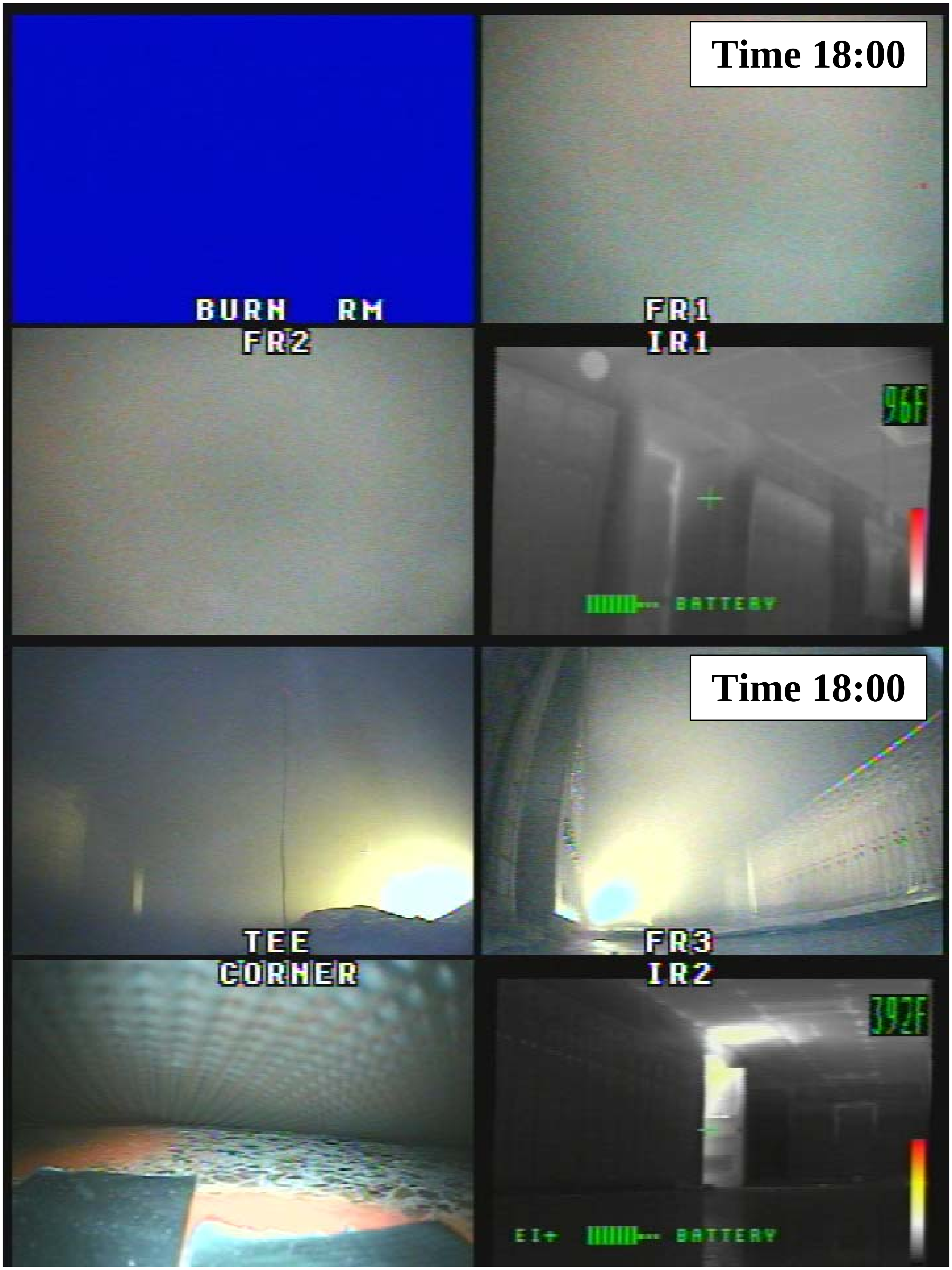

Figure 74. Experiment CF4 video images captured at 18 min

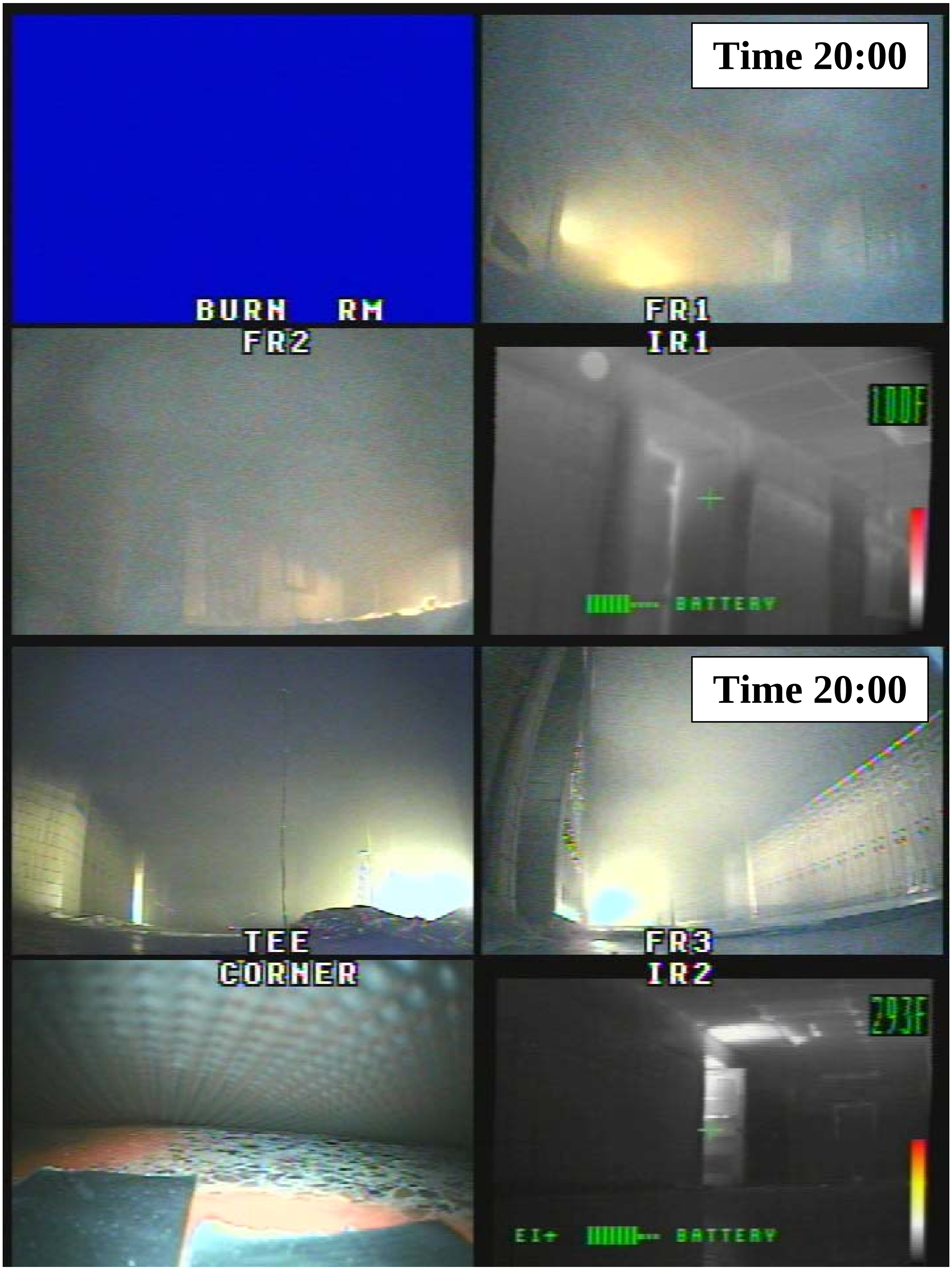

Figure 75. Experiment CF4 video images captured at 20 min

Experiment CF5 Video Images

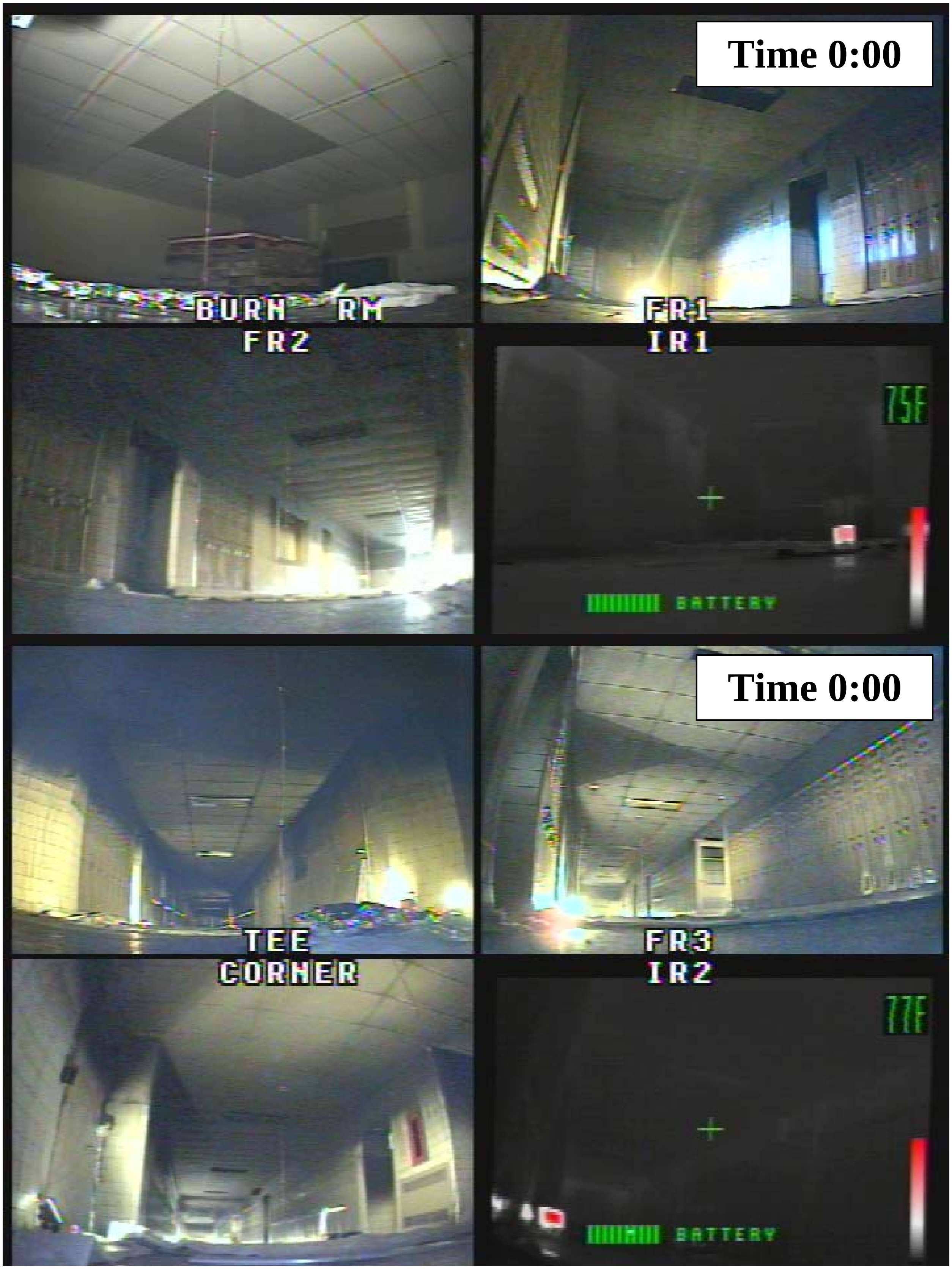

Figure 76. Experiment CF5 video images captured at 0 min

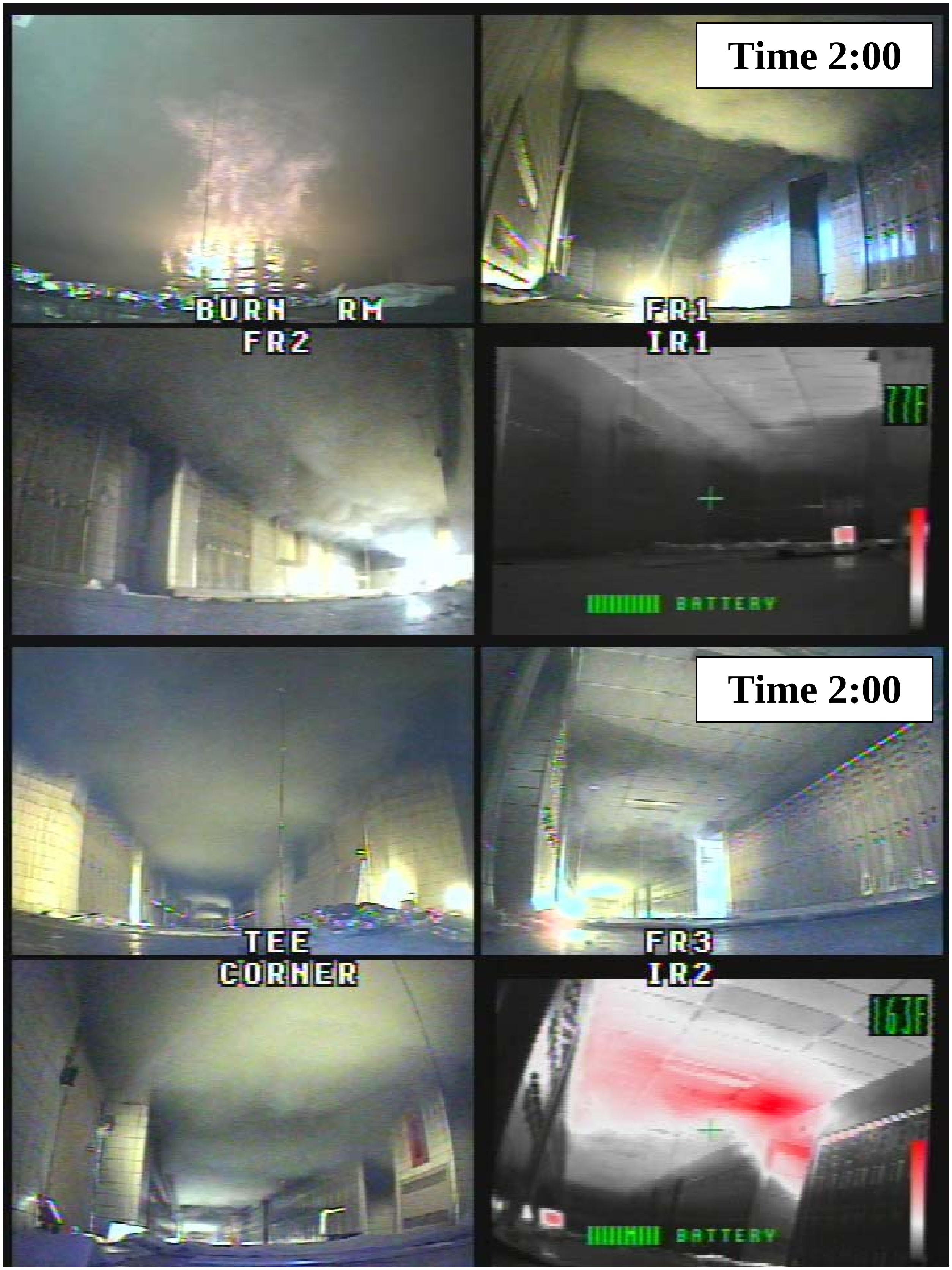

Figure 77. Experiment CF5 video images captured at 2 min

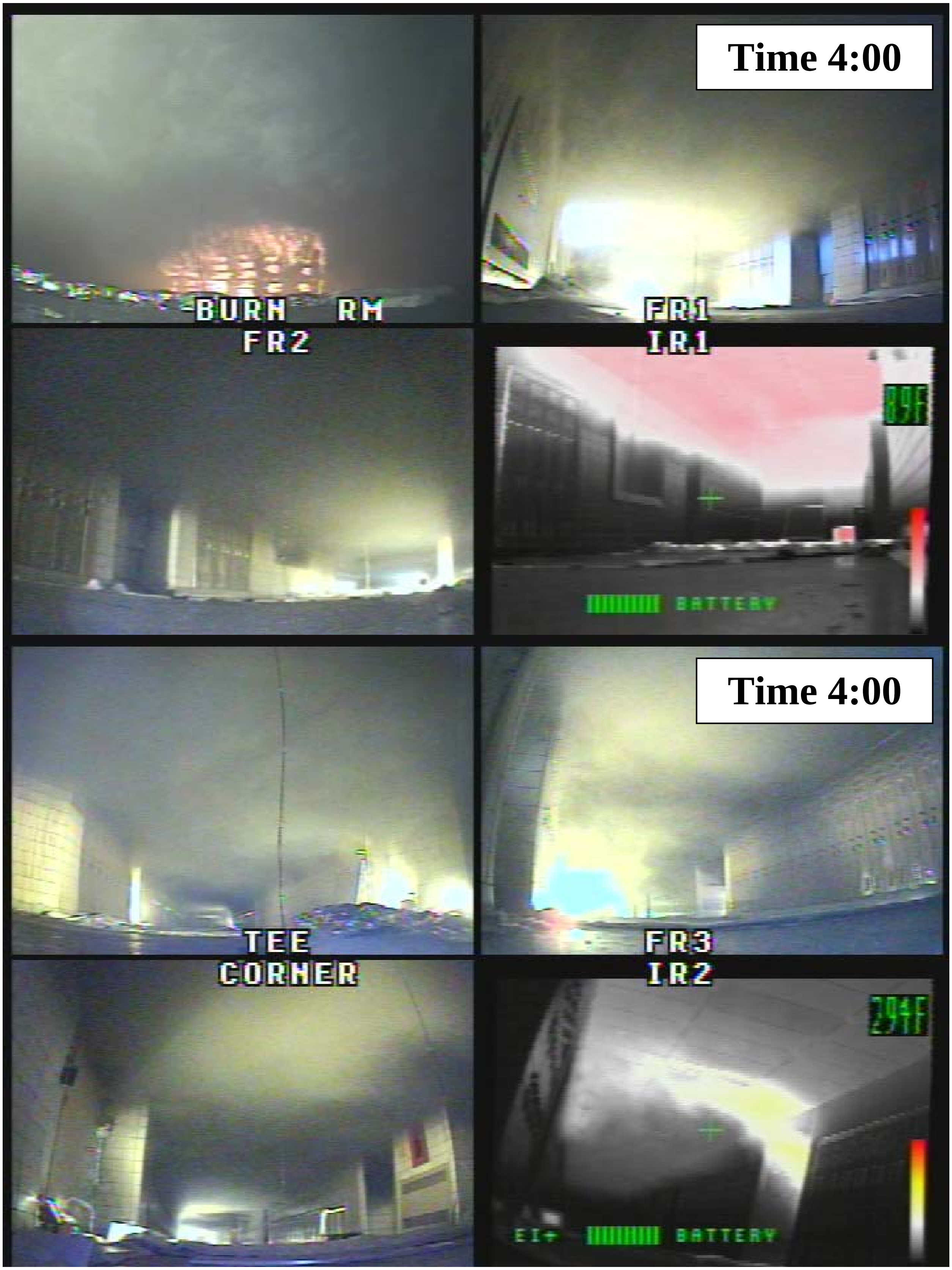

Figure 78. Experiment CF5 video images captured at 4 min

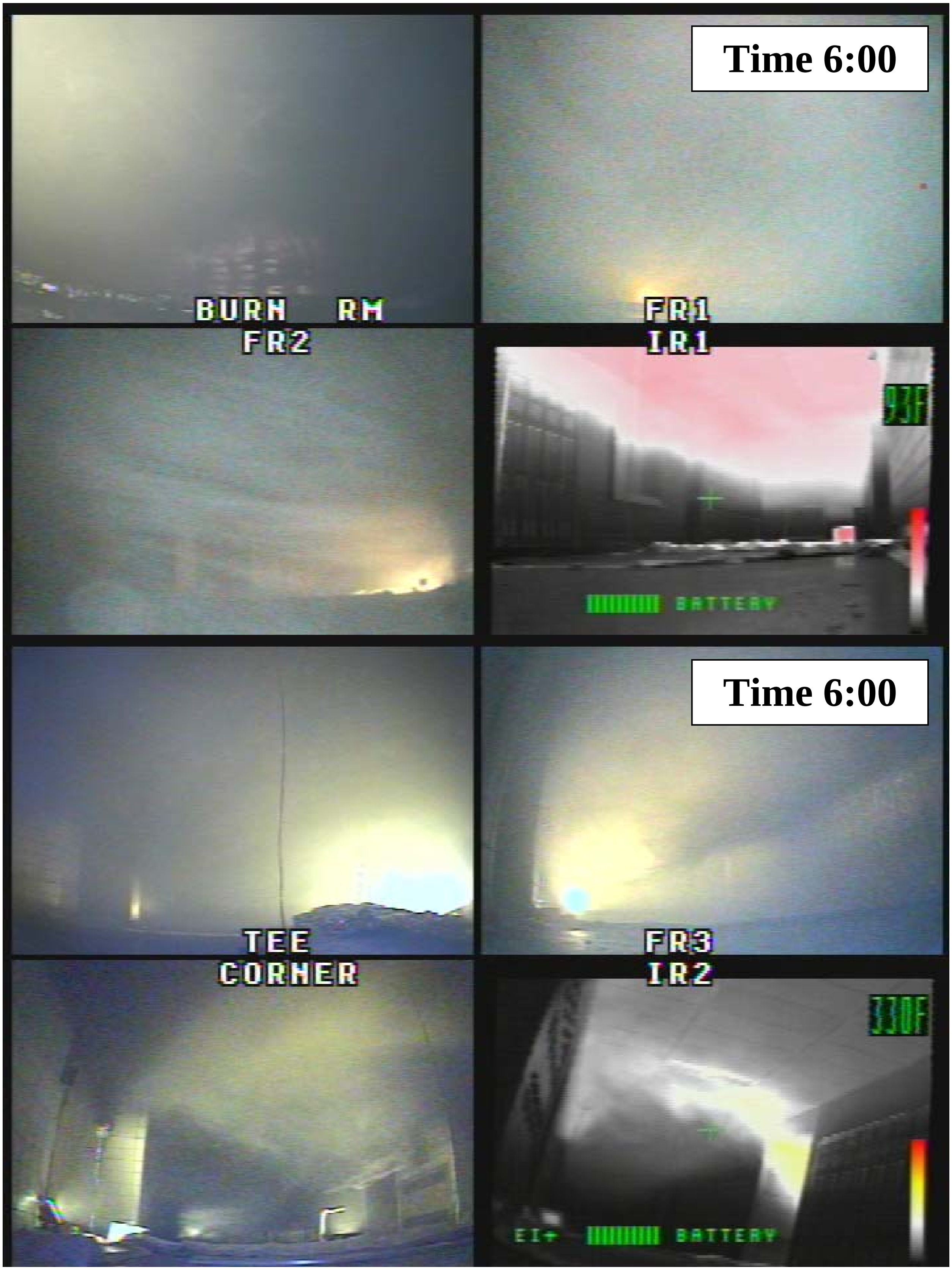

Figure 79. Experiment CF5 video images captured at 6 min

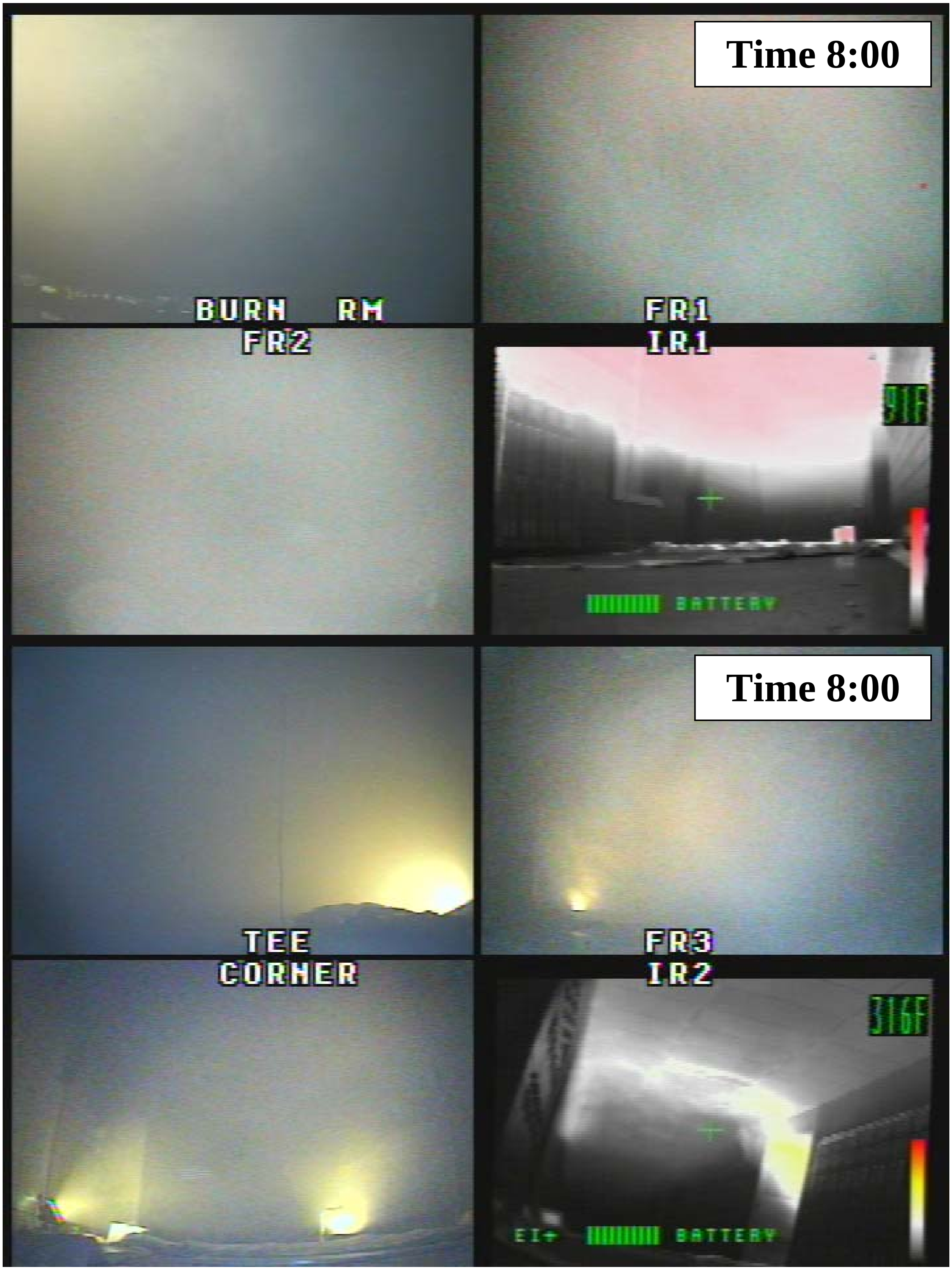

Figure 80. Experiment CF5 video images captured at 8 min

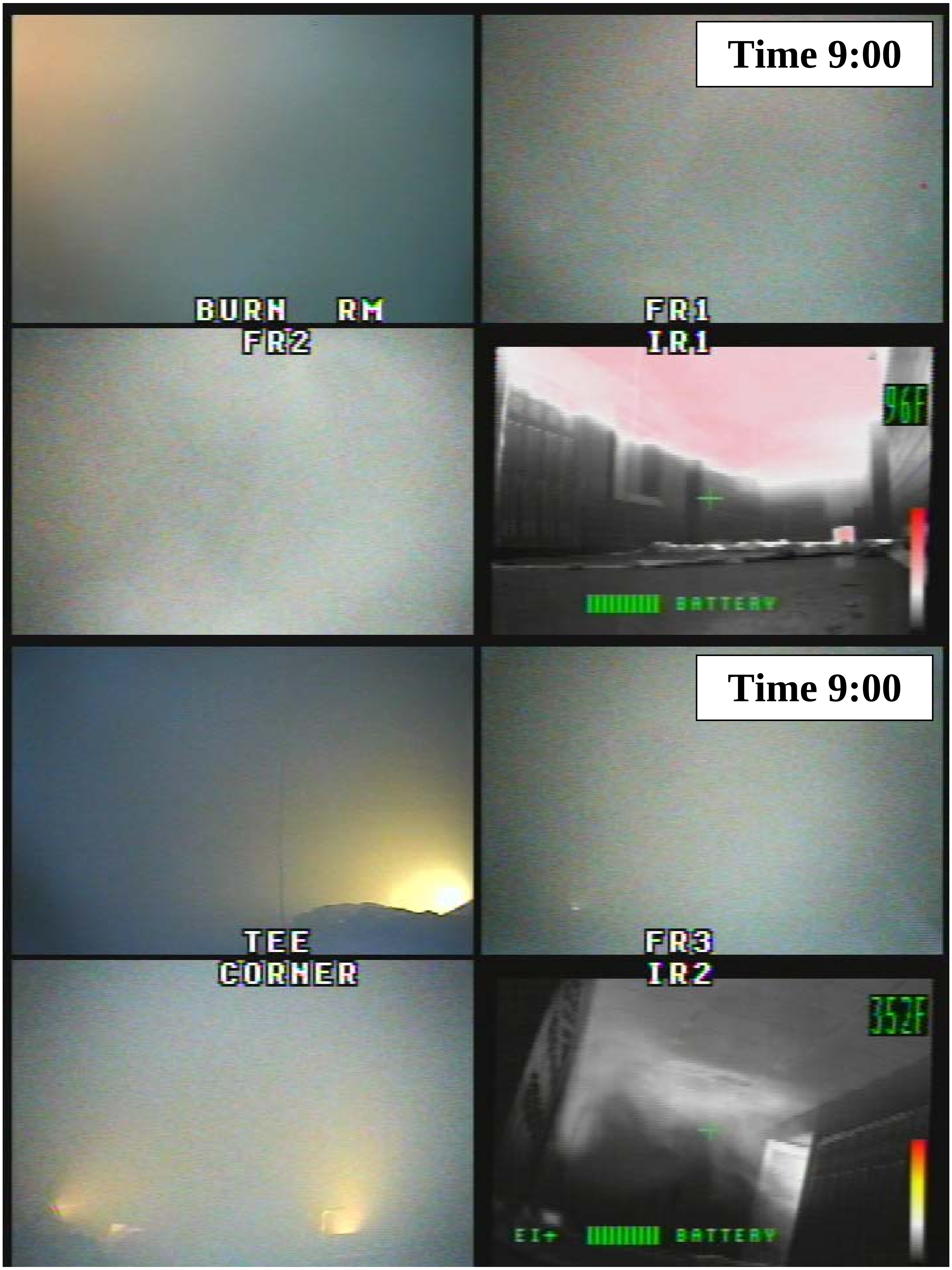

Figure 81. Experiment CF5 video images captured at 9 min

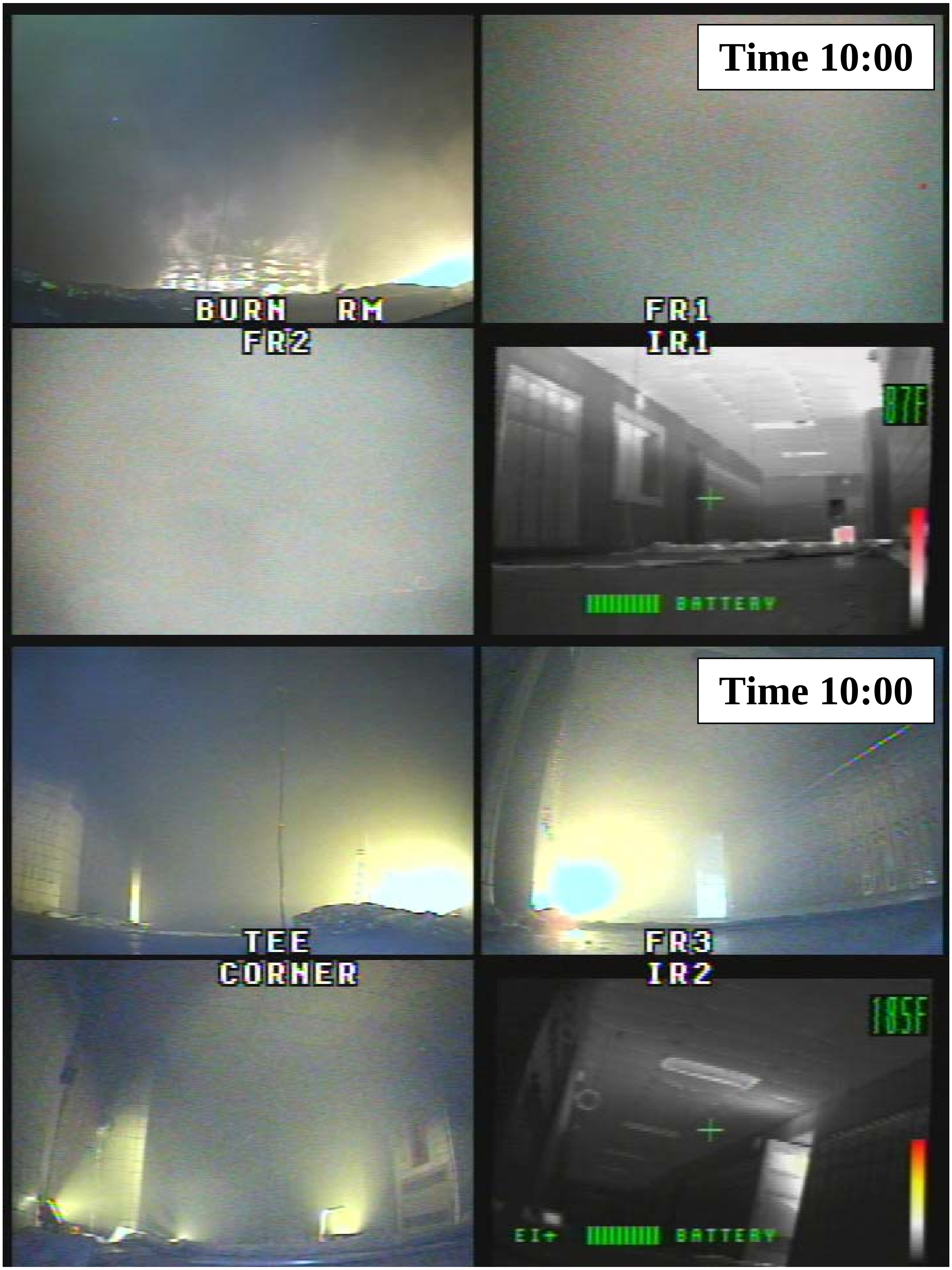

Figure 82. Experiment CF5 video images captured at 10 min

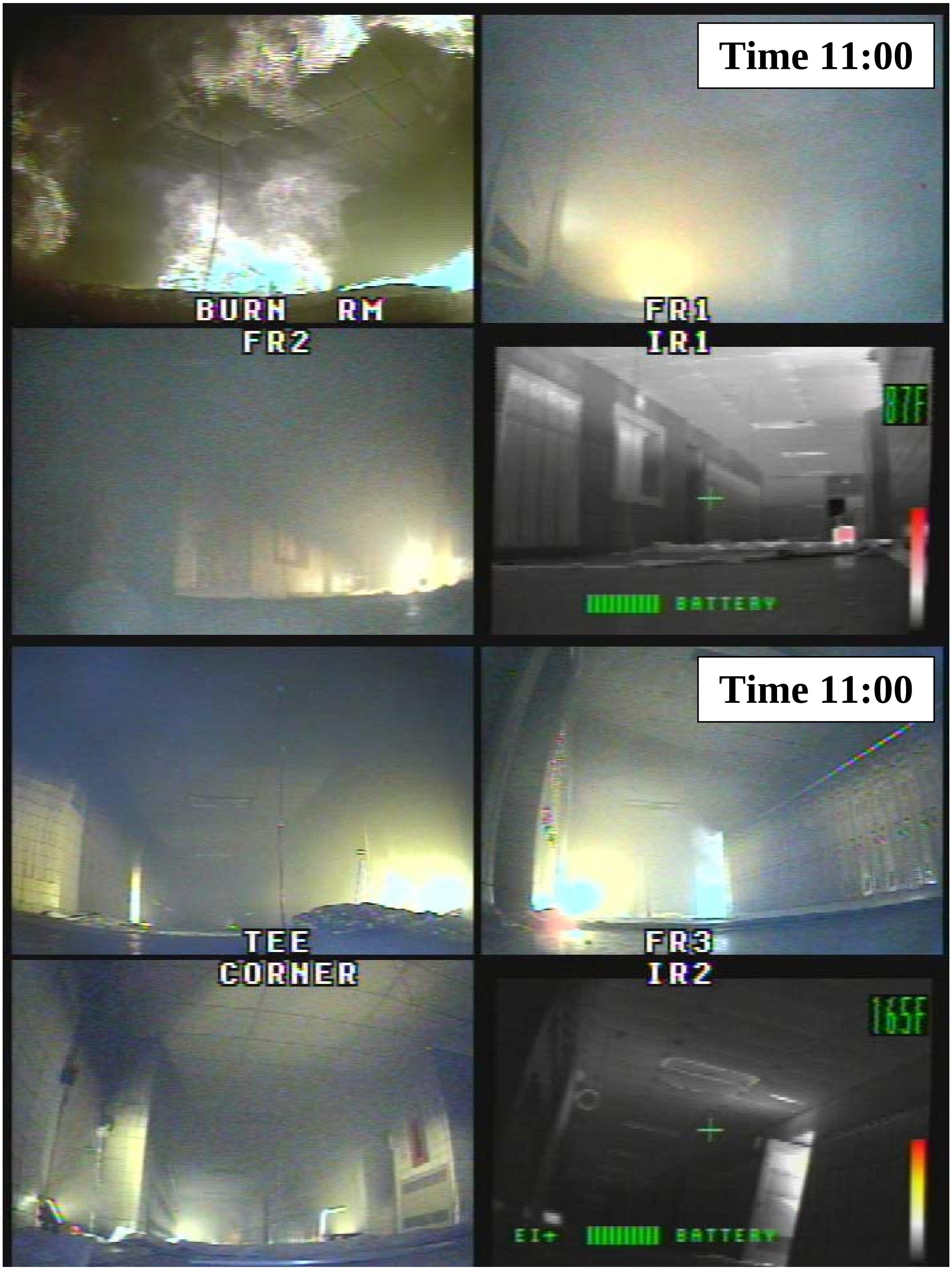

Figure 83. Experiment CF5 video images captured at 11 min

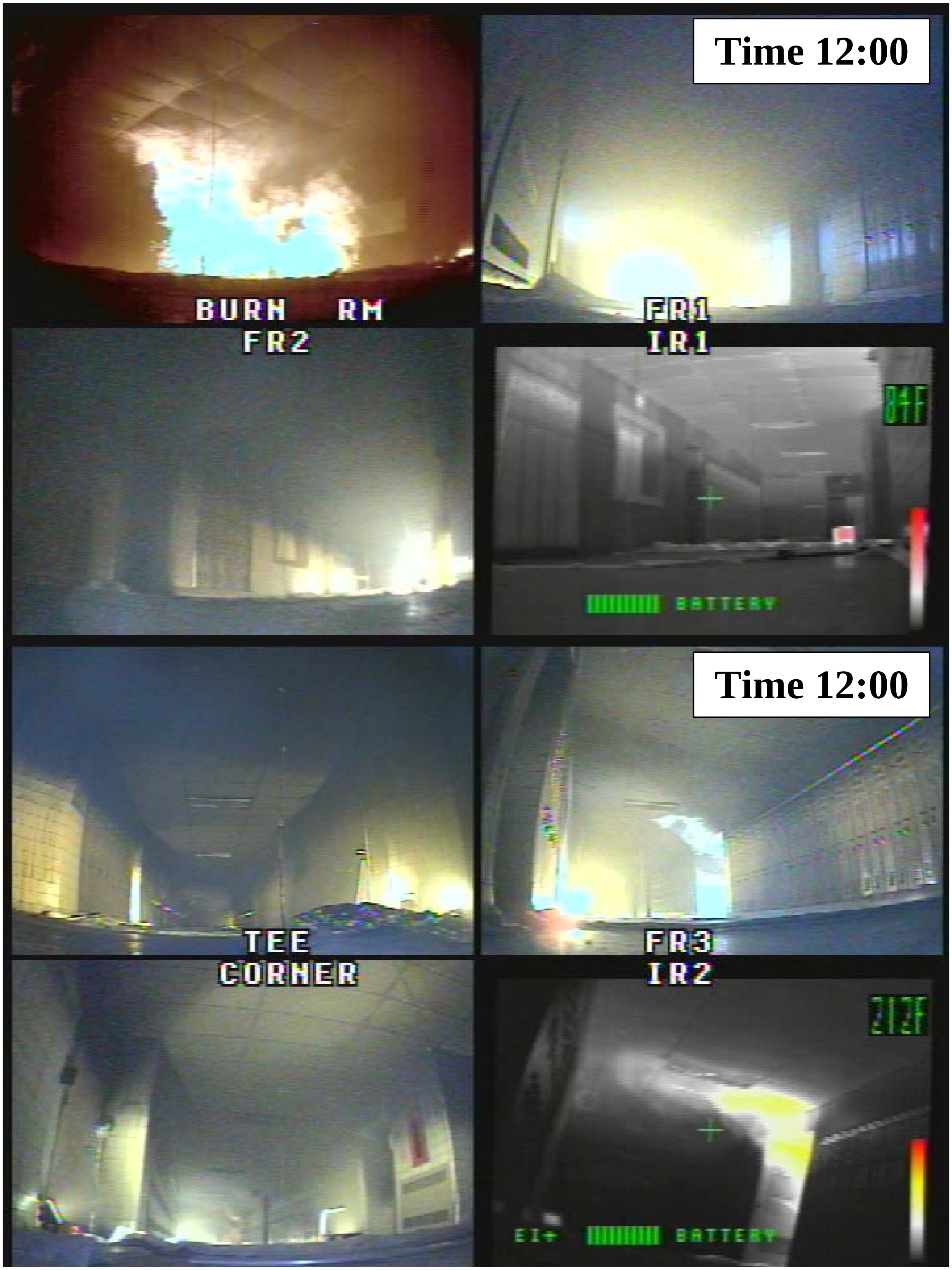

Figure 84. Experiment CF5 video images captured at 12 min

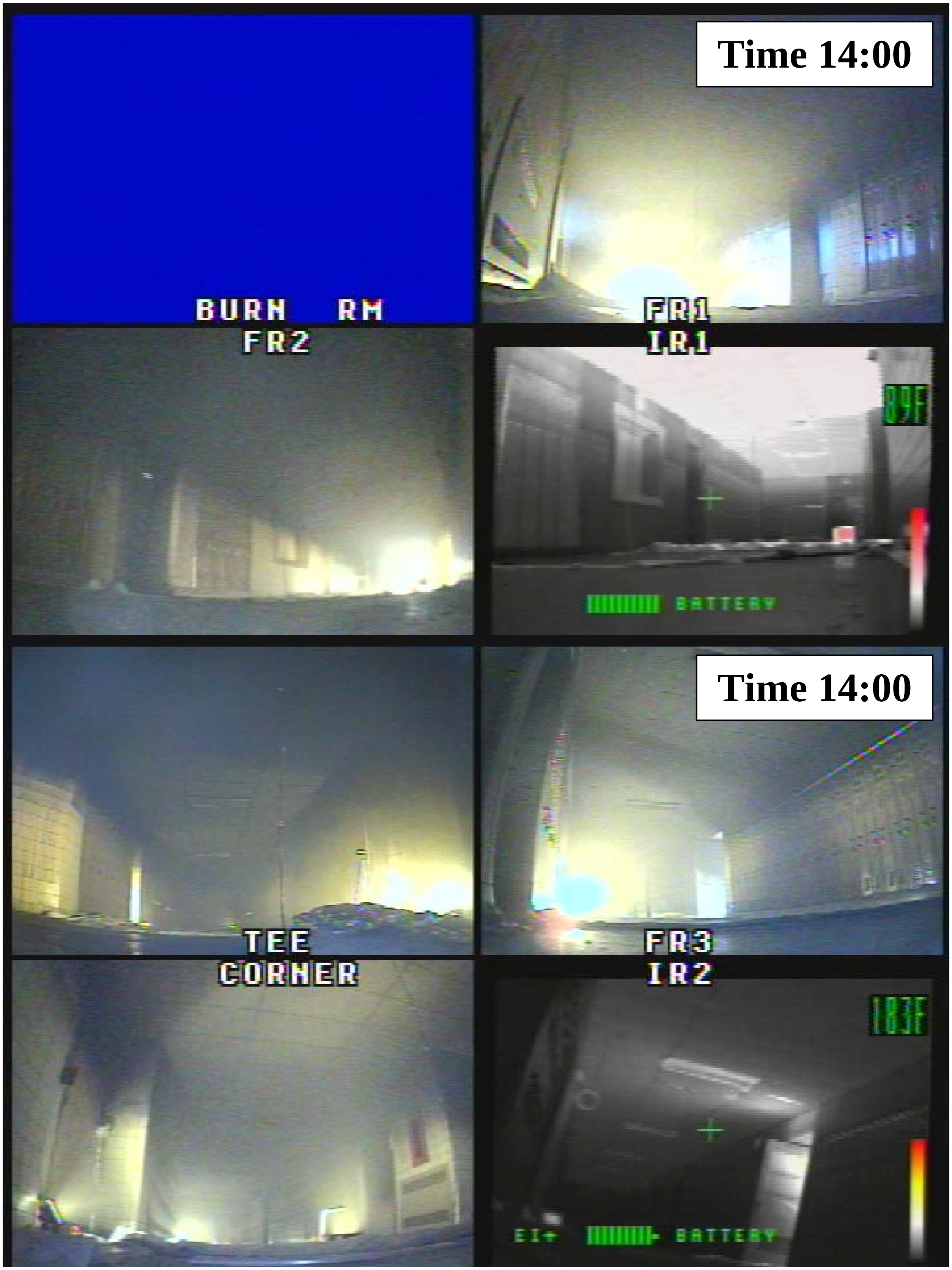

Figure 85. Experiment CF5 video images captured at 14 min

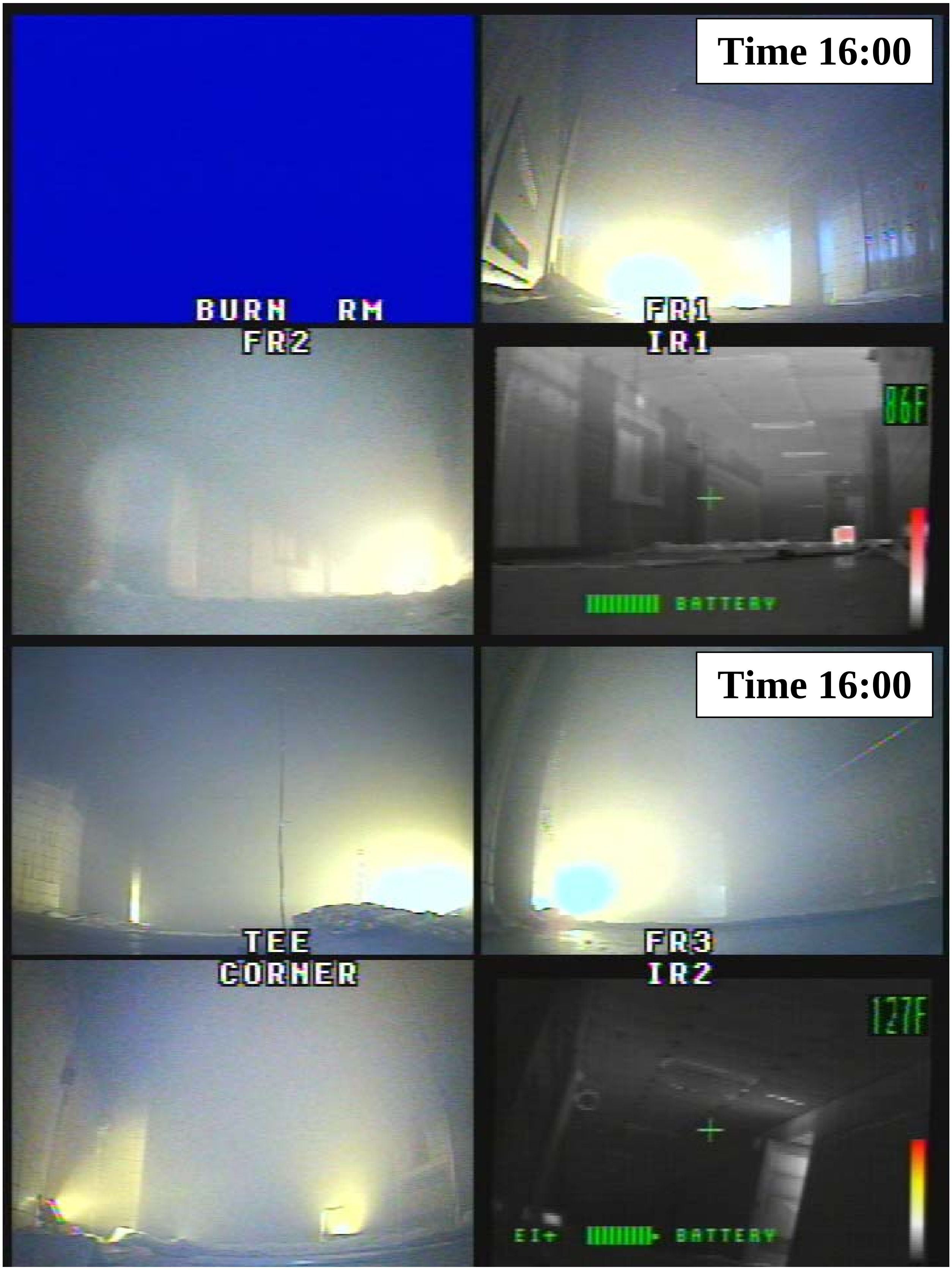

Figure 86. Experiment CF5 video images captured at 16 min

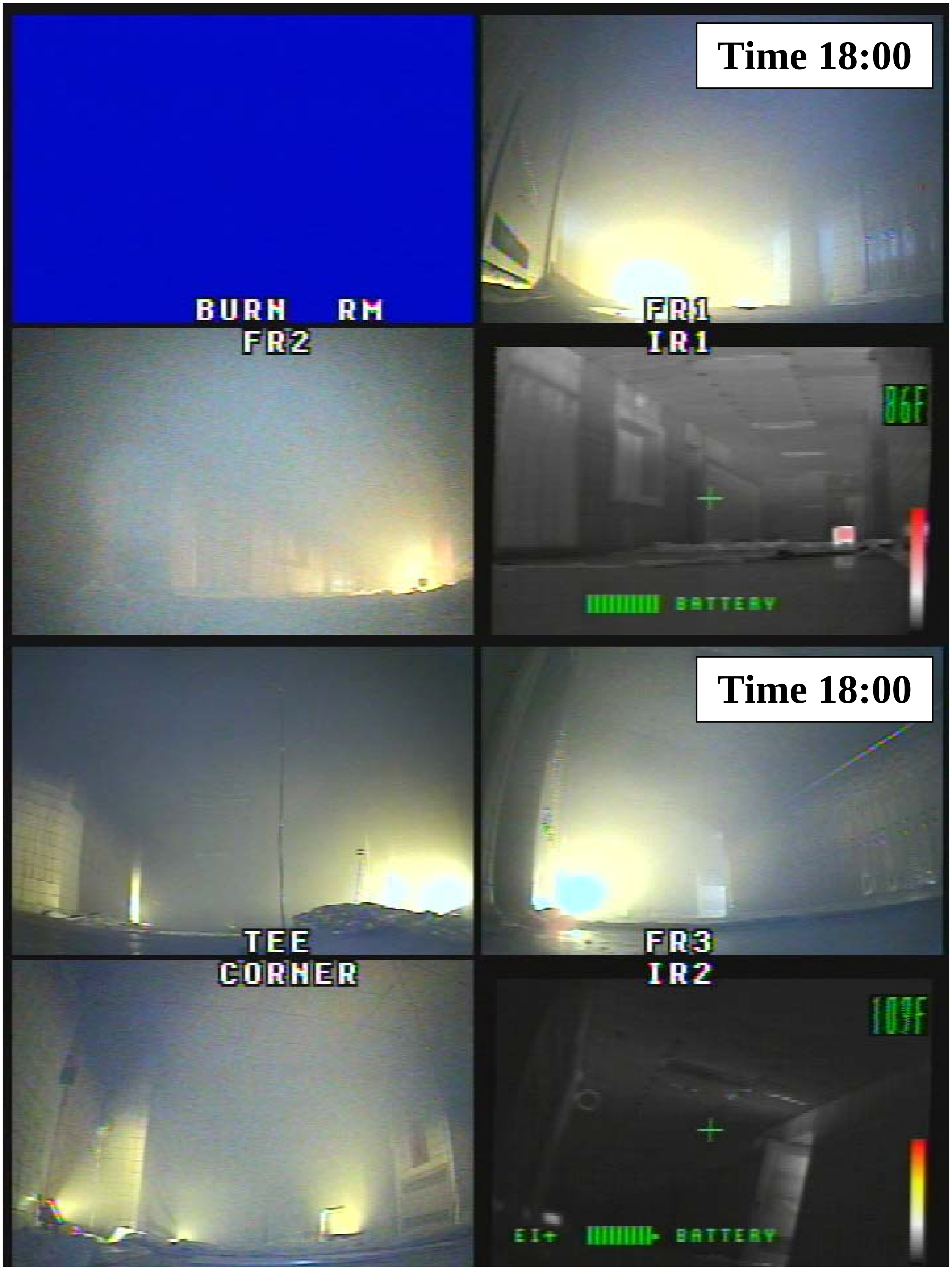

Figure 87. Experiment CF5 video images captured at 18 min

Experiment CF6 Video Images

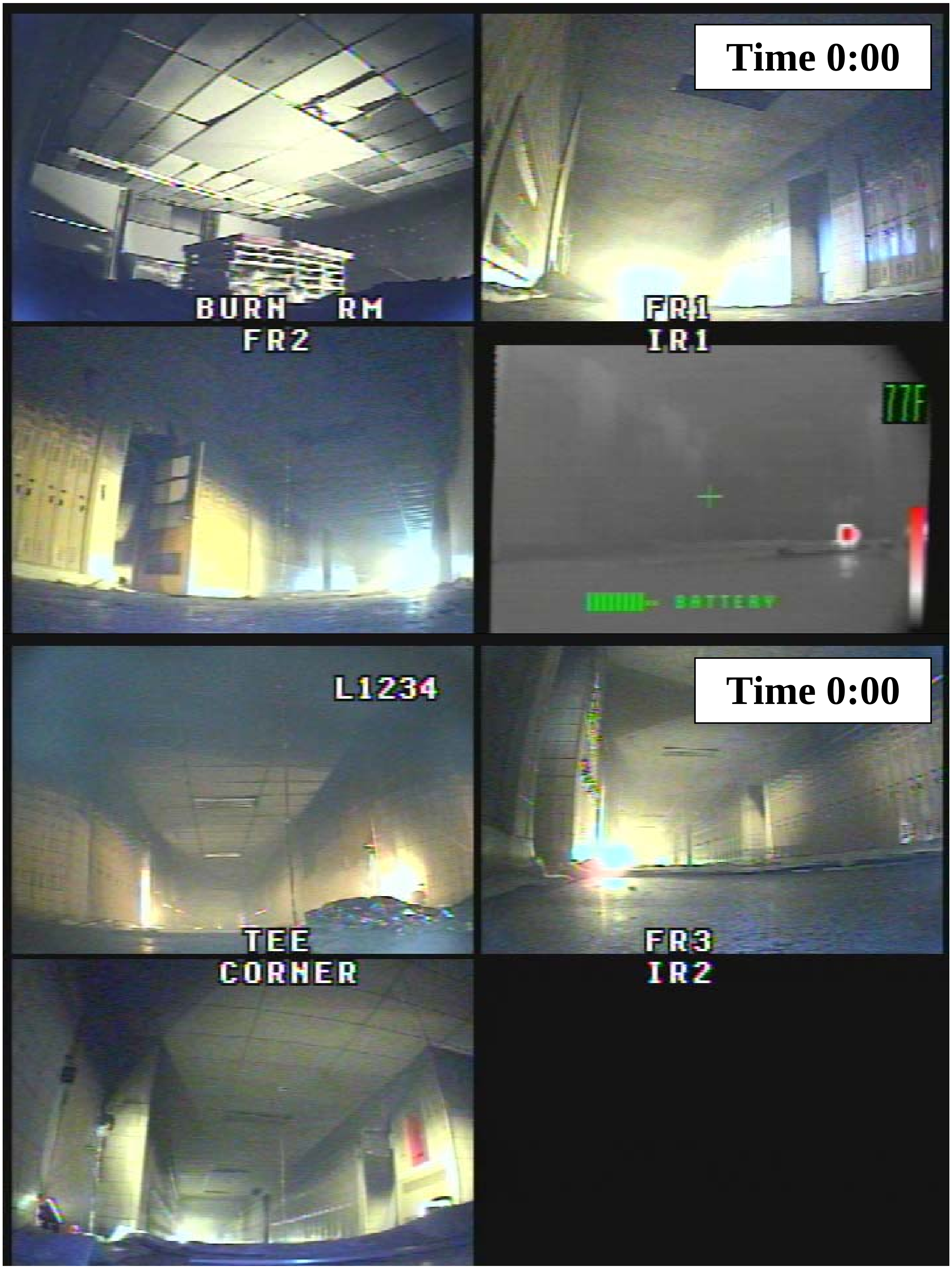

Figure 88. Experiment CF6 video images captured at 0 min

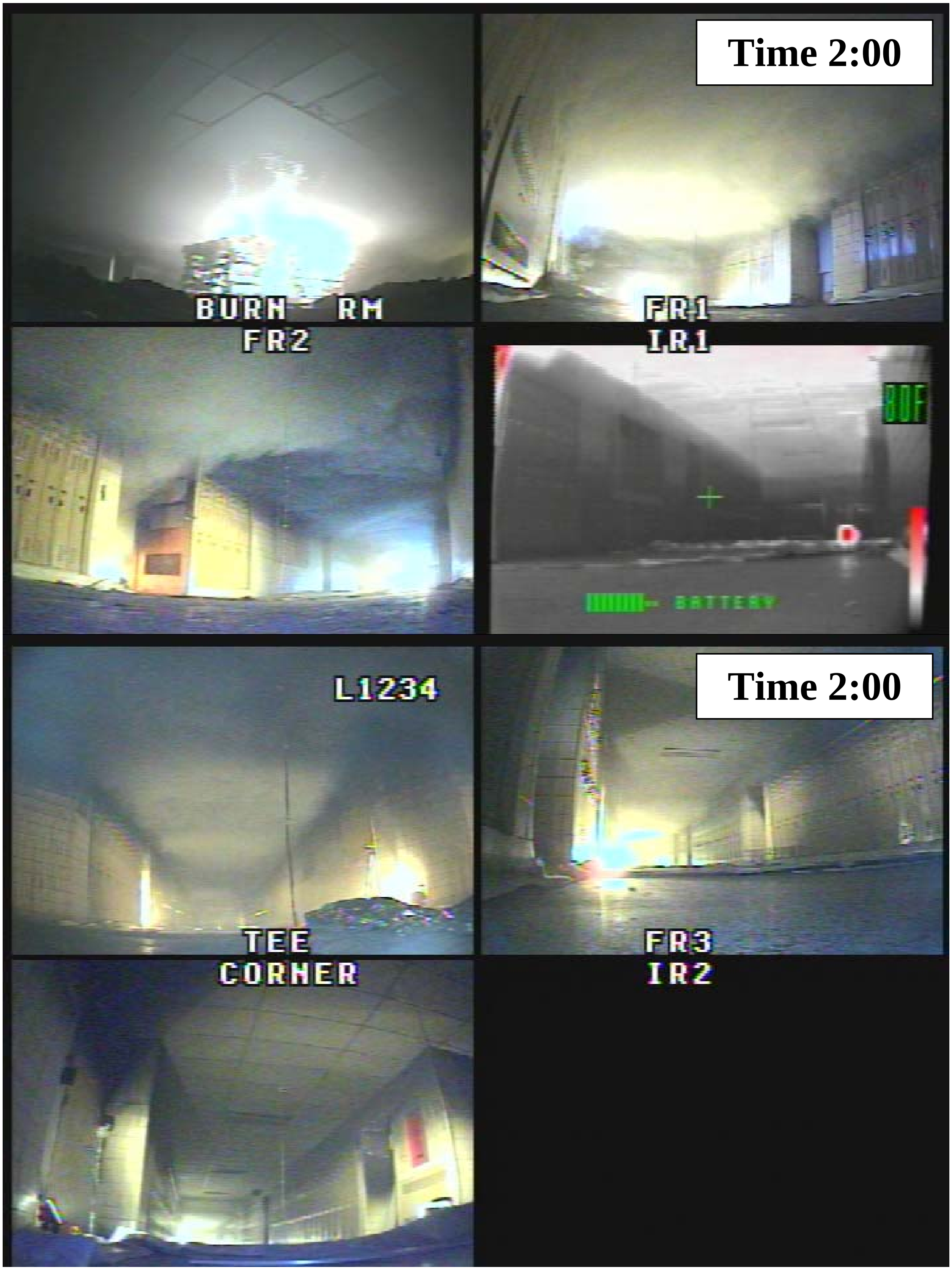

Figure 89. Experiment CF6 video images captured at 2 min

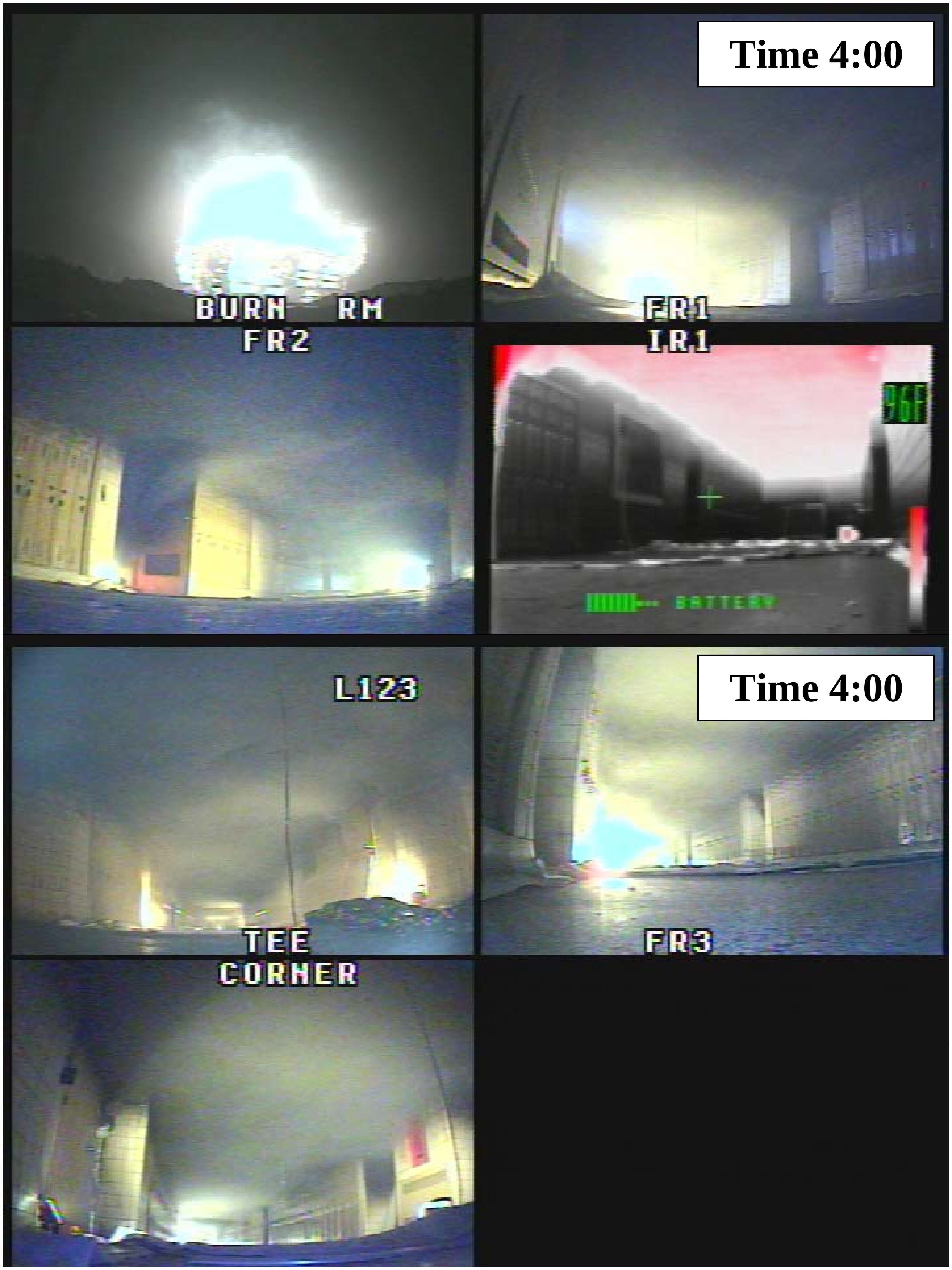

Figure 90. Experiment CF6 video images captured at 4 min

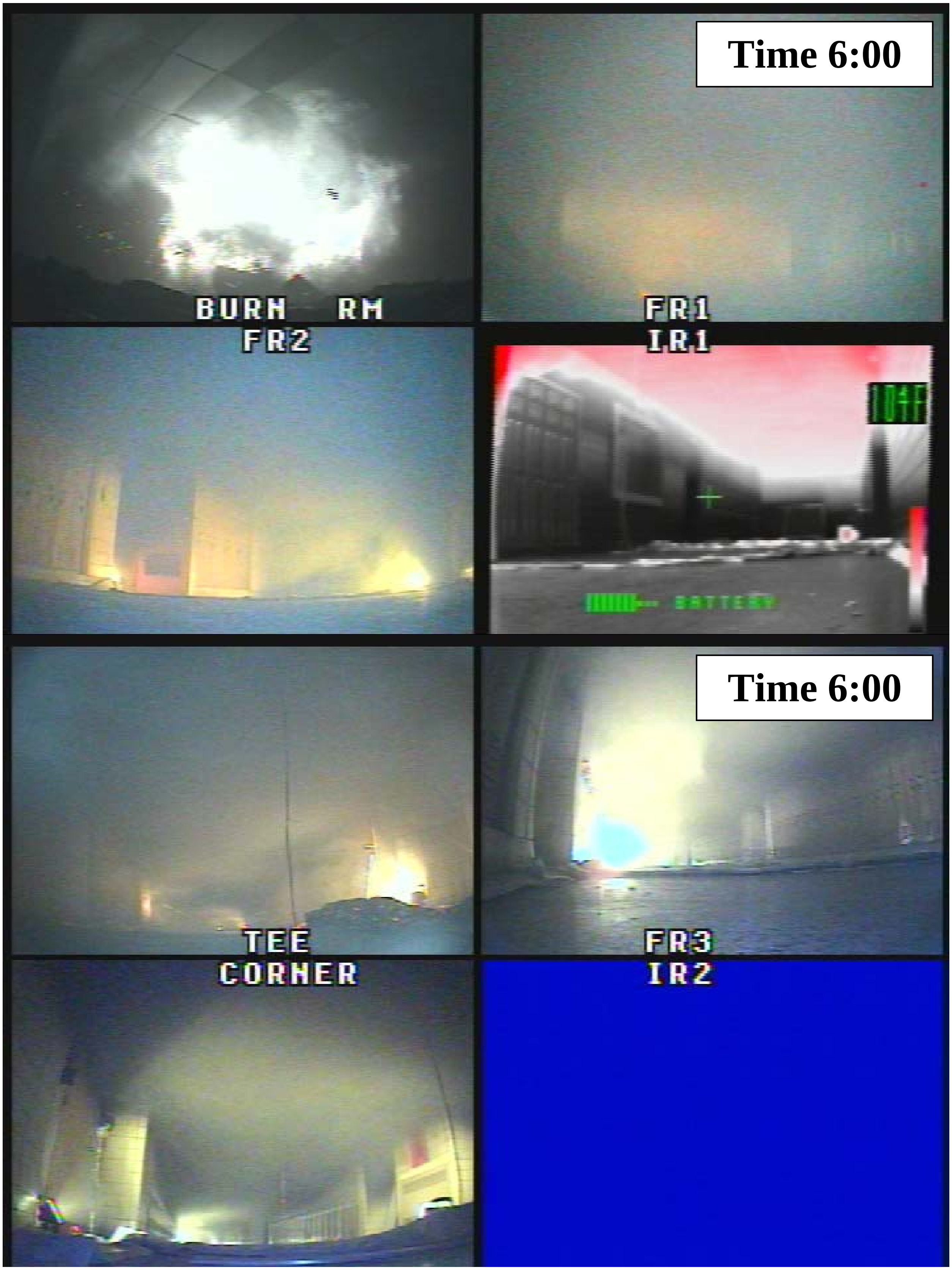

Figure 91. Experiment CF6 video images captured at 6 min

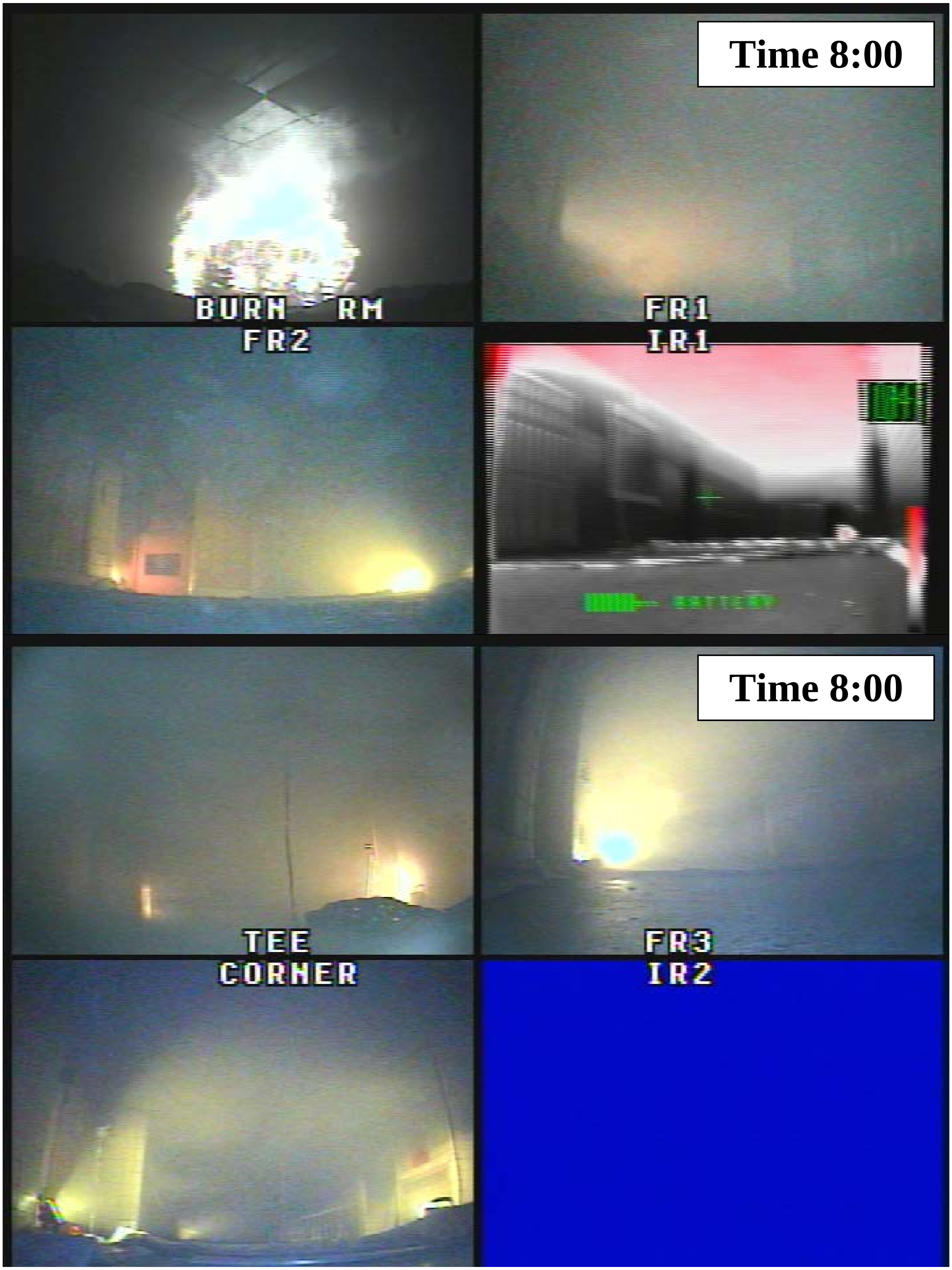

Figure 92. Experiment CF6 video images captured at 8 min

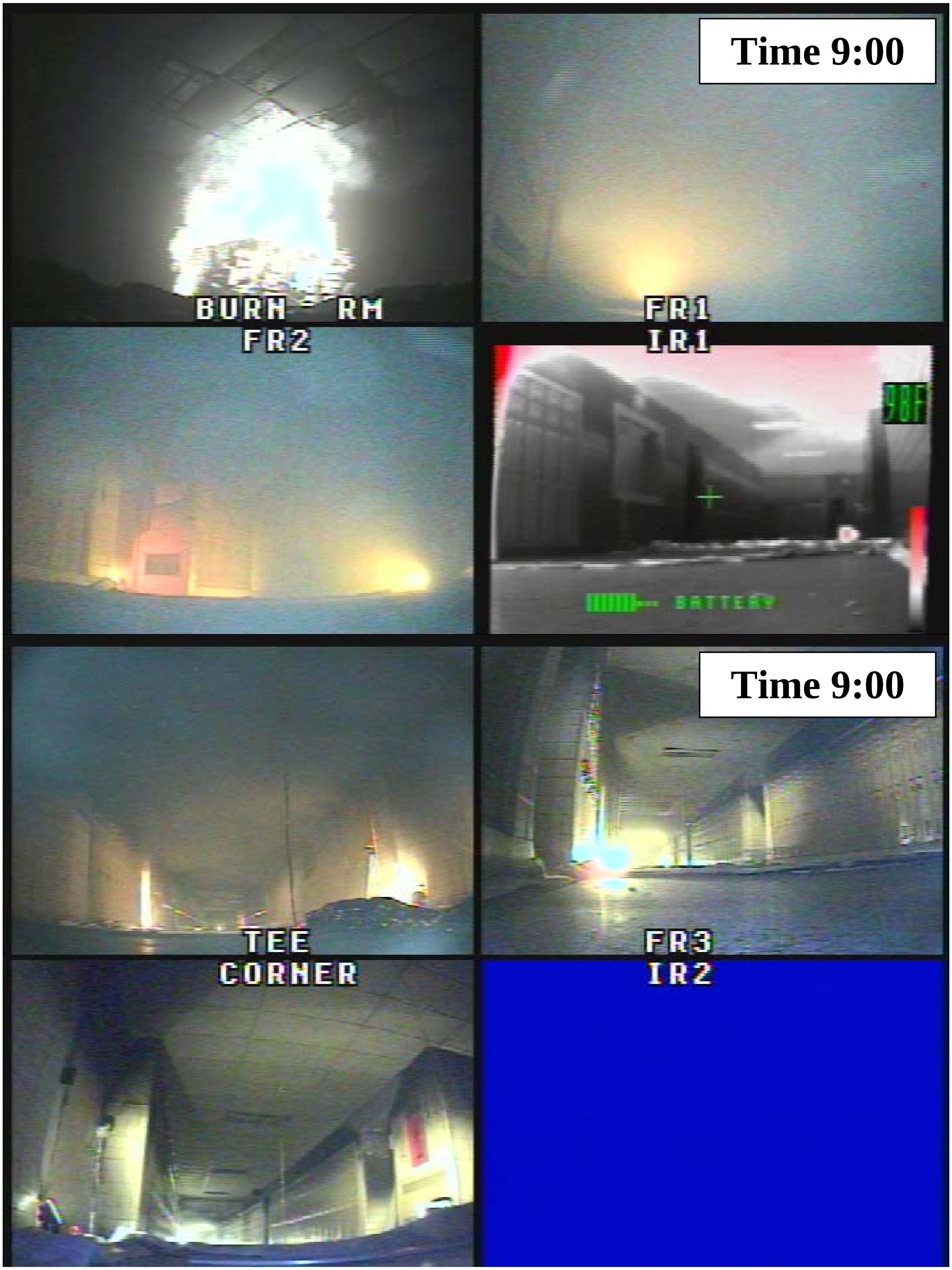

Figure 93. Experiment CF6 video images captured at 9 min

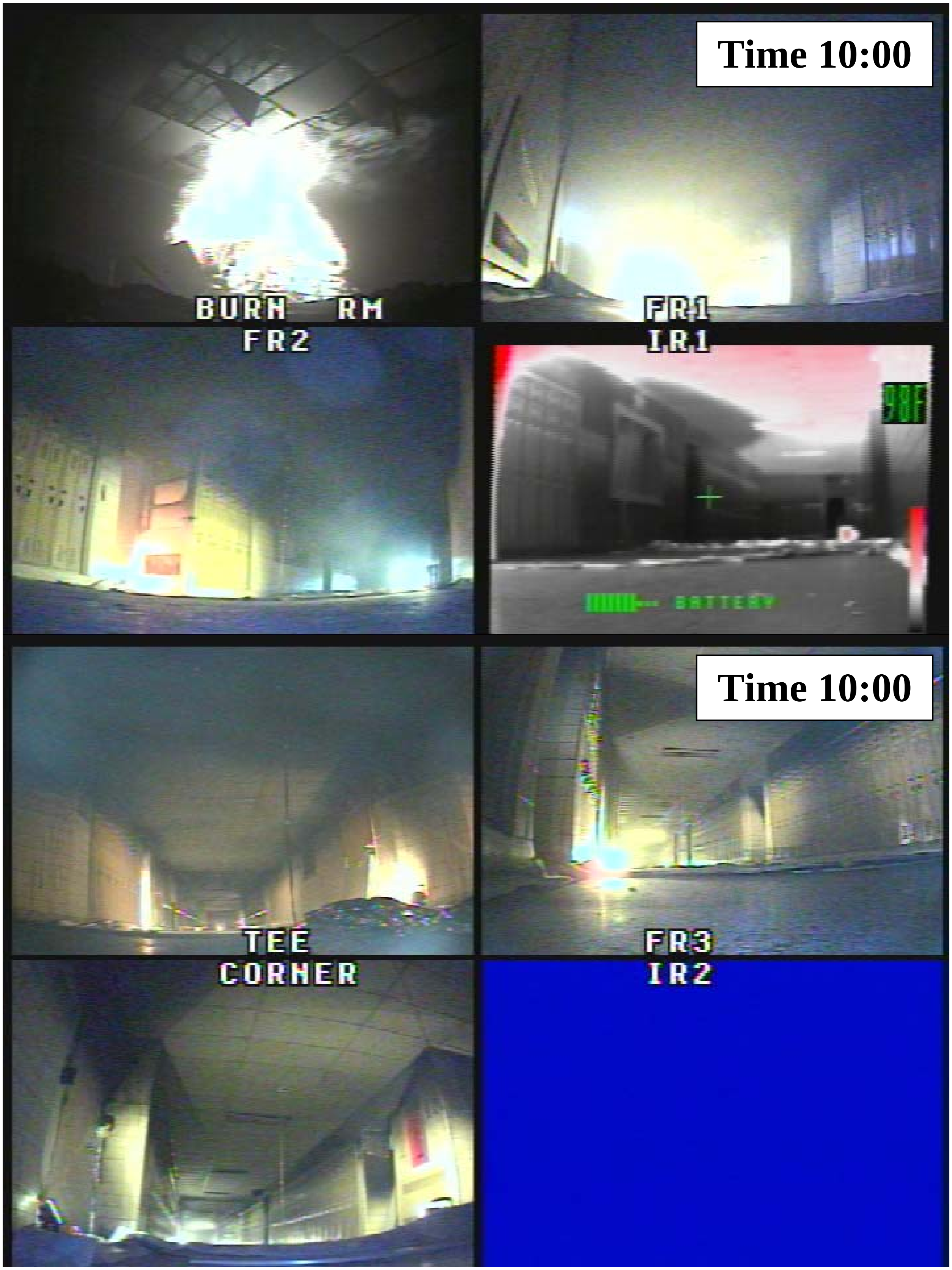

Figure 94. Experiment CF6 video images captured at 10 min

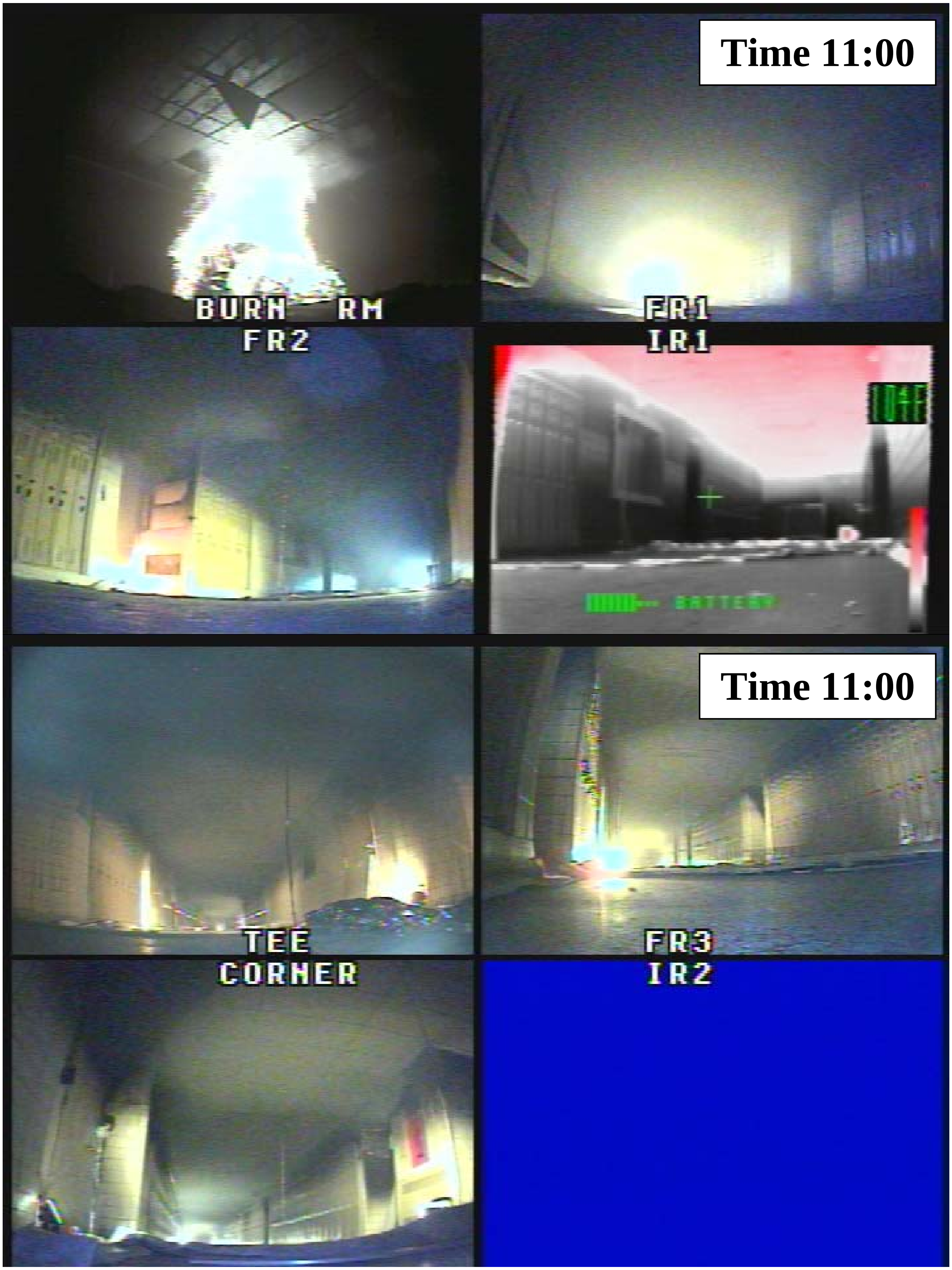

Figure 95. Experiment CF6 video images captured at 11 min

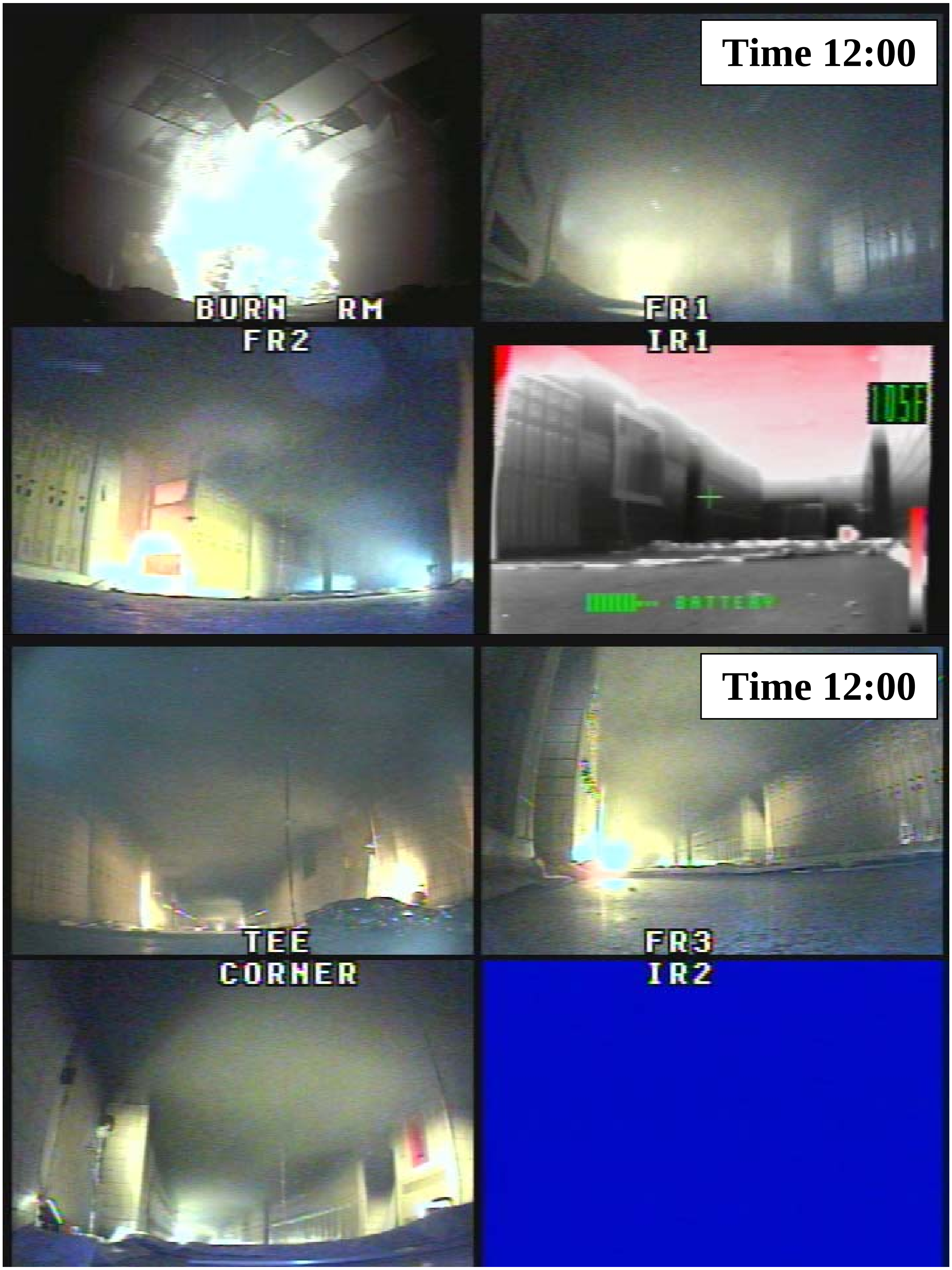

Figure 96. Experiment CF6 video images captured at 12 min

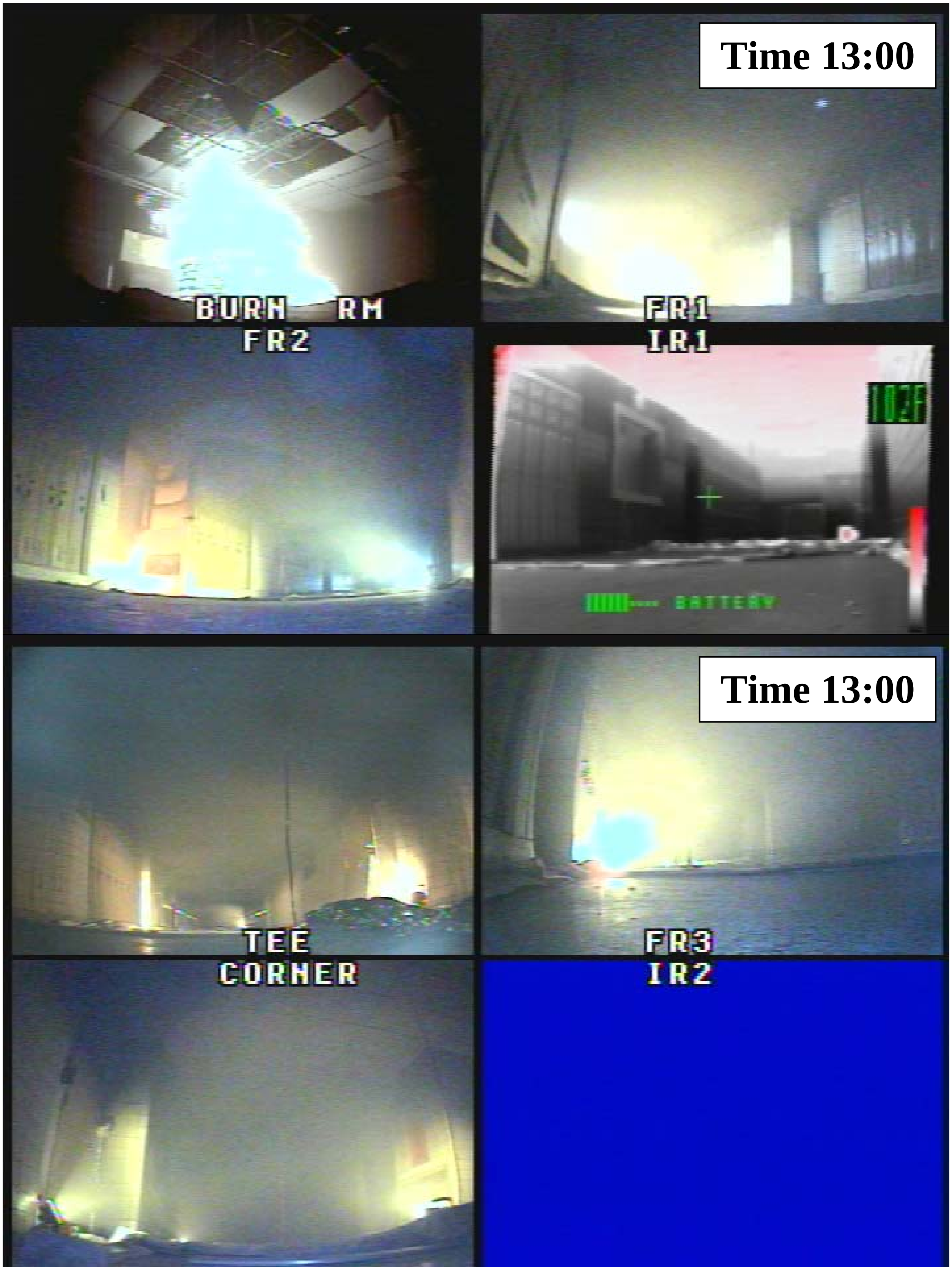

Figure 97. Experiment CF6 video images captured at 13 min

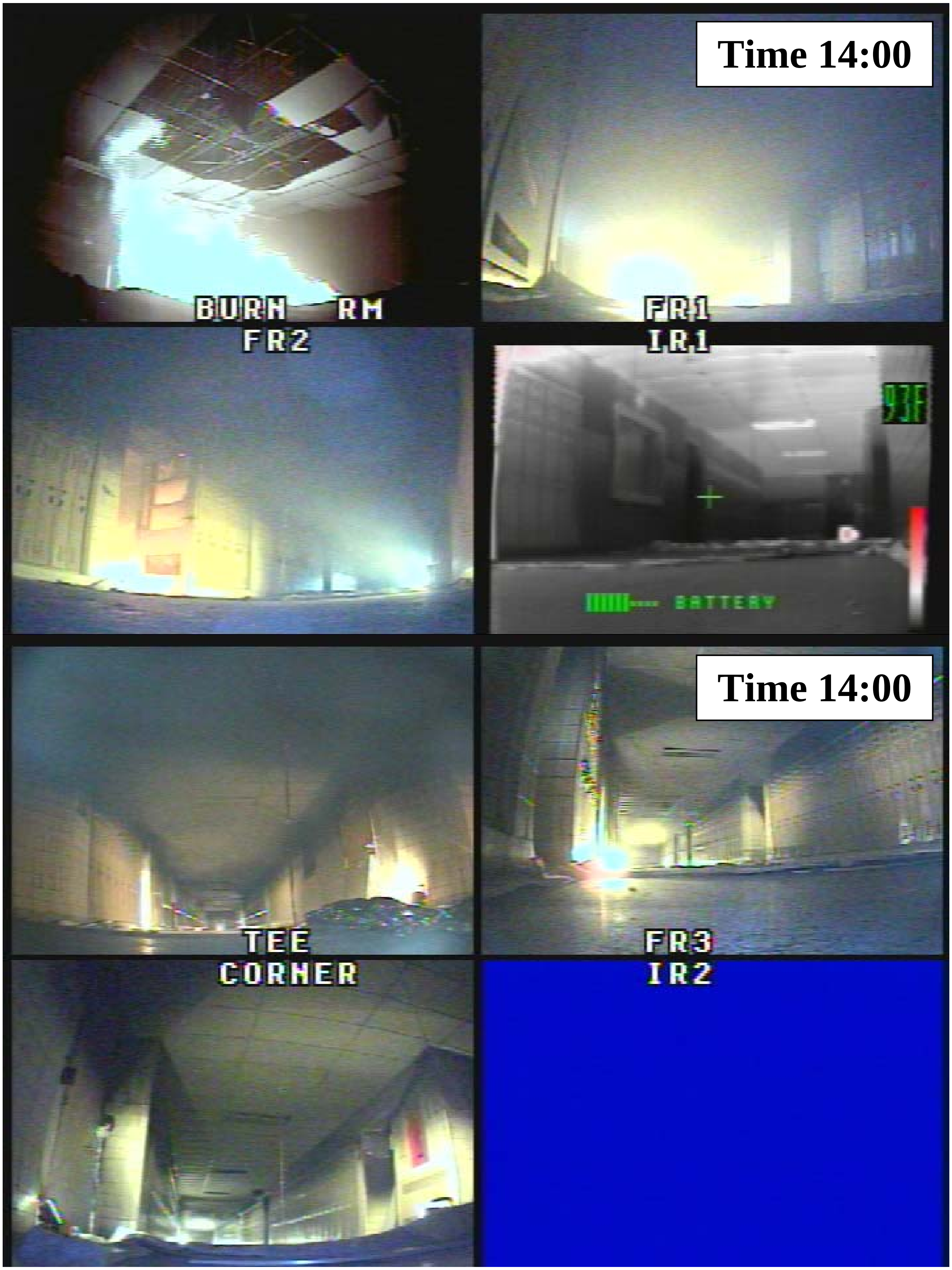

Figure 98. Experiment CF6 video images captured at 14 min

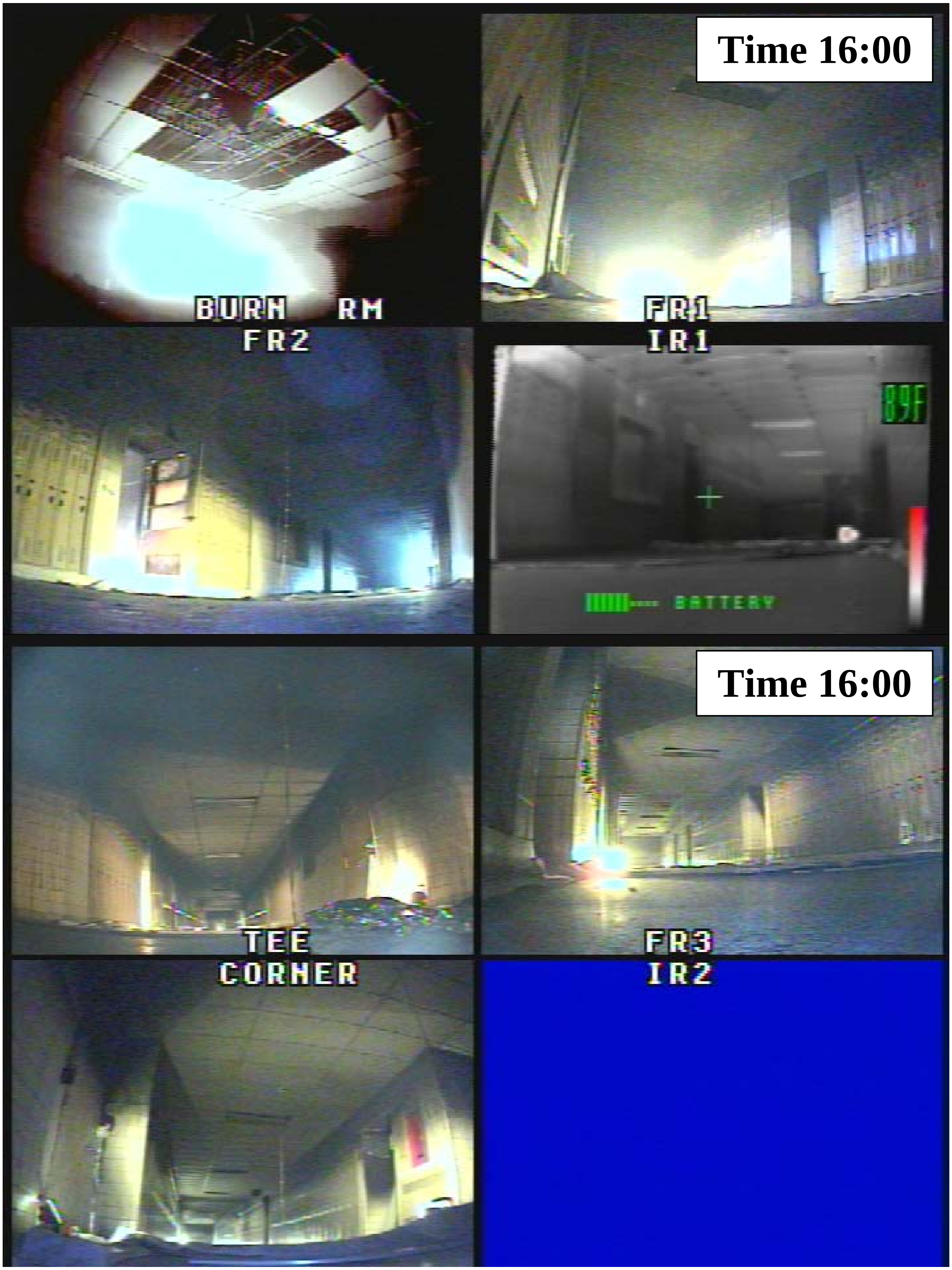

Figure 99. Experiment CF6 video images captured at 16 min

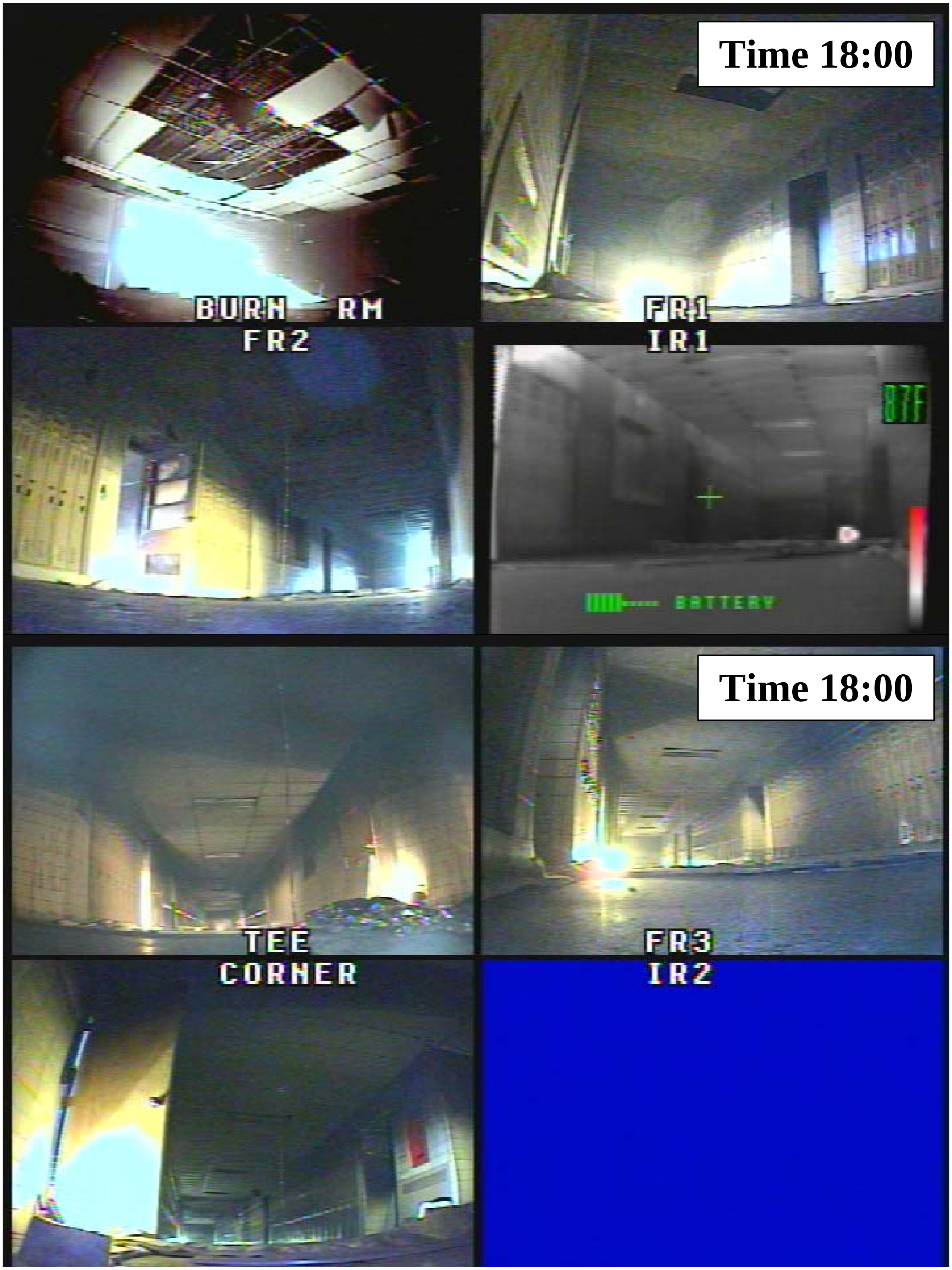

Figure 100. Experiment CF6 video images captured at 18 min

3.5. Discussion

In this limited series of experiments in the long hallways of this masonry educational building, the positive pressure ventilation increased the pressure, reducing temperatures, limiting smoke spread and increasing visibility. The pressure, temperature and video data suggested that a single 0.7 m (27 in.) fan did not create enough pressure to improve conditions when there was a well-developed classroom fire. Adding a second 0.7 m (27 in.) fan was effective and the mounted fans were very effective at generating pressures above 25 Pa in this building.

The use of horizontal natural ventilation at both the fire room window as well as the hallway door remote from the fire was not very effective at reducing temperatures or increasing visibility. Positive pressure ventilation through the fire room via the windows was ideal for improving conditions in the hallway. Ventilating through the hallway door, while not ideal, was effective in improving conditions. The data shows no indication that the flow created by the fan pulls fire gases out of the fire room or pushes increased fire gases down the hallway. In most cases, the increased pressure from the fans was enough to stop the flow of hot gases into the hallway, even with an open ventilation point remote from the fire.

4. Gymnasium Fire Experiments

Fires in spaces having large volumes can pose challenges for fire fighters, because of the potential for large heat release rate (HRR) fires, large areas to search for victims, and difficulties with ventilation. A large volume structure can have sufficient amounts of oxygen to support larger fires as well as longer burning, can be very difficult to systematically search, and can take hours to naturally ventilate. These experiments analyze fire growth, smoke filling and smoke removal as it relates to fire fighting activities.

Six fire experiments were conducted in the gymnasium. Four different fan configurations were utilized during the experiments with three different types of fans (Table 35). Three of the experiments used mounted fans and three used portable fans. The fans were all positioned at Fan Location 2 and were started after natural ventilation took place. During some of the experiments, the portable fans were moved inside to the doors between the lobby and the gymnasium. Two ventilation points were used at the rear of the gymnasium as well as an opening in the roof. Each of the rear doors measured 0.9 m (3 ft) wide by 2.1 m (6.9 ft) tall. The roof opening was approximately the same size as a single rear door. The locations of the ventilation points are shown in Figure 21. Note that two sets of double doors were closed and removed from Figure 20 and Figure 21. These two sets of double doors remained closed during the experiments.

4.1. Experimental Procedure

Each experiment began with all of the ventilation points, doors and windows closed, with the exception of the door(s) from the fan location to the lobby. The fuel package was ignited and the fire was allowed to grow for 9 to 14 min depending on fuel load or smoke conditions. This was approximately the time when the smoke layer reached its maximum. Using the interior cameras and thermocouples, it was determined when the smoke layer had dropped to the point where tenability would be compromised. At this time, the structure was ventilated, through either the rear doors of the gymnasium or through the roof opening. The fire was naturally ventilated or positive pressure ventilated, dependent upon the scenario. The effects of different fan configurations were observed and recorded, and then the fire was suppressed. After suppression, the smoke was ventilated with fans and was included in the Section 4.4.3.

Table 35. Gymnasium Fire Experimental Overview

Experiment	Fire Location (Figure 20)	Fan(s)	Fan Location	Fan Configuration
GF7	Center (Orange)	1 – 24	2	Setback 1.8 m (6 ft), 80°
GF8	Center (Orange)	1 – 27	2	Setback 1.2 m (4 ft), 80°
GF9	Center (Orange)	SVU	2	Setback 3.7 m (12 ft), 100°
GF10	Foul Lines (Red)	2 – 27	2	Setback 1.2 m (4 ft), 80°
GF11	Foul Lines (Red)	MVU	2	Setback 6.6 m (21.5 ft), 90°
GF12	Corners (Yellow)	MVU	2	Setback 6.6 m (21.5 ft), 90°

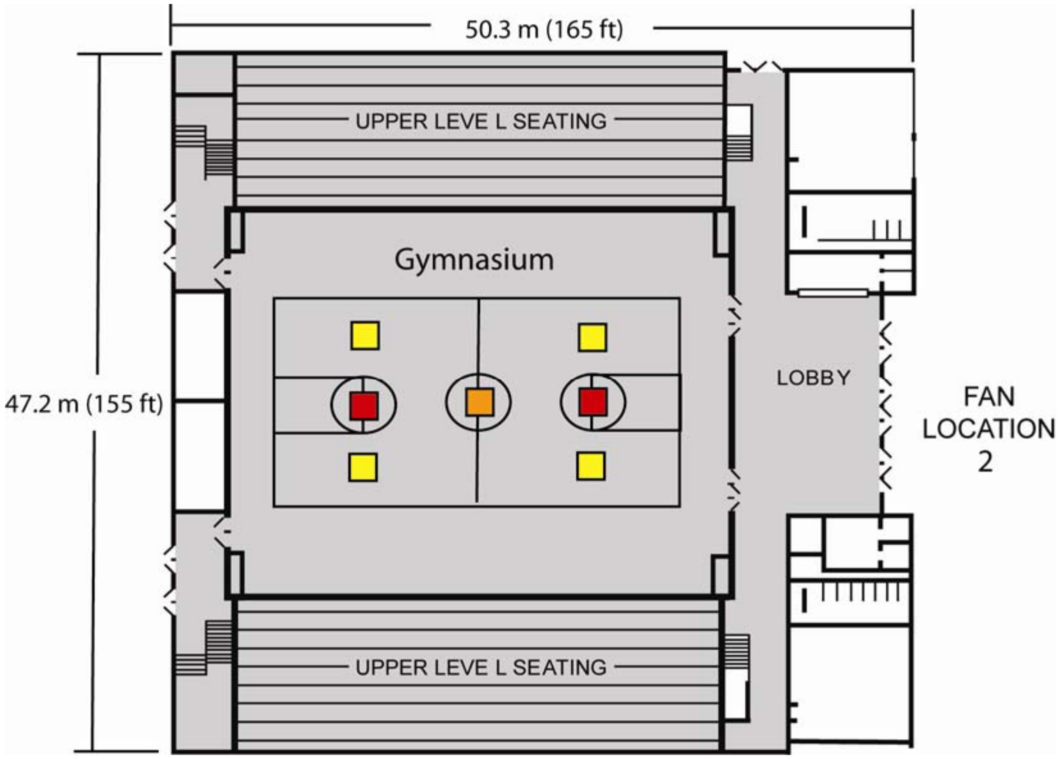

Figure 101. Gymnasium Dimensions and Fuel Load Locations (Color key in Table 35)

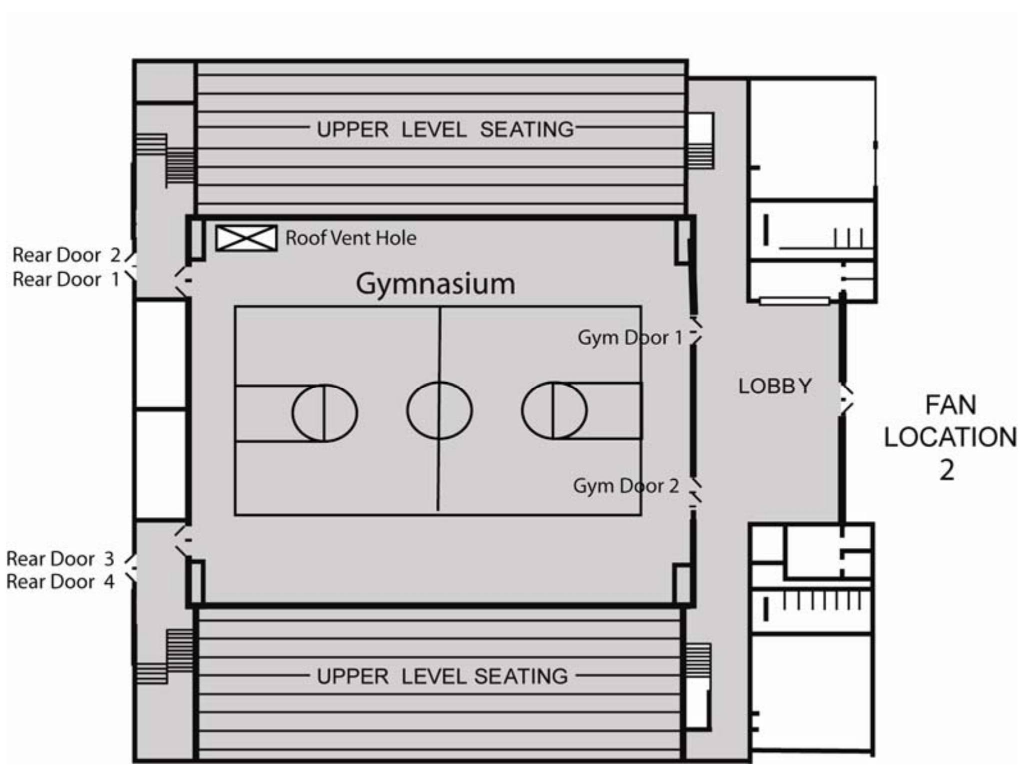

Figure 102. Gymnasium Ventilation Points

4.2. Fuel Load

The fuel load for the gymnasium fire experiments consisted of three components and each fuel load can be seen in Figures 22 through 27. The main component was the wood pallets. The wood pallets were stacked flat as shown in the fuel load figures. The second component was excelsior or shredded wood to allow the electric match ignition source to ignite the pallets. Each experiment utilized excelsior layered between the pallets. The amount of excelsior used is in Table 42. The final component was foam or rubber mats. The foam mats measured 1.5 m x 0.6 m x 0.05 m (4.8 ft x 2 ft x 0.2 ft), weighed 9.0 kg and were used in experiment GF8. Rubber mats were added to experiments GF9 through GF11 to increase the smoke production of the fuel load. The rubber mats in experiment GF9 measured 1.2 m x 1.8 m x 0.02 m (4 ft x 6 ft x 0.05 ft). The rubber mats in experiment GF10 and GF 11 measured 0.9 m x 1.8 m x 0.01 m (3 ft x 6 ft x 0.04 ft). The fuel packages were positioned as shown in Figure 20 and ignited remotely with electric matches positioned at the base of the pallets at the open ends. As a first order estimate, each stack of 6 pallets, without mats, produced a heat release rate of 2.5 MW and a stack of 10 pallets produced 3.5 MW. This is calculated using the correlation from Babrauskas [7] and is consistent with the author's heat release rate experiments in [3]. The estimated heat release rates for each experiment would be 2.5 MW, 5 MW, 10 MW, 10 MW, 10 MW and 56 MW.

Table 42. Gymnasium Fire Fuel Loads

Experiment	Pallets	Stacks	Excelsior (kg)	Mats	Total Pallet Weight (kg)
GF7	6	1	8	None	128.3 (± 0.6)
GF8	12	2	8	6 Foam	224.7 (± 1.1)
GF9	24	4	14.5	6 Rubber	437.4 (± 2.2)
GF10	24	4	16	2 Rubber	456 (± 2.2)
GF11	24	4	16	4 Rubber	441.9 (± 2.2)
GF12	160	16	32	None	2960 (± 14.8)

Figure 103. Experiment GF7 Fuel Load

Figure 104. Experiment GF8 Fuel Load


Figure 105. Experiment GF9 Fuel Load


Figure 106. Experiment GF10 Fuel Load


Figure 107. Experiment GF11 Fuel Load


Figure 108. Experiment GF12 Fuel Load

4.3. Timelines

The timelines of the experimental configuration changes are shown in Tables 36 through 41.

Table 36. Experiment GF7

Time (s)	Event
0	Ignition
840	24 Fan On
960	Rear Door 1 Open
1380	Fan Off (Move Inside)
1500	Fan On
1936	Fan Off
2026	SVU to 2000 rpm
2145	SVU to 4000 rpm
2380	End of Data

Table 37. Experiment GF8

Time (s)	Event
0	Ignition
720	27 Fan On
840	Rear Door 1 Open
1140	Fan Off (Move Inside)
1260	Fan On
1690	Fan Off
1840	SVU 4000 rpm
2180	End of Data

Table 38. Experiment GF9

Time (s)	Event
0	Ignition
612	Roof Vent
780	SVU On
940	SVU Off
1110	MVU On
1110	Rear Door 1, 2 Open
1500	Suppression
1640	End of Data

Table 39. Experiment GF10

Time (s)	Event
0	Ignition
600	Rear Door 1 Open
750	2 – 27 Fans On
900	Rear Door 2 Open
1140	Rear Doors 3, 4 Open
1140	Suppression
1455	Rear Doors 3, 4 Closed
1680	Fans Off (Move Inside)
1740	Fans On
1880	End of Data

Table 40. Experiment GF11

Time (s)	Event
0	Ignition
600	Rear doors 1, 2 Open
720	MVU On
853	Rear doors 3, 4 Open
1080	Suppression
1130	End of Data

Table 41. Experiment GF12

Time (s)	Event
0	Ignition
540	Rear doors 1, 2 Open
600	Rear doors 3, 4 Open
660	MVU On
722	Roof Open
767	Suppression
880	End of Data

4.4. Results

The pressure, temperature and video recordings were analyzed to determine the impact of the various ventilation tactics on the conditions inside the school. Graphs displaying the pressure during the experiment at every measurement point are located in Appendix D (Page 306). Temperature plots versus time are in Appendix E (Page 320). All of these graphs have lines showing the events and when they occurred during the experiment.

4.4.1. Pressure

The pressure was analyzed in the lobby as well as the gymnasium. The fans were placed outside the lobby to pressurize the lobby and prevent smoke and hot gas flow out of the gymnasium into other parts of the school. The fans also increased the pressure in the gymnasium in order to increase the flow out of the rear doors and remove smoke and heat to improve tenability.

The pressure transducers in the gymnasium were located at 1.2 m, 3.0 m, 4.9 m and 6.7 m (4 ft, 10 ft, 16 ft and 22 ft) above the floor. There were two vertical arrays of transducers, one on the side closest to the fan and one on the side opposite the fan (Figure 28). The transducers in the lobby were located as shown in Figure 28 and were 1.2 m (4 ft) above the floor.

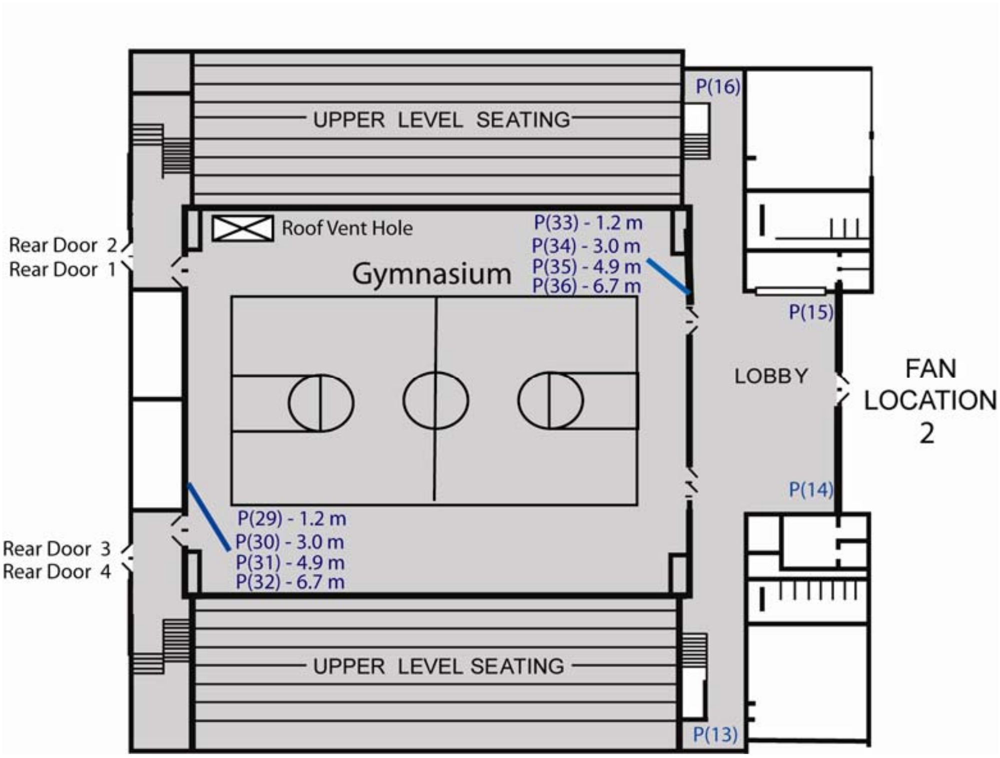

Figure 109. Gymnasium Pressure Measurement Locations

Table 43 shows the peak gymnasium experiment pressures in the lobby and in the gymnasium prior to activation of the fans. A door from the gym to the lobby was open as well as the door from the lobby to the fan location. The lobby had no pressure increase for the small fuel load, slight pressure increases for the moderate fuel loads and a large pressure increase for the ventilation limited fire in GF12. The pressure peaks inside the gymnasium also increased with fuel load as would be expected. Experiment GF7's pressure increased to 11 Pa, and GF8's gymnasium pressure was 19 Pa. GF9 through GF11 had similar fuel loads and similar pressures of approximately 30 Pa. The last experiment had pressures of 75 Pa prior to a ventilation limited condition that had temperatures high enough to damage all of the transducers, so the pressures reported for GF12 are assumed to be underestimations, because they were already compromised by the time the fire reached its peak output. The peak pressures corresponded to the filling of the gymnasium with combustion products, with the higher pressures at the upper level transducers.

Table 43. Peak Gymnasium Experiment Pressures Prior to Ventilation

Experiment	Lobby (Pa)	Gymnasium (Pa)
GF7	0 (± 0.0)	11 (± 1.1)
GF8	3 (± 0.3)	19 (± 1.9)
GF9	5 (± 0.5)	32 (± 3.2)
GF10	7 (± 0.7)	30 (± 3.0)
GF11	7 (± 0.7)	30 (± 3.0)
GF12	33 (± 3.3)	75 (± 7.5)

After ventilation, the pressures became a combination of the pressure created by the fire and the pressure created by the fans. Table 44 has the average lobby pressures with the fan operating. It is important to note that several fan configurations were used during each experiment, and for the experiments with multiple configurations listed, the first configuration tested was closest to the time of peak fire output. Therefore, the contribution to total pressure was the greatest earlier in the experiment.

Each of the fans was able to create pressures that forced the products of combustion back through the lobby into the gymnasium, improving conditions in the lobby. All of the fans created higher pressures in the gymnasium, which increased the flow out of the ventilation points (Table 45). Since the volume of the lobby was not very large as compared to the gymnasium, moving fans inside to the interior gymnasium doorways did not provide substantially higher pressures. The ability of a single portable to fan to produce elevated pressures for a volume of this magnitude is not very effective. Adding a second fan in parallel approximately doubled the pressure increase, and using a mounted fan approximately tripled the pressures created by the two portable fans in this building.

Table 44. Average Lobby Pressures

Experiment	Fan Configuration	Average Lobby Pressures with Fans Operating (Pa)	
		Unventilated	Ventilated out Rear Gym Doors
GF7	24 Fan Outside	17 (± 1.7)	8 (± 0.8) (1 Door)
	24 Fan Inside	NA	NA
	SVU (2000 RPM)	NA	35 (± 3.5) (1 Door)
	SVU (4000 RPM)	NA	75 (± 7.5) (1 Door)
GF8	27 Fan Outside	14 (± 1.4)	11 (± 1.1) (1 Door)
	27 Fan Inside	NA	NA
	SVU (4000 RPM)	NA	50 (± 5.0) (1 Door)
GF9	SVU	65 (± 6.5) (Roof Open)	80 (± 8.0) (Roof and 2 Doors Open)
GF10	2 – 27 Fans Outside	NA	25 (± 2.5) (1 Door)
			18 (± 1.8) (2 Doors)
			17 (± 1.7) (4 Doors)
	2 – 27 Fans Inside	NA	NA
GF11	MVU	NA	70 (± 7.0) (2 Doors)
			65 (± 6.5) (4 Doors)
GF12	MVU	NA	80 (± 8.0) (4 Doors)

Table 45. Average Gymnasium Pressures

Experiment	Fan Configuration	Average Gymnasium Pressures with Fans Operating (Pa)	
		Unventilated	Ventilated out Rear Gym Doors
GF7	24 Fan Outside	20 (± 2.0)	7 (± 0.7) (1 Door)
	24 Fan Inside	NA	8 (± 0.8) (1 Door)
	SVU (2000 RPM)	NA	15 (± 1.5) (1 Door)
	SVU (4000 RPM)	NA	35 (± 3.5) (1 Door)
GF8	27 Fan Outside	14 (± 1.4)	11 (± 1.1) (1 Door)
	27 Fan Inside	15 (± 1.5)	10 (± 1.0) (1 Door)
	SVU (4000 RPM)	NA	30 (± 3.0) (1 Door)
GF9	SVU	75 (± 7.5) (Roof Open)	70 (± 7.0) (Roof and 2 Doors Open)
GF10	2 – 27 Fans Outside	NA	30 (± 3.0) (1 Door)
			20 (± 2.0) (2 Doors)
			10 (± 1.0) (4 Doors)
	2 – 27 Fans Inside	NA	15 (± 1.5) (2 Doors)
GF11	MVU	NA	50 (± 5.0) (2 Doors)
			30 (± 3.0) (4 Doors)
GF12	MVU	NA	NA

4.4.2. Temperature

In the first five gymnasium experiments the purpose was to fill the gymnasium with combustion products and examine the ability of the fan to remove them. The last experiment, GF12, examined the impact of ventilation on a very large ventilation limited fire. Thermocouple arrays were placed in the lobby and in the gymnasium to examine the fans ability to cool as it forced out the combustion products. The thermocouple array locations are in Figure 29. Temperature measurement locations in the gymnasium were every 0.3 m (1 ft) from the bottom of the roof deck for the top 1.8 m (6 ft) of the array and then every 0.6 m (2 ft) below that, down to 0.9 m (3 ft) above the floor. There was a fire rated drop ceiling that was 1.2 m (4 ft) below the roof deck so the 1.2 m (4 ft) measurement point was right below the drop ceiling. Complete temperature versus time graphs with event markers are provided in Appendix E (Page 320).

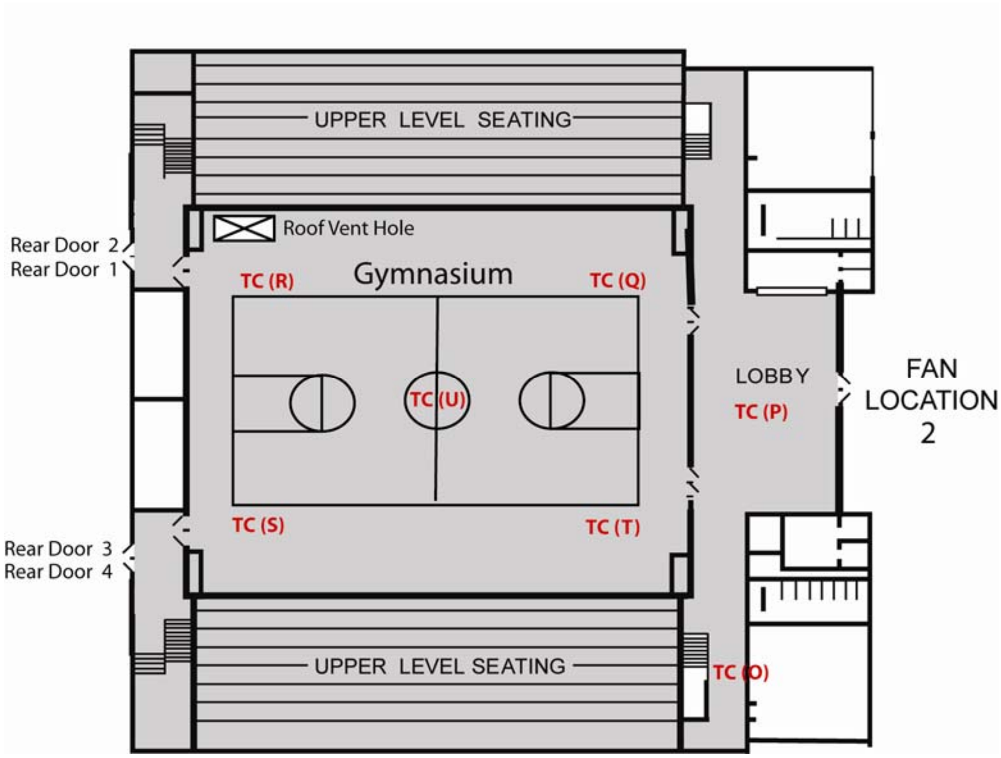

Figure 110. Gymnasium Temperature Measurement Locations

In these scenarios, the lobby acts like the hallways did in the classroom fire experiments. It is potentially a contaminated and heated path for the fire fighters to get to the fire room. In order to increase fire fighter safety it is desired to have the lobby area free of heat in order to have a safe area in which to perform operations but also to isolate the hazard from the rest of the structure increasing tenability of any occupants that may be in the other sections of the building, allowing them to shelter safely in place. Table 46 shows the impact of the ventilation configurations on the temperatures in the lobby. In experiments GF7 and GF8, no combustion products reached the lobby and therefore there was no temperature increase. Experiments GF9 through GF11 had similar fuel loads and positive impacts from ventilation. Ventilating the roof of the gymnasium, utilizing 2 portable fans and utilizing a mounted fan all forced the heat back into the gymnasium lowering the temperatures in the lobby to near ambient. The final experiment utilized a mounted fan on a ventilation-limited, high temperature fire. The lobby was untenable due to the temperature threshold for occupants down to 0.9 m (3 ft) above the floor prior to ventilation. The fan quickly lowered that temperature from 140 ^oC (285 ^oF) to ambient.

Table 46. Ventilation Effects on Lobby Temperature

Experiment	Vent Configuration	Prior to Ventilation	After Ventilation	Difference
		^oC	^oC	^oC
GF7	24 in. Fan Outside	24	24	0
GF8	27 in. Fan Outside	27	26	-1
GF9	Roof Vent	65	35	-30
GF10	2 – 27 in. Fans Outside	50	28	-22
GF11	MVU	65	30	-35
GF12	MVU	140	30	-110

The gymnasium had a large foot print (33.5 m x 26.1 m [110 ft x 86 ft]) and a high ceiling (7.0 m [23 ft]) which allowed for a long smoke filling time. In this particular scenario, as is common in many gymnasiums, there was seating on both sides that extended all the way to the ceiling. This allows for a life hazard very quickly as opposed to someone on the floor of the gymnasium that might have 20 min before the products of combustion reach their height. In order to analyze the impact of the temperature on possible occupants the same criterion will be used as was used in the classroom fire analysis. Rapid skin burns would occur at 100 °C (212 °F), and 150 °C (302 °F) was the exposure temperature at which escape was not considered to be likely [8].

Tables 47 through 52 show the impact of the ventilation on the temperatures throughout the gymnasium. Temperatures are shown for each height measured from the bottom of the roof deck. The table provides the peak temperatures, the temperatures just prior to ventilation, the temperatures a certain time after ventilation and the impact as determined by the difference of the temperature just prior to ventilation from the temperature at a certain time after ventilation. The time after ventilation varied based on fire behavior and whether other ventilation configurations were used. The impact of each of the ventilation techniques and fans was isolated as best as possible.

The four thermocouple arrays that were in the gymnasium were located symmetrically in reference to the fuel packages and therefore had similar readings independent of location. The temperature values in the tables were an average of the same elevation from each of the four arrays. While the ventilation mostly took place near arrays Q and R, the temperatures at arrays S and T tracked very closely.

The first two experiments had smaller fuel loads, so their temperatures did not get very high, therefore the impact of the fans was minimal. Although the impact was minimal it had a positive impact on lowering the temperatures throughout the gymnasium. In both of these experiments, temperatures remote from the fire reached levels that would be dangerous to occupants, especially higher up in the bleachers. These higher elevations were also where the fans had the best impact on cooling (Tables 47 and 48).

The next three experiments, GF9 through GF11, had similar fuel loads and similar resulting temperatures prior to ventilation. The upper half of the gymnasium exceeded the 150 °C (300 °F) exposure temperature at which escape was not likely and the lower half of the gymnasium, down to 1.2m (4 ft) above the floor, exceeded 100 °C (210 °F) where rapid skin burns could occur. In GF9, the roof was opened to ventilate and the temperatures in the lower portion of the gymnasium decreased slightly, but had little improvement on tenability. After 170 s of roof ventilation, the SVU was turned on to ventilate through the roof. This configuration decreased the average temperature in the gymnasium by 28 ^{o}C (50 ^{o}F) which lifted the 100 °C (210 °F) tenability threshold 1.8 m (6 ft) (Table 49).

Experiment GF10 utilized two 27 in portable fans ventilating out of two open rear doors. At 200 s after ventilation the average gymnasium temperature dropped 30 °C (54 °F). This lifted the 100 °C (210 °F) tenability threshold 1.8 m (6 ft). This also returned the entire gymnasium to or below the 150 °C (300 °F) threshold for tenability (Table 50).

Experiment GF11 utilized the MVU, ventilating out of two open rear doors. At 200 s after ventilation, the average gymnasium temperature dropped 32 °C (58 °F). This lifted the 100 °C

(210 °F) tenability threshold 1.2 m (4 ft). This also returned the entire gymnasium to below the 150 °C (300 °F) threshold for tenability (Table 51).

Experiment GF12 was different from the previous experiments. This experiment utilized a very large fire load of 160 pallets in order reach a ventilation-limited condition in the gymnasium. The wooden bleachers and foam pads on the walls also contributed to the fire package. Prior to ventilation, the entire gymnasium was in excess of 200 °C (390 °F) with ceiling temperatures in excess of 700 °C (1290 °F) (Table 52). These temperatures exceed those compatible with life of any occupants. Even with 4 doors open in the rear of the gymnasium and 2 doors open in the front of the gymnasium the fire remained ventilation-limited. Activating the MVU and opening the roof of the gymnasium provided enough oxygen to drive the gymnasium to flashover. Temperatures in the entire gymnasium increased to approximately 700 °C (1290 °F). These temperatures declined quickly with the commencement of suppression.

The single portable fans positioned outside cooled the gymnasium at a rate of approximately 3 ^{o}C/min to 6 ^{o}C/min. The mounted fans and the two portable fans in parallel cooled the gymnasium at the rate of 8 ^{o}C/min to 15 ^{o}C/min. These rates are based on the ventilation of the gymnasium in the decay stage of the fire.

Table 47. Average Gymnasium Temperatures for Experiment GF7 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (^{o}C)	At Ventilation (^{o}C)	200 s After Ventilation (^{o}C)	Impact of Ventilation (^{o}C)
Roof Deck				
0.02	30	30	30	0
0.15	32	32	32	0
0.3	32	32	32	0
0.6	32	32	32	0
0.9	32	32	32	0
Drop Ceiling				
1.2	98	75	63	-12
1.5	100	80	65	-15
1.8	92	75	65	-10
2.4	68	65	60	-5
3.0	60	57	55	-2
3.7	50	50	52	+2
4.3	45	45	45	0
4.9	38	38	42	+4
5.5	36	36	38	+2
6.1	34	34	32	-2
6.7	32	32	32	0
7.3	30	30	30	0
Floor				

Table 48. Average Gymnasium Temperatures for Experiment GF8 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (°C)	At Ventilation (°C)	200 s After Ventilation (°C)	Impact of Ventilation (°C)
Roof Deck				
0.02	53	53	60	+7
0.15	53	53	58	+5
0.3	50	50	51	+1
0.6	50	50	51	+1
0.9	50	50	51	+1
Drop Ceiling				
1.2	180	137	118	-19
1.5	185	137	118	-19
1.8	175	137	118	-19
2.4	140	130	110	-20
3.0	118	118	103	-15
3.7	110	110	97	-13
4.3	100	97	90	-7
4.9	87	85	80	-5
5.5	76	76	62	-14
6.1	70	70	51	-19
6.7	62	62	51	-11
7.3	50	50	45	-5
Floor				

Table 49. Average Gymnasium Temperatures for Experiment GF9 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (°C)	At Ventilation Roof Opened (°C)	170 s After Roof Open (°C)	160 s After SVU (°C)	Impact of Roof Open (°C)	Impact of SVU (°C)
Roof Deck						
0.02	65	65	70	80	+5	+10
0.15	65	65	70	90	+5	+20
0.3	60	60	70	85	+10	+15
0.6	60	60	70	85	+10	+15
0.9	60	60	70	85	+10	+15
Drop Ceiling						
1.2	230	230	220	175	-10	-45
1.5	230	230	220	175	-10	-45
1.8	210	210	210	175	0	-35
2.4	200	200	190	175	-10	-15
3.0	170	170	175	170	5	-5
3.7	160	160	160	145	0	-15
4.3	152	152	150	120	-2	-30
4.9	145	145	140	85	-5	-55
5.5	130	130	120	75	-10	-45
6.1	118	118	105	65	-13	-40
6.7	105	105	88	65	-17	-23
7.3	75	75	60	65	-15	+5
Floor						

Table 50. Average Gymnasium Temperatures for Experiment GF10 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (^oC)	At Ventilation (^oC)	200 s After Ventilation (^oC)	Impact of Ventilation (^oC)
Roof Deck				
0.02	52	52	54	+2
0.15	55	55	55	0
0.3	53	53	54	+1
0.6	53	53	54	+1
0.9	53	53	55	+2
Drop Ceiling				
1.2	205	185	150	-35
1.5	205	185	150	-35
1.8	195	180	150	-30
2.4	180	175	150	-25
3.0	165	160	140	-20
3.7	155	150	130	-20
4.3	152	150	130	-20
4.9	145	140	125	-15
5.5	140	125	95	-30
6.1	130	120	70	-50
6.7	125	115	60	-55
7.3	105	80	60	-20
Floor				

Table 51. Average Gymnasium Temperatures for Experiment GF11 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (^oC)	At Ventilation (^oC)	200 s After Ventilation (^oC)	Impact of Ventilation (^oC)
Roof Deck				
0.02	50	51	52	+1
0.15	50	52	55	+3
0.3	48	52	55	+3
0.6	48	52	55	+3
0.9	48	52	55	+3
Drop Ceiling				
1.2	215	190	145	-45
1.5	218	190	145	-45
1.8	205	185	142	-43
2.4	190	175	138	-37
3.0	168	160	134	-26
3.7	155	155	130	-25
4.3	145	148	125	-23
4.9	140	140	110	-30
5.5	125	130	92	-38
6.1	120	120	82	-38
6.7	100	90	72	-18
7.3	80	70	56	-14
Floor				

Table 52. Average Gymnasium Temperatures for Experiment GF12 (Uncertainty 15%)

Measurement Below Roof Deck (m)	Peak Before Ventilation (°C)	At Ventilation (°C)	200 s After Ventilation (°C)	Impact of Ventilation (°C)
Roof Deck				
0.02	120	120	700	+580
0.15	140	140	700	+560
0.3	120	120	700	+580
0.6	120	120	700	+580
0.9	120	120	700	+580
Drop Ceiling				
1.2	710	680	700	+20
1.5	720	690	700	+10
1.8	560	560	700	+140
2.4	510	470	700	+230
3.0	430	410	700	+290
3.7	390	370	700	+330
4.3	370	350	700	+350
4.9	350	330	700	+370
5.5	320	300	700	+400
6.1	310	270	700	+430
6.7	300	250	700	+450
7.3	230	220	700	+480
Floor				

4.4.3. Smoke/Visibility Observations

In many of the gymnasium experiments, the smoke layer descended to the floor level. Visibility was obstructed throughout the gymnasium, which would compromise the ability of occupants to evacuate and slow the fire fighters search of the area. Occupants with reduced visibility from smoke may become disoriented, lost or slow down, which all increase their exposure to toxic gases and reduce their chances of getting out of the structure safely. Fire fighters searching for both occupants and the seat of the fire can be slowed greatly, especially when faced with large open areas and multiple levels. A systematic approach, using search lines to effectively search the gymnasium is very time consuming and searching the many levels of bleachers on both sides of the gymnasium is very labor and resource intensive with reduced visibility.

Each experiment was recorded with eight cameras located inside and outside the structure, six visual and two thermal imaging. These views, combined with the data, facilitated the event changes and allowed the smoke and heat movement to be analyzed. Figure 111 shows the camera locations for the gymnasium fires and their labels, which are used in the timeline images at the end of the section. Images were captured every four min and at times when an important event occurred such as the activation of a fan or opening of a ventilation point.

The temperature displayed in the top right view of the thermal imaging images is the average surface temperature of the object or objects within the crosshairs in the center of the image. The camera has a fixed emissivity of 0.95 [10] which is representative of most surfaces found in the field of view of the thermal imaging camera. This temperature is not the gas temperature.

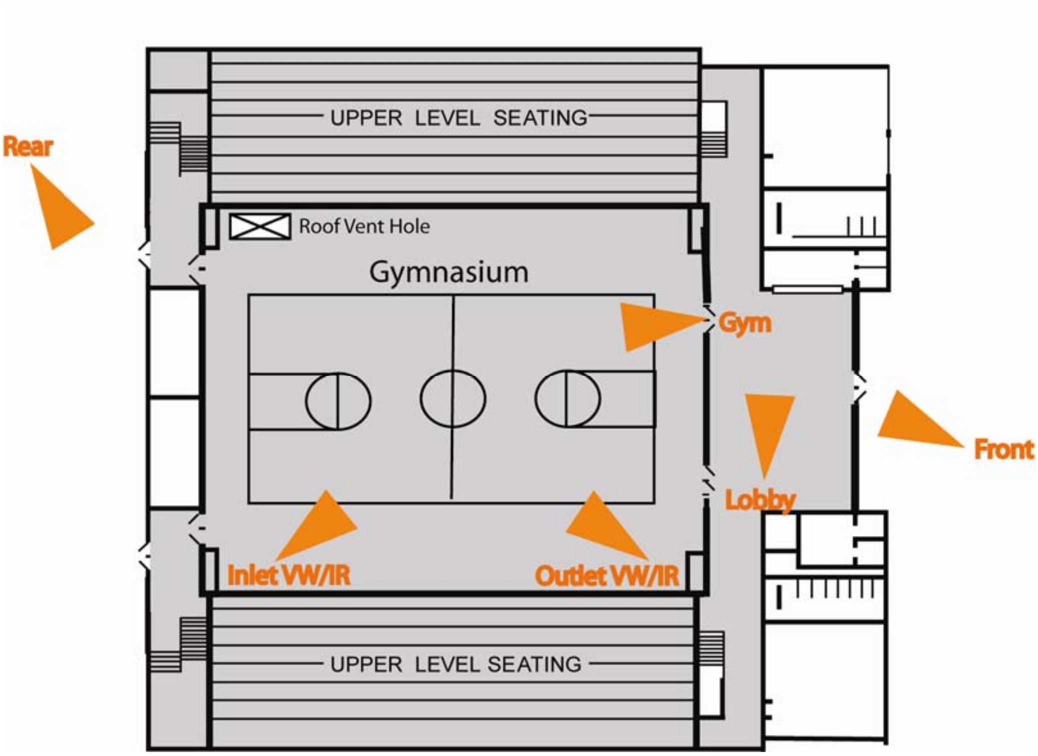

Figure 111. Gymnasium video view labels and directions.

Experiment GF7 (Figures 112 – 120)

This experiment had a small fuel load for the space, approximately 2.5 MW, and therefore produced very little smoke. The flames never reached the ceiling and there was not a lot of heat build-up in the upper layer as seen on the thermal imaging cameras. By 16 min, the fire had greatly diminished but a haze of smoke could be seen throughout the gymnasium. At 32 min, this haze was reduced but still evident. No smoke entered the lobby during the experiment.

Experiment GF8 (Figures 121 – 129)

Experiment GF8 used a similar fuel load to that of the classroom fire experiments, with foam mats for more smoke production. By 4 min, the flames were reaching close to the ceiling and a smoke layer was forming. At 12 min, just prior to ventilation, the fire had burned down and there was limited visibility in the gymnasium. It was possible to make out the rear gym door but it was difficult to see up into the upper level seating. By 28 min, there was a slight lift in the smoke layer but visibility was still poor and there was large volumes of smoke still in the gymnasium.

Experiment GF9 (Figures 130 - 140)

This experiment had a fuel load that was double that of the previous experiment, approximately 5 MW, and rubber mats were used in place of the foam mats for even more smoke production. At 8 min, visibility had been greatly decreased and it was no longer possible to see across the gymnasium to the rear doors. By 10 min the fuel load was burned down to rubble and visibility had decreased to the point where the fire load in the middle of the gymnasium couldn't be seen from the entrance. Right after these images the roof was opened. At 12 min the roof had been opened for 2 min and visibility had not improved. At 13 min the SVU was started and it was forcing air out through the roof vent. The images at 14 min show the impact of this configuration for 1 min. The smoke was cleared from the lobby area and the smoke layer in the gymnasium was lifting slightly and the fuel load could be seen. Twenty seconds prior to 16 min the SVU had a mechanical malfunction, was shut off, and ventilation was only out of the roof. By 16 min visibility was improved further but the rear doors still couldn't be seen. At 18 min and 30 s, the MVU was in place and functioning and 2 rear gymnasium doors were opened to supplement the roof as exit points for ventilation. It's not that until 32 min one really sees an impact with the lobby free of smoke and visibility returning in the gymnasium. There was still a large amount of smoke that needed to be evacuated at 32 min into this evolution.

Experiment GF10 (Figures 141 – 149)

This experiment had a similar fuel load as GF9 but instead of being in the center of the gym it was split between the two foul lines because of ceiling degradation in the center of the gymnasium. Four min after ignition the smoke layer descended to the top of the doorways so that smoke was entering the lobby. At 8 min, the lobby was obscured and the rear doors of the gymnasium were no longer visible. By 12 min, there was little visibility in the lobby and smoke was coming out through the front fan location doors.

At 16 min, the 2 portable fans were operating for 3.5 min. The lobby was clear of smoke and both fire locations were visible in the gymnasium. By 24 min, the rear doors to the gymnasium were visible from the inlet side. At 32 min, the fans had been running for approximately 17 min and the smoke layer was elevated, but there was still a significant amount of smoke in the gymnasium.

Experiment GF11 (Figures 150 – 157)

The fuel load for this experiment was similar to the previous experiment so the initial fire growth and smoke spread was similar. In the first 4 min the smoke layer descended down to door height allowing smoke to flow into the lobby. At 8 min the lobby is mostly obscured, both fires were still visible in the gymnasium but the rear doors were not visible from the "GYM" view. Just prior to activation of the MVU the second fire was no longer visible and the fires were burned down significantly. After 4 min of ventilation the lobby was clearing and the second fire was visible again in the "GYM" view. By 24 min, the lobby was clear and the rear doors of the gymnasium were all easily visible. At 28 min, 16 min into ventilation and 10 min after suppression, visibility was greatly improved but there was still a considerable haze of smoke throughout the top half of the gymnasium.

Experiment GF12 (Figures 158 – 173)

Experiment GF12 was conducted to examine extreme fire conditions in a large volume that was ventilation limited. The fuel load for this experiment consisted of 16 stacks of 10 pallets distributed throughout the gymnasium as shown in Figure 101 with an estimated heat release rate of 56 MW. At 4 min, the 4 fire locations had flames reaching the ceiling and there were significant amounts of smoke flowing out of the front fan location doorways. By 8 min there were still 4 individual plumes and the gymnasium had become ventilation limited with some detached flames. Nine min after ignition visibility was decreased and the views of the thermal imaging cameras were changing as the plastic connectors on their tripods were melting. By10 min 2 rear doors had been open for a min and white smoke was flowing out of the rear doors as well as the front doors. Visibility in the gymnasium was greatly decreased but one could see the fire closest to the inlet doorway. There was zero visibility in the rest of the gymnasium. The views at 11 min were the conditions prior to the MVU being turned on. There is little visibility in the lobby and the gymnasium, just white smoke throughout. At 12 min the fan has been flowing through the front doors and ventilating out of the 4 open rear gymnasium doorways. The lobby was clearing and the flames were visible in the gymnasium again. At 12 min and 2 seconds the roof was opened to try to slow down flashover but accomplished the opposite. At 12 min and 7 seconds the gymnasium was transitioning to flashover and all of the views in the gymnasium were lost due to camera failure. The smoke transitioned from white to dark black and the flames were spreading across the floor to the inlet doors.

At 12 min 30 seconds, the flow was forced back through the lobby by the MVU and lobby conditions were greatly improved and the glow of the fire could be seen at the interior door to the gymnasium. Seventeen seconds later, a 64 mm (2.5 in) hose line was directed into the interior gymnasium doorway. By 14 min, the smoke was changing to gray and by 15 min, the fire was mostly extinguished and the volume of smoke was diminished. While there was a haze in the lobby, visibility was such that fire crews could see each other throughout the lobby. At 16 min, mostly steam was being ventilated out of the rear and top of the structure. By 24 min, the lobby visibility completely returned and the fire was under control.

Experiment GF7 Video Images

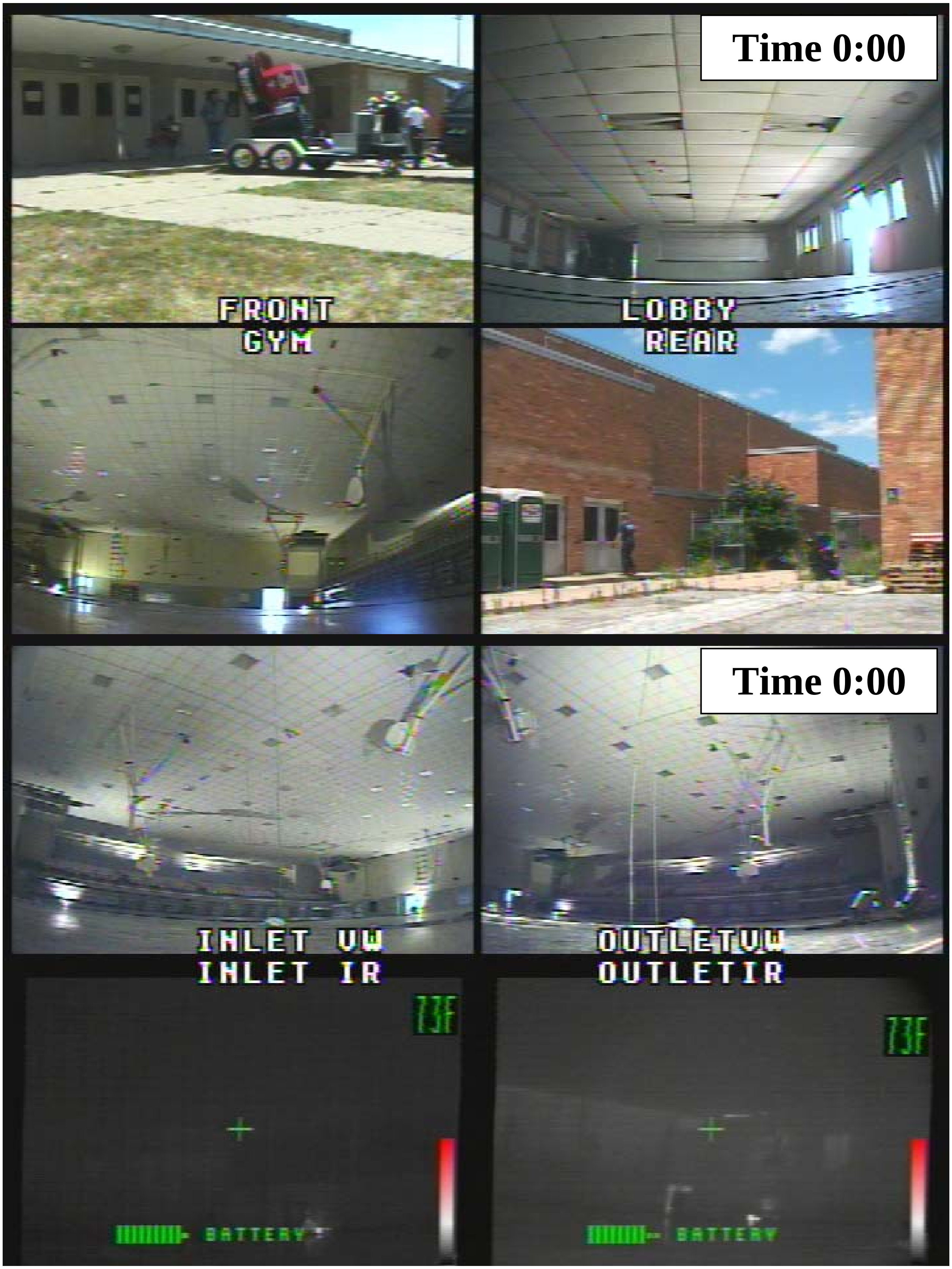

Figure 112. Experiment GF7 video images captured at 0 min

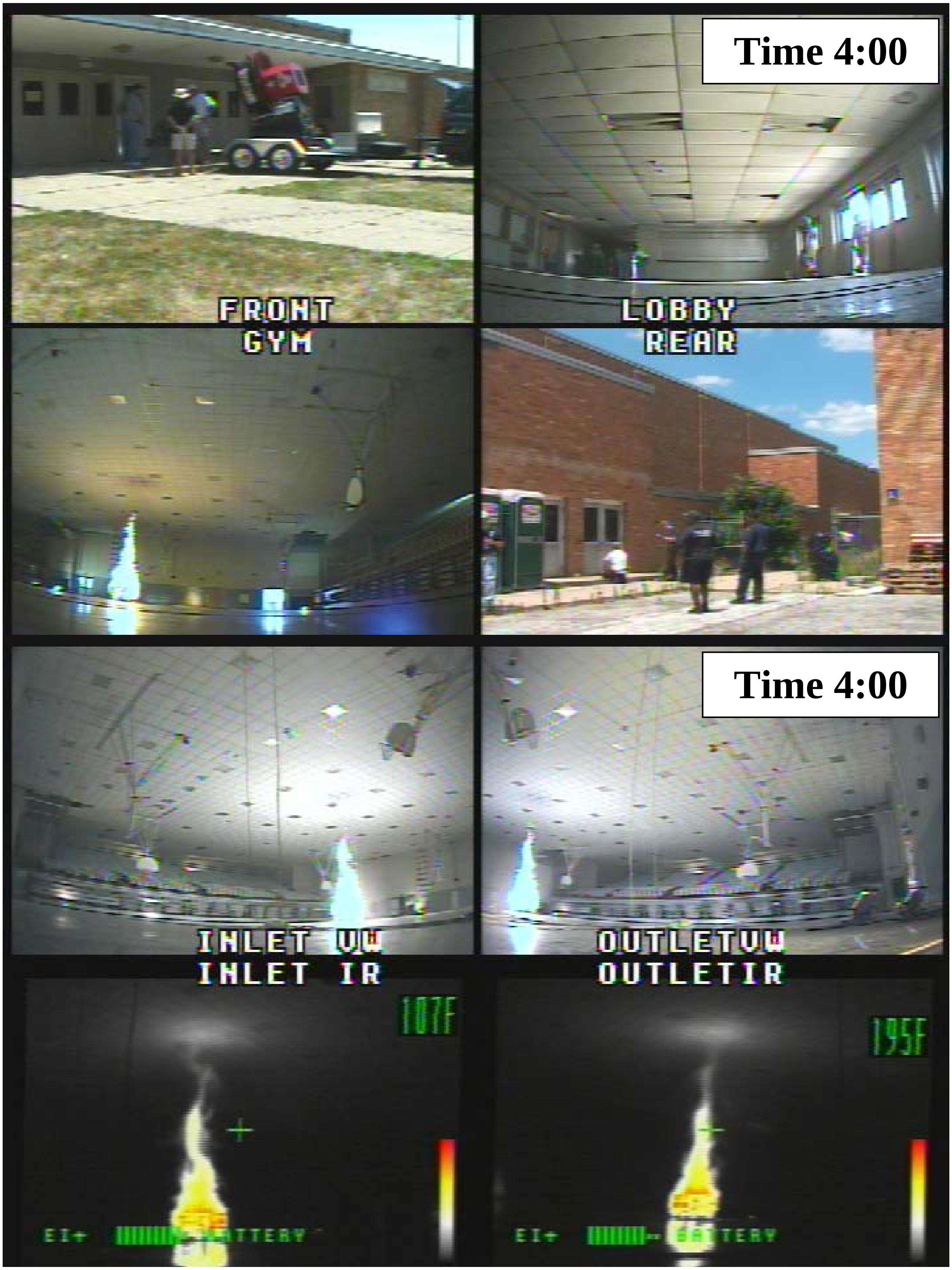

Figure 113. Experiment GF7 video images captured at 4 min

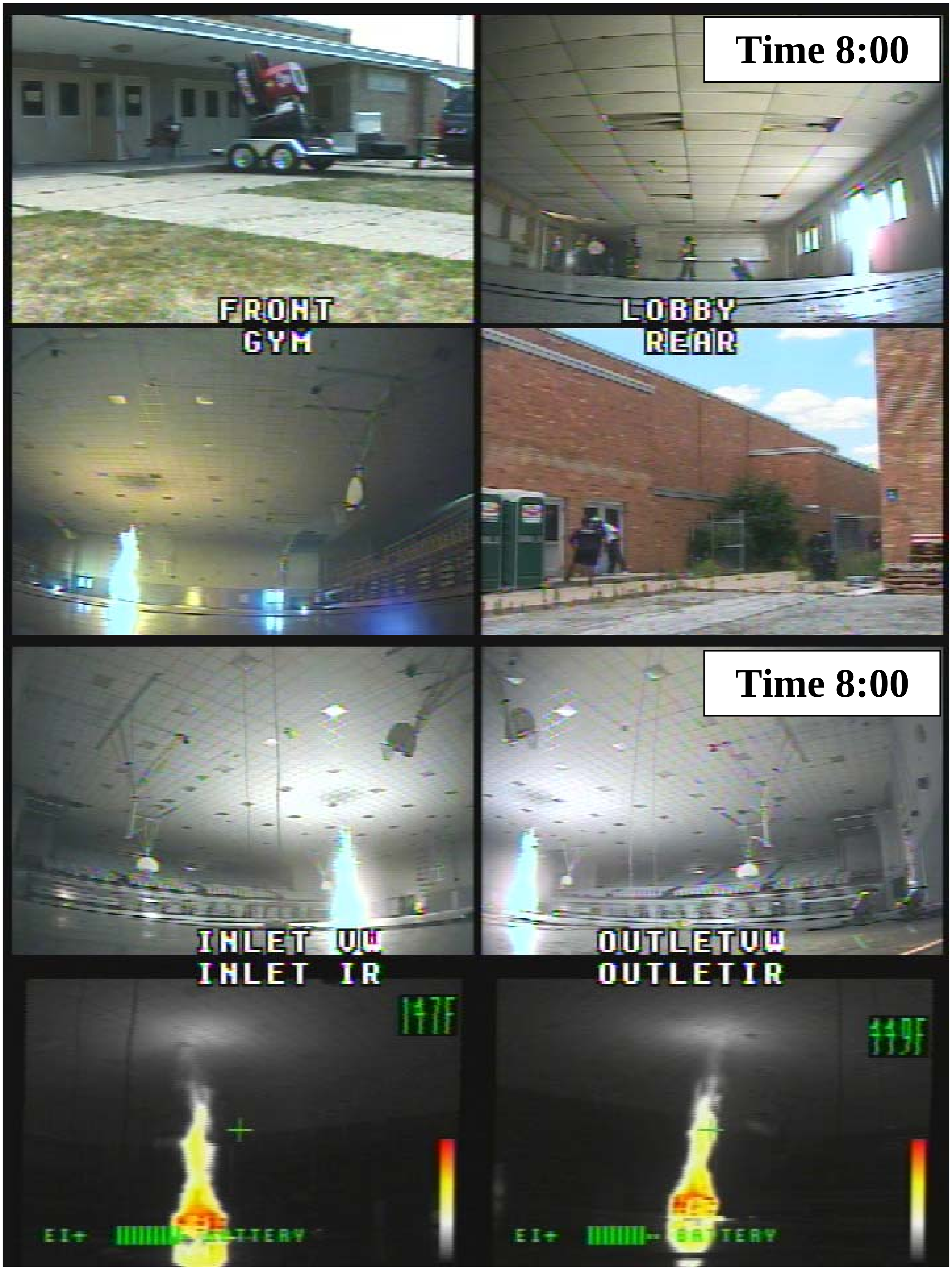

Figure 114. Experiment GF7 video images captured at 8 min

Figure 115. Experiment GF7 video images captured at 12 min

Figure 116. Experiment GF7 video images captured at 16 min

Figure 117. Experiment GF7 video images captured at 20 min

Figure 118. Experiment GF7 video images captured at 24 min

Figure 119. Experiment GF7 video images captured at 28 min

Figure 120. Experiment GF7 video images captured at 32 min

Experiment GF8 Video Images

Figure 121. Experiment GF8 video images captured at 0 min

Figure 122. Experiment GF8 video images captured at 4 min

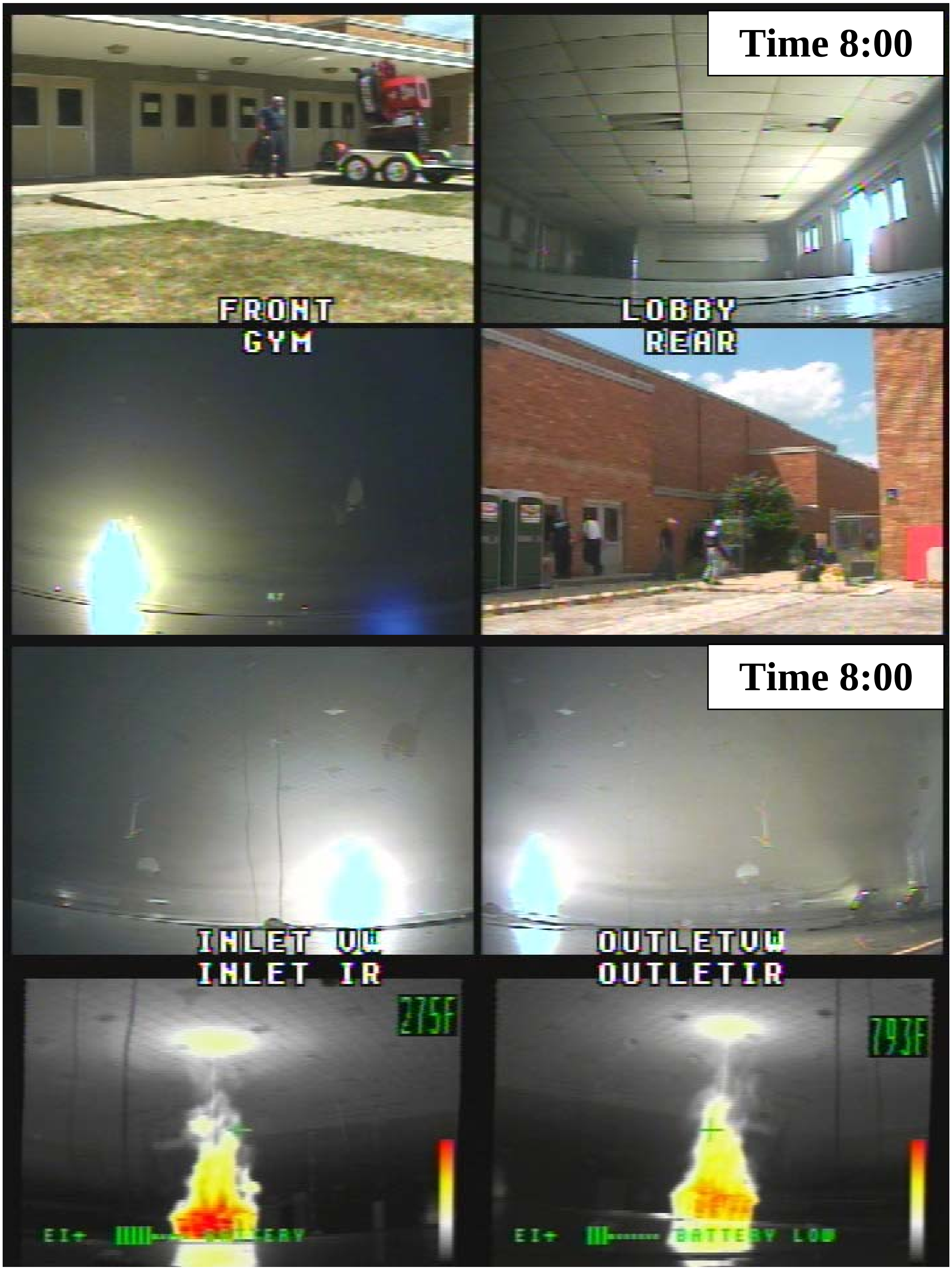

Figure 123. Experiment GF8 video images captured at 8 min

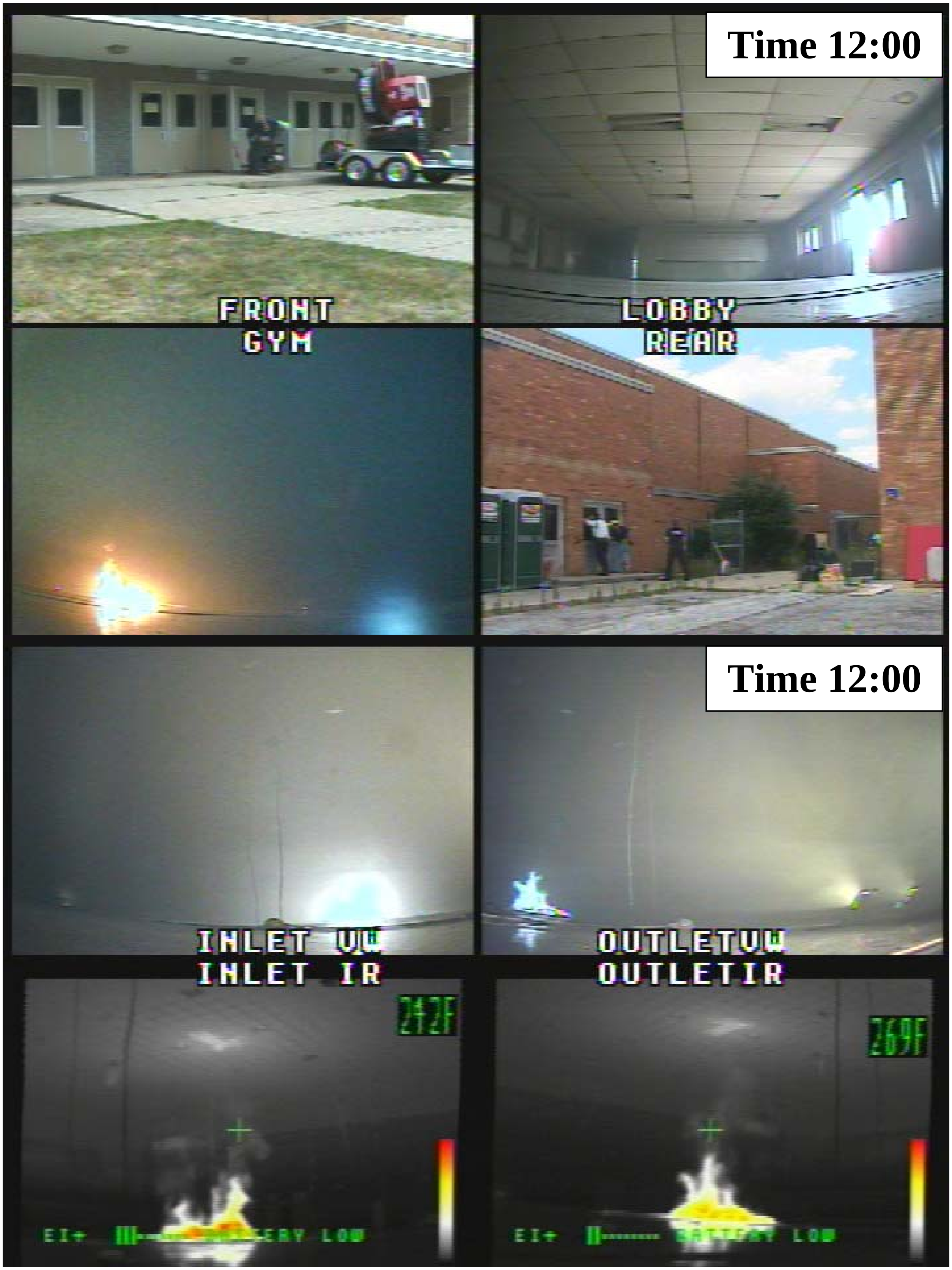

Figure 124. Experiment GF8 video images captured at 12 min

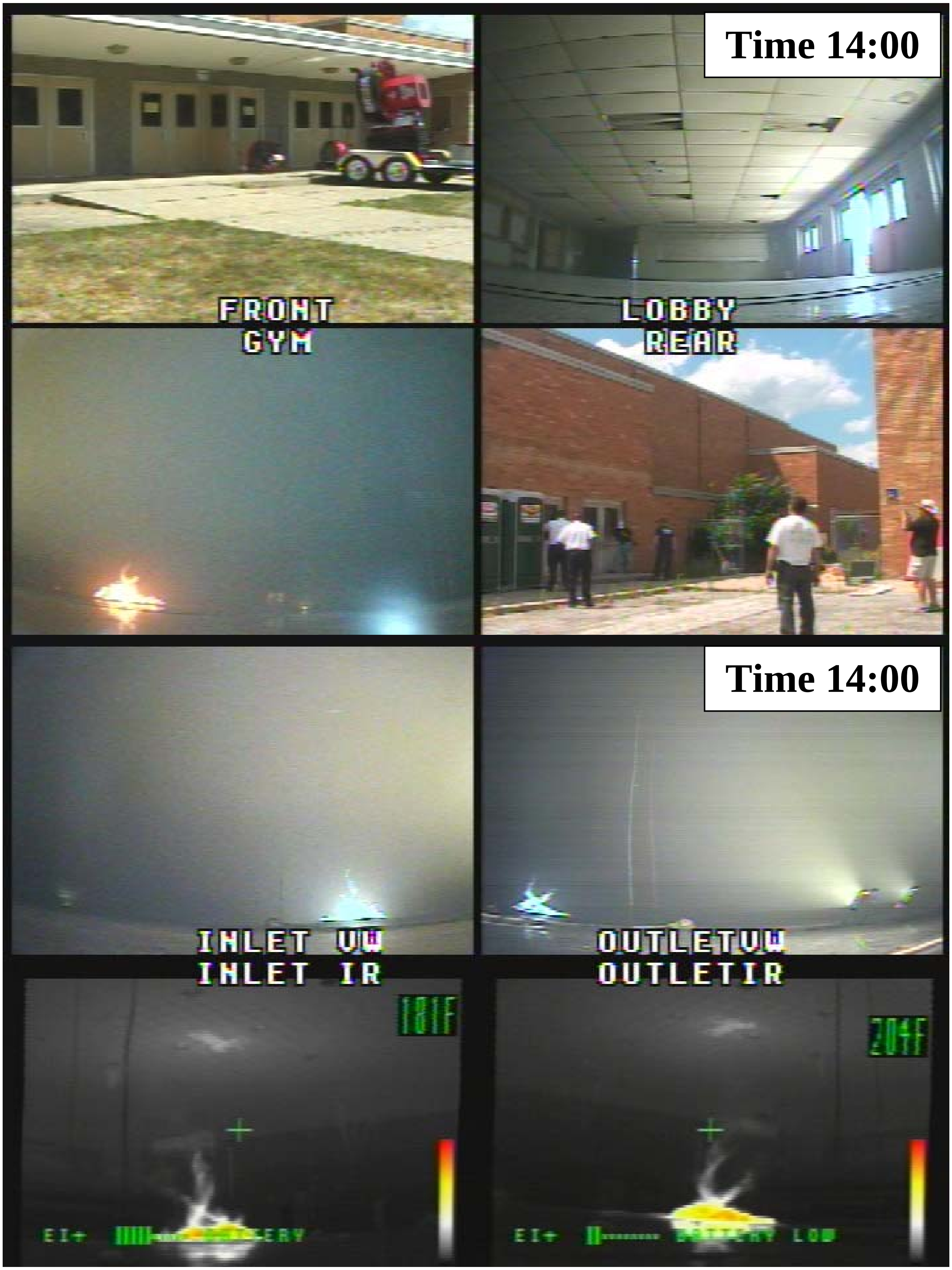

Figure 125. Experiment GF8 video images captured at 14 min

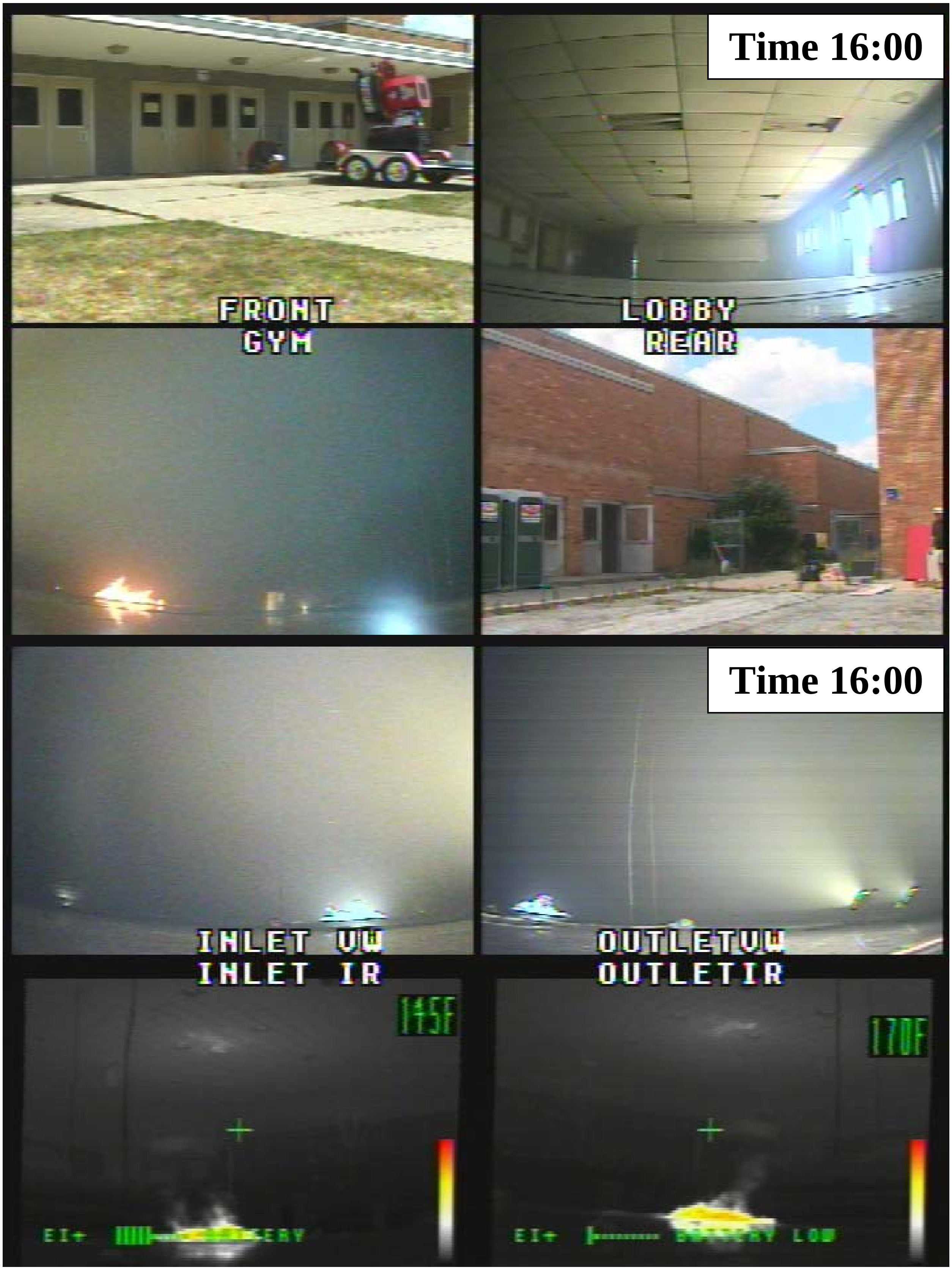

Figure 126. Experiment GF8 video images captured at 16 min

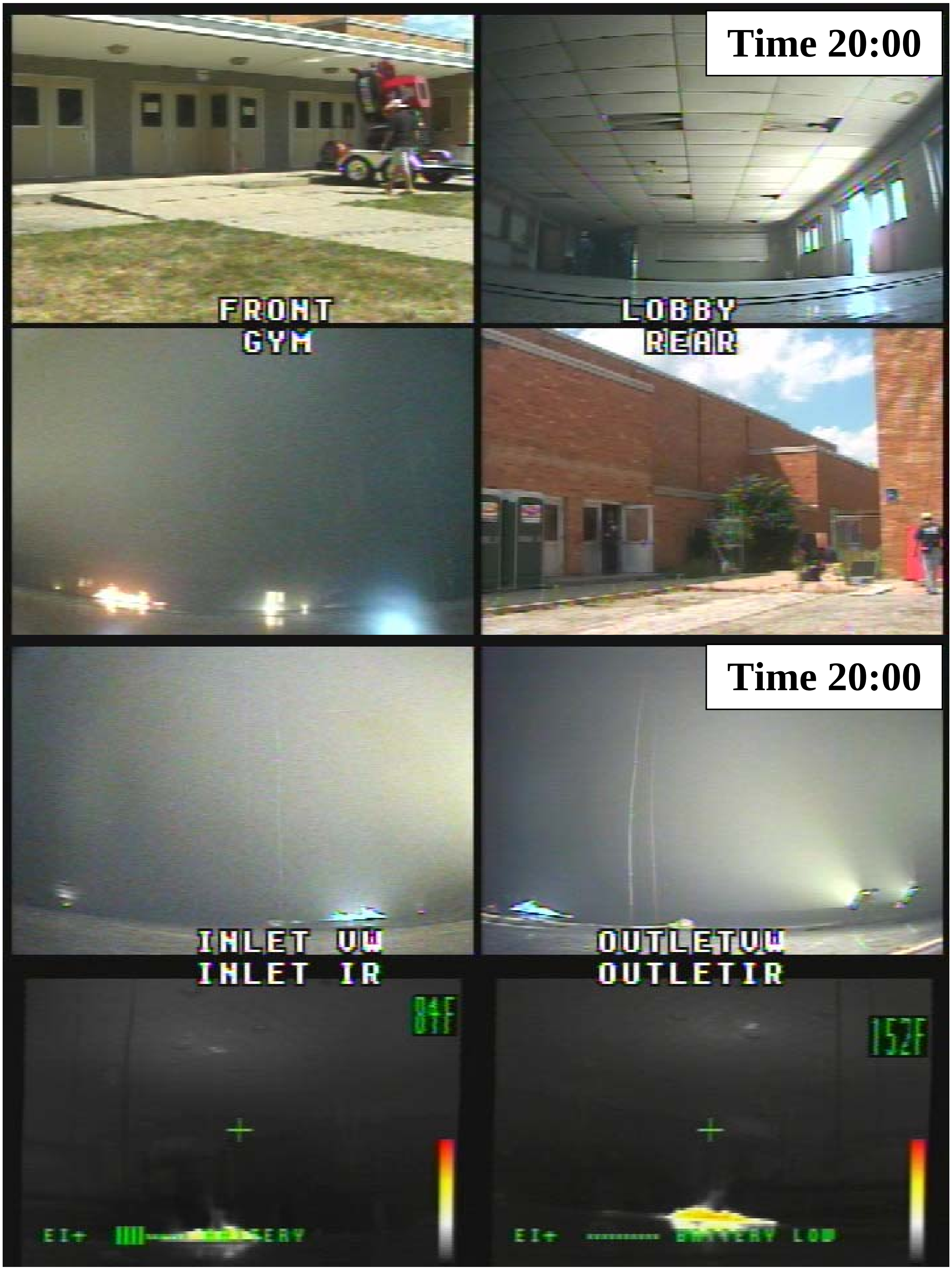

Figure 127. Experiment GF8 video images captured at 20 min

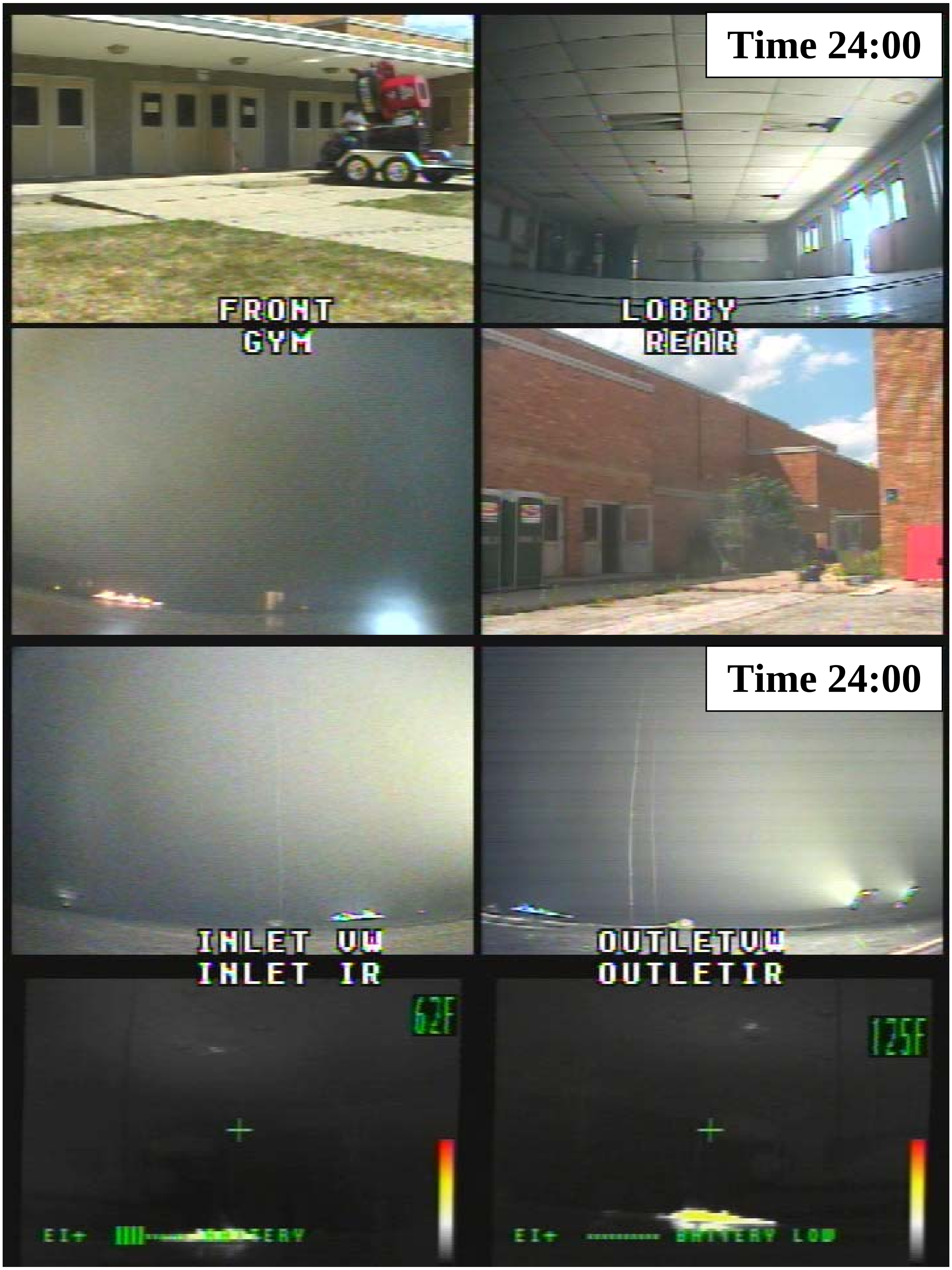

Figure 128. Experiment GF8 video images captured at 24 min

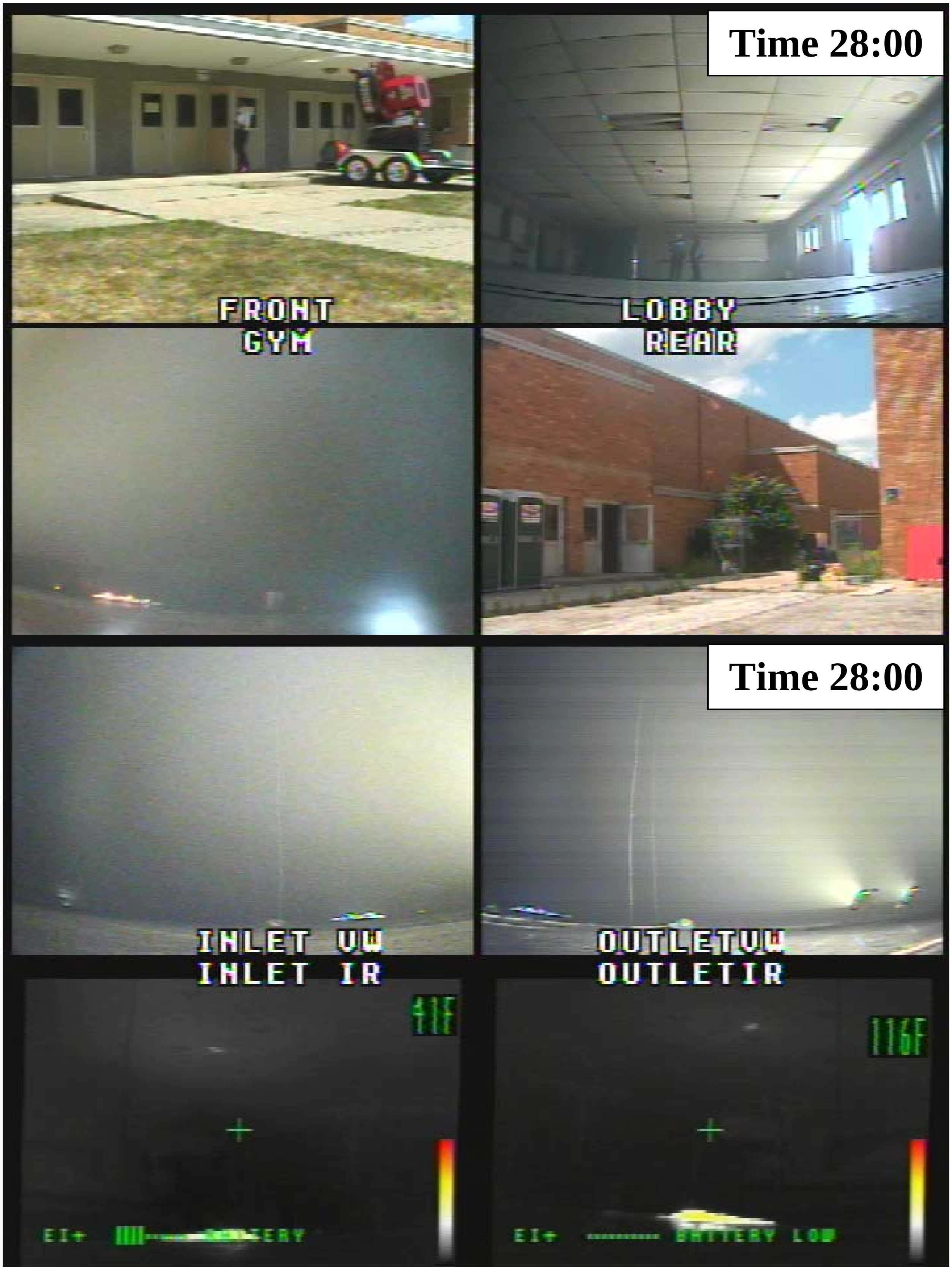

Figure 129. Experiment GF8 video images captured at 28 min

Experiment GF9 Video Images

Figure 130. Experiment GF9 video images captured at 0 min

Figure 131. Experiment GF9 video images captured at 4 min

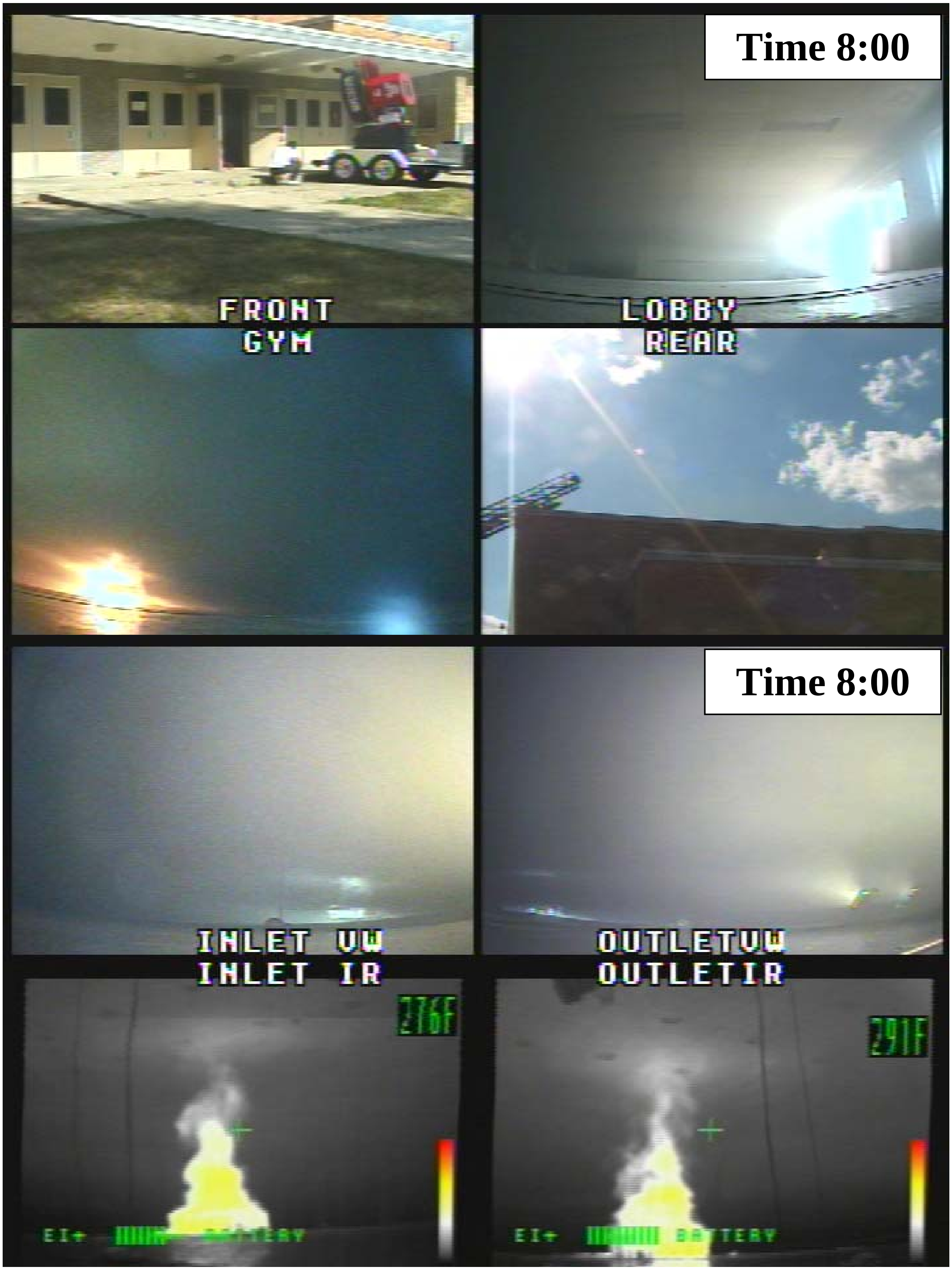

Figure 132. Experiment GF9 video images captured at 8 min

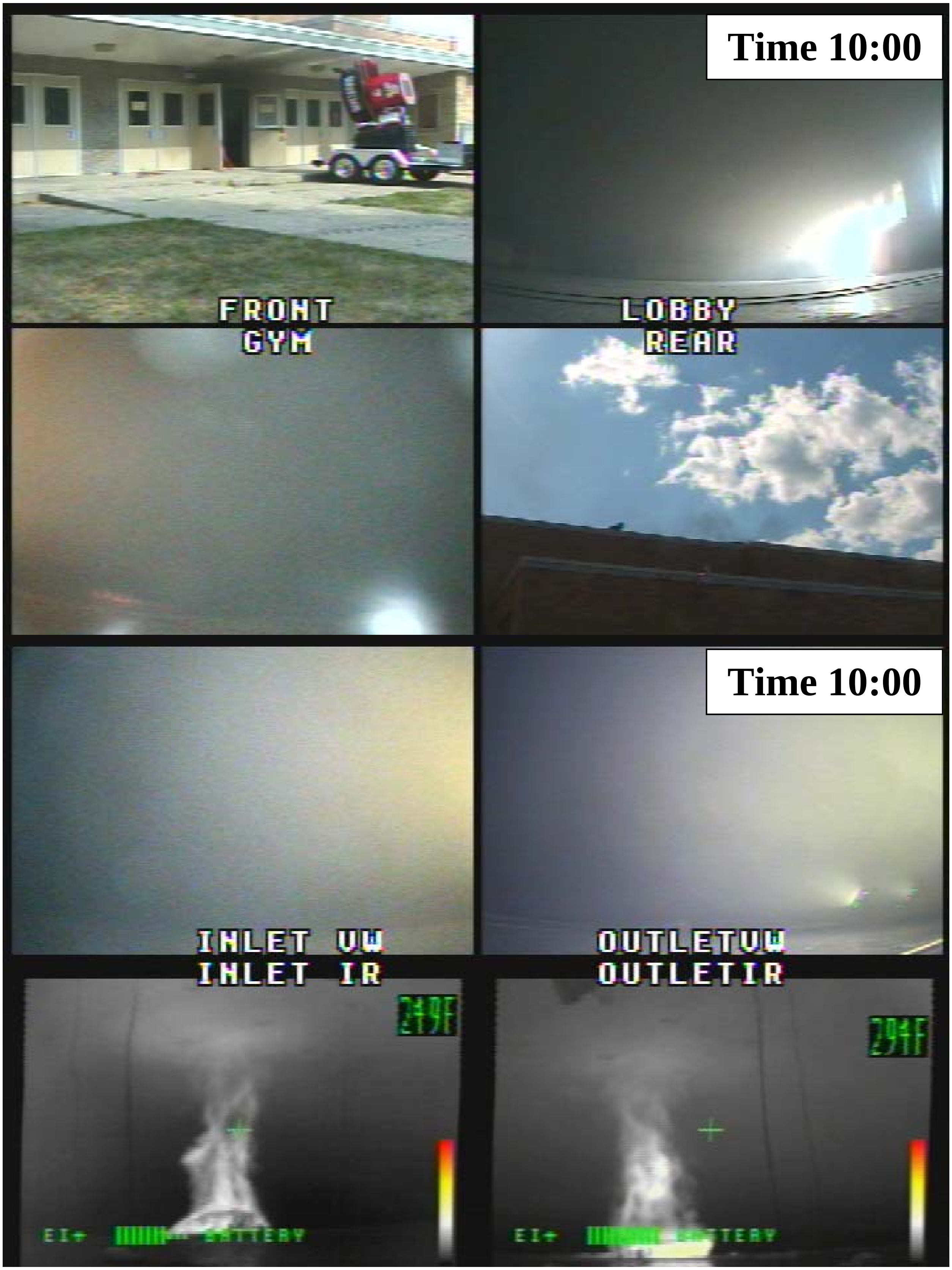

Figure 133. Experiment GF9 video images captured at 10 min

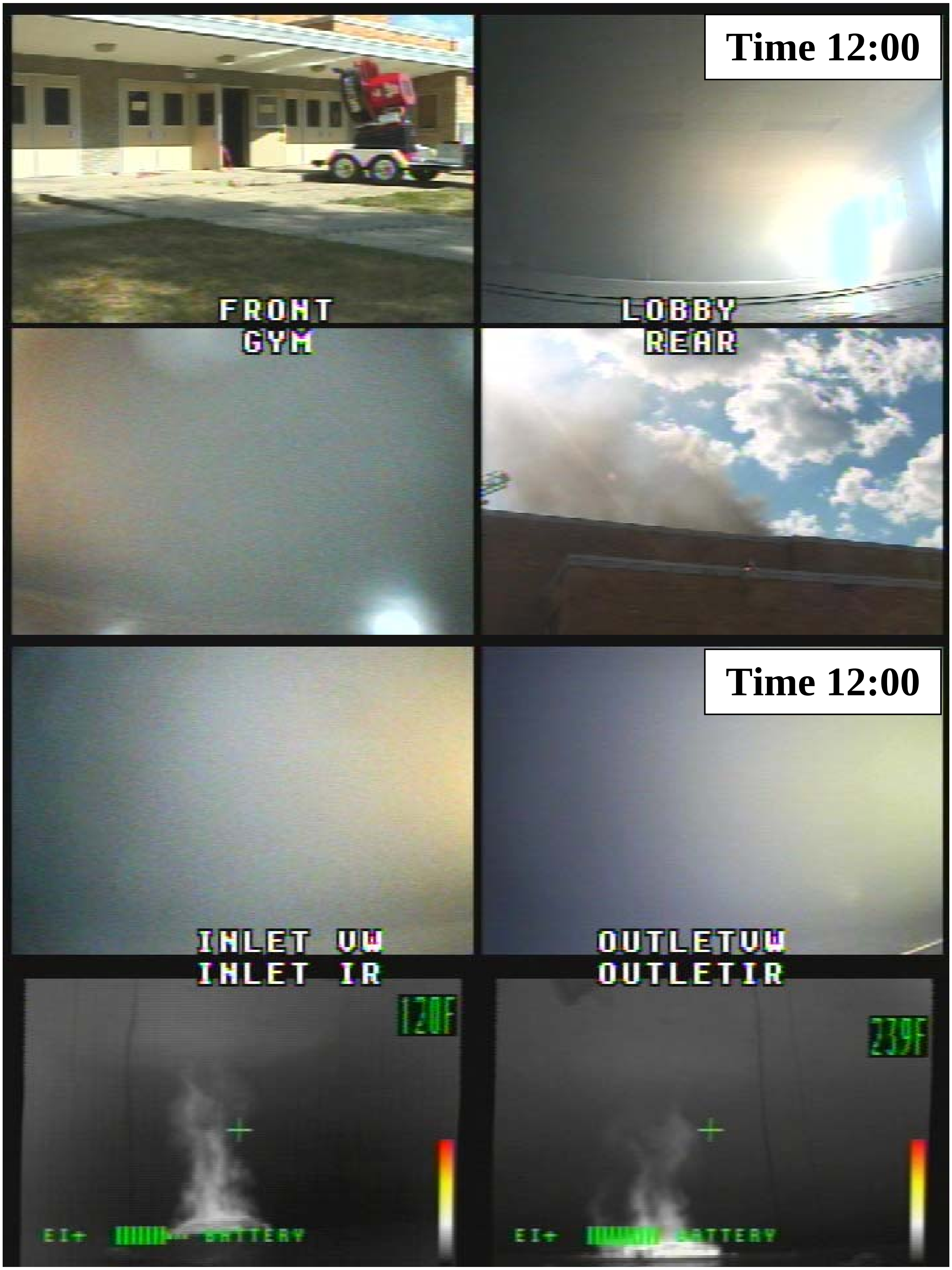

Figure 134. Experiment GF9 video images captured at 12 min

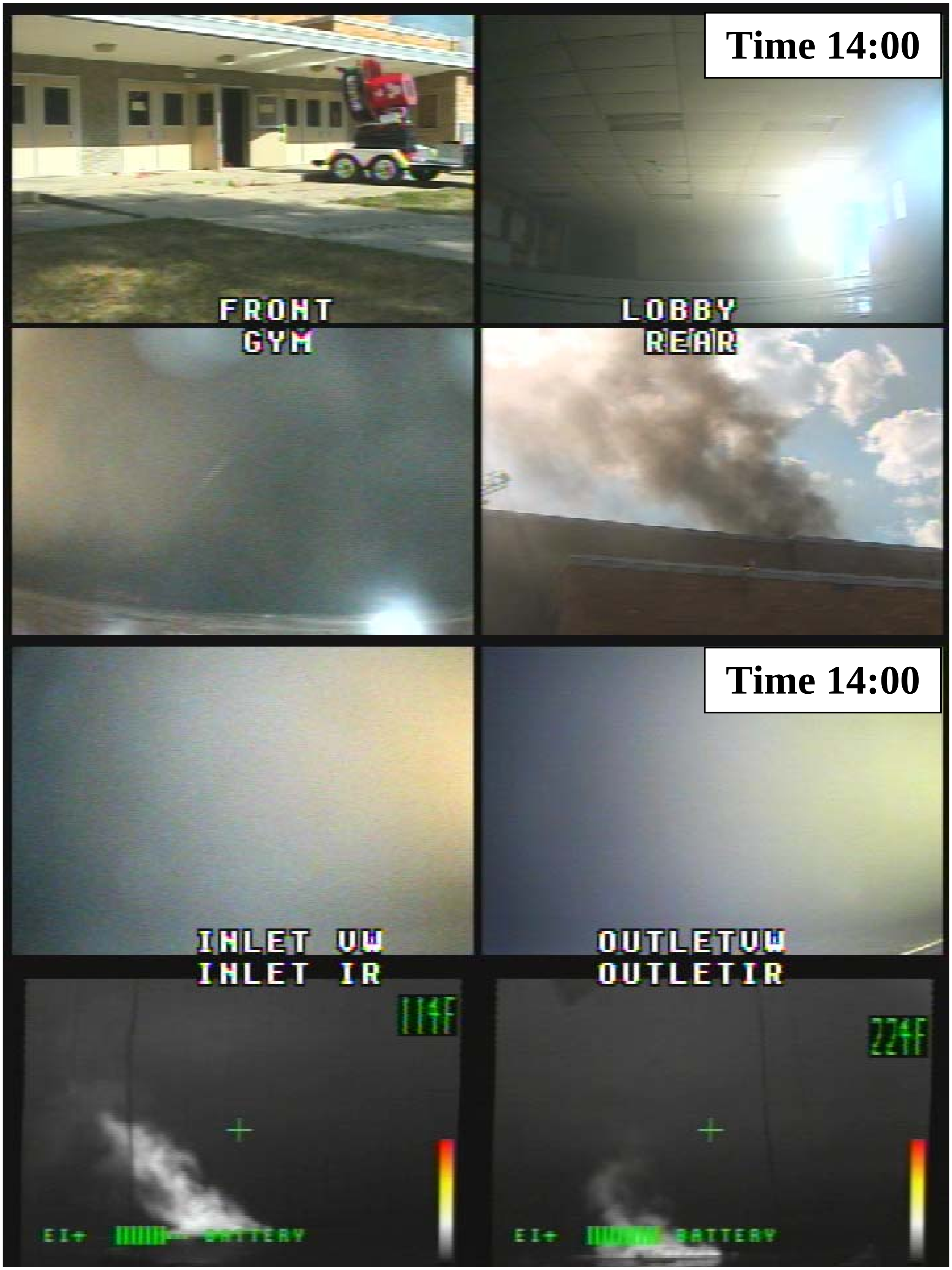

Figure 135. Experiment GF9 video images captured at 14 min

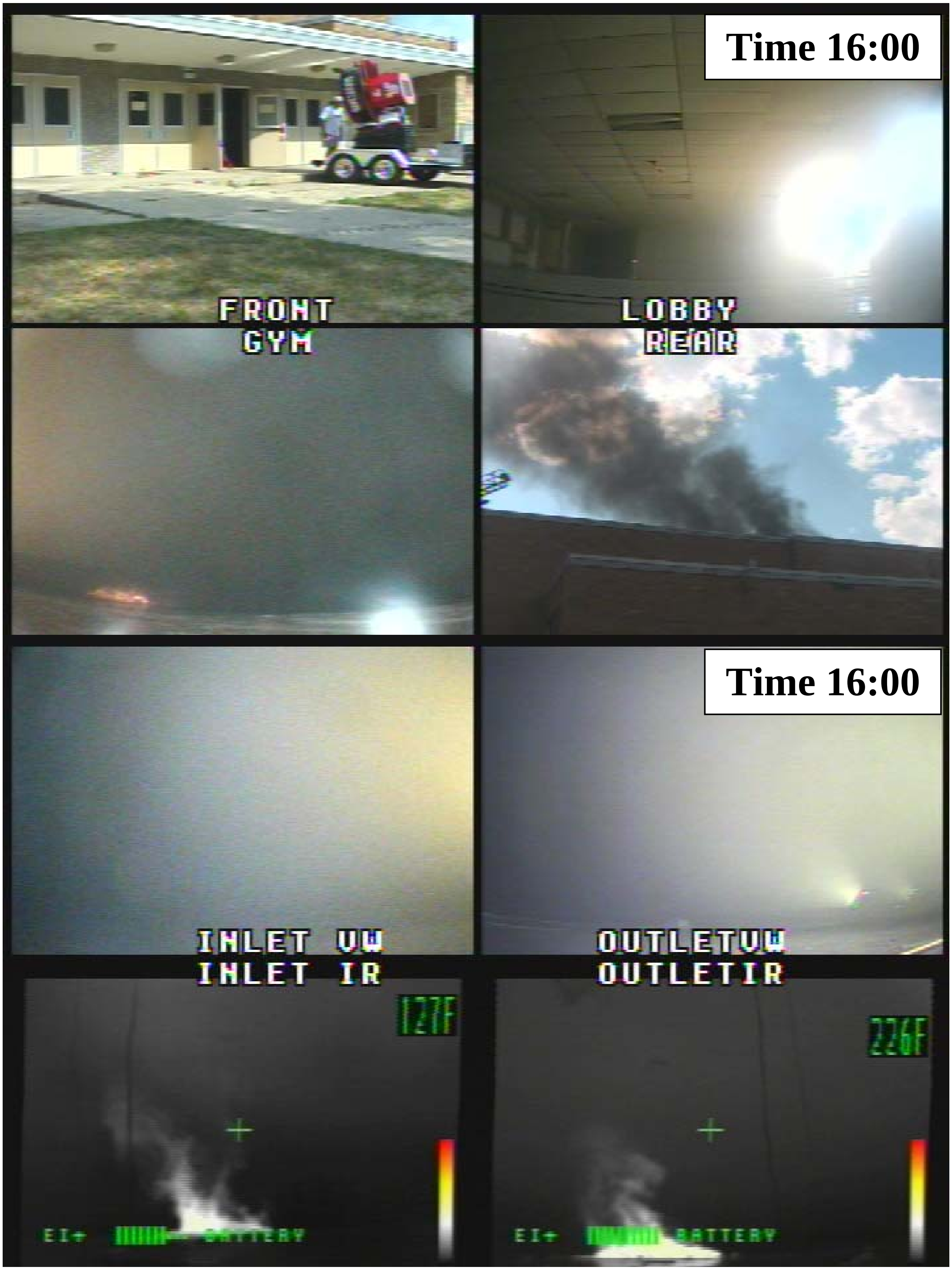

Figure 136. Experiment GF9 video images captured at 16 min

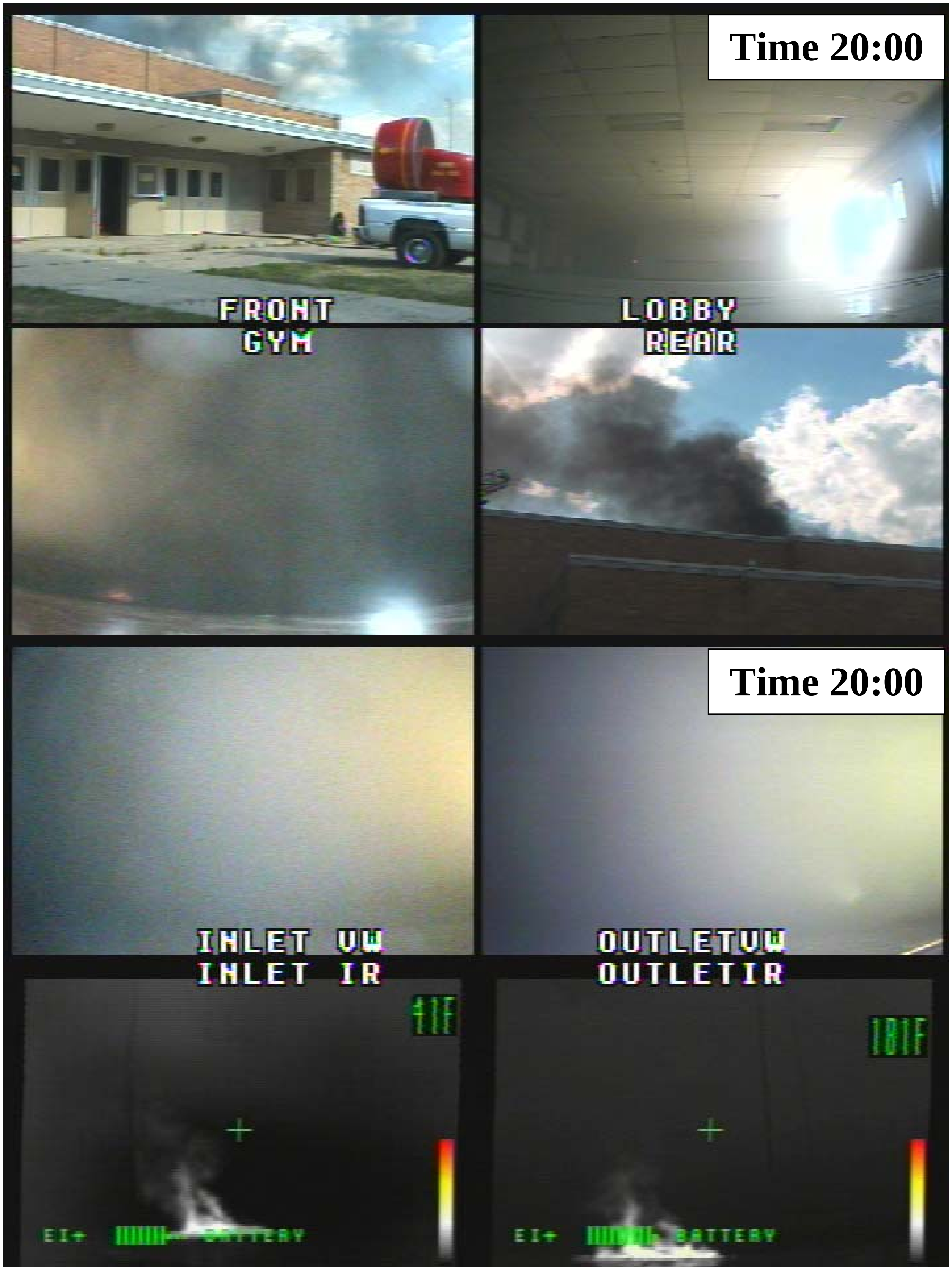

Figure 137. Experiment GF9 video images captured at 20 min

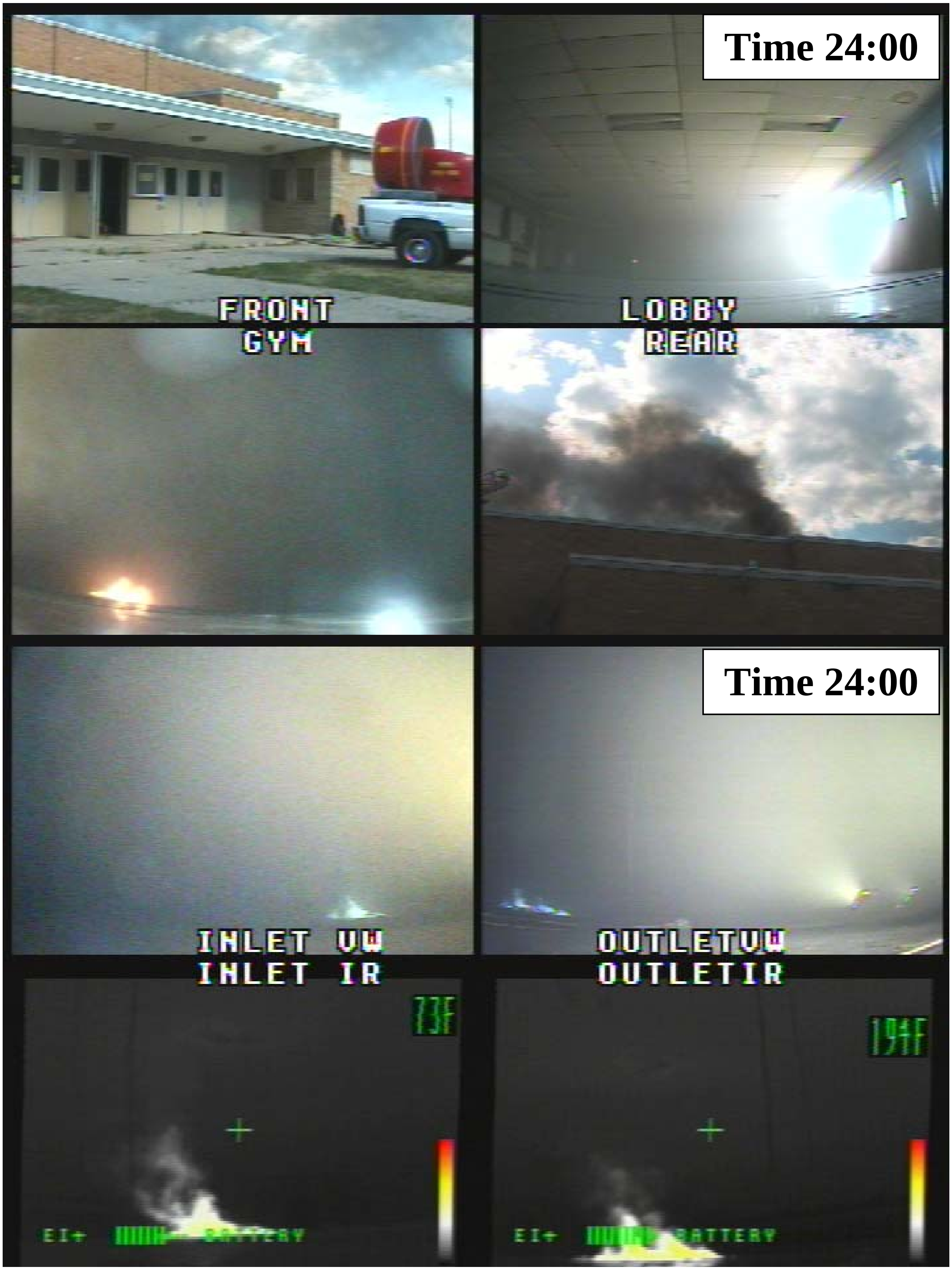

Figure 138. Experiment GF9 video images captured at 24 min

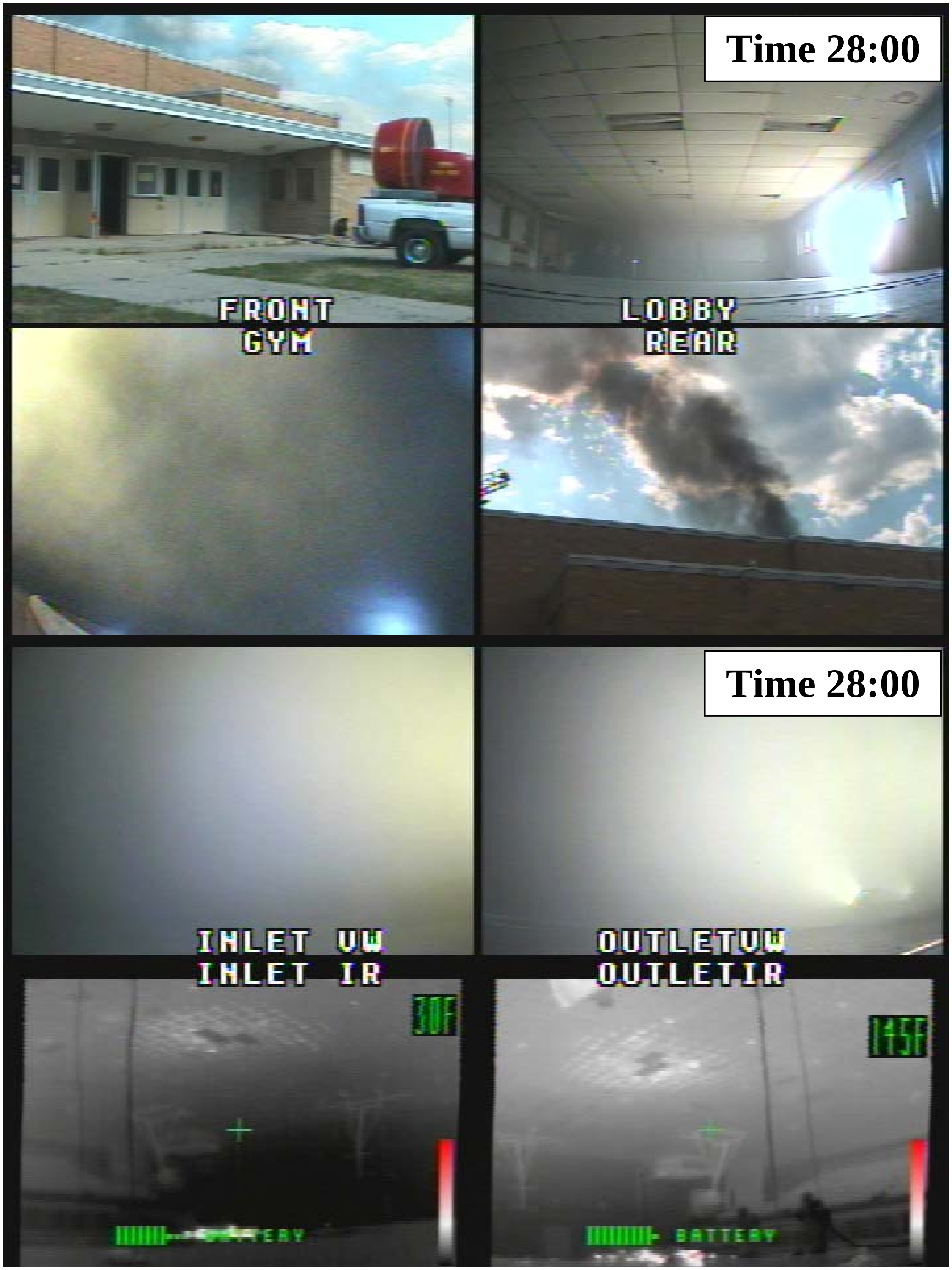

Figure 139. Experiment GF9 video images captured at 28 min

Figure 140. Experiment GF9 video images captured at 32 min

Experiment GF10 Video Images

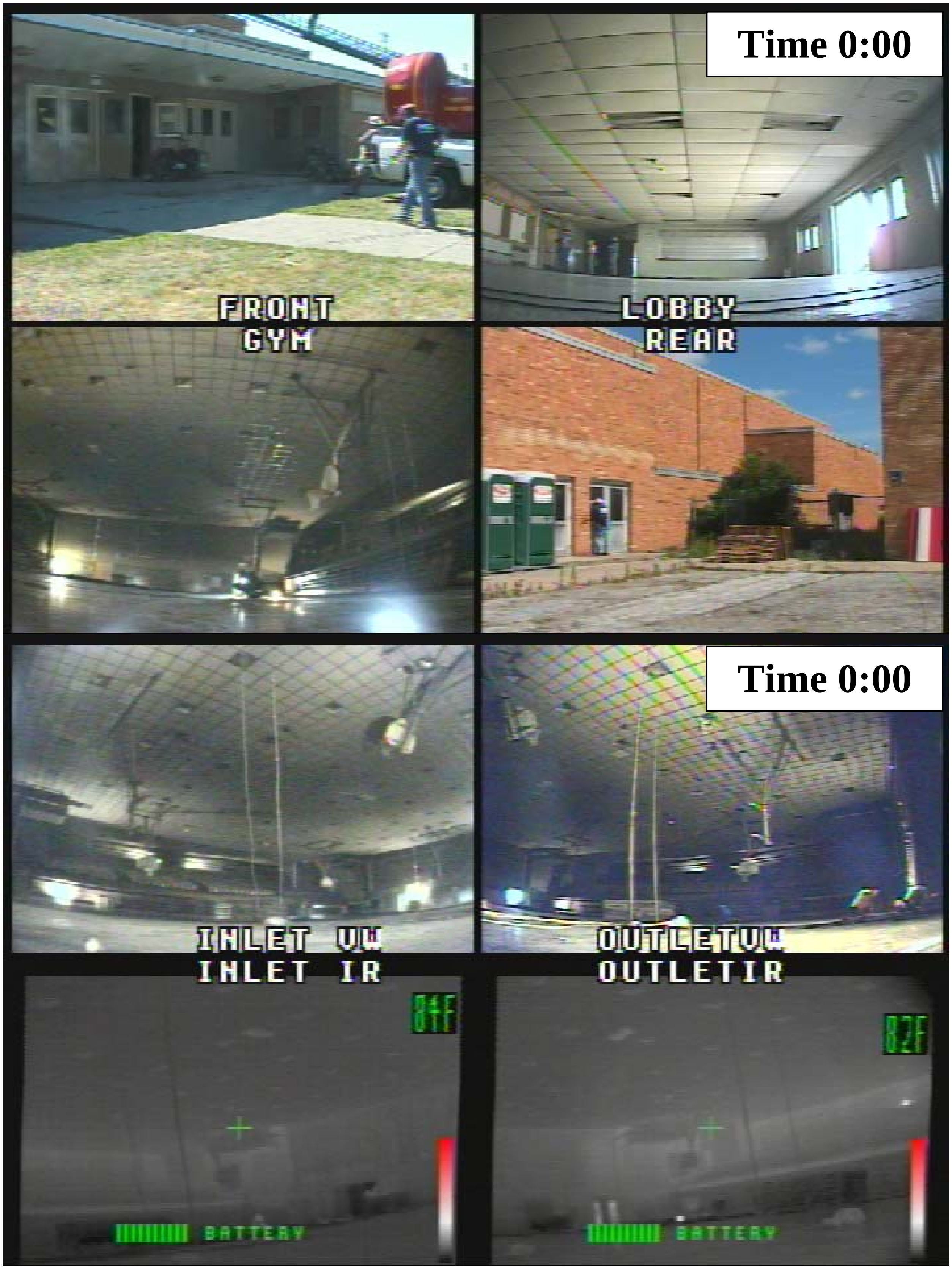

Figure 141. Experiment GF10 video images captured at 0 min

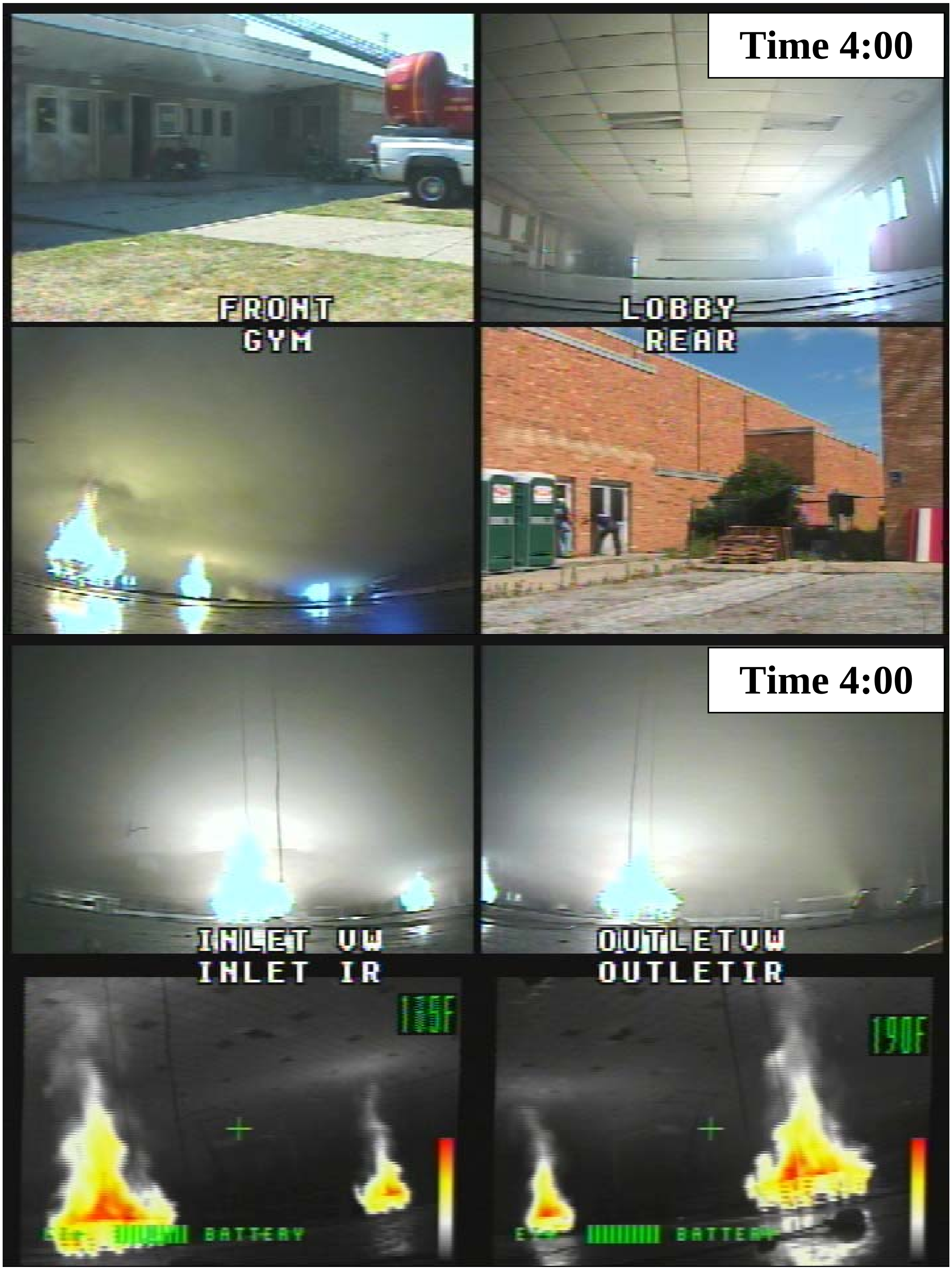

Figure 142. Experiment GF10 video images captured at 4 min

Figure 143. Experiment GF10 video images captured at 8 min

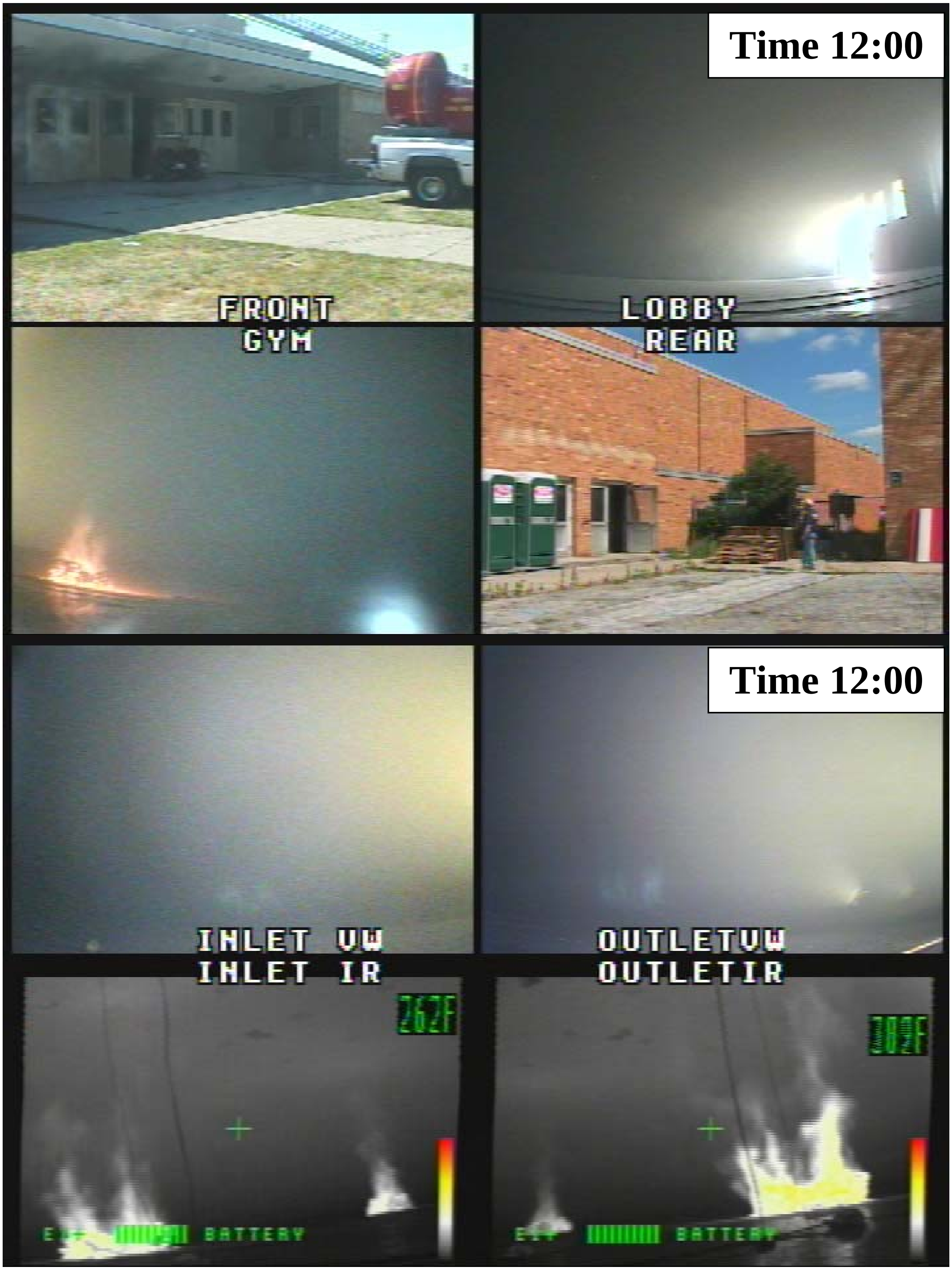

Figure 144. Experiment GF10 video images captured at 12 min

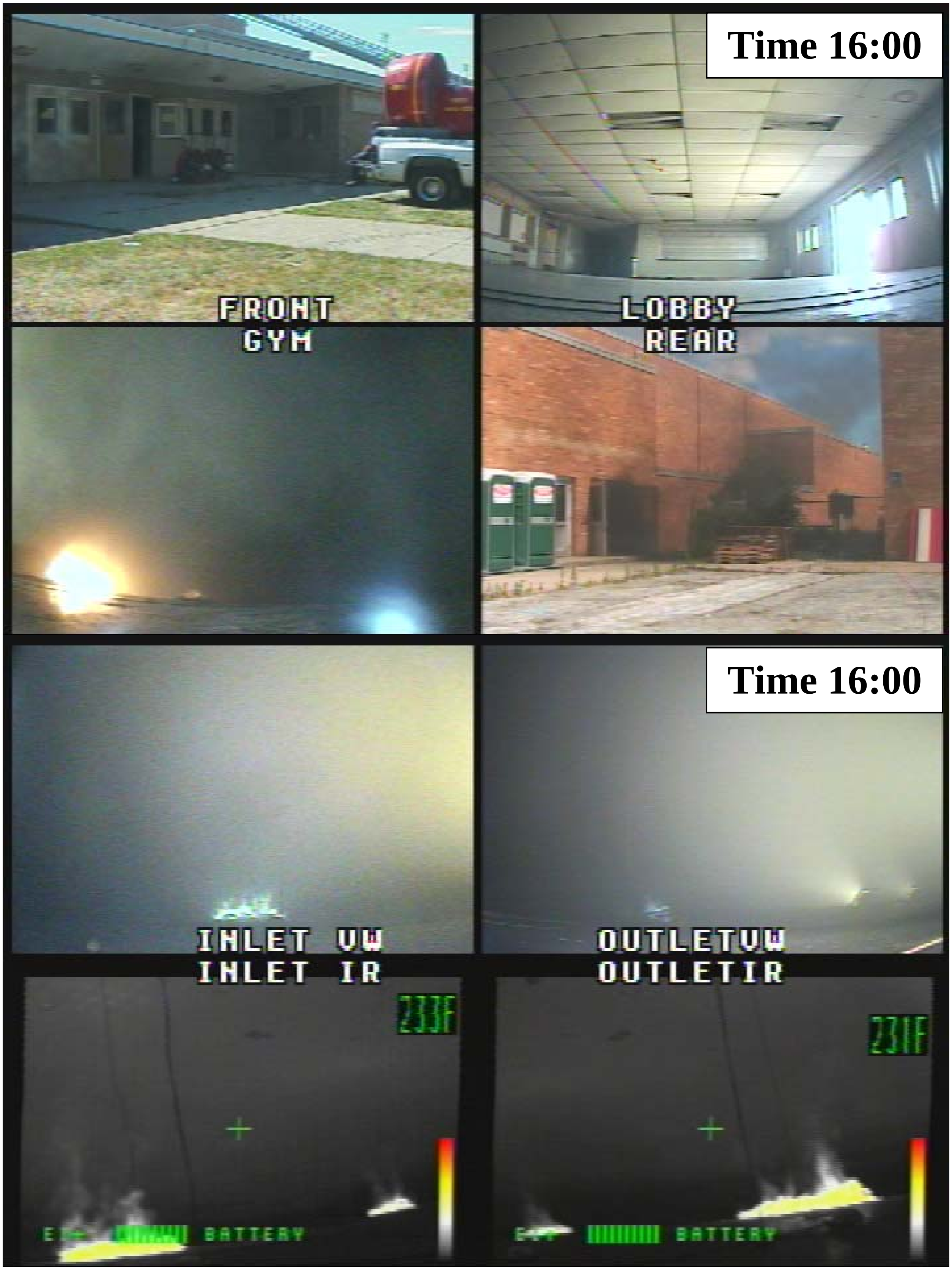

Figure 145. Experiment GF10 video images captured at 16 min

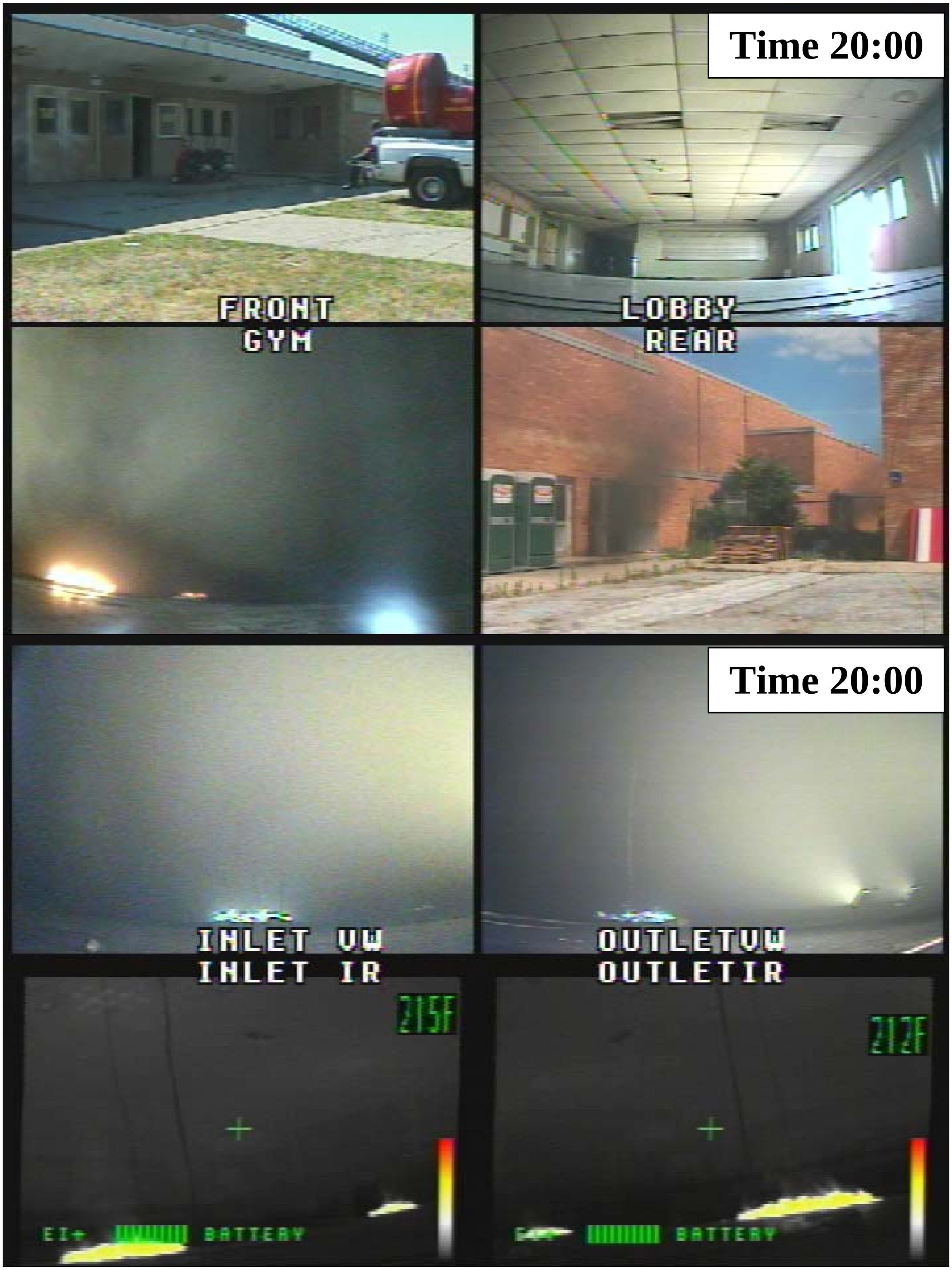

Figure 146. Experiment GF10 video images captured at 20 min

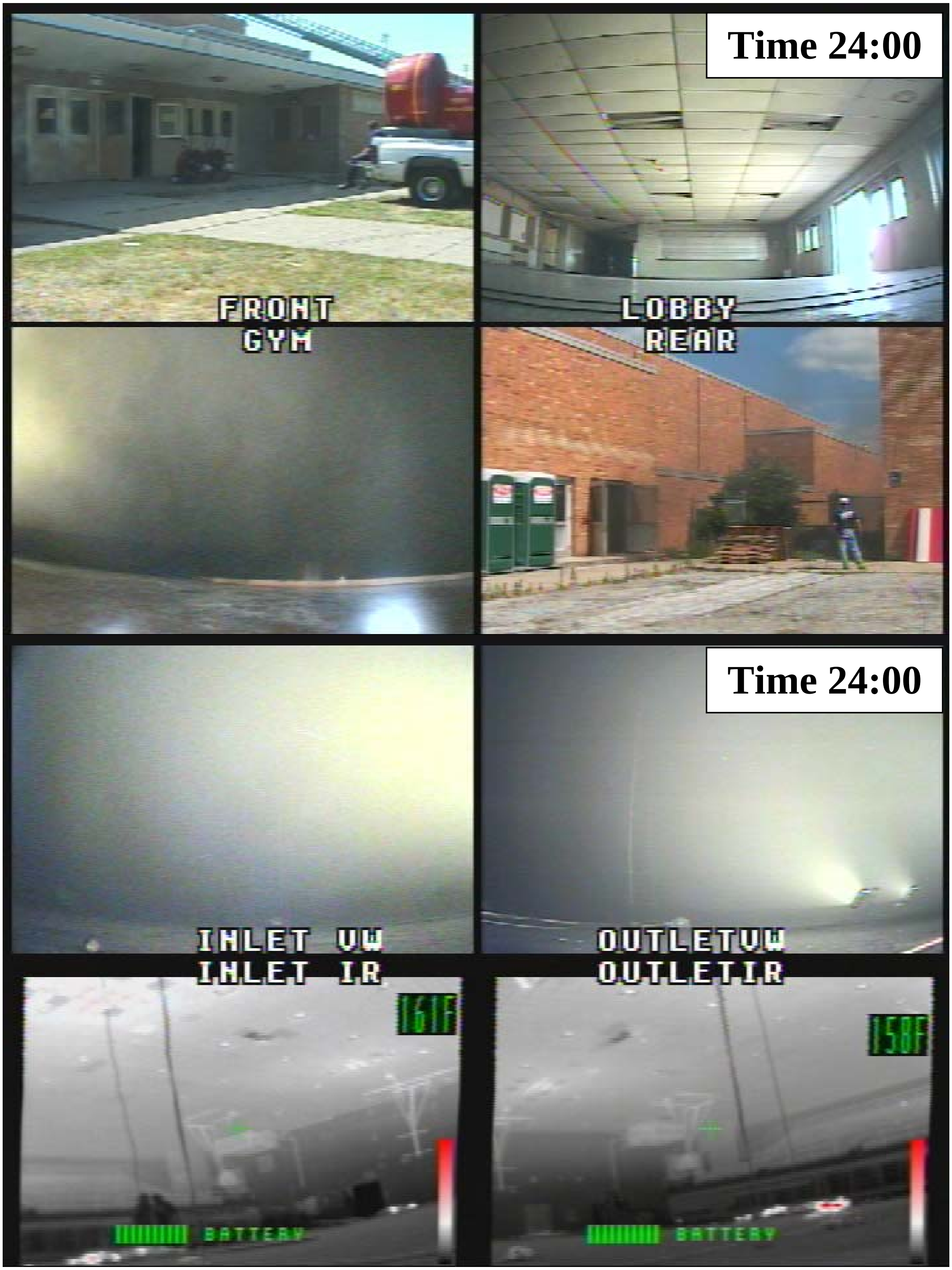

Figure 147. Experiment GF10 video images captured at 24 min

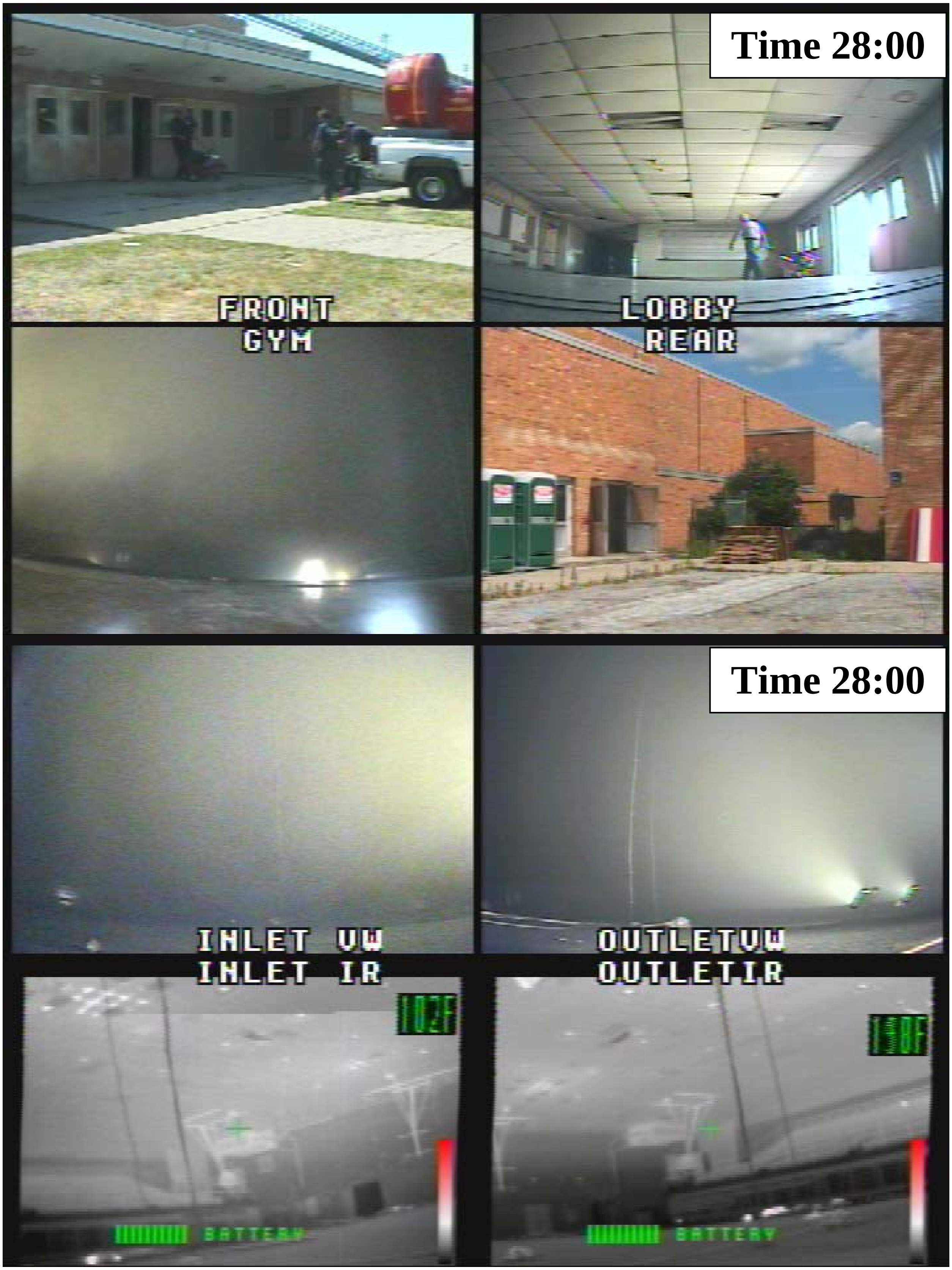

Figure 148. Experiment GF10 video images captured at 28 min

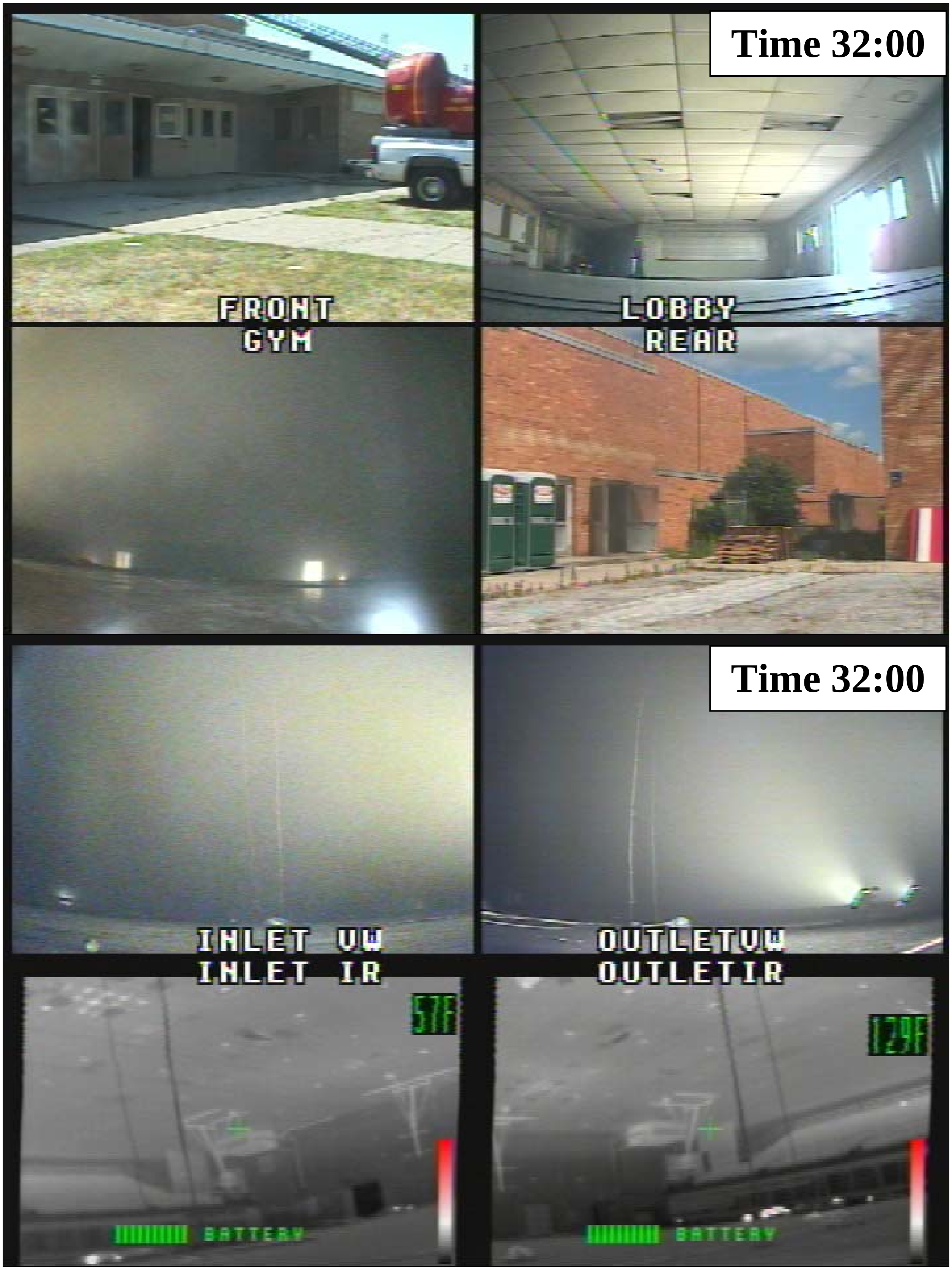

Figure 149. Experiment GF10 video images captured at 32 min

Experiment GF11 Video Images

Figure 150. Experiment 11 video images captured at 0 min

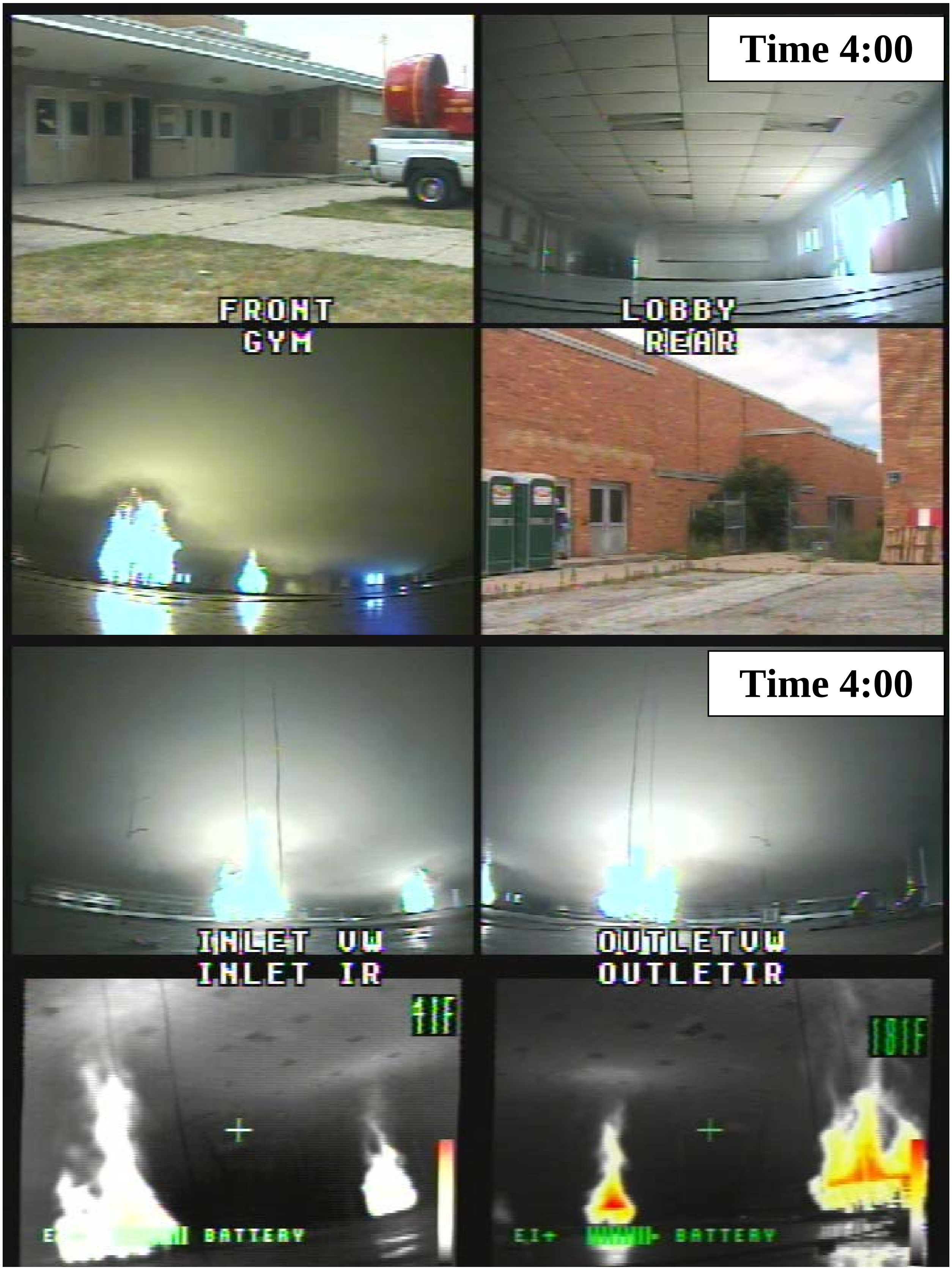

Figure 151. Experiment 11 video images captured at 4 min

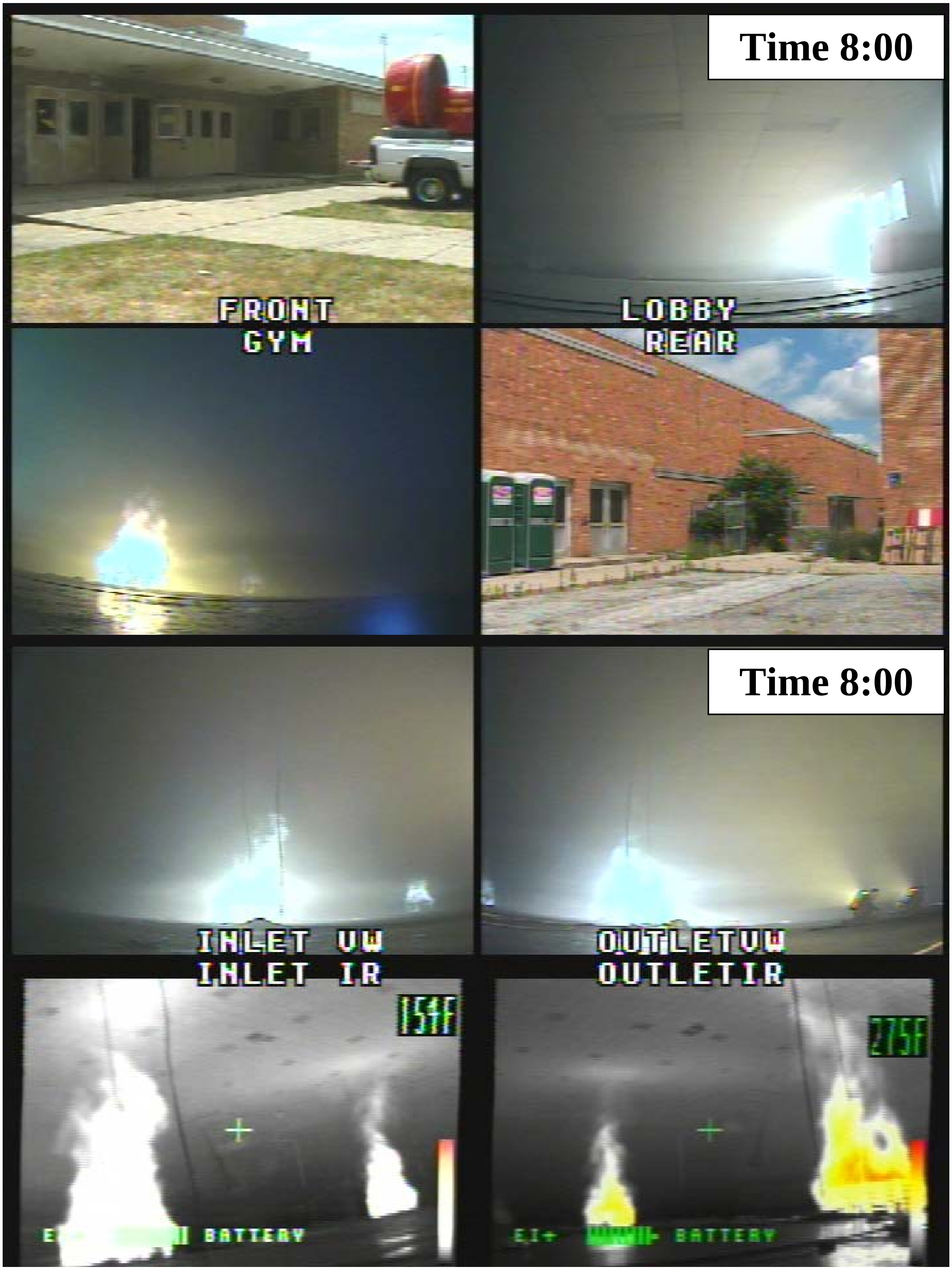

Figure 152. Experiment 11 video images captured at 8 min

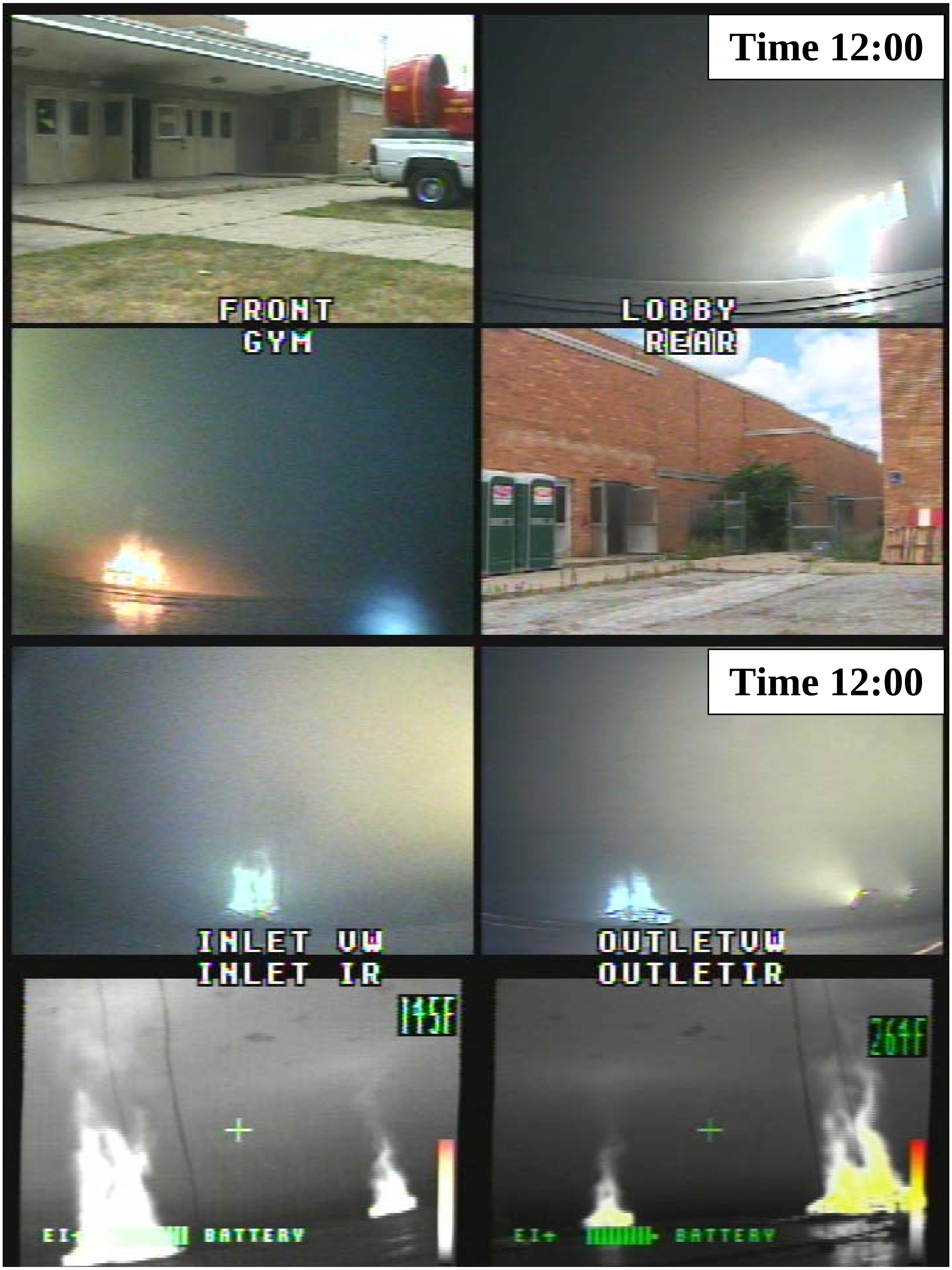

Figure 153. Experiment 11 video images captured at 12 min

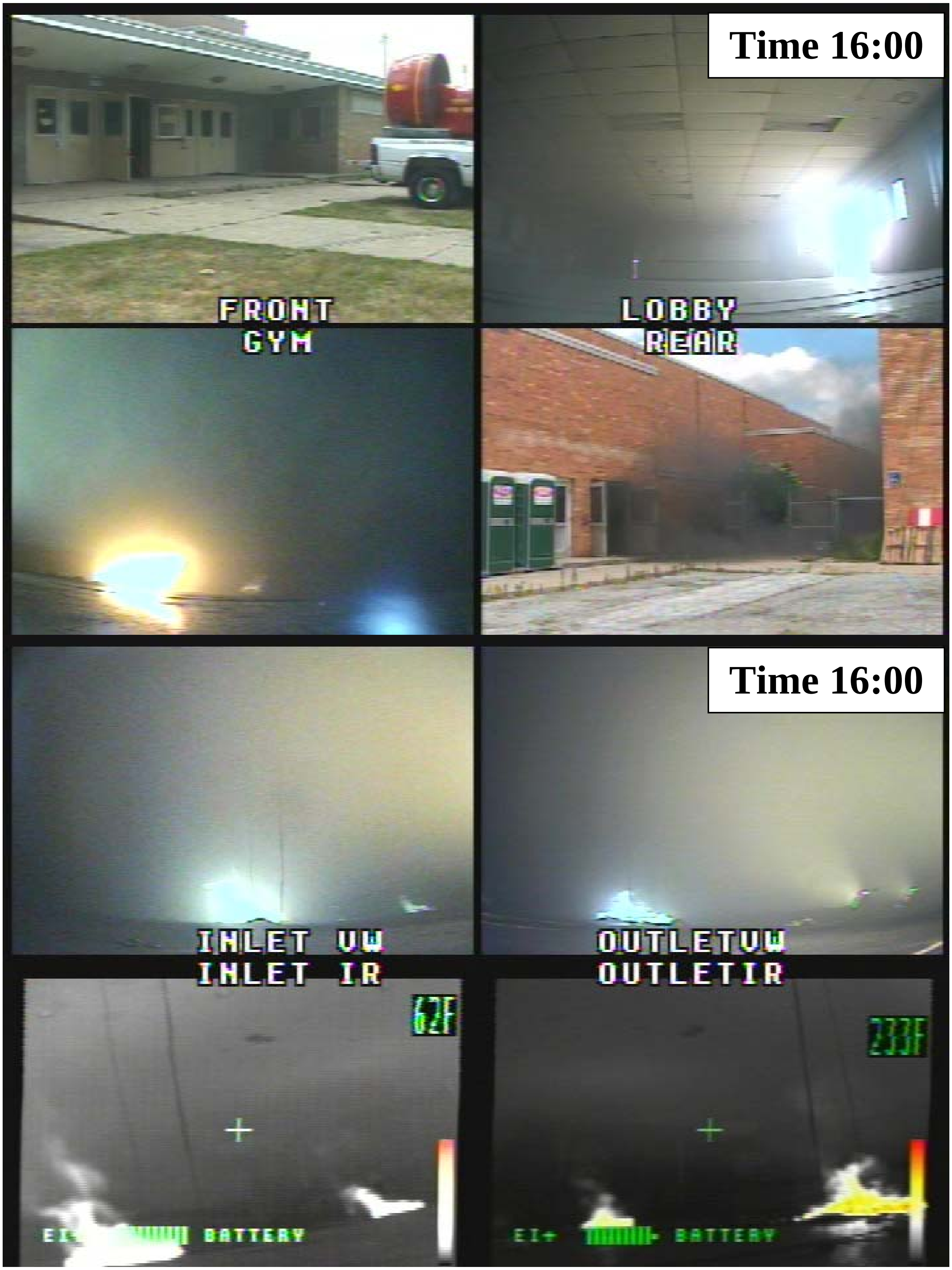

Figure 154. Experiment 11 video images captured at 16 min

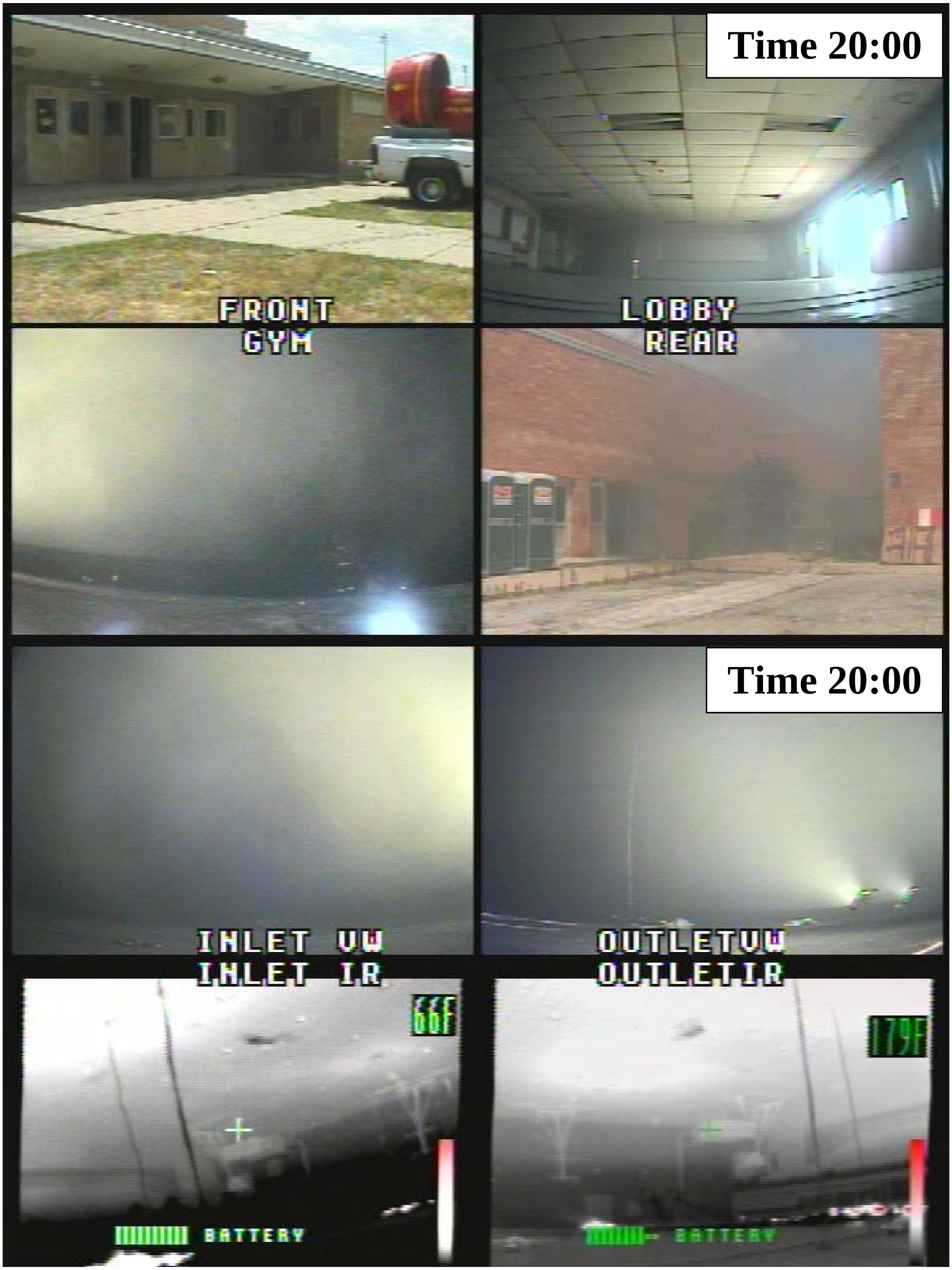

Figure 155. Experiment 11 video images captured at 20 min

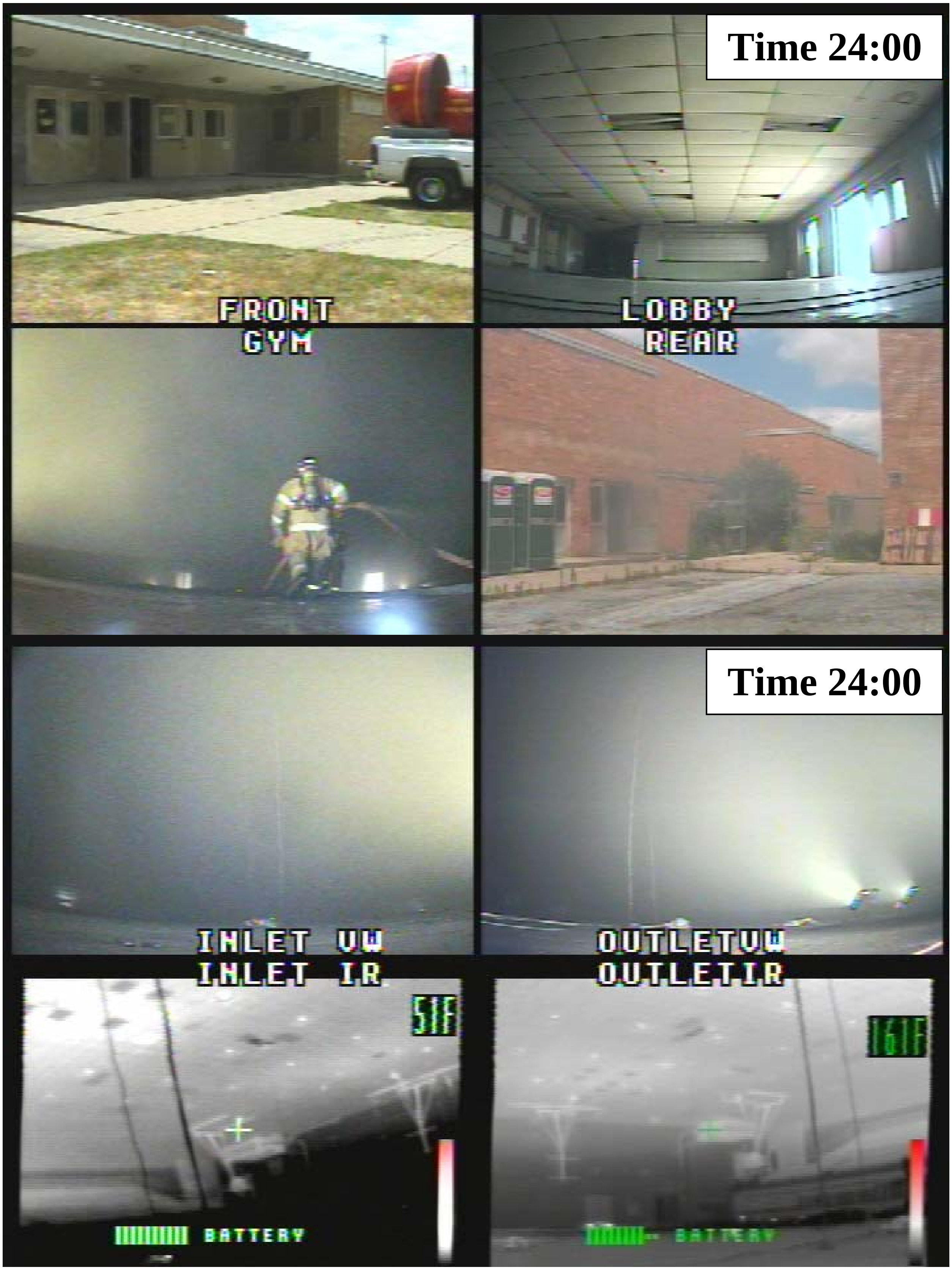

Figure 156. Experiment 11 video images captured at 24 min

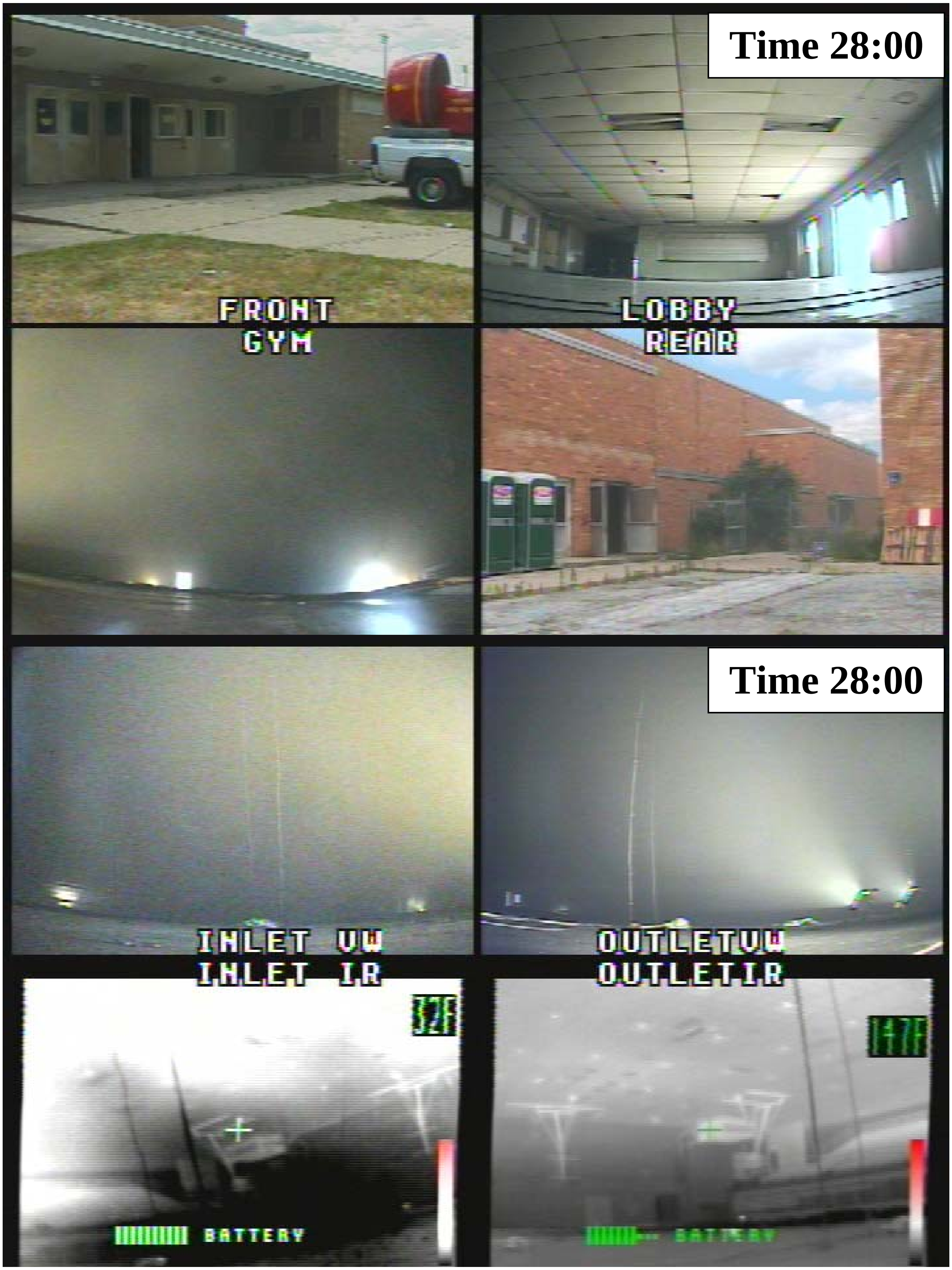

Figure 157. Experiment 11 video images captured at 28 min

Experiment GF12 Video Images

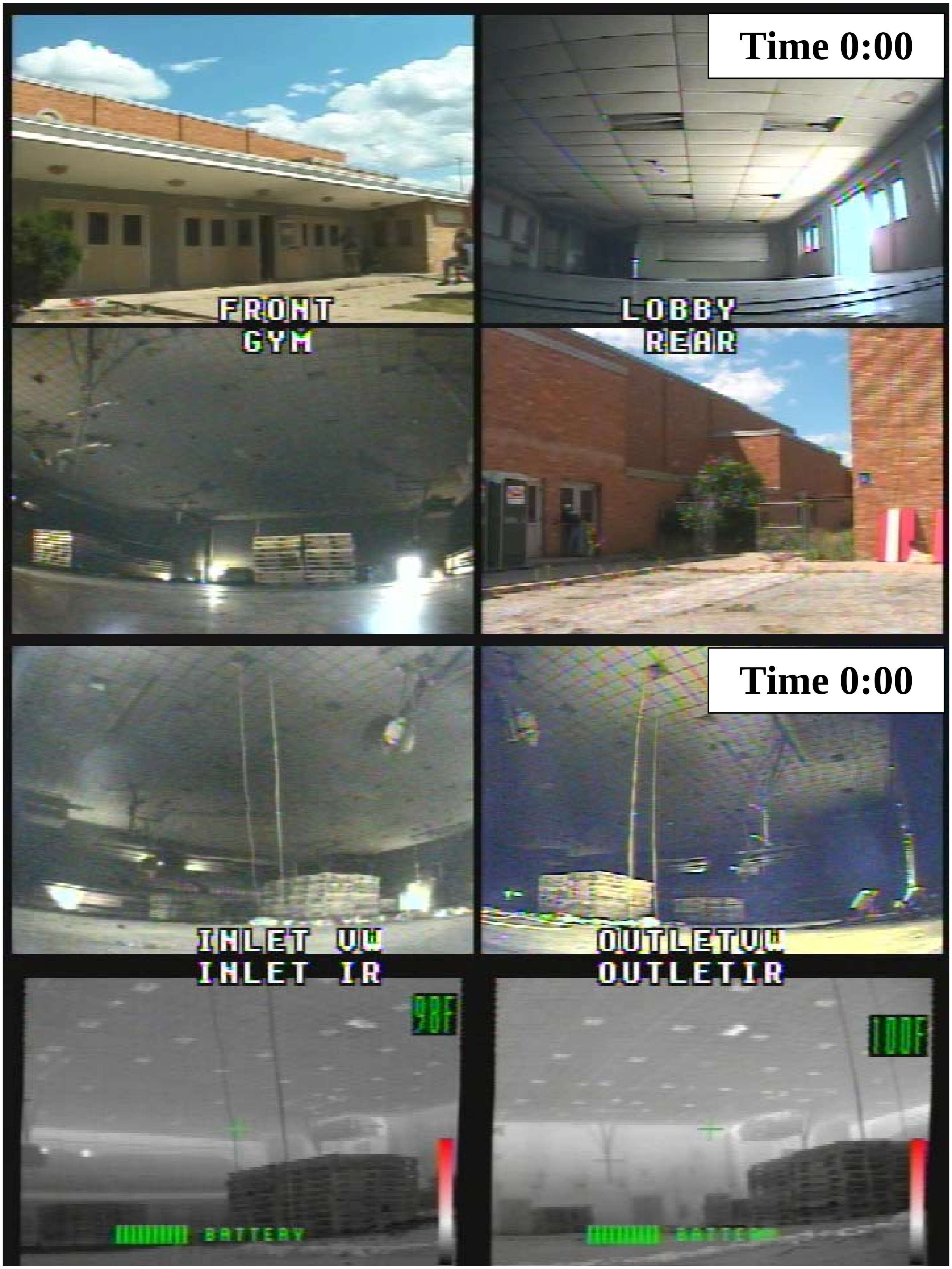

Figure 158. Experiment 12 video images captured at 0 min

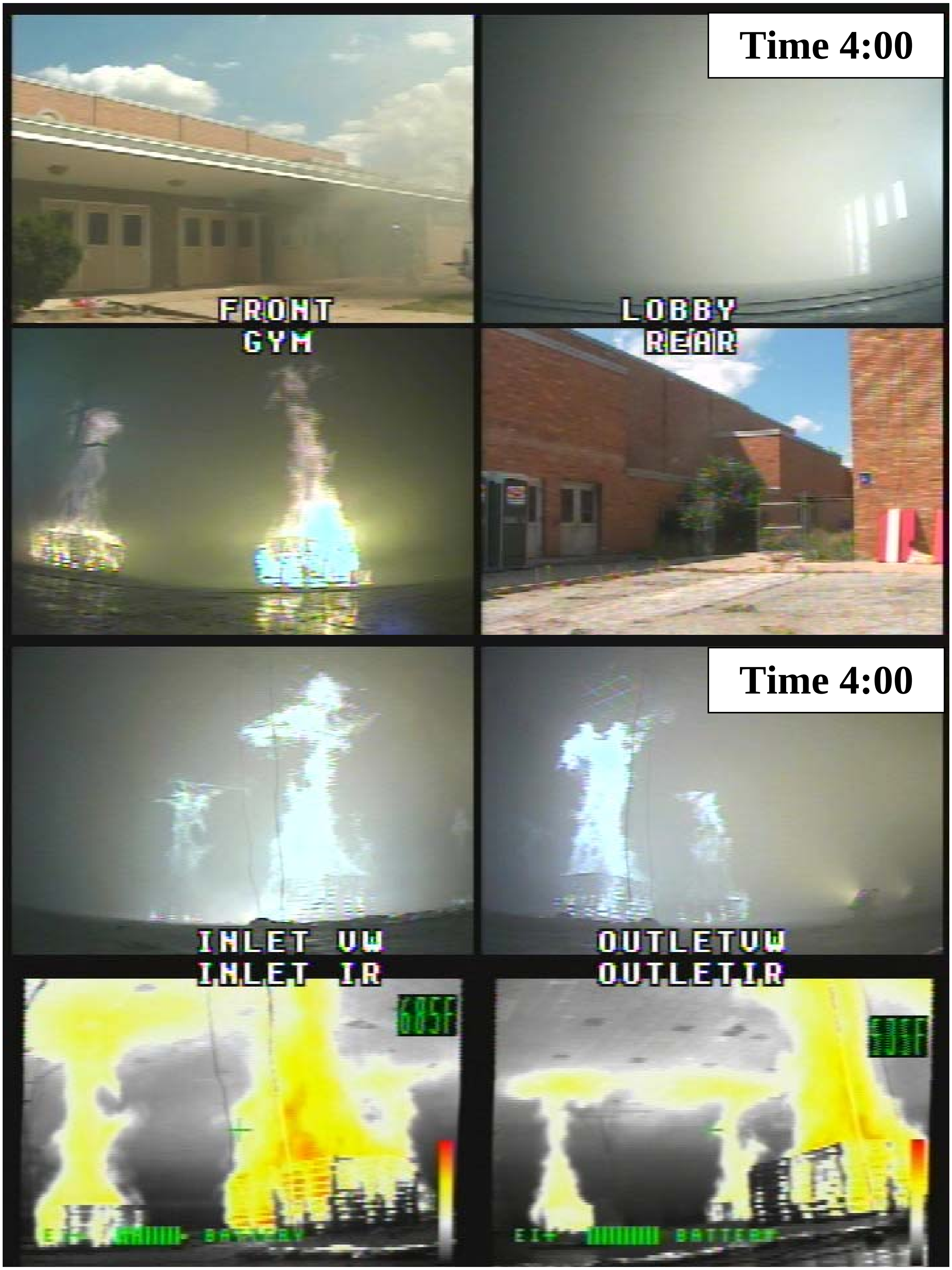

Figure 159. Experiment 12 video images captured at 4 min

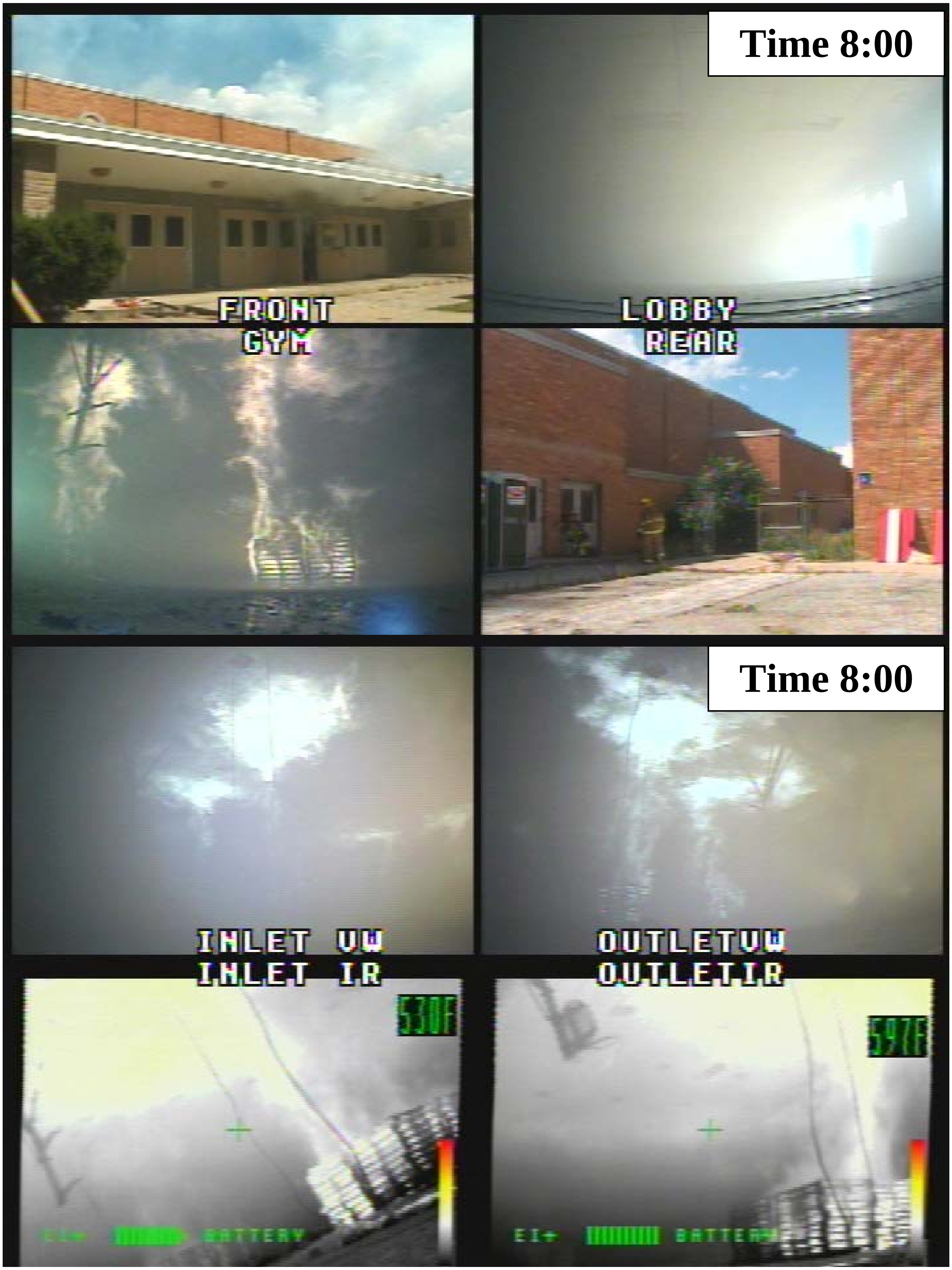

Figure 160. Experiment 12 video images captured at 8 min

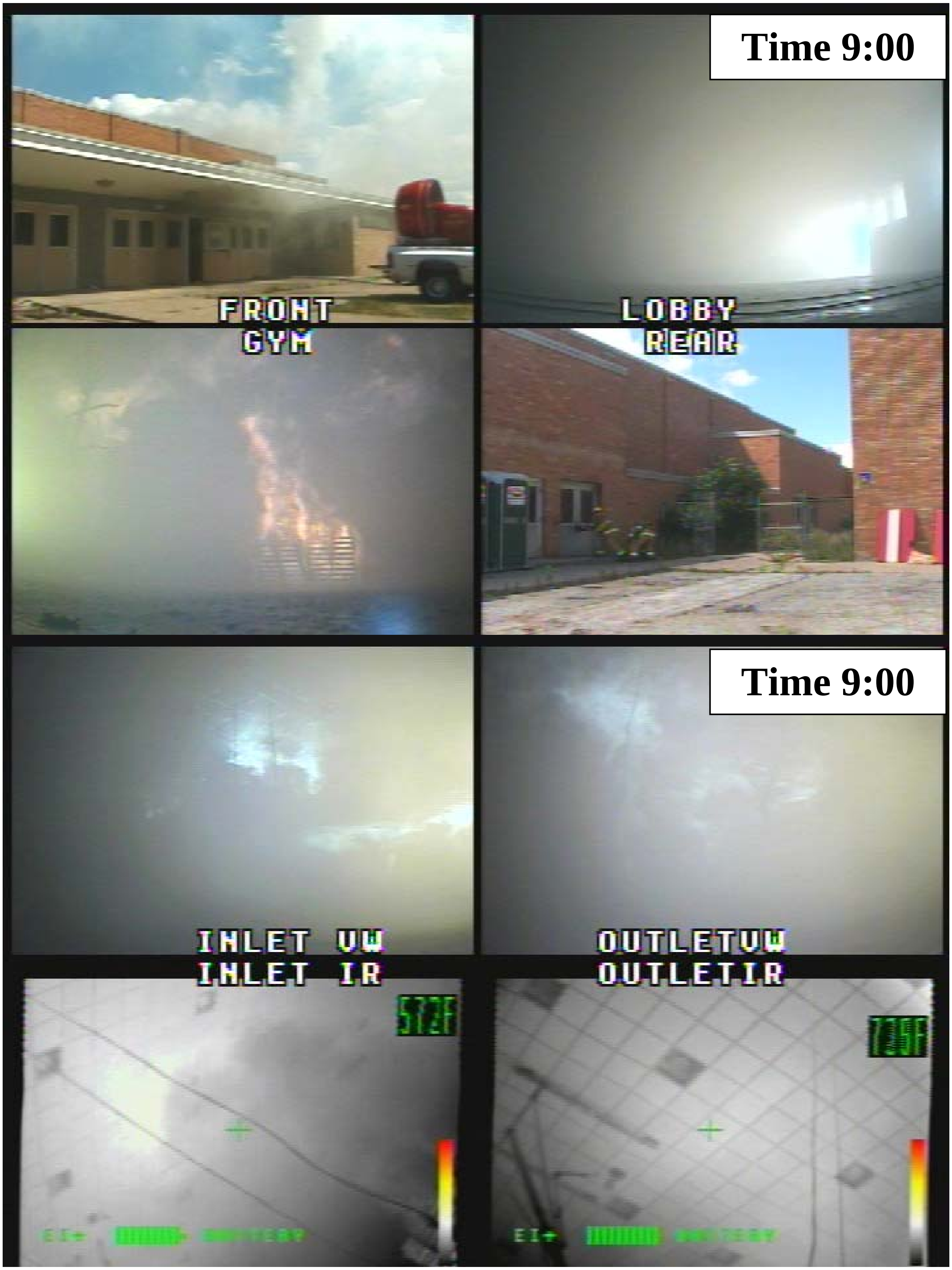

Figure 161. Experiment 12 video images captured at 9 min

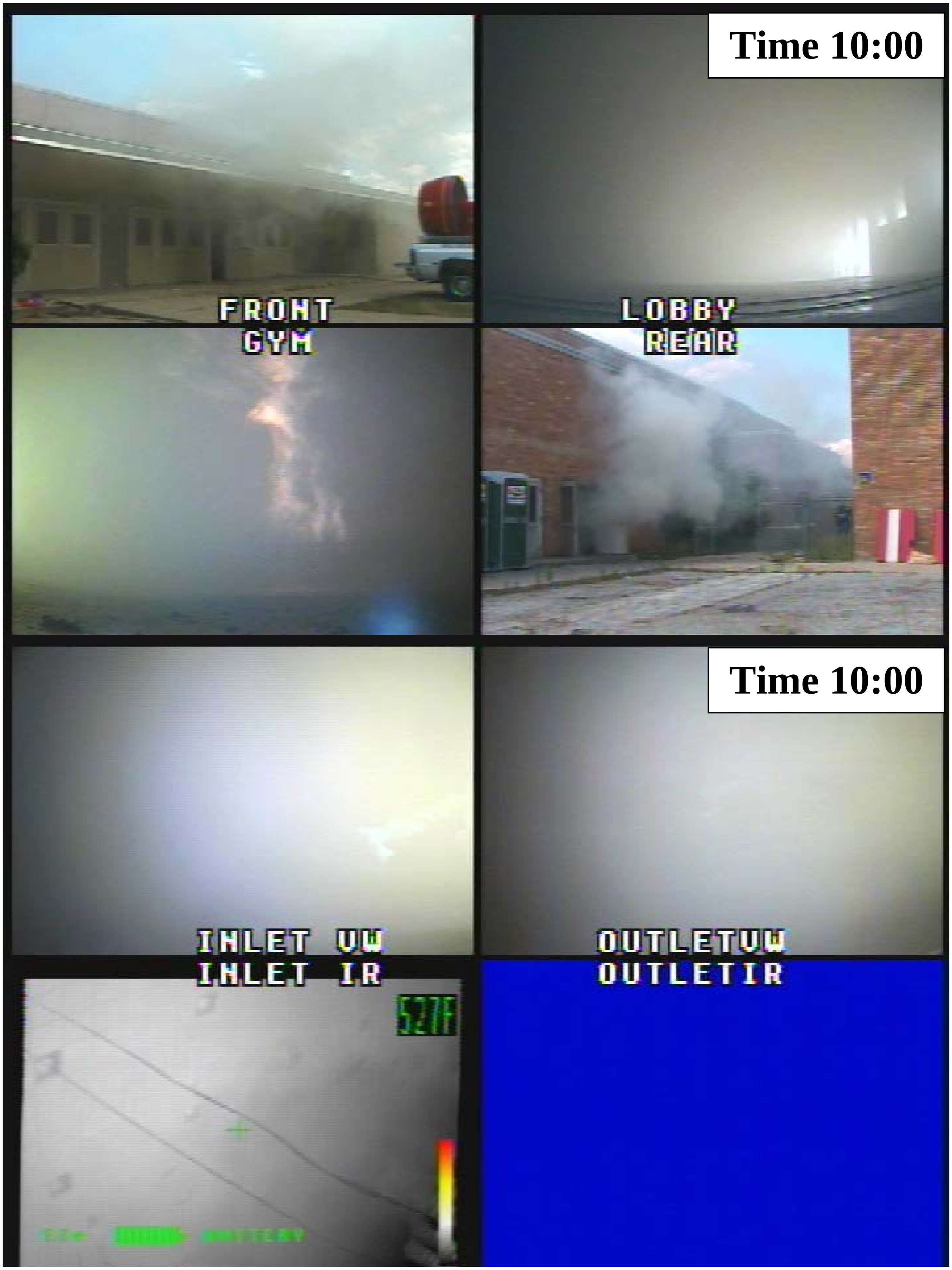

Figure 162. Experiment 12 video images captured at 10 min

Figure 163. Experiment 12 video images captured at 11 min

Figure 164. Experiment 12 video images captured at 12 min

Figure 165. Experiment 12 video images captured at 12 min 7s

Figure 166. Experiment 12 video images captured at 12 min 30 s

Figure 167. Experiment 12 video images captured at 13 min

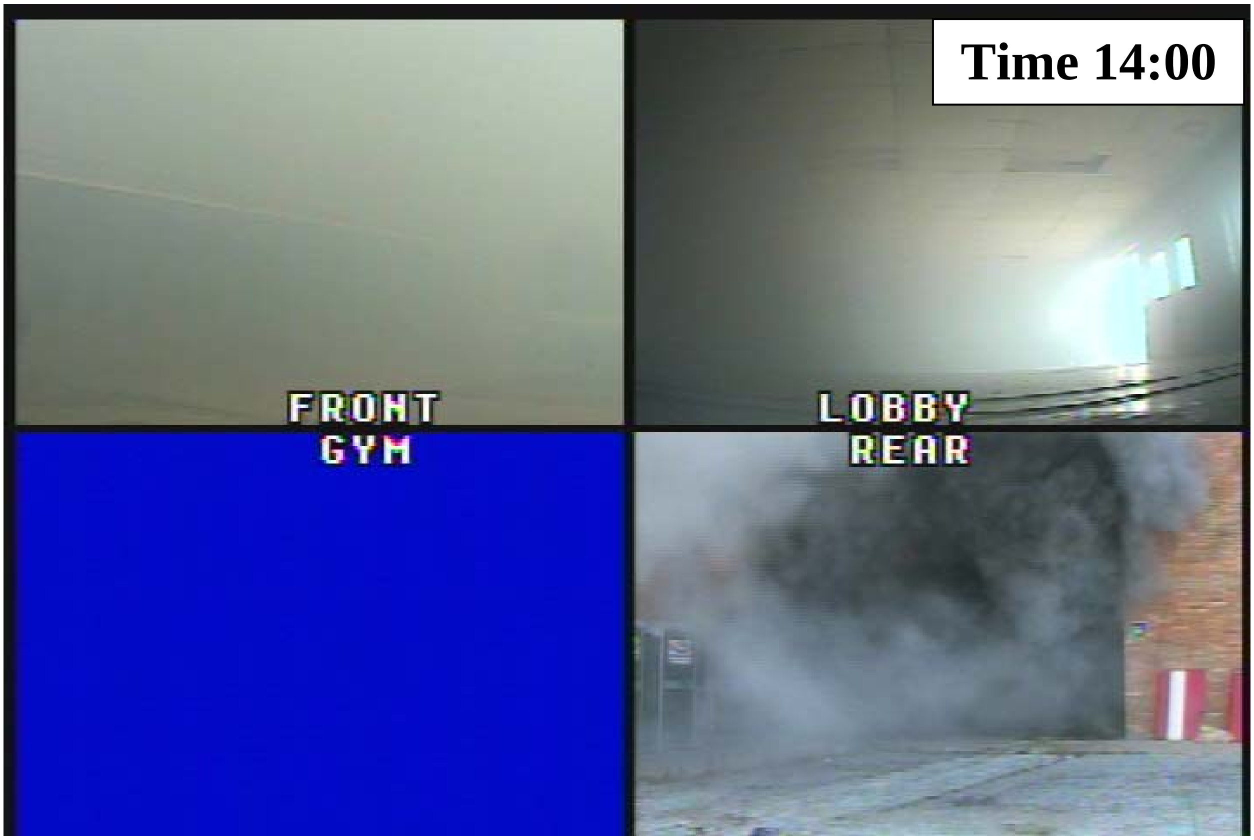

Figure 168. Experiment 12 video images captured at 14 min

Figure 169. Experiment 12 video images captured at 15 min

Figure 170. Experiment 12 video images captured at 16 min

Figure 171. Experiment 12 video images captured at 18 min

Figure 172. Experiment 12 video images captured at 20 min

Figure 173. Experiment 12 video images captured at 24 min

4.5. Discussion

In this limited series of experiments in the 9630 m^3 gymnasium of this masonry educational building, the use of positive pressure ventilation to increase pressure to reduce temperatures, limit smoke, and increase visibility was effective. The pressure, temperature and video data suggest that each of the fans was able to create pressures that forced the products of combustion back through the lobby into the gymnasium, improving conditions in the lobby. This ability is very important in a structure like this, because the smoke is limited to an area and the remainder of the building is protected from smoke, allowing more of the structure tenable for occupants and easier and safer for fire fighters to search.

All of the fans created higher pressures in the gymnasium, which increased the flow out of the ventilation points. The first five experiments created conditions in the large volume gymnasium that are consistent with a fire that is contained and in the decay stage. A single portable fan produced elevated pressures to increase ventilation for a volume of this magnitude but had limited effectiveness. Adding a second fan in parallel approximately doubled the pressure increase and using a mounted fan approximately tripled the pressures created by the two portable fans. The difference between the gymnasium and the lobby is that the purpose of elevating the pressure in the lobby is to prohibit the flow where it's not wanted, while the purpose of elevating the pressures in the gymnasium is to increase the flow out of the ventilation points. The benefit of this technique is that you are able to accomplish either exposure protection alone or both, exposure protection and ventilation at the same time if there is an opening.

Ideally, many ventilation points were opened and the fans were able to keep the gymnasium at an elevated pressure such that combustion products flowed outside and were replaced with fresh air. The single portable fans were most effective with one ventilation door open. Utilizing two portable fans was effective with two ventilation doors open and the trailer mounted fans were most effective with four or more doors open.

The single portable fans positioned outside reduced temperatures in the gymnasium at the rate of approximately 3 ^{o}C/min to 6 ^{o}C/min. The mounted fans and the two portable fans in parallel cooled the gymnasium at the rate of 8 ^{o}C/min to 15 ^{o}C/min. These rates are based on the ventilation of the gymnasium in the decay stage of the fire for 5 min of ventilation after the peak output of the fire. Ventilation later in the fire had lower rates of cooling and ventilation after a larger fire had larger rates of cooling but these numbers were reasonable expectations for a contained fire, decaying in a large volume.

Returning visibility to such a large volume space was demonstrated to be difficult since removing all of the smoke could require a very long time. The fans, independent of size, all decreased the time this process took. In the hallways, the fans were able to push the smoke down the hallway, top to bottom, and out of the ventilation point. The flow path was the size of the total hallway, whereas that same flow path in the gymnasium was only a fraction of the total size. The use of the fans did return visibility in the lower portion of the gymnasium making it easier to search the floor area for the fire fighters. Improving visibility to potentially search in the bleachers took much longer, but was also improved with the use of the fans.

The fan created a flow path from the inlet doorway to the ventilation doorway which allowed for some ventilation of the smoke that was drawn into this flow. In order to speed up this process the ventilation points should be maximized and should be changed periodically, if there are multiple ventilation points available. In this situation, using the two portable fans at the lobby entrance, ventilation should be switched between the two sets of rear doors (from 1 and 2 to 3 and 4). Switching this flow path periodically increased the amount of smoke ventilated.

The mounted fans forced enough flow into the structure that many ventilation points could be opened at once creating multiple flow paths. This was ideal but it was important to remember that most of the flow was going to go to the path of least resistance. Therefore in order to ventilate further from the fan, the closer ventilation points may need to be closed. The further the ventilation point was from the fan the more mixing and smoke entrainment that would occur as long as that path was all in the contaminated area. Ventilating through a non-contaminated area should always be avoided if possible.

Waiting for a gymnasium of this volume to naturally ventilate could take many hours. When the roof was opened in Experiment GF9 there was little improvement to visibility or heat levels in the gymnasium after 2 min. The fan worked well with the roof vent to lift the smoke layer but it was not significantly more effective than using the rear doors. The size of the roof ventilation opening was about the same size as the single rear door. This hole would have needed to be the size of 4 rear doors to take advantage of the flow from the trailer mounted fans.

In the final experiment the combination of positive pressure ventilation and vertical ventilation caused the ventilation limited fire in the gymnasium to transition to flashover. While this was not desired, it was important to note that this entire space was untenable prior to any ventilation. Once flashover occurred, the fan was able to keep the combustion products in the gymnasium and protect the rest of the structure. It was also able to improve conditions and visibility such that the fire fighters could walk through the lobby to the glow from the entrance of the gymnasium and extinguished the fire safely and rapidly.

The fire also did not burn out of the gymnasium toward the fan because the pressure created by the fan was much greater than that of the fire. If fire fighters had to search for the fuel rich, oxygen limited fire they may have found themselves between the fire and the ventilation point/source of oxygen that they opened to enter the structure. If the fire found air by burning through the roof, or by additional doors being opened by other crews, then fire fighters inside searching for the seat of the fire may have found themselves in a rapidly transitioning fire. Ventilation of oxygen limited or fuel rich fires, either naturally or mechanically, can cause rapid fire growth. Ventilation is not synonymous with cooling. Venting must be coordinated with all other operations happening on the fire ground.

5. Uncertainty Analysis

There are different components of uncertainty in the length, differential pressure and gas temperature data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means [11]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 % confidence interval (2σ).

Components of uncertainty are tabulated in Table 53. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as differential pressure, include past experience with the instruments.

Each length measurement was taken carefully. However, due to some issues, such as obstructions and unleveled terrain, the total expanded uncertainty was estimated at 6 %. These issues impacted the instrument locations, fan locations and building dimensions.

Differential pressure reading uncertainty components are derived from pressure transducer instrument specifications and previous experience with pressure transducers. The transducers were factory calibrated and the zero and span of each was checked in the laboratory prior to the experiments. The total expanded uncertainty was estimated at 10 %.

The uncertainty in the gas temperature measurements includes radiative cooling in the each of the tests series, but also includes radiative heating for thermocouples located in the lower layer of the full-scale tests. Small diameter thermocouples were used to limit the impact of radiative heating and cooling. This resulted in an estimate of 15 % total expanded uncertainty.

Table 53. Uncertainty

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Length Measurements			
Instrumentation Locations	± 1 %		
Fan Location	± 1 %		
Building Dimensions	± 1 %	± 3 %	± 6 %
Repeatability[1]	± 2 %		
Random[1]	± 2 %		
Differential Pressure			
Calibration [12]	± 2 %		
Accuracy [12]	± 1 %	± 5 %	± 10 %
Repeatability [1]	± 3 %		
Random [1]	± 3 %		
Gas Temperature [13]			
Calibration	± 1 %		
Radiative Cooling	- 5 % to + 0 %	± 8 %	± 15 %
Radiative Heating	- 0 % to + 5 %		
Repeatability [1]	± 5 %		
Random [1]	± 3 %		
Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.			

6. Tactical Considerations

This series of experiments aimed to answer the question; can fire service positive pressure ventilation fans be successfully used in large structures? Success can be gauged by the increased tenability for potential victims and improved conditions for firefighting crews. The use of PPV fans in the classroom fires as well as the gymnasium fires demonstrated that both of these criteria were met successfully. There was a large amount of data and observations produced by these experiments and the following bulleted items are research results that the fire service may choose to consider in developing tactics.

- The use of PPV fans during the attack stages of the fires did not negatively impact the conditions in the structure.
- A ventilation point near the seat of the fire provided maximum change in the response of fire conditions.
- A ventilation opening remote from the fire, either before the fire room or after the fire room, did not make conditions worse.
- Fans were able to make locations tenable that were not tenable, but never made areas untenable that were tenable.
- A single 27 in. fan was not sufficient during the peak stage of a classroom fire with long hallways to completely stop combustion gases from entering the hallway however conditions still were improved over natural ventilation. When operating a building this large, resources beyond single portable fans may be more effective.
- A single 27 in. fan and larger was effective at ventilating during overhaul conditions but adding a second portable fan greatly increased effectiveness of smoke and heat removal.
- When a second fan inlet entrance will be used for ventilating, the fan sizes should be the same size and positioned the same to avoid losing flow back through an inlet.
- There was no evidence of the flow created by the fan pulling fire gases out of the fire room or pushing increased fire gases down the hallway. In most cases, the fans created a pressure high enough, even with a vent open, to stop or greatly limit the flow of combustion gases into the hallway.
- The conditions leading to the fire room always improved with the use of fans.
- Ceiling height played a significant role in fan effectiveness. Fans were able to ventilate the gymnasium lobby quickly, but ventilating the gymnasium was much more time consuming.
- When ventilating a large volume, a single portable fan was most effective with one ventilation door open. Utilizing two portable fans was effective with two ventilation doors open and the trailer mounted fans were most effective with four or more doors open.
- The use of the fans did return visibility in the lower portion of the gymnasium making it easier for the fire fighters to search the floor area. Improving visibility to search the bleachers took much longer, but was improved with the use of the fans.
- The fan created a flow path from the inlet doorway to the ventilation doorway which allowed for some ventilation of the smoke that was drawn into this flow. In order to speed up this process the ventilation points should be maximized and should be changed periodically if there are multiple ventilation points available.
- The fan worked well with the roof vent to lift the smoke layer, but it was not significantly more effective than using the rear doors.

- The size of the roof opening was about the same size as the single rear door. This hole would have needed to be at least the size of 4 rear doors to take advantage of the flow from the trailer mounted fans.
- When the gymnasium flashed over, the fire did not extend into the lobby because of the increased pressure from the fan and the cool air that it introduced.
- **Ventilation of oxygen limited or fuel rich fires, either naturally or mechanically, can cause rapid fire growth. Ventilation is not synonymous with cooling. Venting was most effective when coordinated with other operations on the fire ground.**

7. Conclusions

A series of experiments was run in a masonry educational building examining the ability of PPV fans to increase pressure to reduce temperatures, limit smoke spread and increase visibility. Preliminary experiments examined the pressure increase created by portable fans and mounted fans in different configurations and locations. The two main fire scenarios included a long hallway with classrooms and a gymnasium. Both scenarios included fires that produced a large amount of smoke and hot gases and instrumentation was placed to assess tenability criteria and how PPV tactics can either increase or decrease survivability. Measurements included temperature, pressure, thermal imaging and video views.

In this limited series of experiments the pressure was increased sufficiently to: reduce temperatures, giving potential occupants a more survivable environment and increase fire fighter safety, limit smoke spread, keeping additional parts of the structure safe for occupants and undamaged and reducing the scale of the emergency for the fire fighters, and increase visibility, allowing occupants a better chance to self evacuate and providing fire fighters with an easier atmosphere to operate in. Positive pressure ventilation is a tool the fire service can utilize to make their job safer and more efficient.

8. Acknowledgments

The authors would like to thank Tony Chakalis, Laurean DeLauter, Jay McElroy, Roy McLane, Michael Selepak, David Stroup and Robert Vettori of the Building and Fire Research Laboratory for their invaluable support during the preparation and implementation of the experimental series, and Jonathan Kent for his assistance during the composition of the report. The authors would also like to thank Deputy Chief John Coleman and the Toledo Fire and Rescue Department for inviting NIST to participate, and the endless support they provided. Special thanks to Battalion Chief Jerry Tracy, Chief of Training Thomas Galvin, Battalion Chief George Healy and Lieutenant John Ceriello from the Fire Department of New York, and Director of Training Richard Edgeworth, Battalion Chief Peter VanDorpe and Battalion Chief Keith Witt from the Chicago Fire Department for their guidance and assistance during the experiments. Priceless assistance was also provided by Toledo Public Schools, especially Ken Swartz, Richard Browne and Adam Mead. Tempest, SuperVac and Ventry supplied resources and provided technical support in order to make the experiments possible. Finally, the authors express gratitude to the Department of Homeland Security for their sponsorship and support of this important and ongoing research.

9. References

1. Kerber, S and Walton, W. D. “Characterizing Positive Pressure Ventilation Using Computational Fluid Dynamics.” National Institute of Standards and Technology, NISTIR 7065, 2003.

2. Kerber, S and Walton, W. D. “Effect of Positive Pressure Ventilation on a Room Fire.” National Institute of Standards and Technology, NISTIR 7213, 2005.

3. Kerber, S and Walton, W. D. “Full Scale Evaluation of Positive Pressure Ventilation in a Fire Fighter Training Building.” National Institute of Standards and Technology, NISTIR 7342, 2006.

4. Kerber, S. “Evaluation of the Ability of Fire Dynamic Simulator to Simulate Positive Pressure Ventilation in the Laboratory and Practical Scenarios.” National Institute of Standards and Technology, NISTIR 7315, 2006.

5. Kerber, S., Madrzykowski, D., Stroup, D. “Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Pressure Experiments.” National Institute of Standards and Technology, NISTIR 7412, 2007.

6. Kerber, S., Madrzykowski, “Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Fire Experiments.” National Institute of Standards and Technology, NISTIR 7468, 2007.

7. Babrauskas, V. Heat Release Rates. *The SFPE Handbook of Fire Protection Engineering,* National Fire Protection Association, Quincy, MA, Third Edition (2002).

8. Krasny, J., Rockett, J. A.,and Huang, D. “Protecting Fire Fighters Exposed in Room Fires: Comparison of Results of Bench Scale Test for Thermal Protection and Conditions During Room Flashover.” *Fire Technology, p.* 5-19, (1988).

9. *Protective Clothing for Structural Firefighting*, NFPA Standard 1971, National Fire Protection Association, Quincy, MA (2003).

10. ISG Thermal Systems USA, Inc. K1000 ELITE Operating Manual. 2005.

11. Taylor, B. N. and C. E. Kuyatt, *Guidelines For Evaluating and Expressing the Uncertainty of NIST Measurement Results*. National Institute of Standards and Technology (U.S.) NIST-TN 1297; September, 20 p. 1994.

12. Setra Systems, Inc., Installation Guide, Setra Systems Model 264 Differential Pressure Transducer. Boxborough, MA., 1999.

13. Omega Engineering Inc., The Temperature Handbook, Vol. MM, pages Z-39-40, Stamford, CT., 2004.

APPENDIX A – Pressure versus time for Experiments P1 through P9

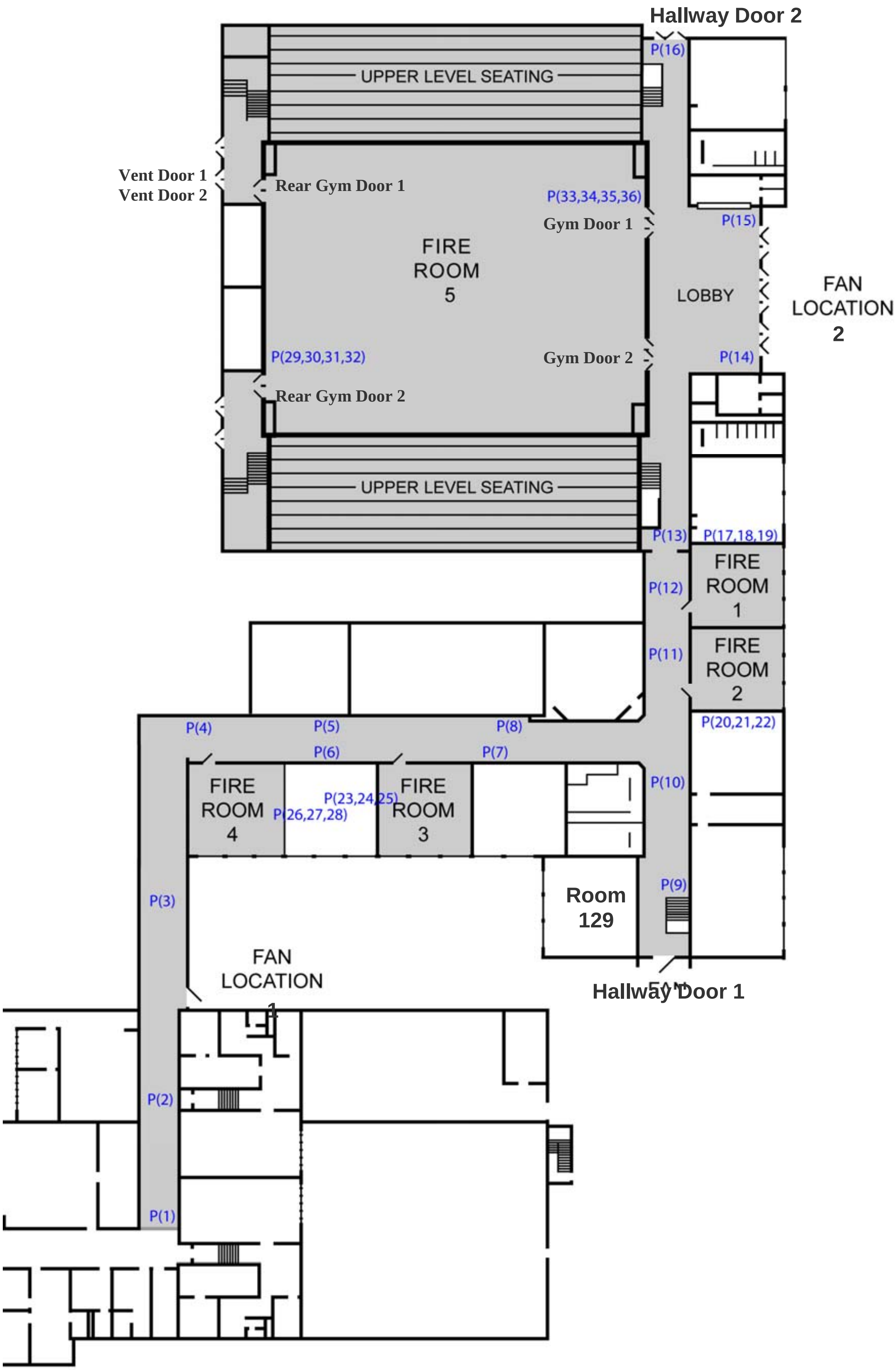

Figure 174 . Pressure Transducer Locations

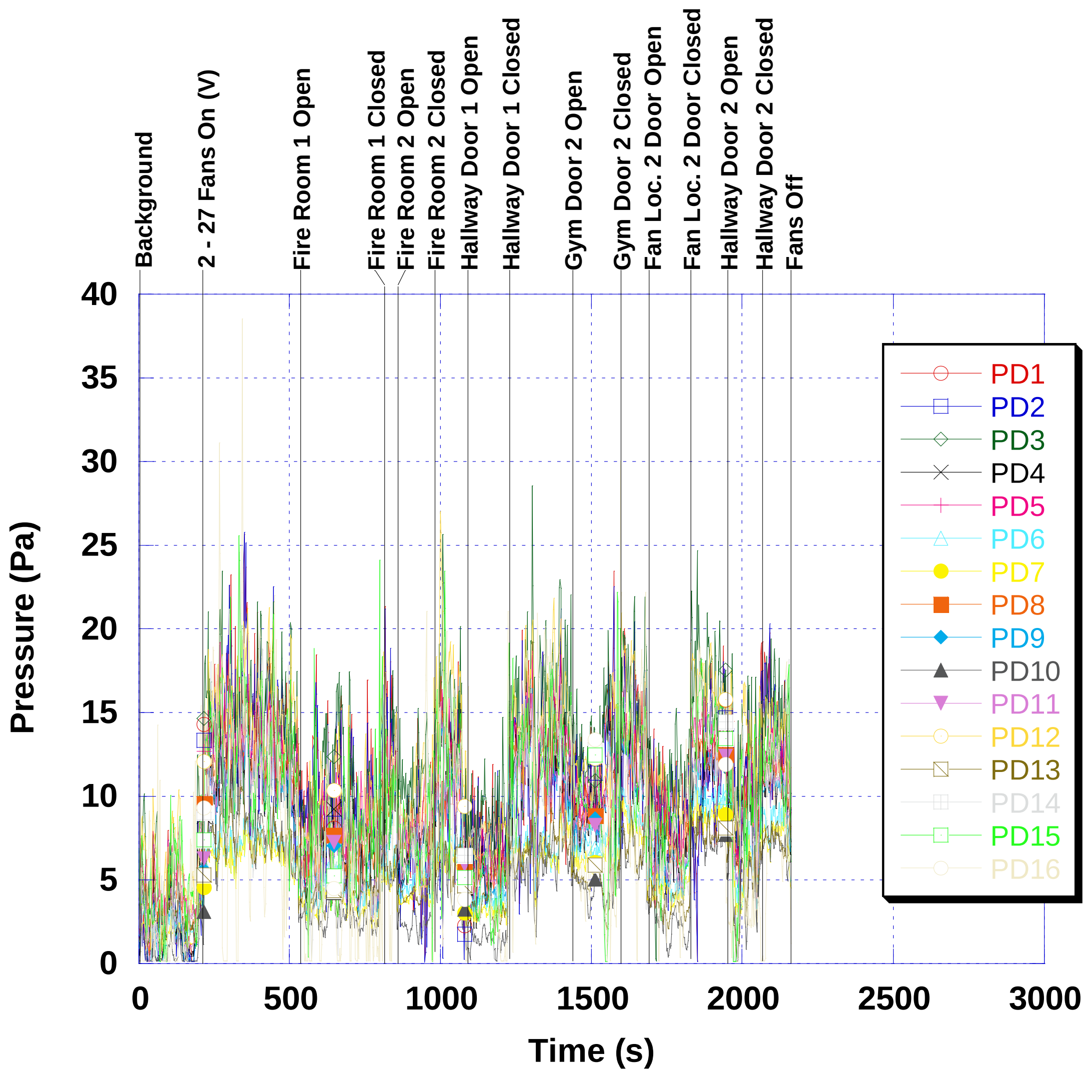

Figure 175. Experiment P1 Pressure vs. Time for transducers 1-16

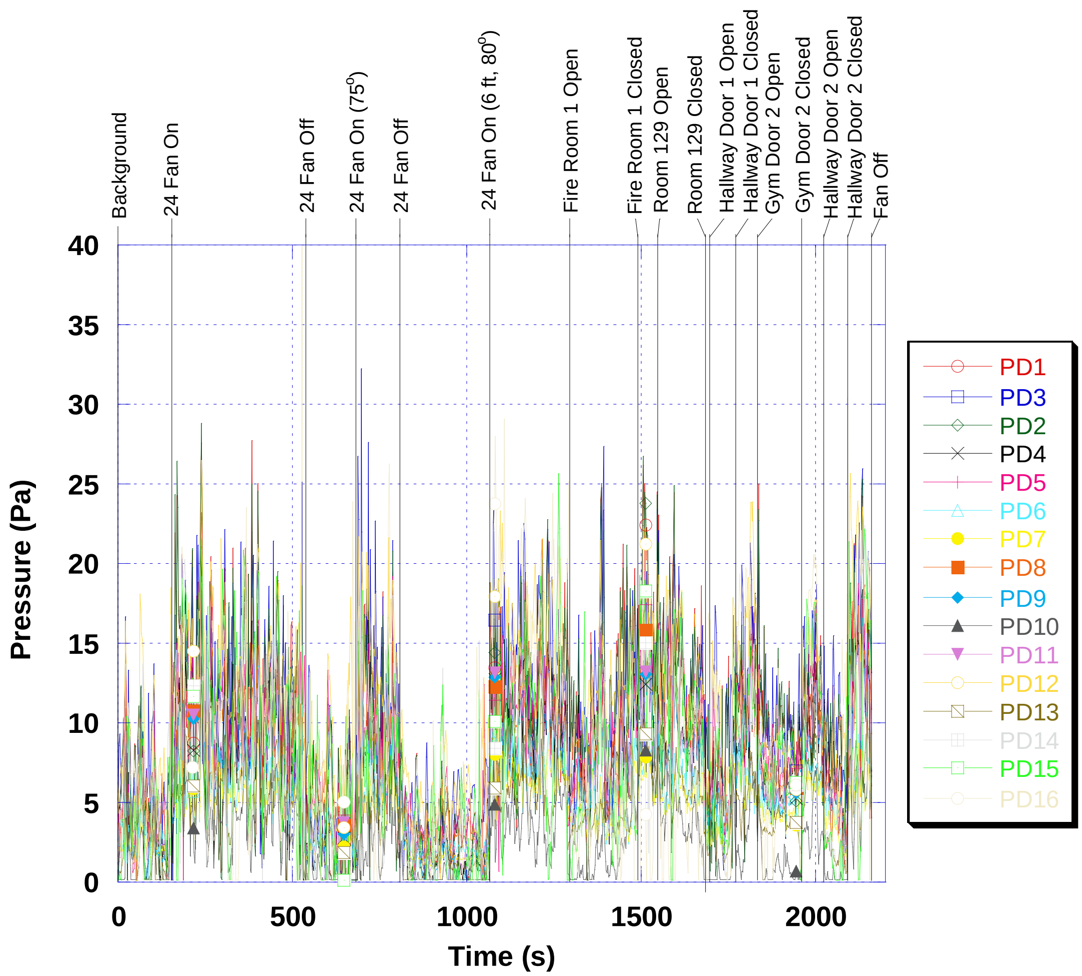

Figure 176. Experiment P2 Pressure vs. Time for transducers 1-16

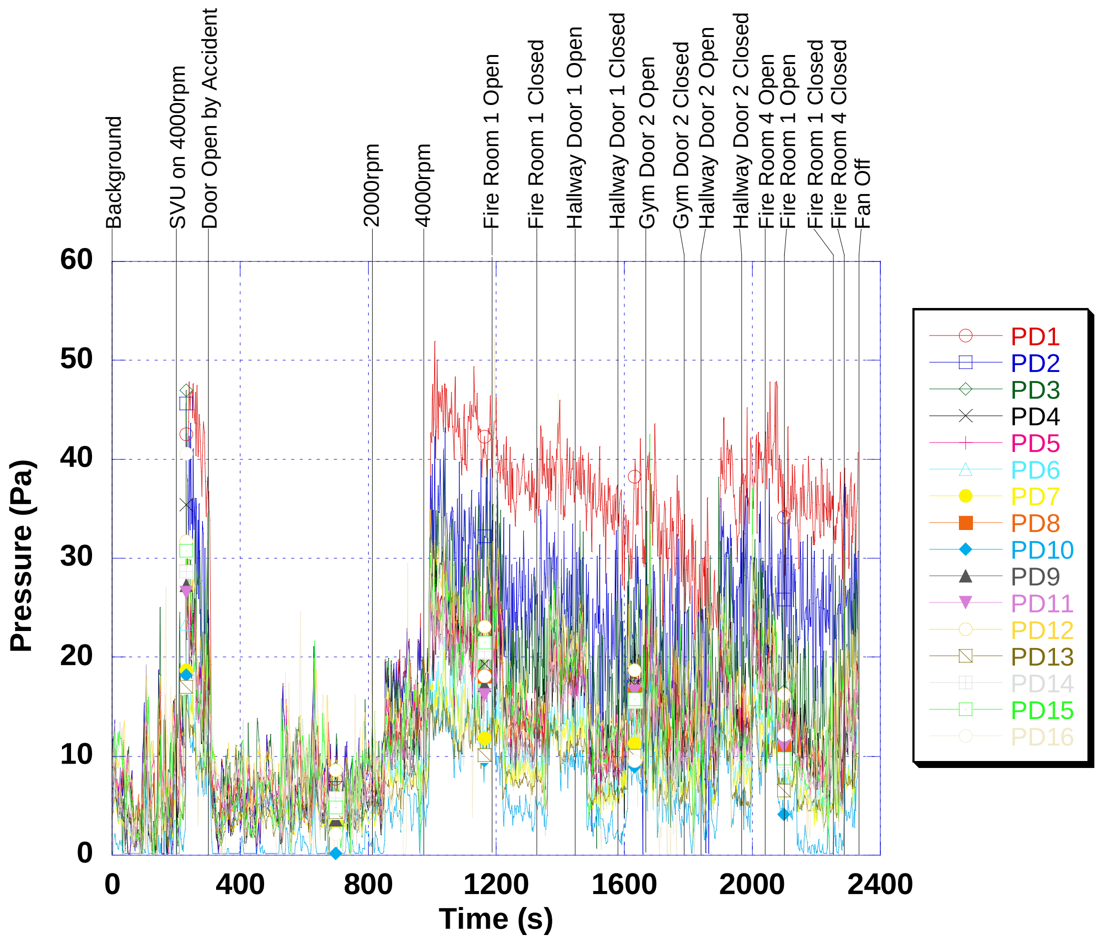

Figure 177. Experiment P3 Pressure vs. Time for transducers 1-16

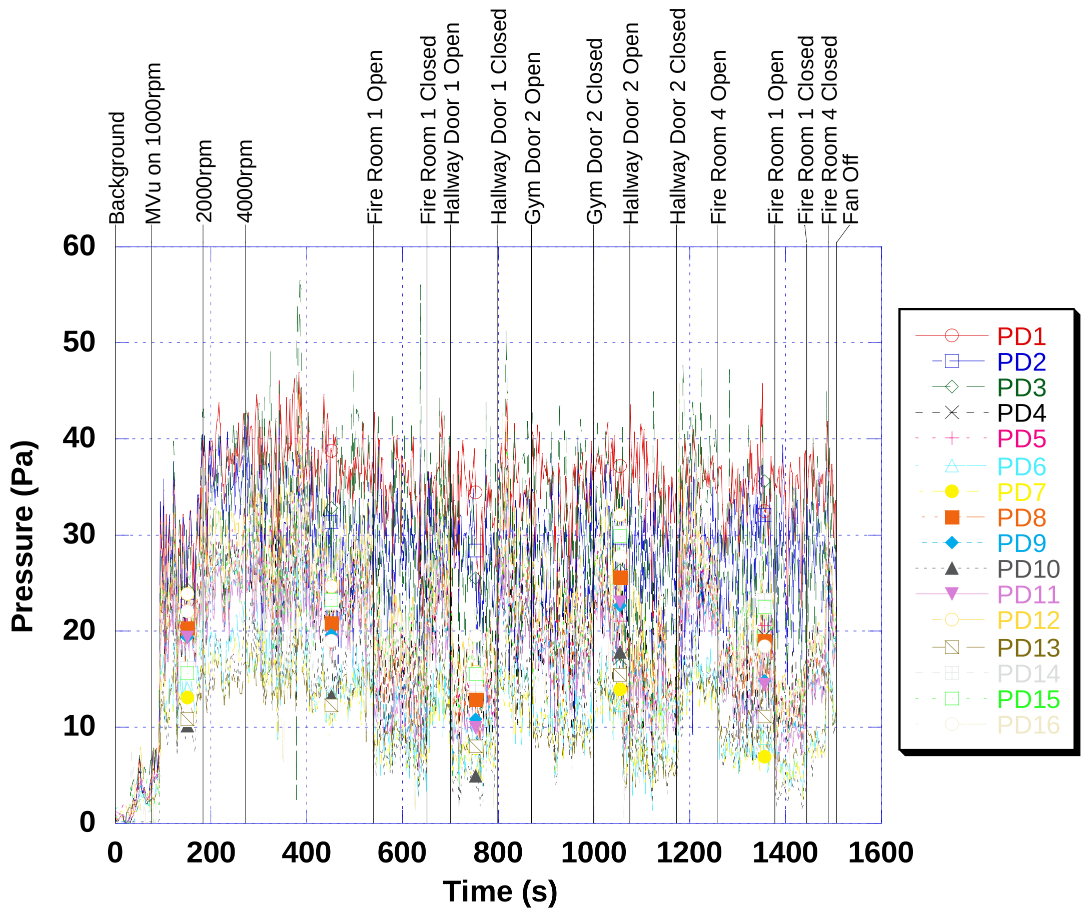

Figure 178. Experiment P4 Pressure vs. Time for transducers 1-16

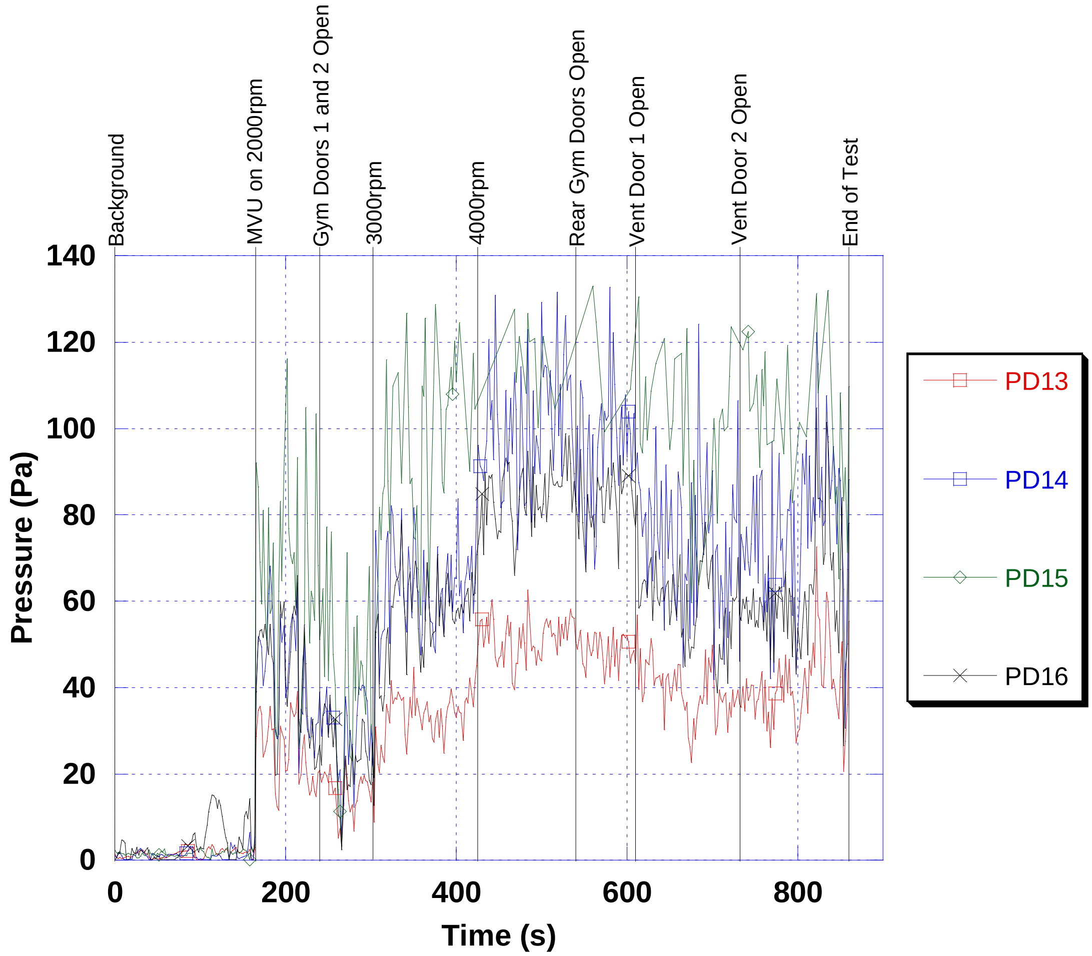

Figure 179. Experiment P5 Pressure vs. Time for transducers 13-16

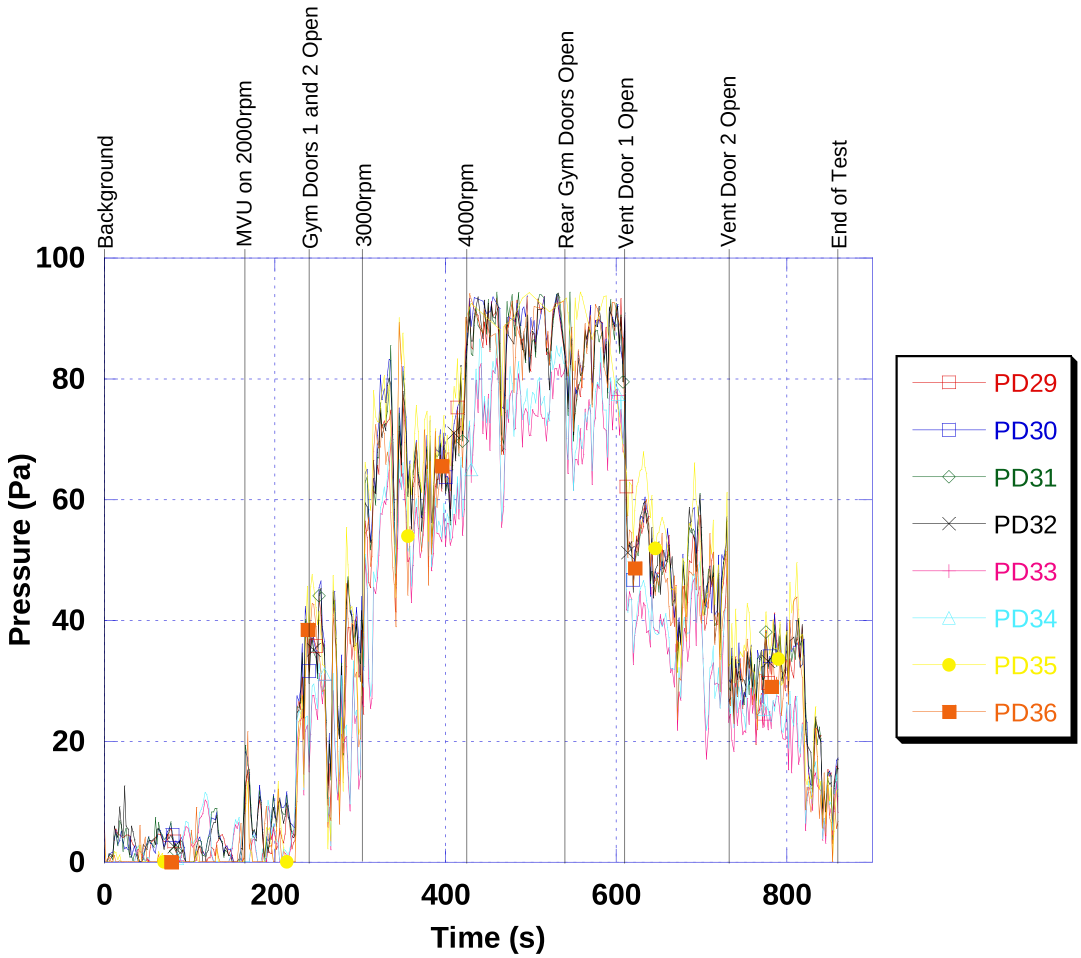

Figure 180. Experiment P5 Pressure vs. Time for transducers 29-36

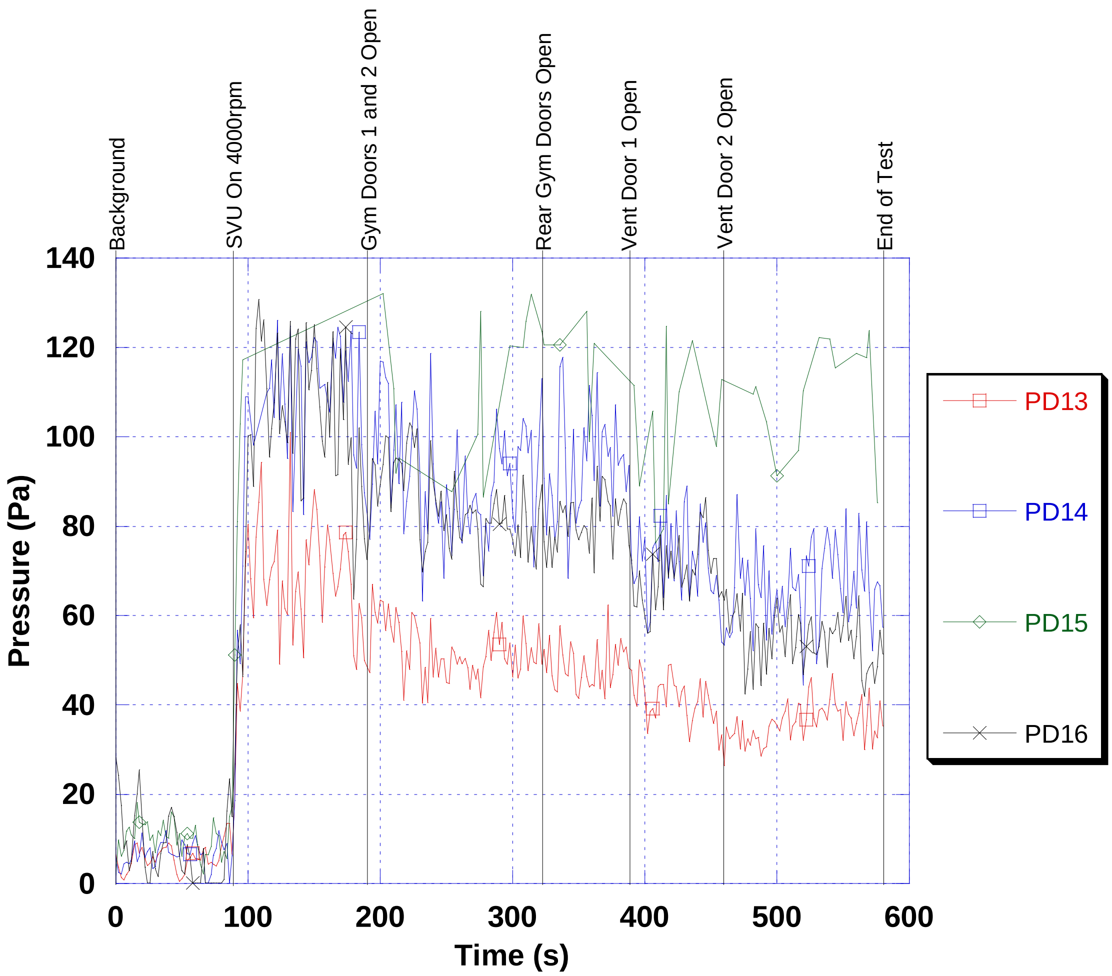

Figure 181. Experiment P6 Pressure vs. Time for transducers 13-16

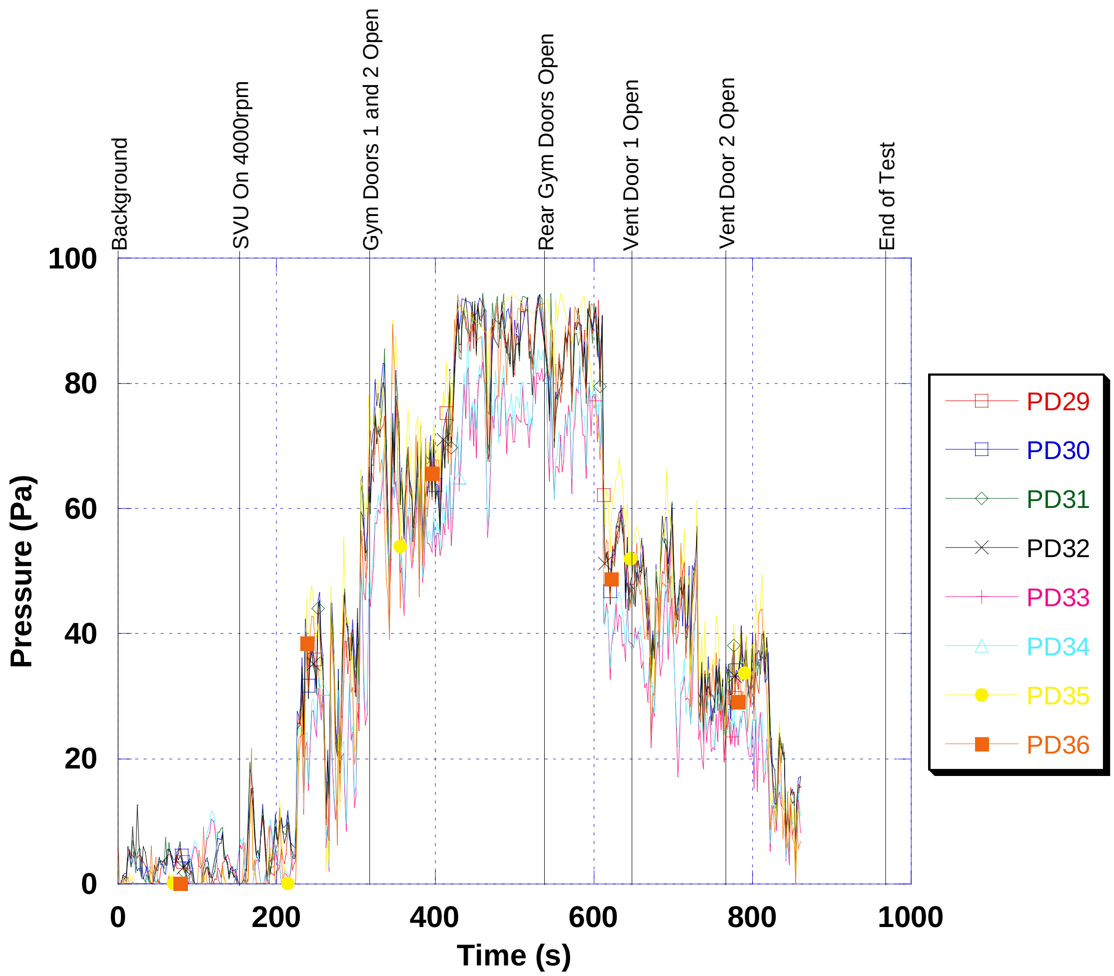

Figure 182. Experiment P6 Pressure vs. Time for transducers 29-36

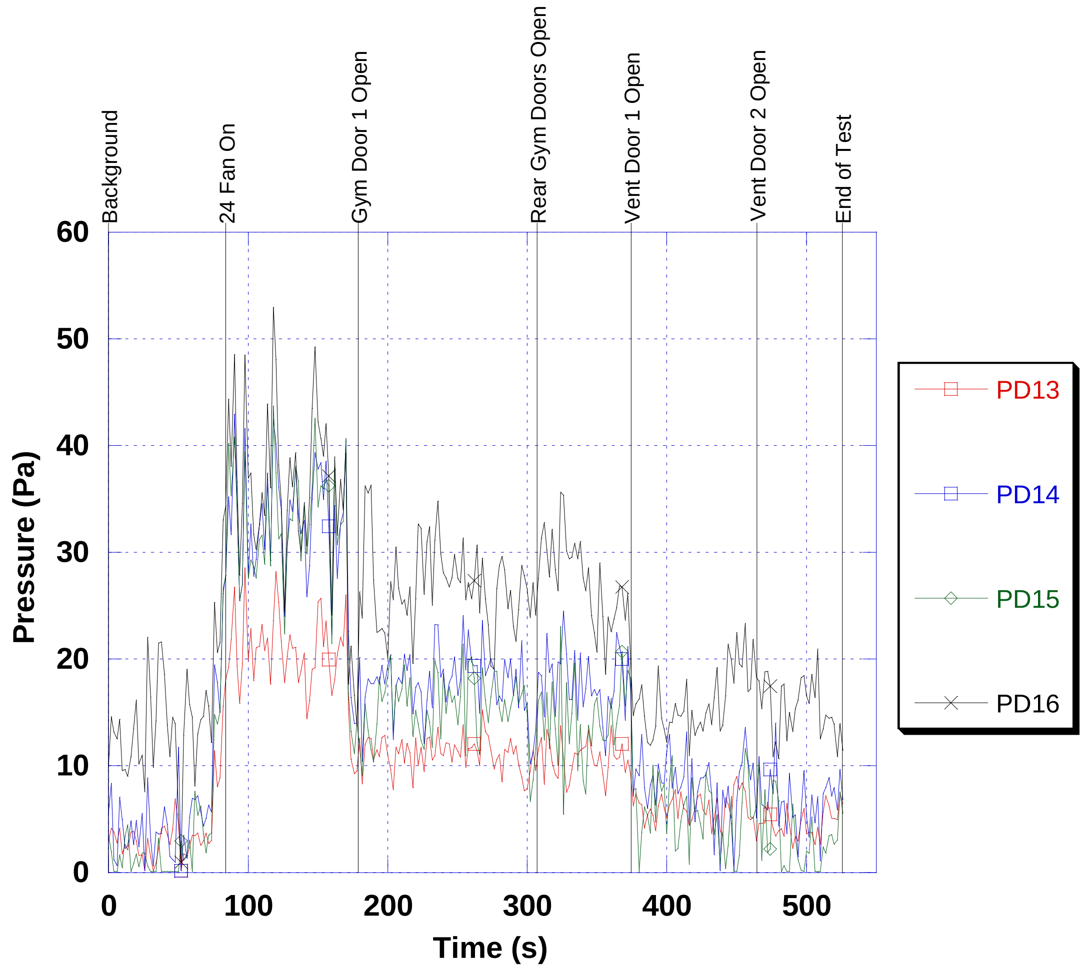

Figure 183. Experiment P7 Pressure vs. Time for transducers 13-16

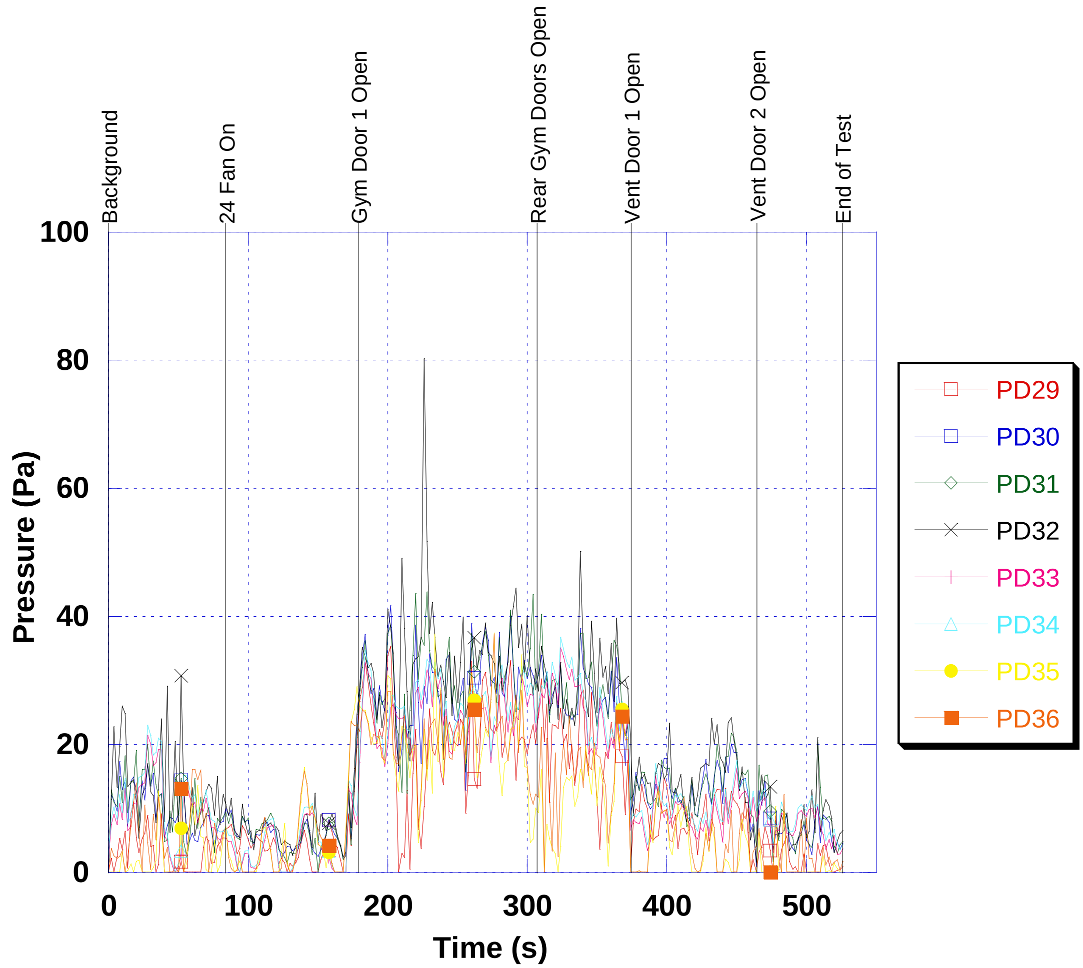

Figure 184. Experiment P7 Pressure vs. Time for transducers 29-36

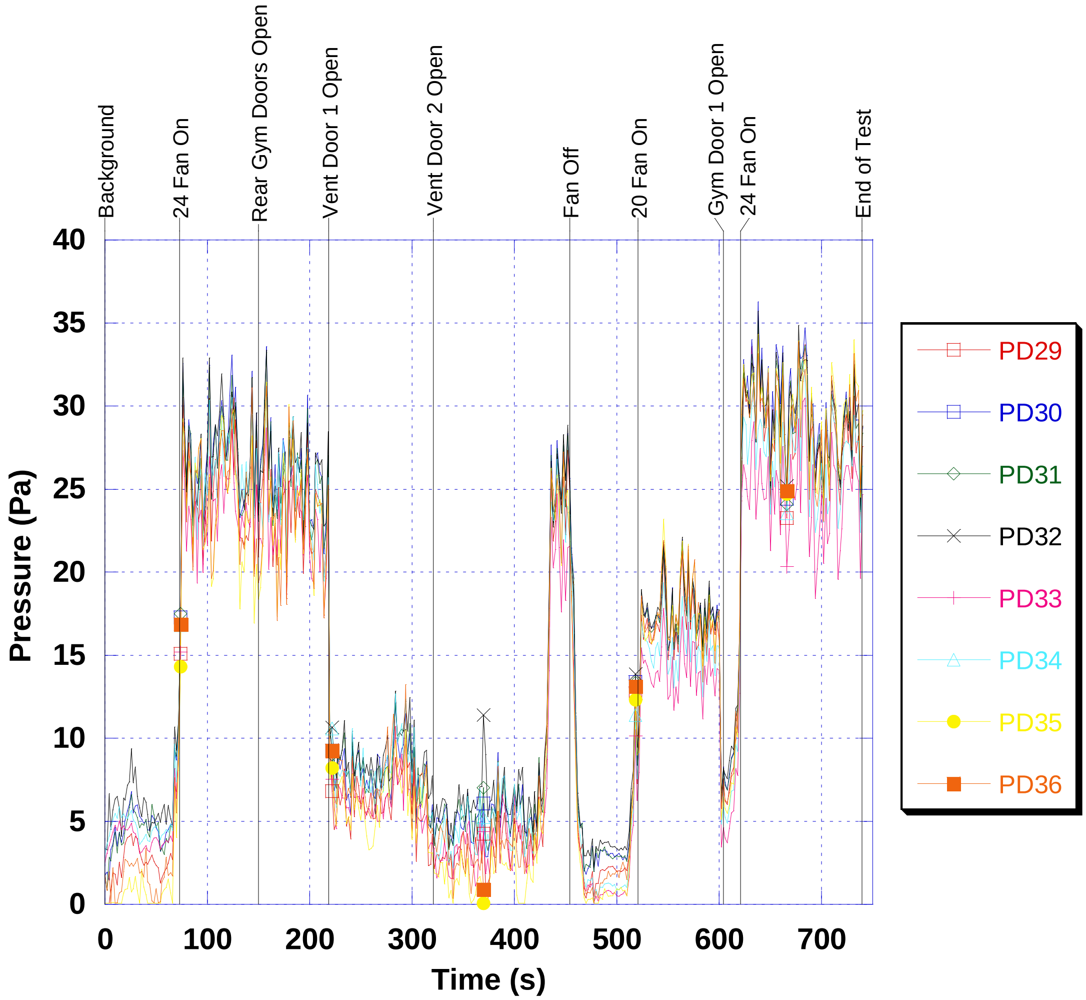

Figure 185. Experiment P8 Pressure vs. Time for transducers 29-36

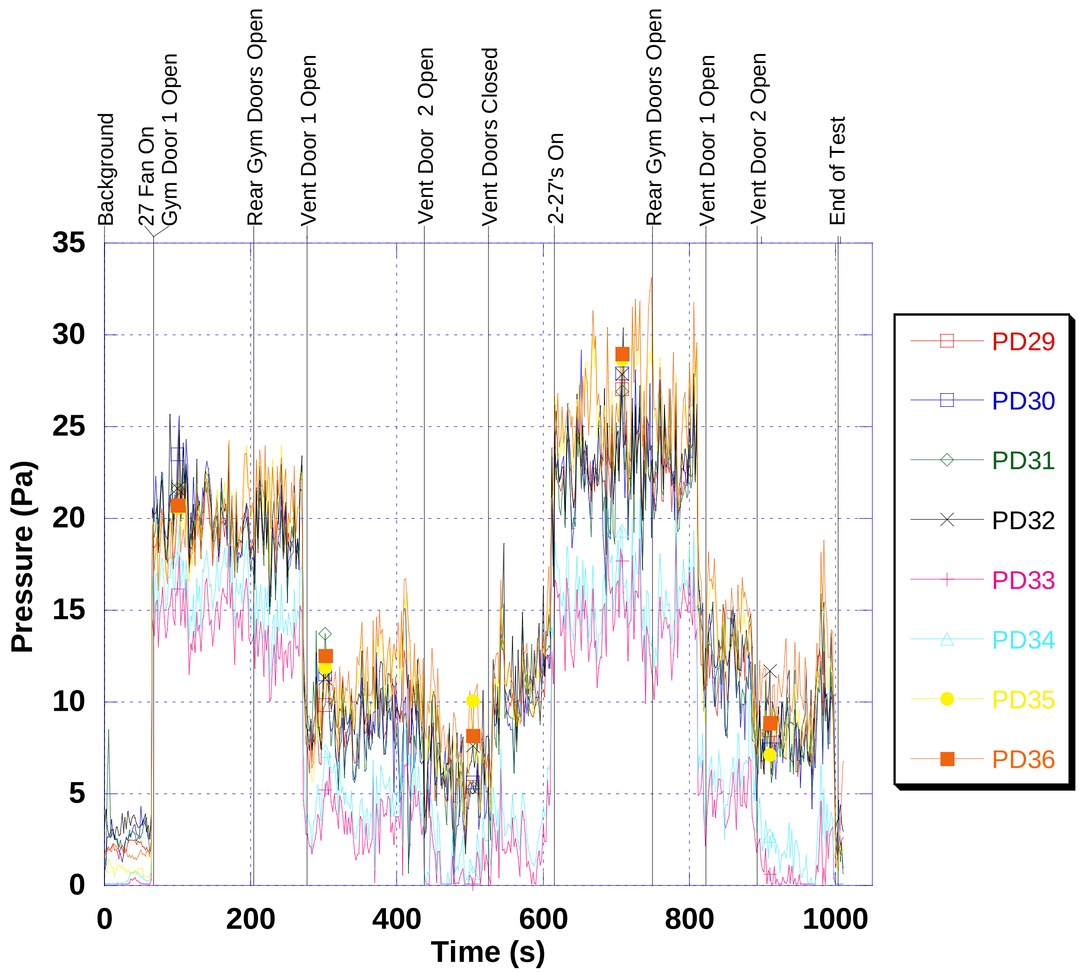

Figure 186. Experiment P9 Pressure vs. Time for transducers 29-36

APPENDIX B – Pressure versus time for experiments CF1 through CF6

Timelines of the experimental configuration changes

Experiment CF1

Time (s)	Event
0	Background
180	Ignition
660	FR 1 Window Open
780	MVU On
1110	Sprinkler On
1140	MVU Off
1380	End Test

Experiment CF2

Time (s)	Event
0	Background
240	Ignition
720	FR 1 Window Open
840	MVU On
1080	MVU Off
1260	MVU On
2520	End of Test

Experiment CF3

Time (s)	Event
0	Background
110	Ignition
490	Hallway Door 1 Open
600	2 -27 in. Fans On
750	2 -27 in. Fans Off
760	Hallway Door 1Closed
820	FR 2 Window Open
910	1 27 in. Fan On
960	2 – 27 in. Fans On
1260	Water Applied
1370	End of Test

Experiment CF4

Time (s)	Event
0	Background
360	Ignition
720	Hallway Door 1 Open
840	27 in. Fan On
930	27 in. Fan Off/Door Closed
995	FR 4 Window Open
1130	27 in. Fan On
1440	Water Applied
1830	End of Test

Experiment CF5

Time (s)	Event
0	Background
60	Ignition
420	Hallway Door 1 Open
560	SVU On
560	Long Ramp Up
750	SVU Off/Door Closed
810	SVU On
1140	SVU Off
1168	Water On
1300	End of Test

Experiment CF6

Time (s)	Event
0	Background
120	Ignition
480	Hallway Door 1 Open
600	MVU On
735	MVU Off/Door Closed
820	FR 2 Window Open
880	MVU On
1165	2nd Floor Stairs Open
1300	End of Test

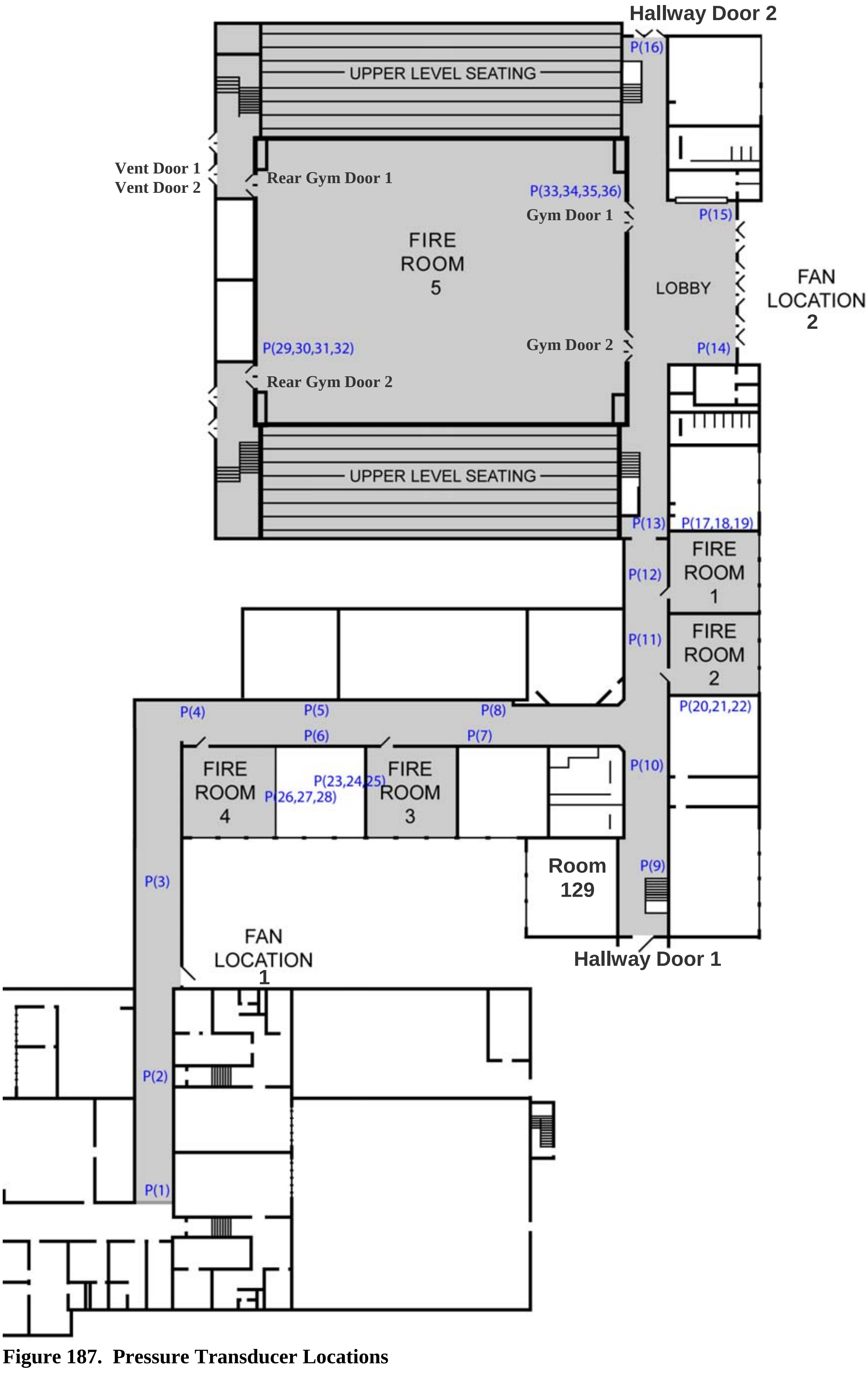

Figure 187. Pressure Transducer Locations

Experiment CF1

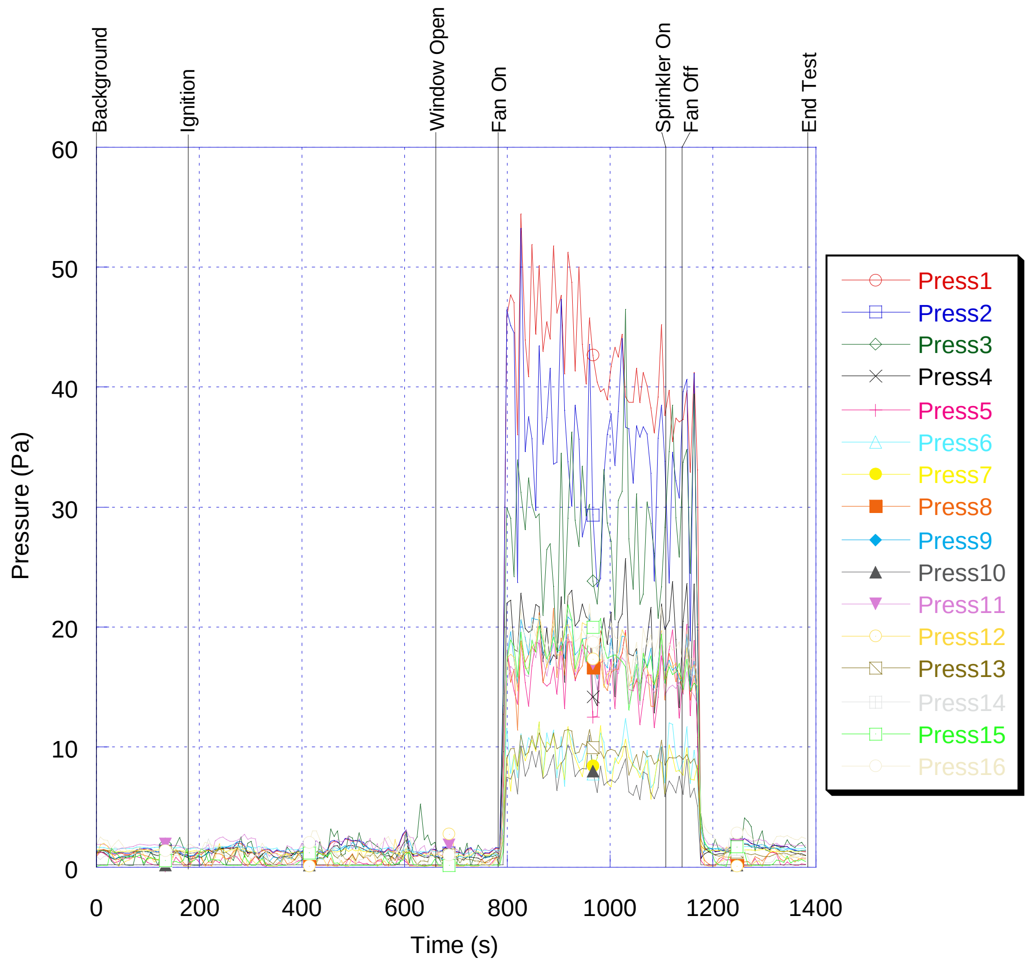

Figure 188. CF1 Pressure vs. Time for transducers 1-16

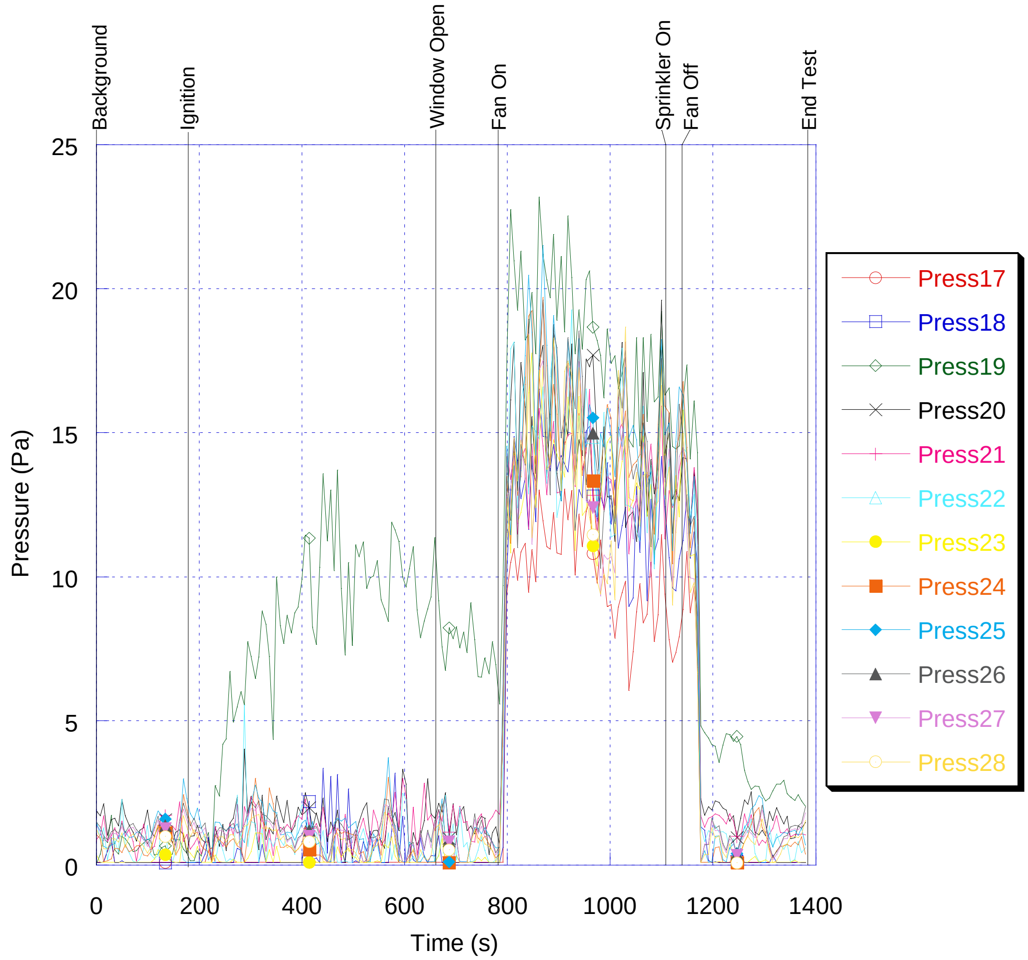

Figure 189. CF1 Pressure vs. Time for transducers 17-28

Experiment CF2

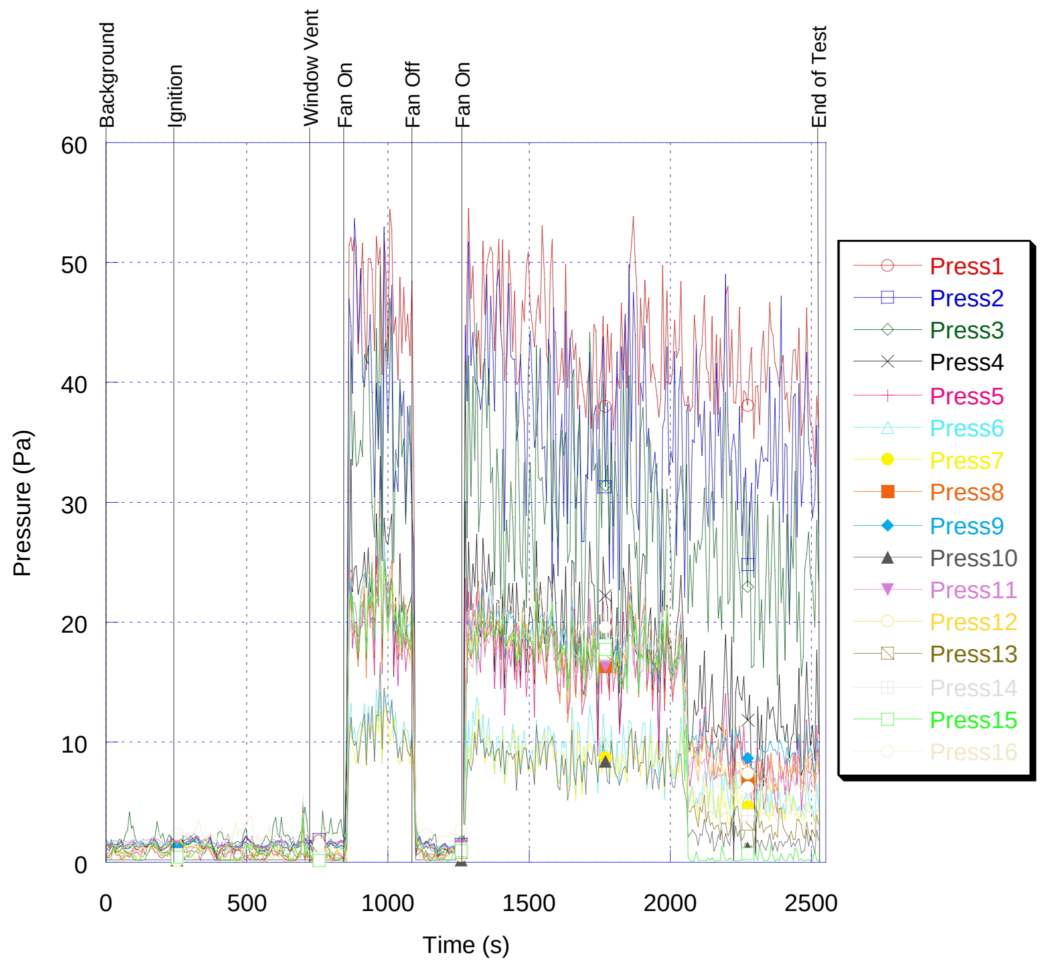

Figure 190. CF2 Pressure vs. Time for transducers 1-16

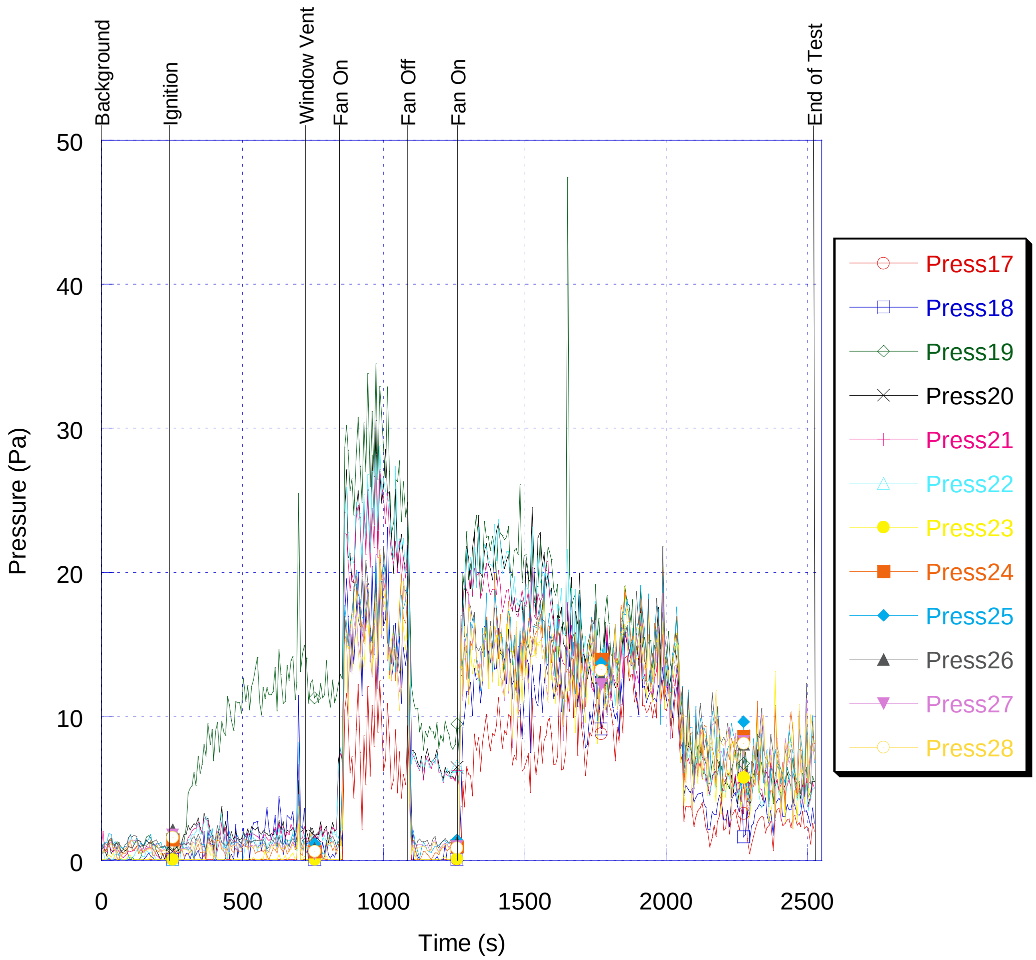

Figure 191. CF2 Pressure vs. Time for transducers 17-28

Experiment CF3

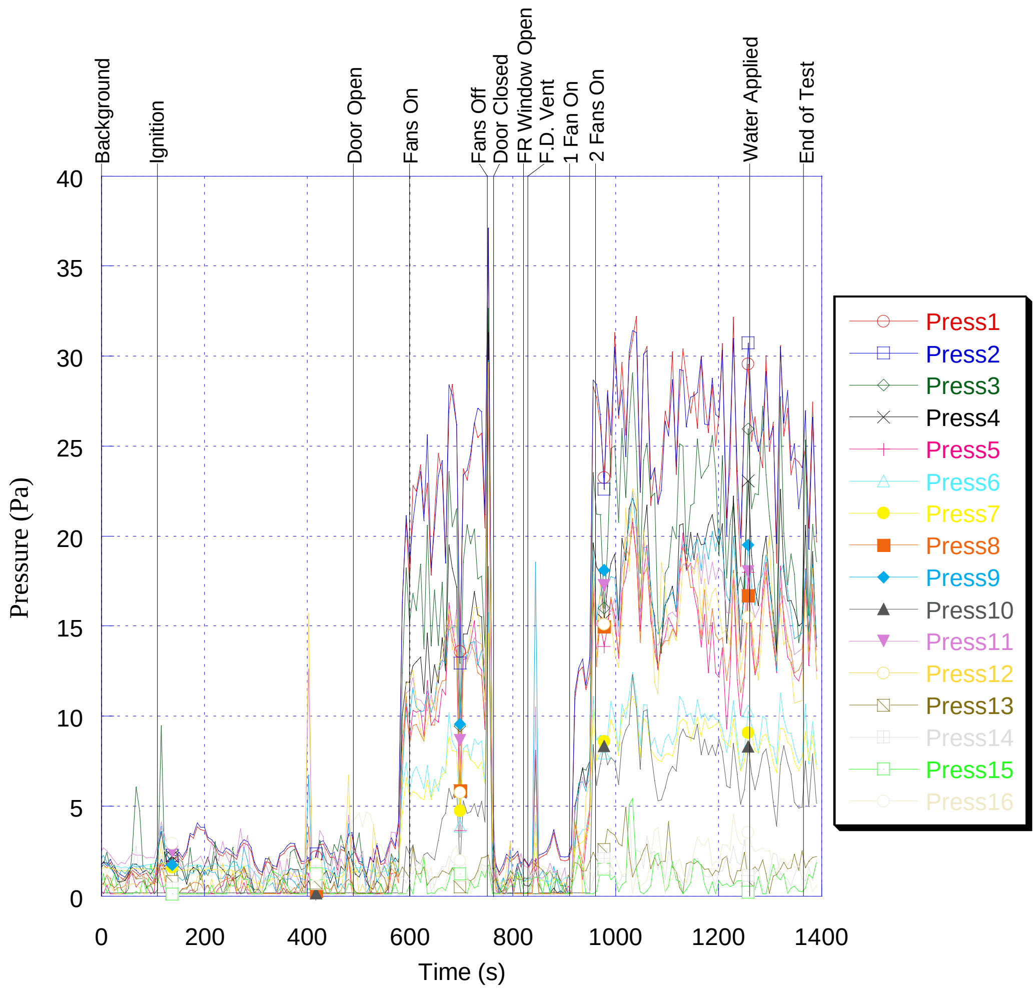

Figure 192. CF3 Pressure vs. Time for transducers 1-16

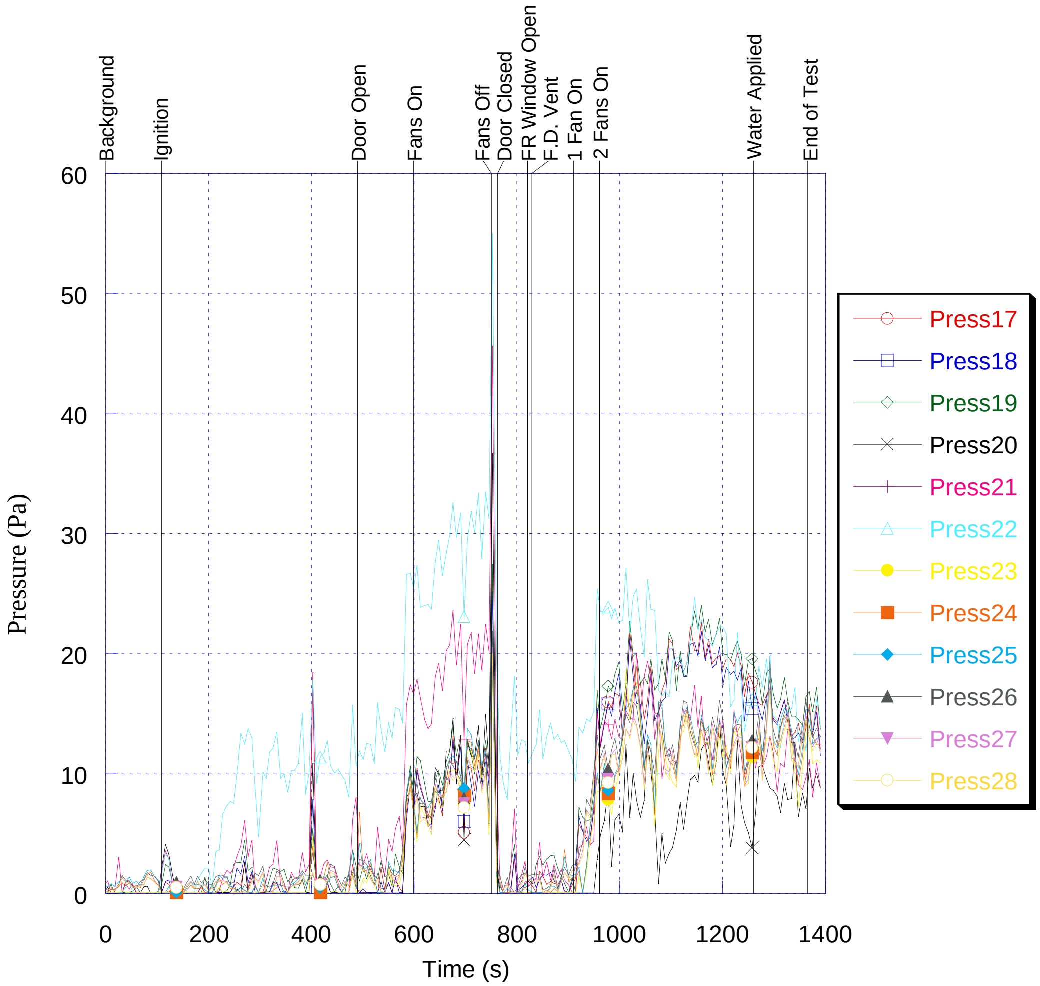

Figure 193. CF3 Pressure vs. Time for transducers 17-28

Experiment CF4

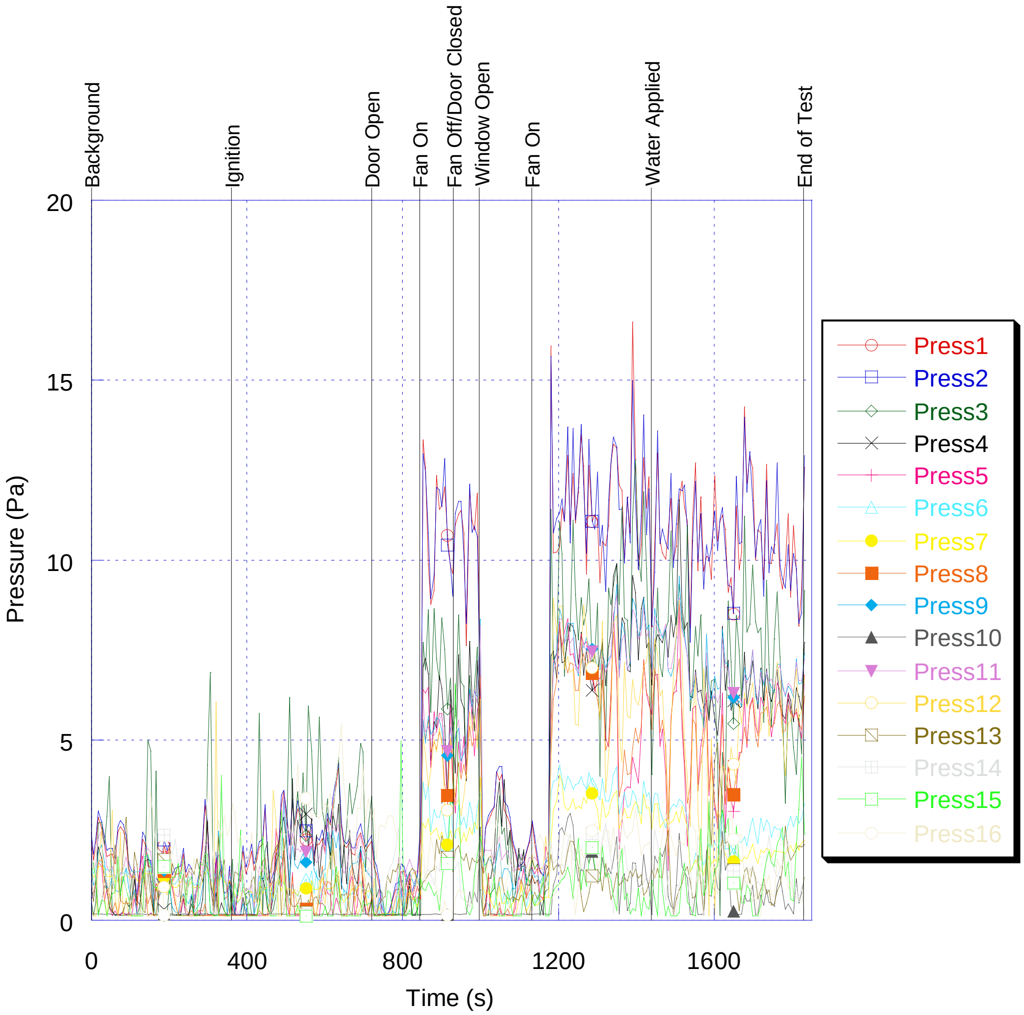

Figure 194. CF4 Pressure vs. Time for transducers 1-16

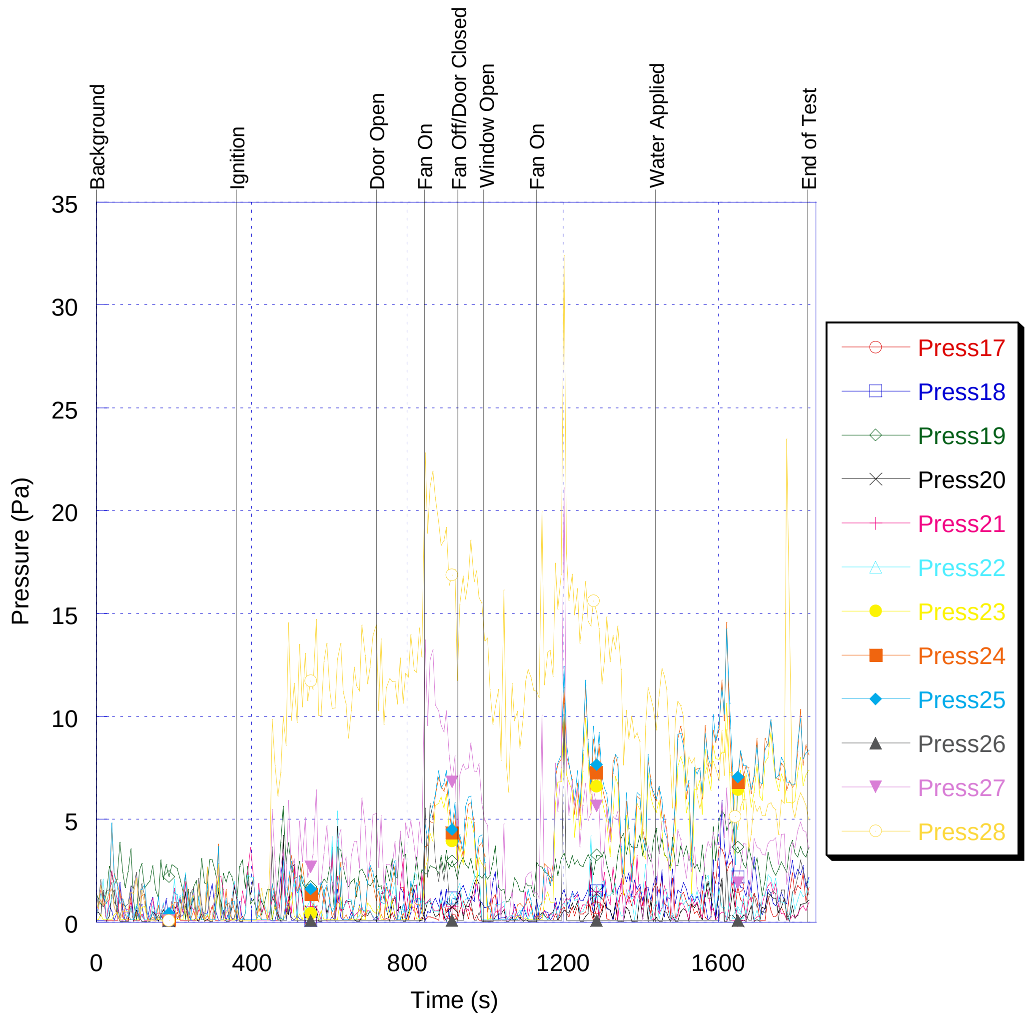

Figure 195. CF4 Pressure vs. Time for transducers 17-28

Experiment CF5

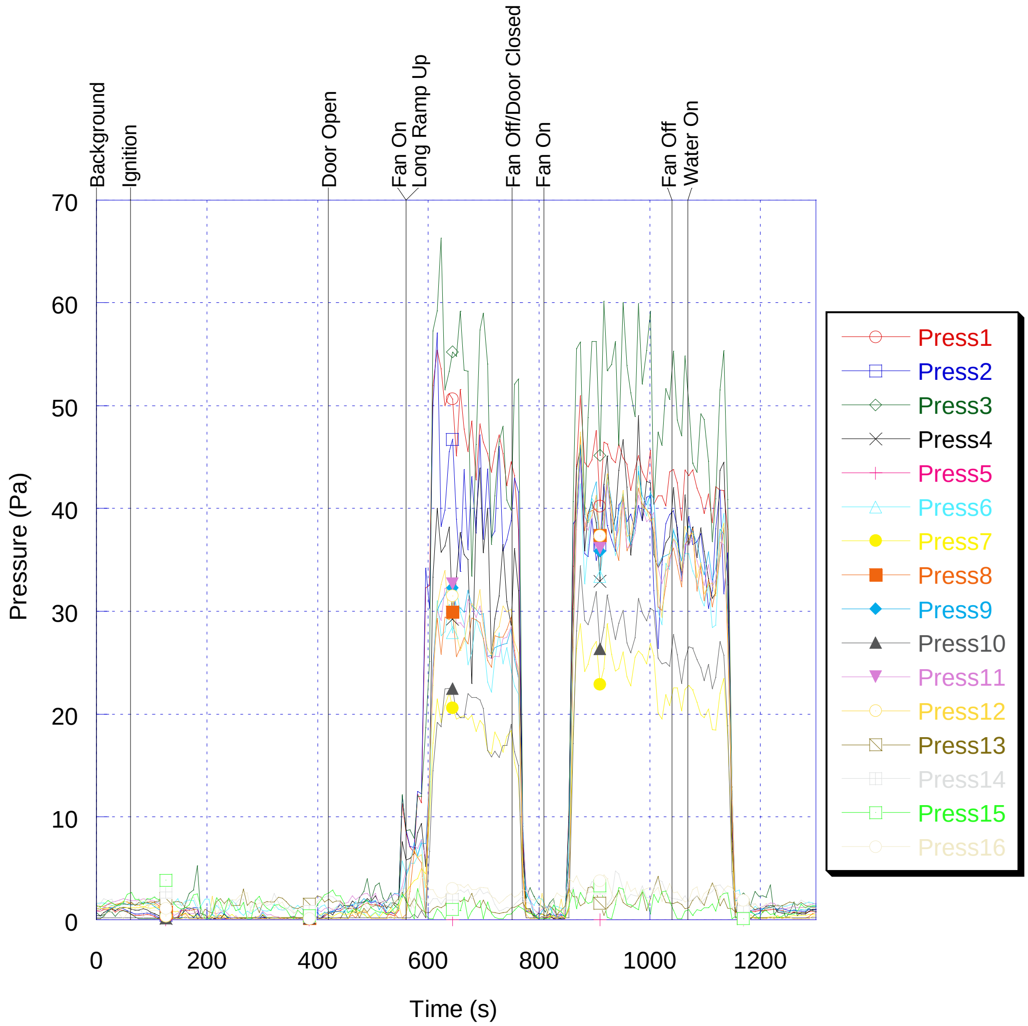

Figure 196. CF5 Pressure vs. Time for transducers 1-16

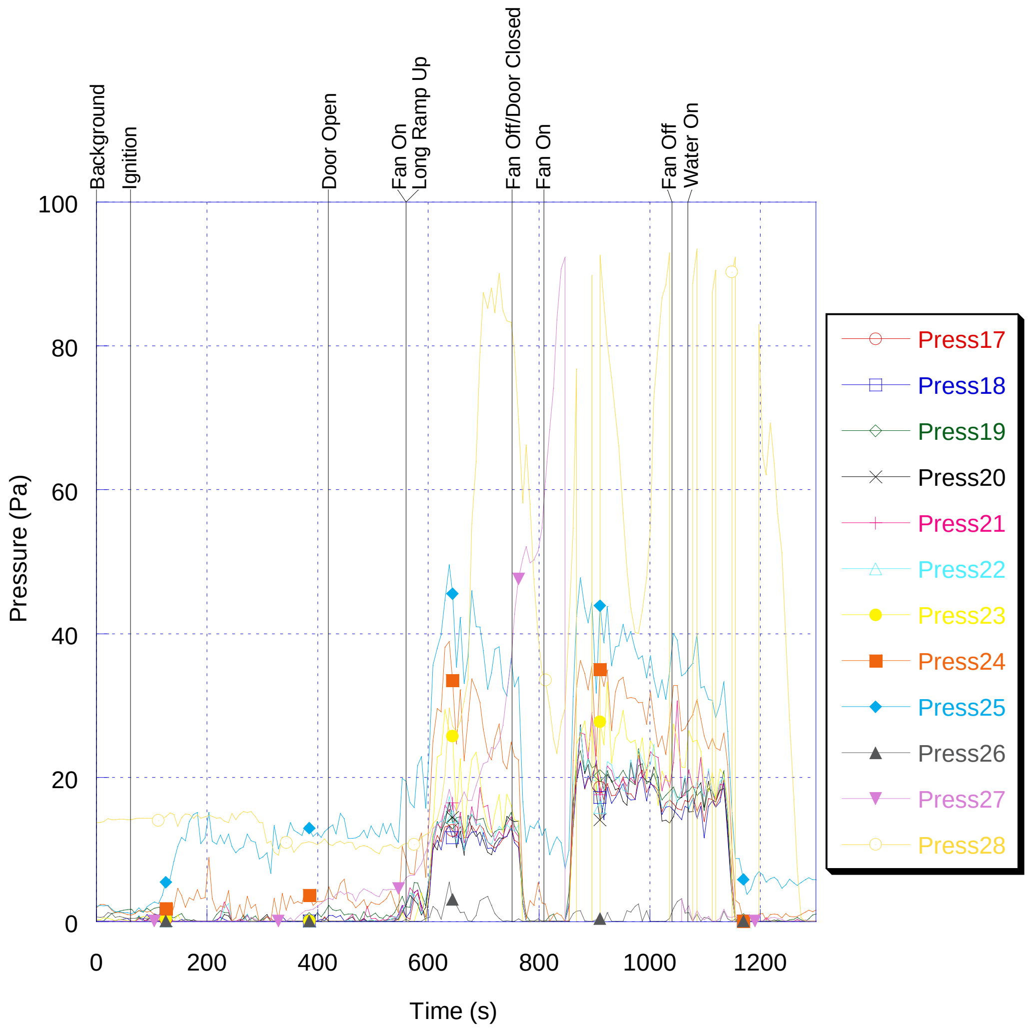

Figure 197. CF5 Pressure vs. Time for transducers 17-28

Experiment CF6

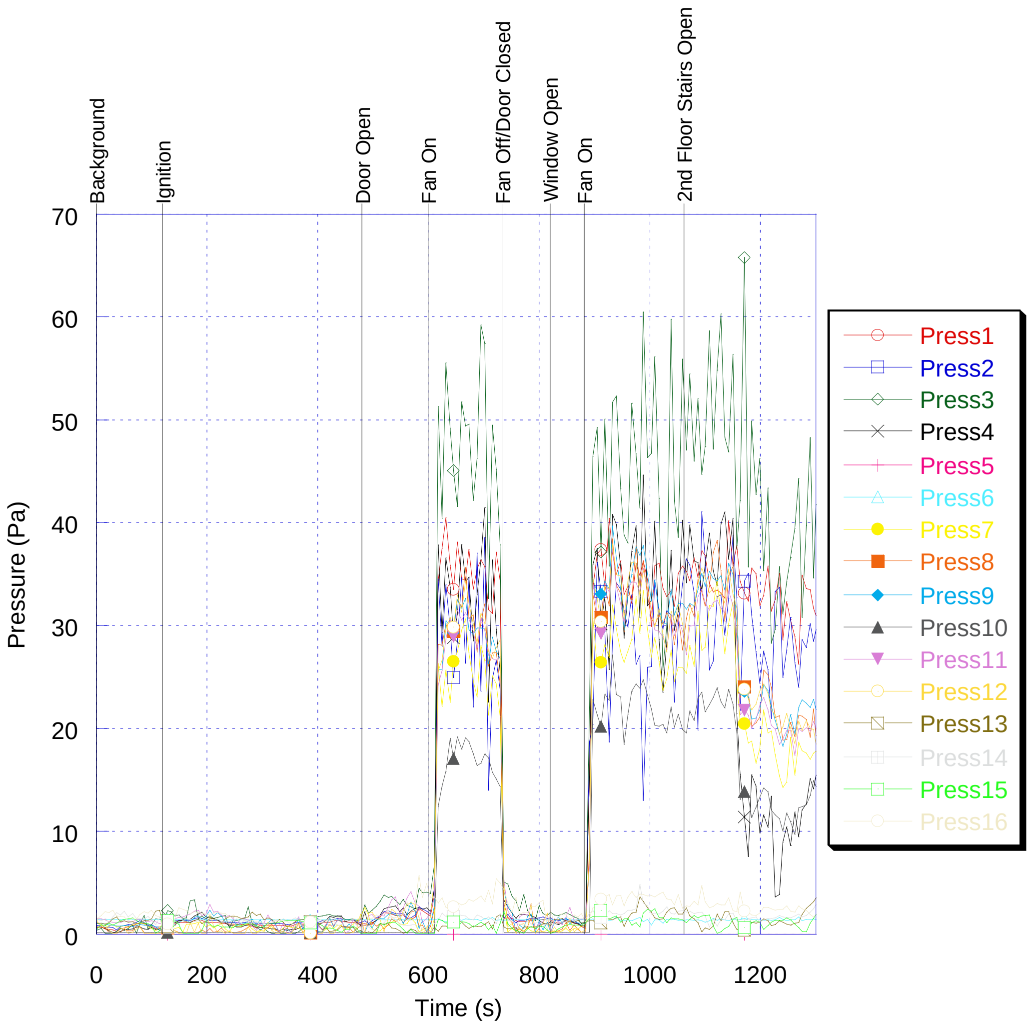

Figure 198. CF6 Pressure vs. Time for transducers 1-16

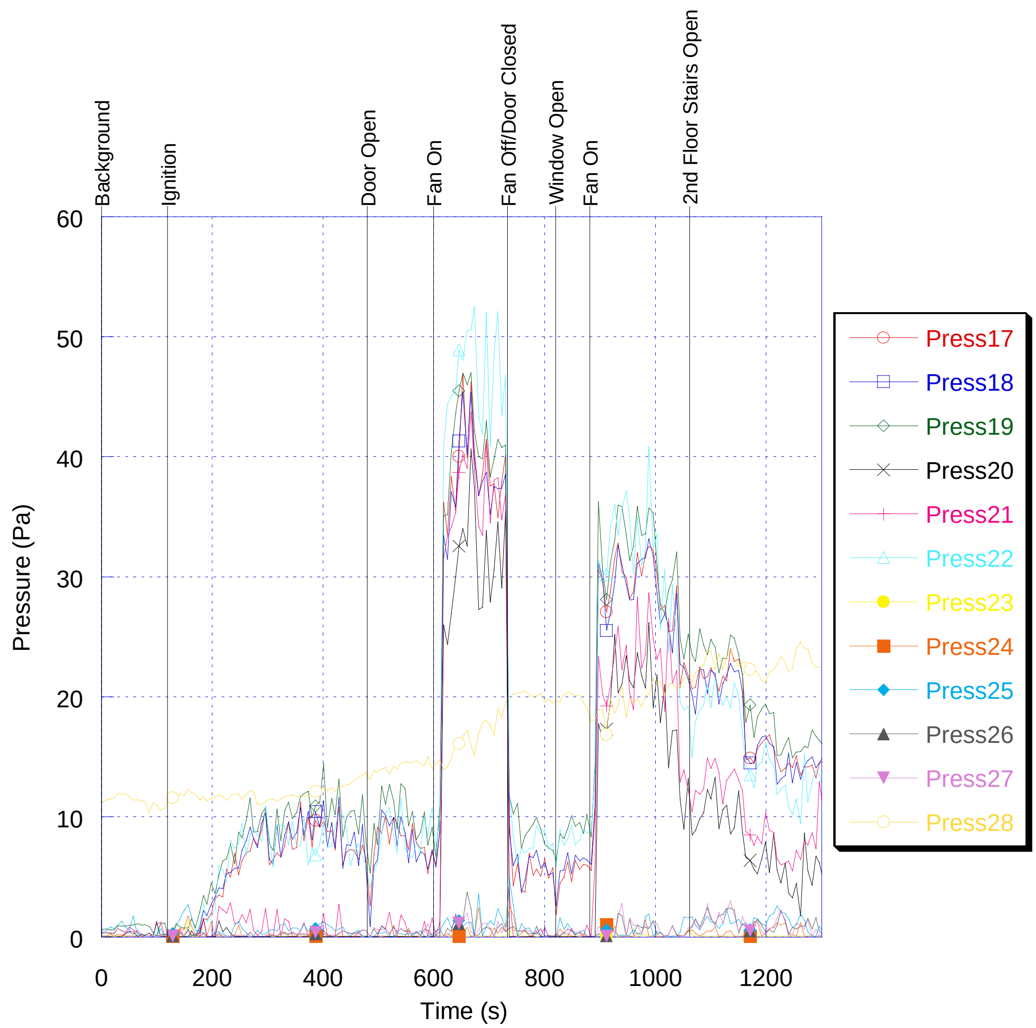

Figure 199. CF6 Pressure vs. Time for transducers 17-28

APPENDIX C – Temperature versus time for experiments CF1 through CF6

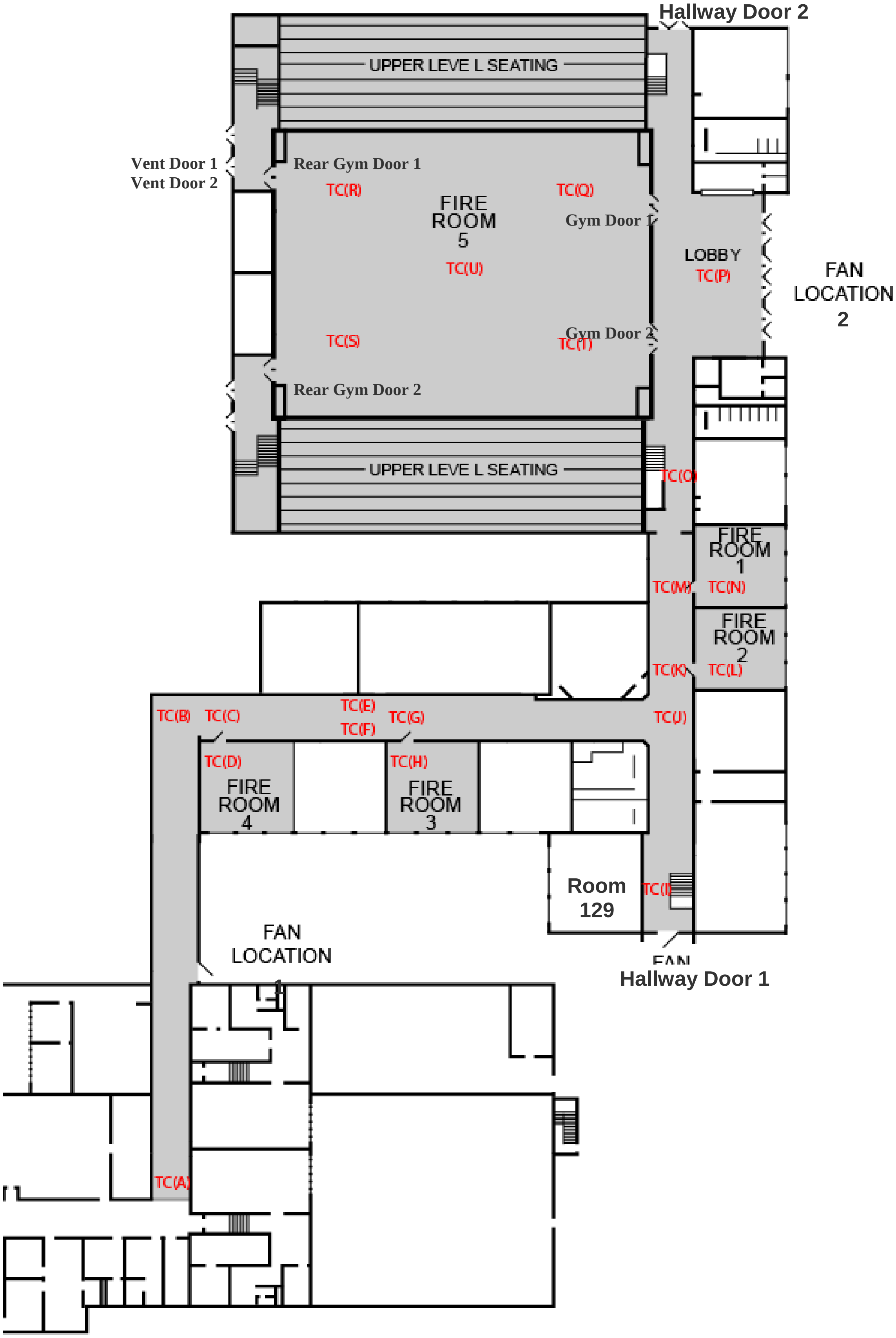

Figure 200. Temperature Measurement Locations

Experiment CF1

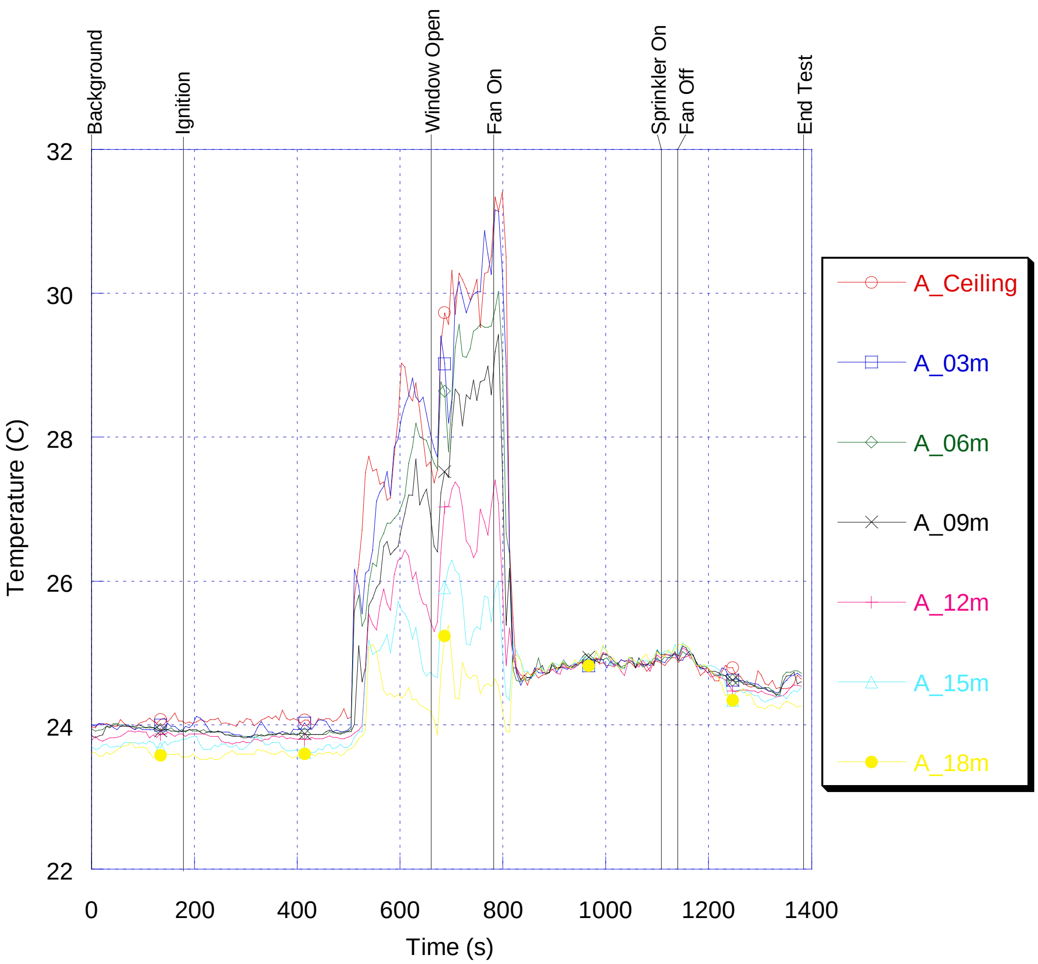

Figure 201. Experiment CF1 Temperature vs. Time for Location A

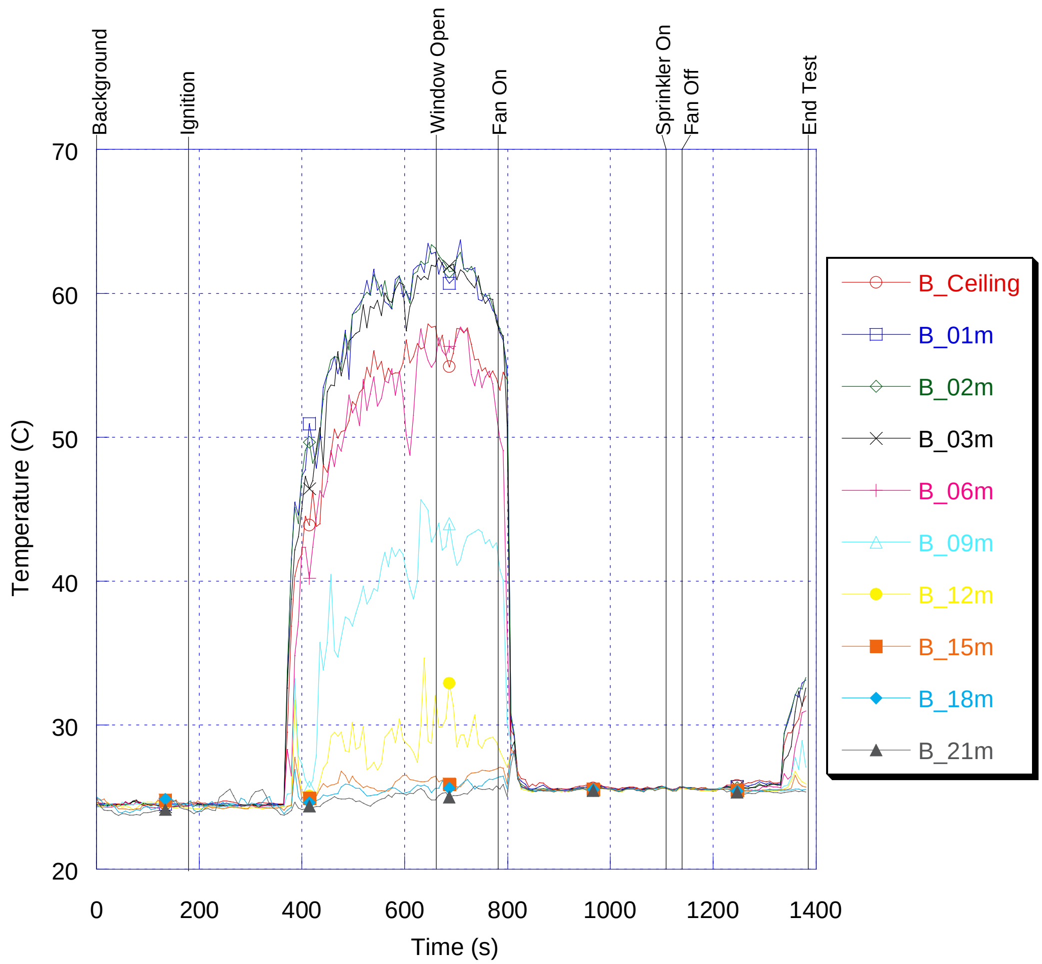

Figure 202. Experiment CF1 Temperature vs. Time for Location B

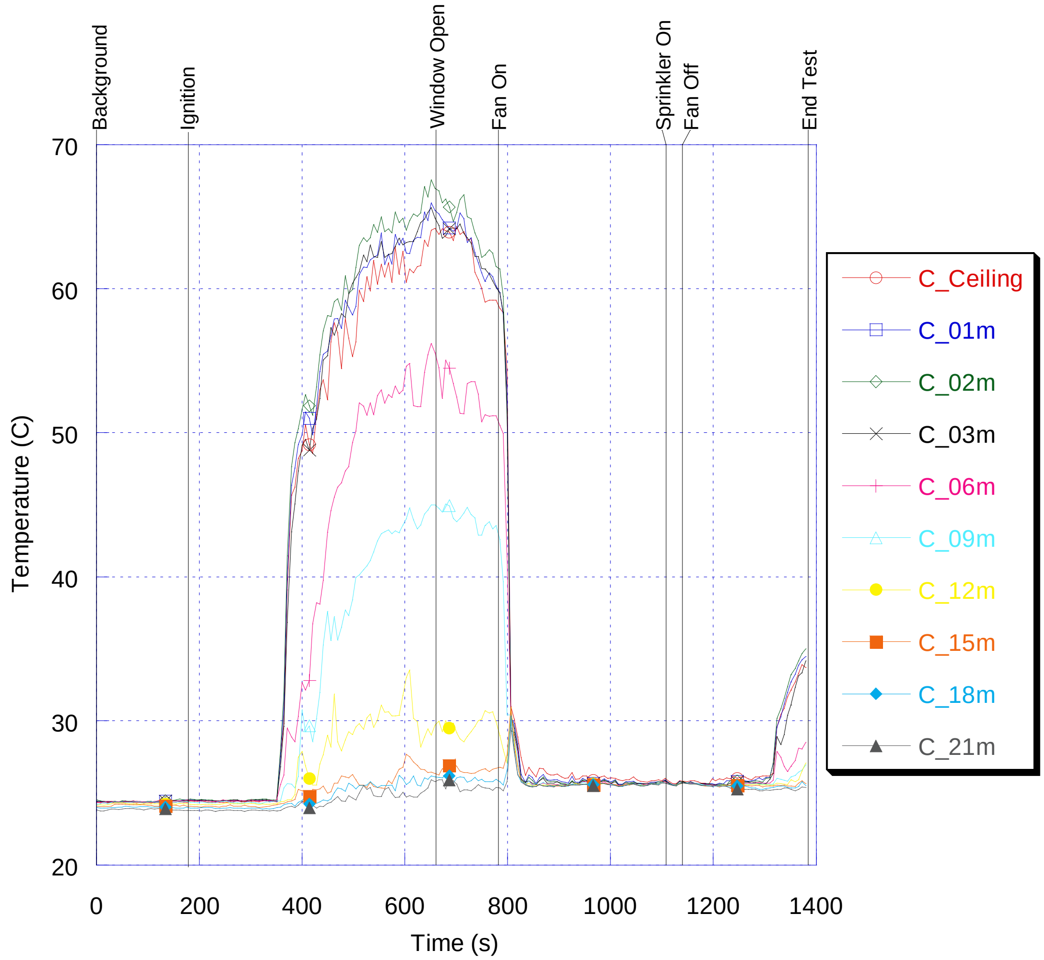

Figure 203. Experiment CF1 Temperature vs. Time for Location C

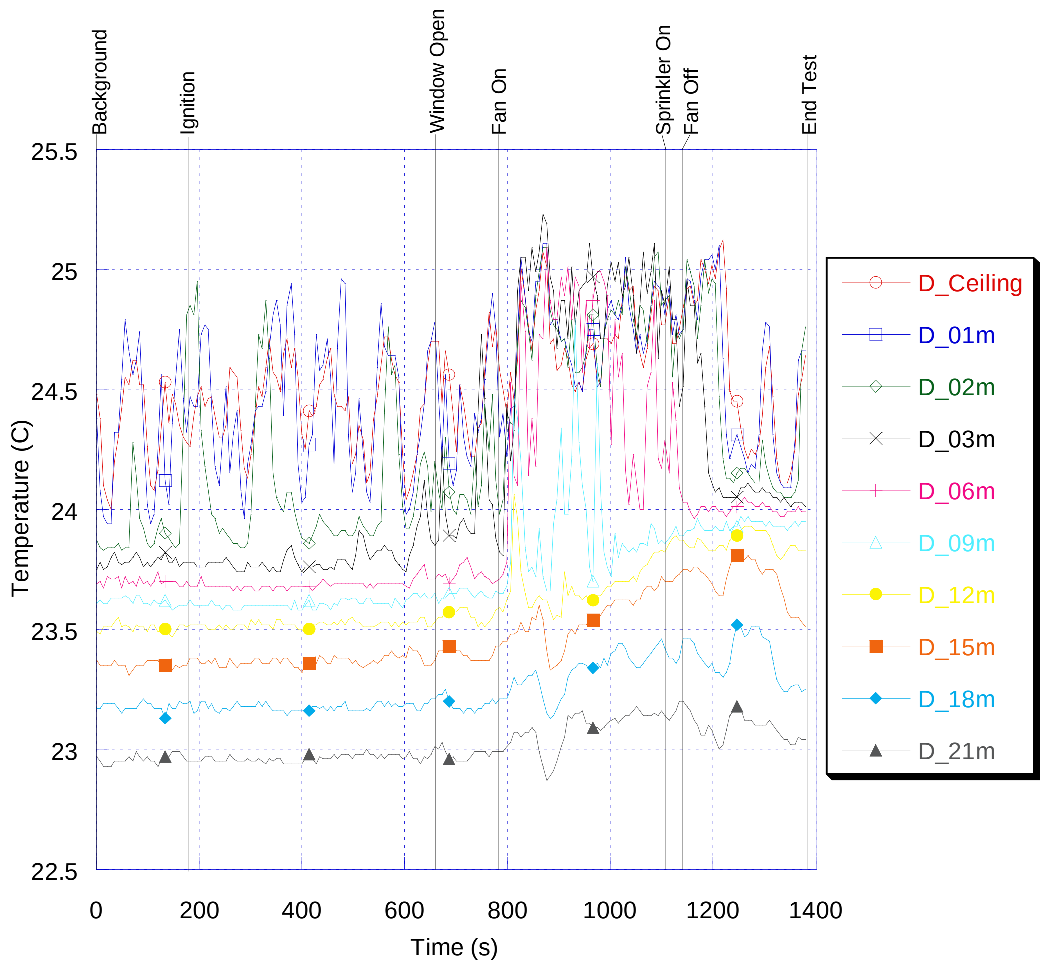

Figure 204. Experiment CF1 Temperature vs. Time for Location D

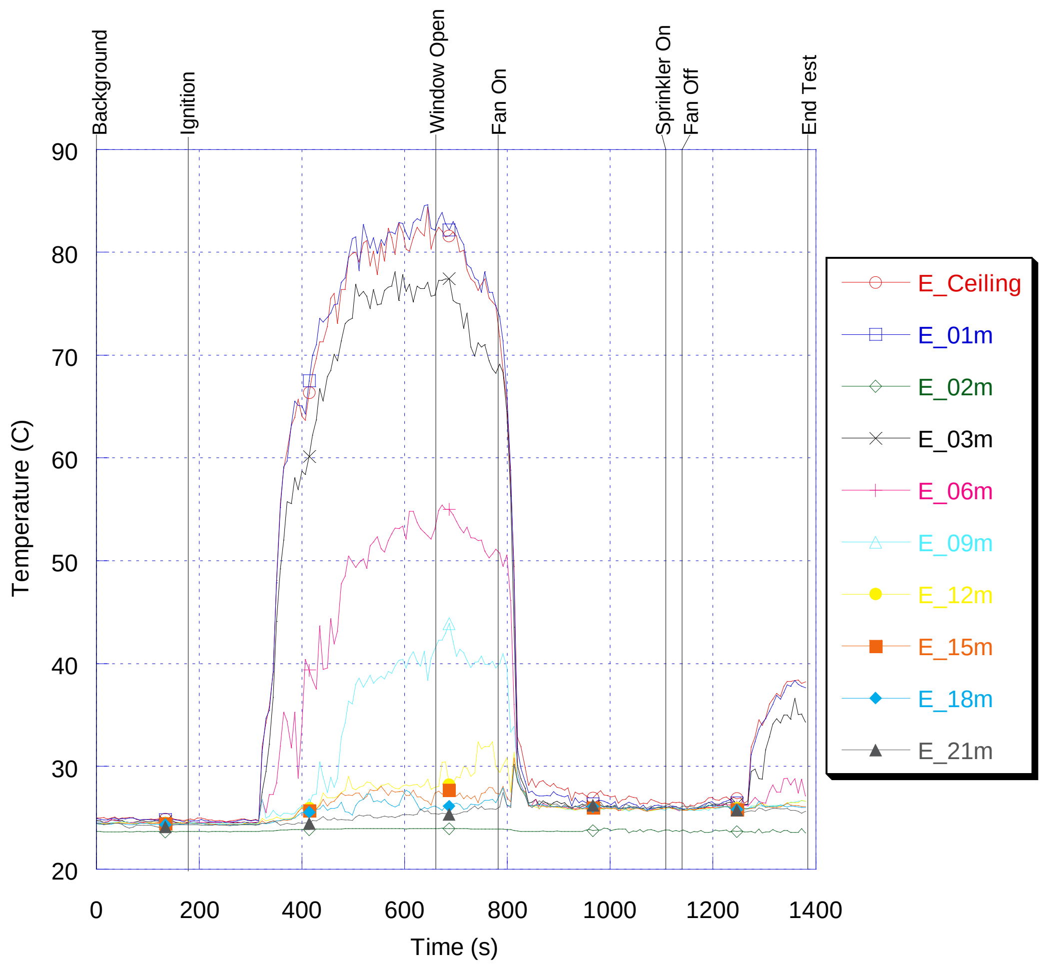

Figure 205. Experiment CF1 Temperature vs. Time for Location E

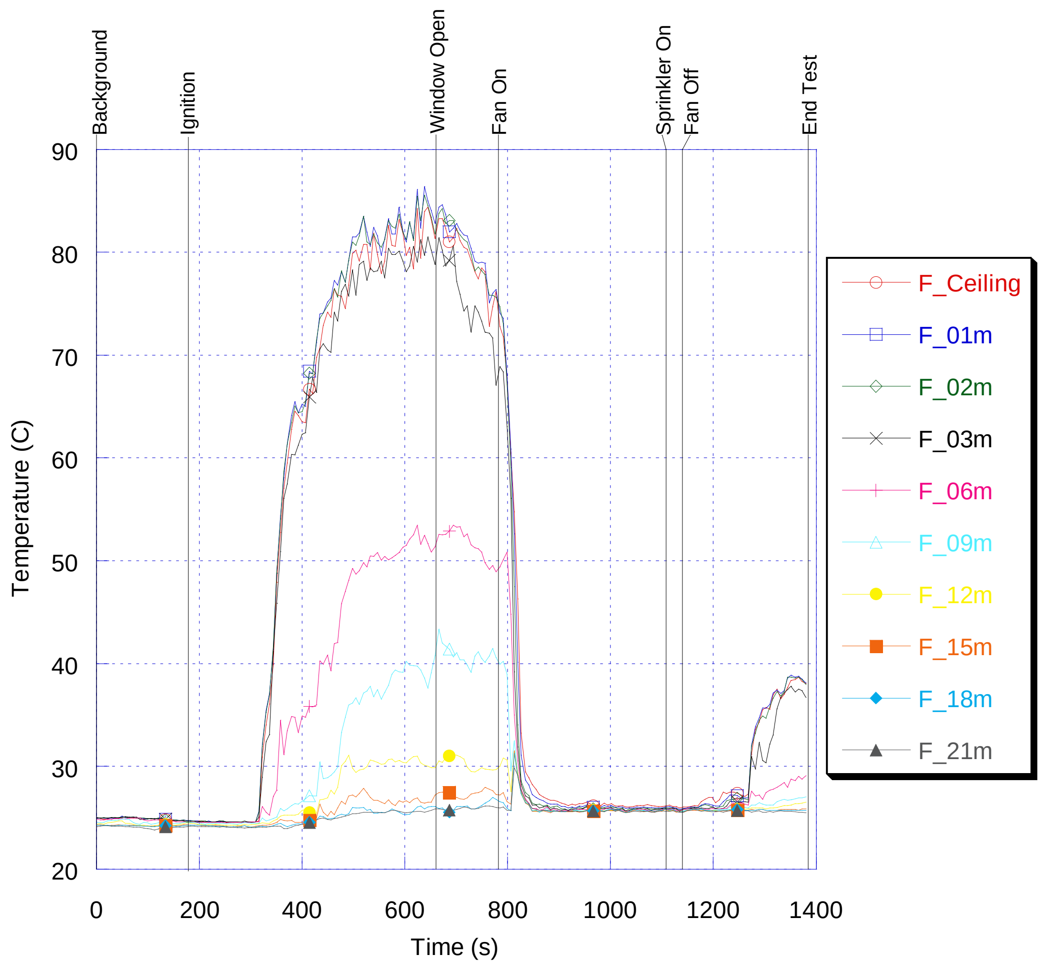

Figure 206. Experiment CF1 Temperature vs. Time for Location F

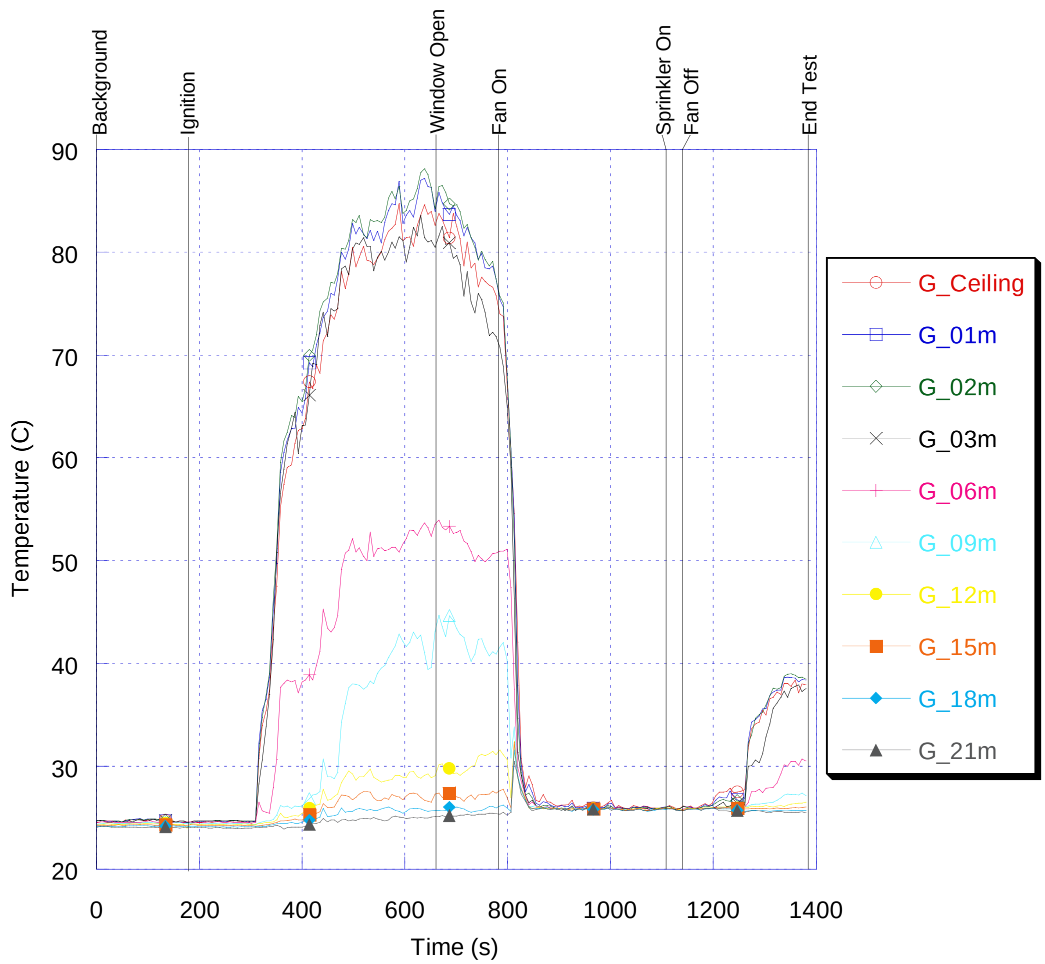

Figure 207. Experiment CF1 Temperature vs. Time for Location G

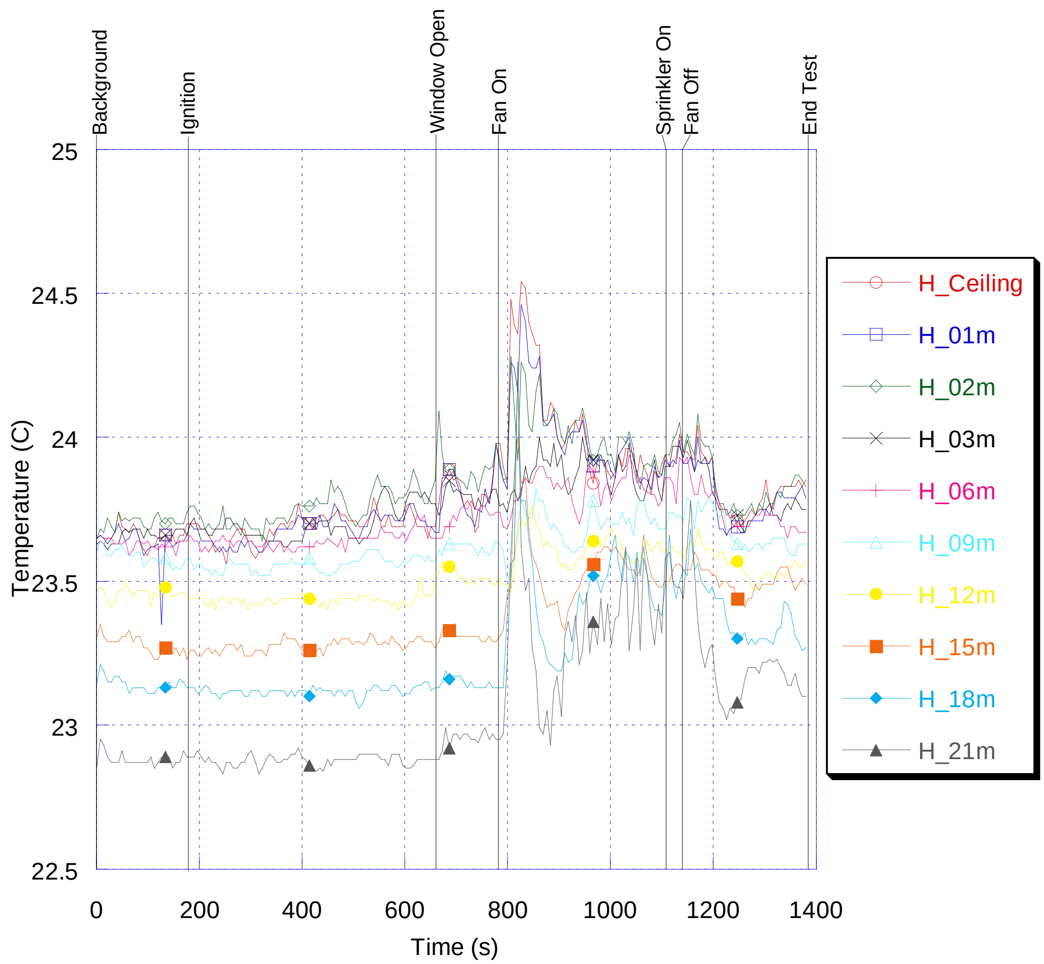

Figure 208. Experiment CF1 Temperature vs. Time for Location H

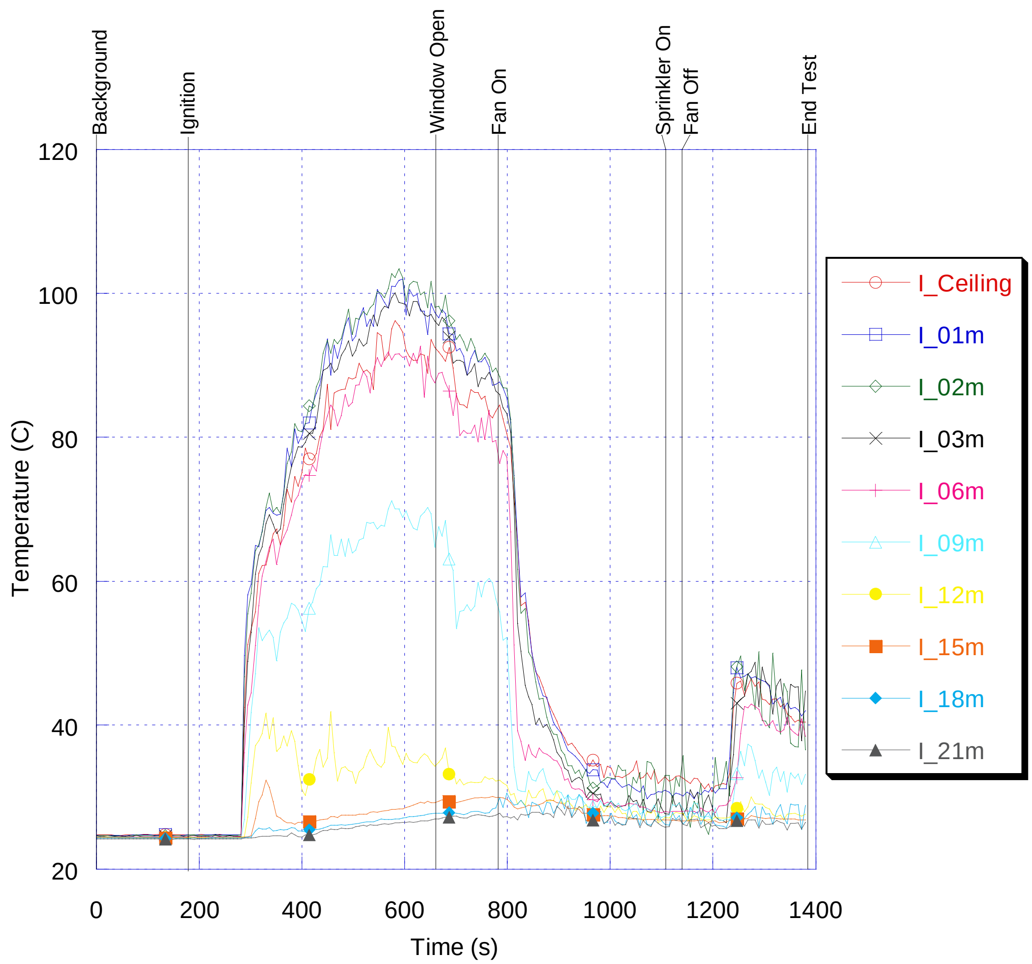

Figure 209. Experiment CF1 Temperature vs. Time for Location I

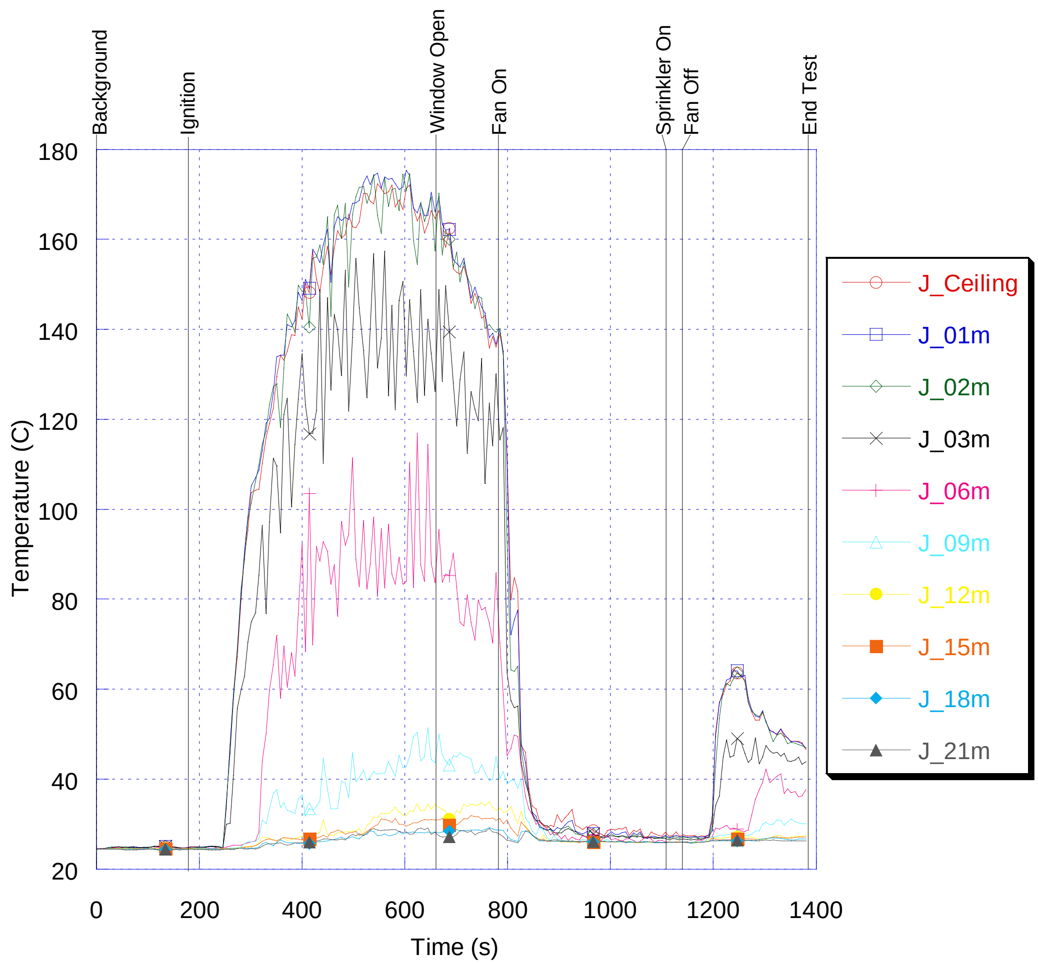

Figure 210. Experiment CF1 Temperature vs. Time for Location J

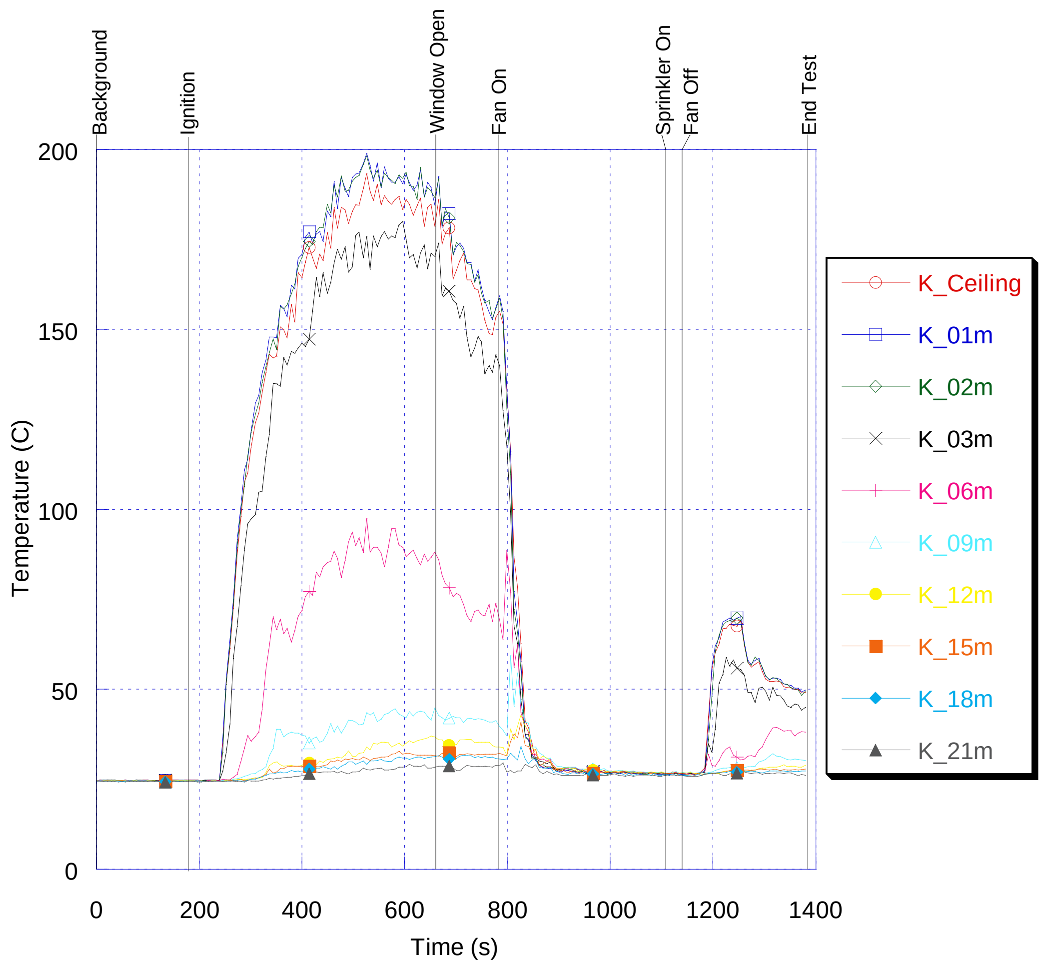

Figure 211. Experiment CF1 Temperature vs. Time for Location K

Experiment CF2

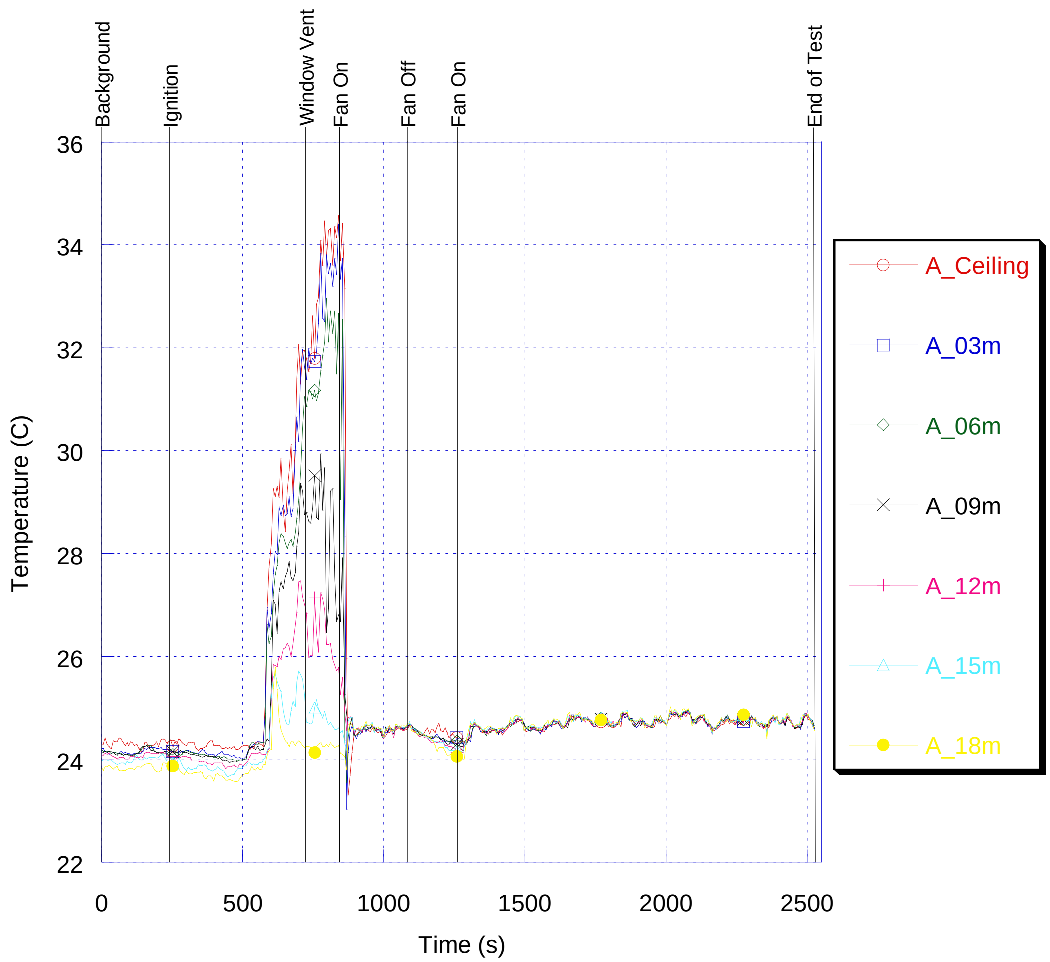

Figure 212. Experiment CF2 Temperature vs. Time for Location A

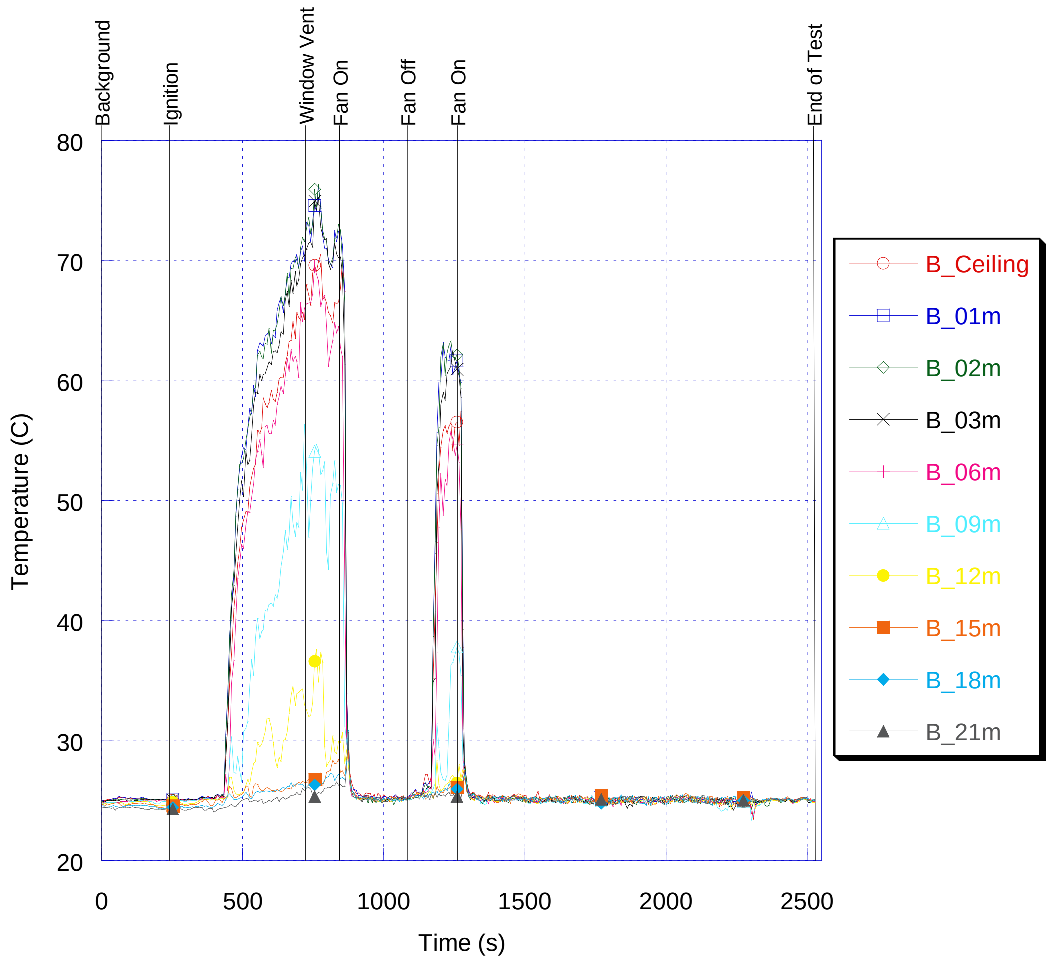

Figure 213. Experiment CF2 Temperature vs. Time for Location B

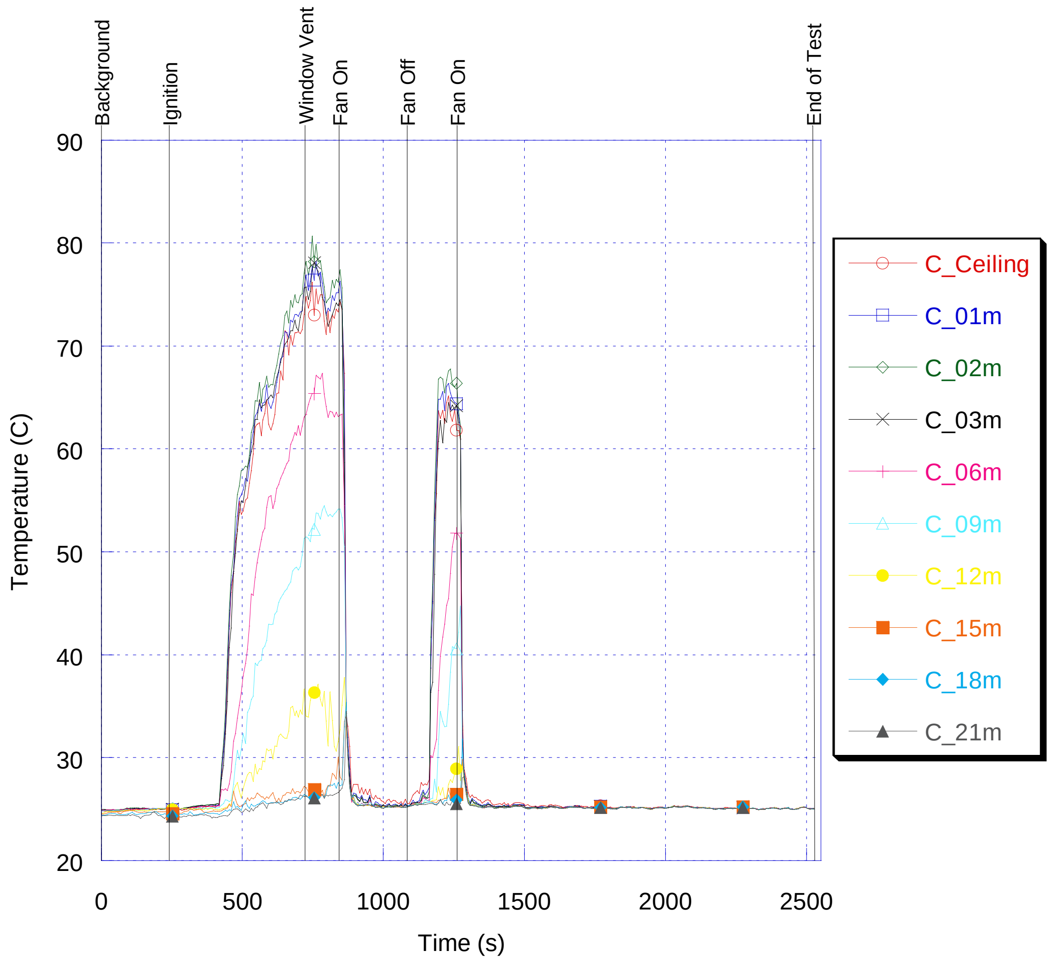

Figure 214. Experiment CF2 Temperature vs. Time for Location C

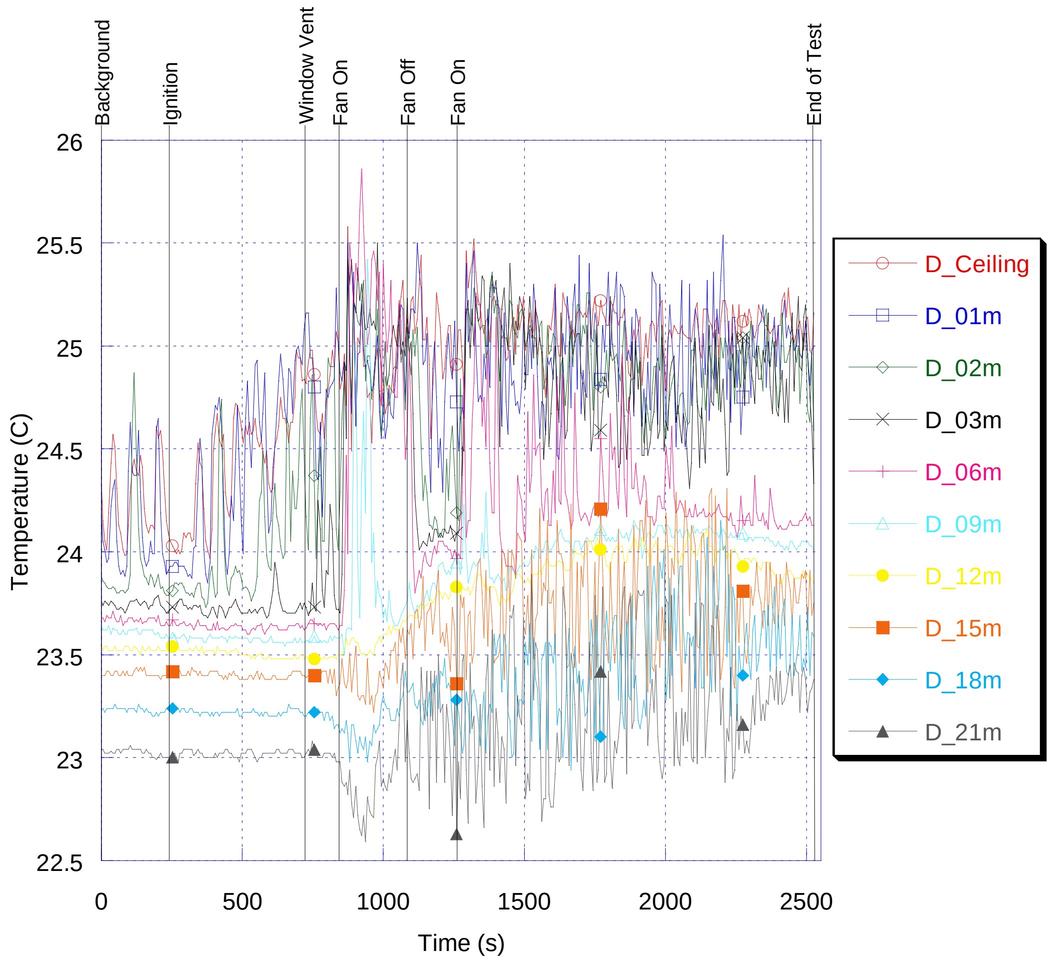

Figure 215. Experiment CF2 Temperature vs. Time for Location D

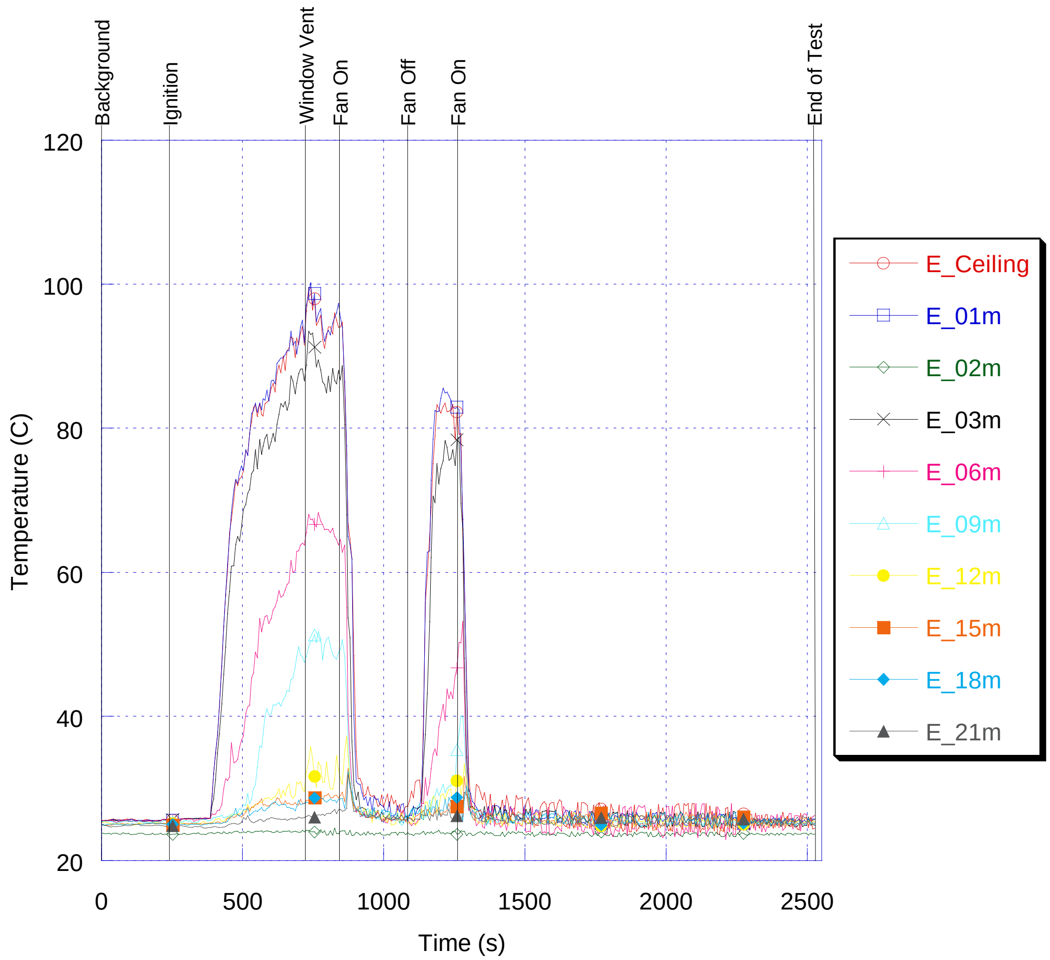

Figure 216. Experiment CF2 Temperature vs. Time for Location E

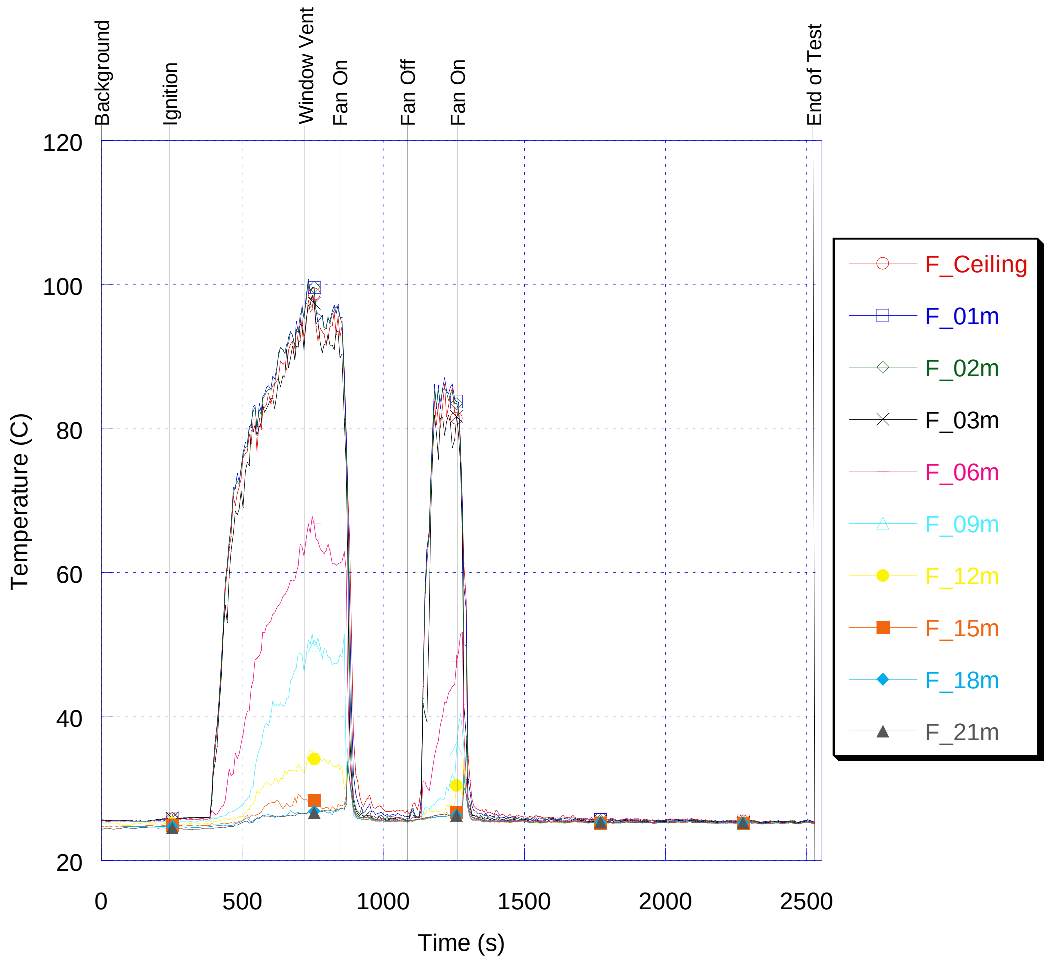

Figure 217. Experiment CF2 Temperature vs. Time for Location F

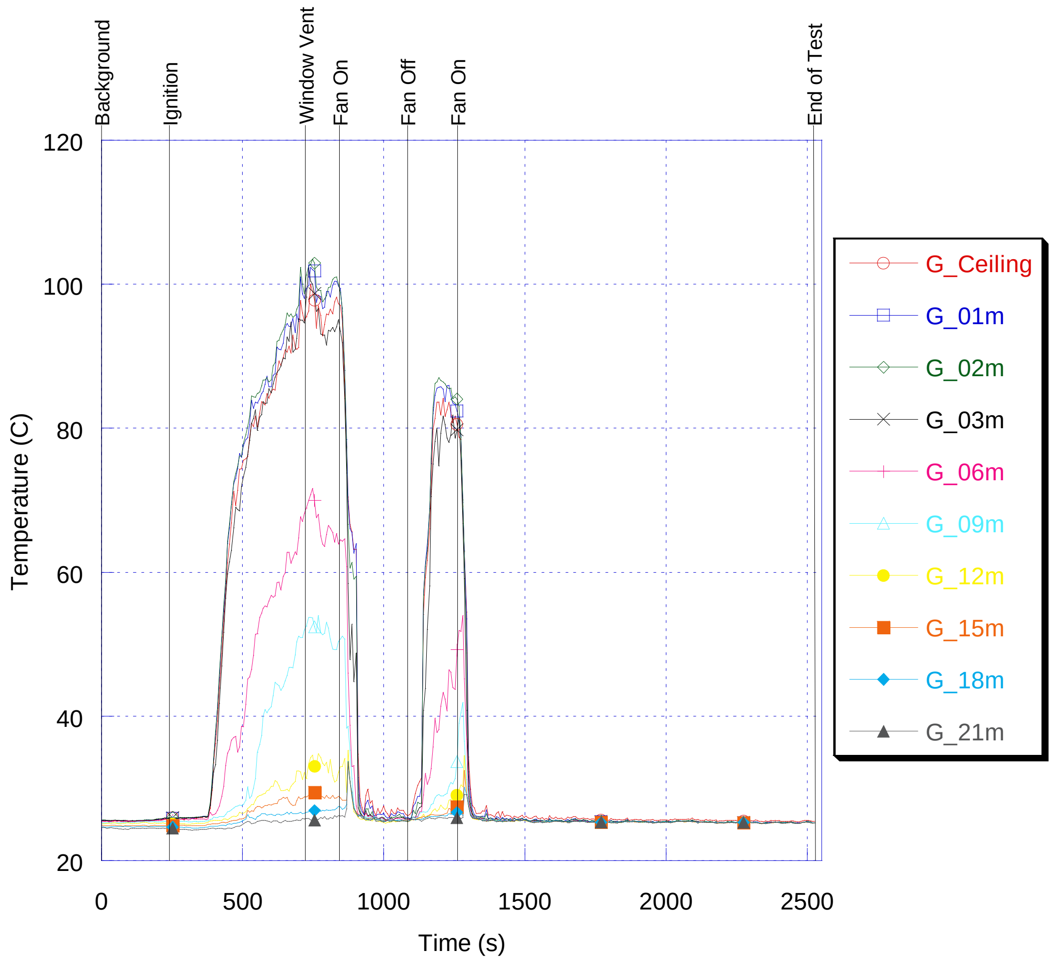

Figure 218. Experiment CF2 Temperature vs. Time for Location G

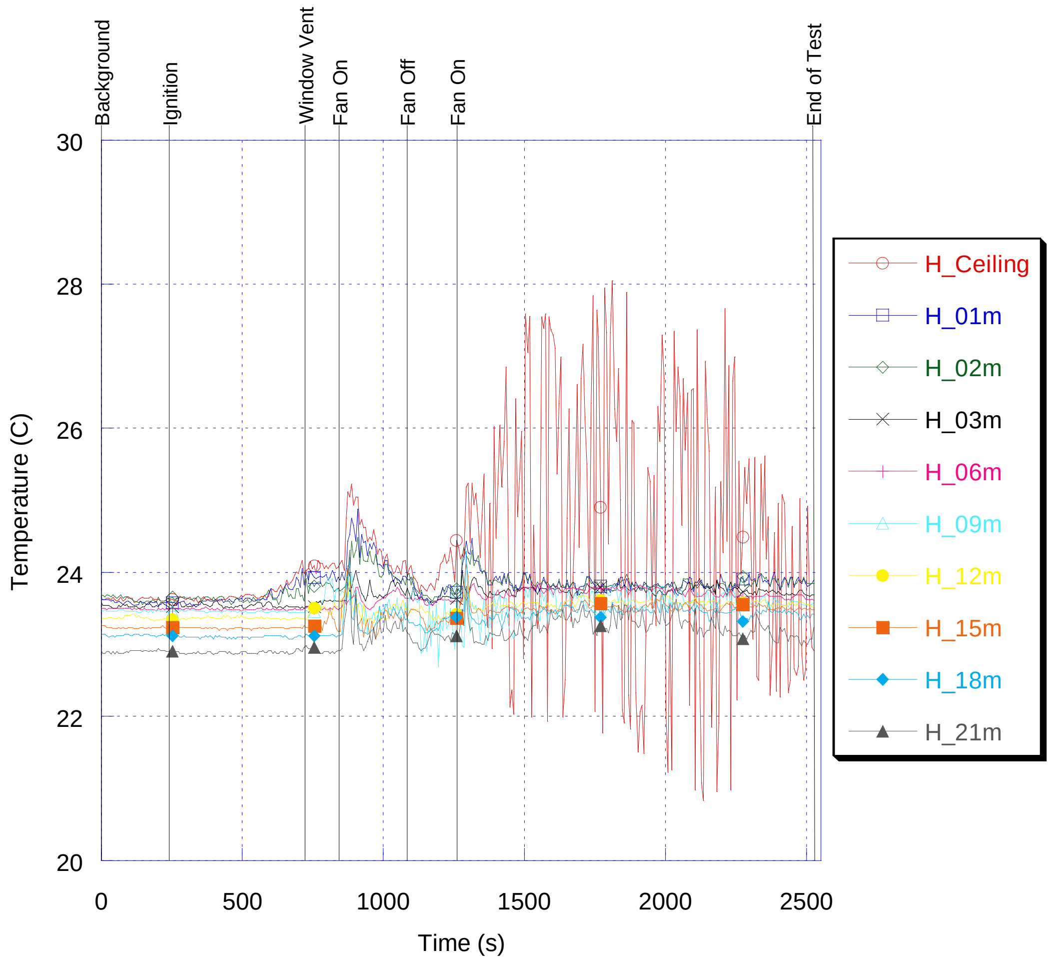

Figure 219. Experiment CF2 Temperature vs. Time for Location H

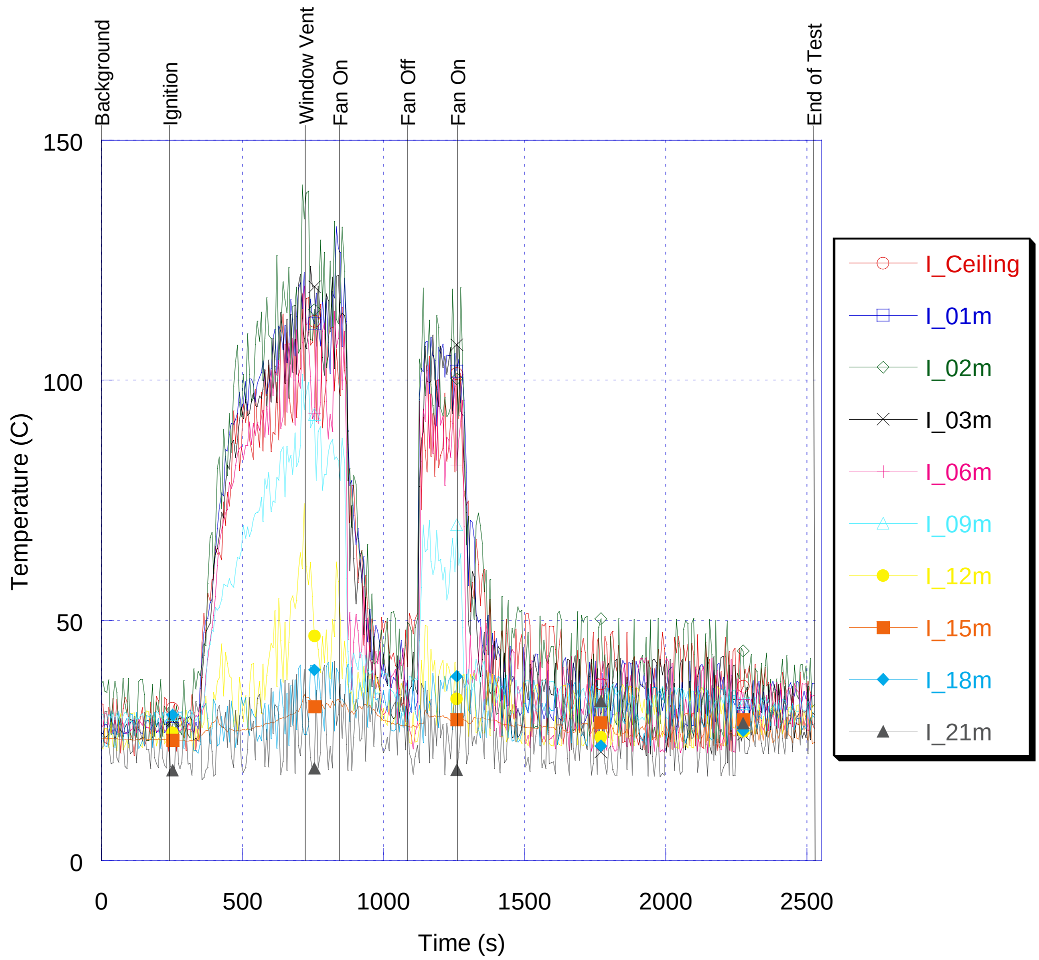

Figure 220. Experiment CF2 Temperature vs. Time for Location I

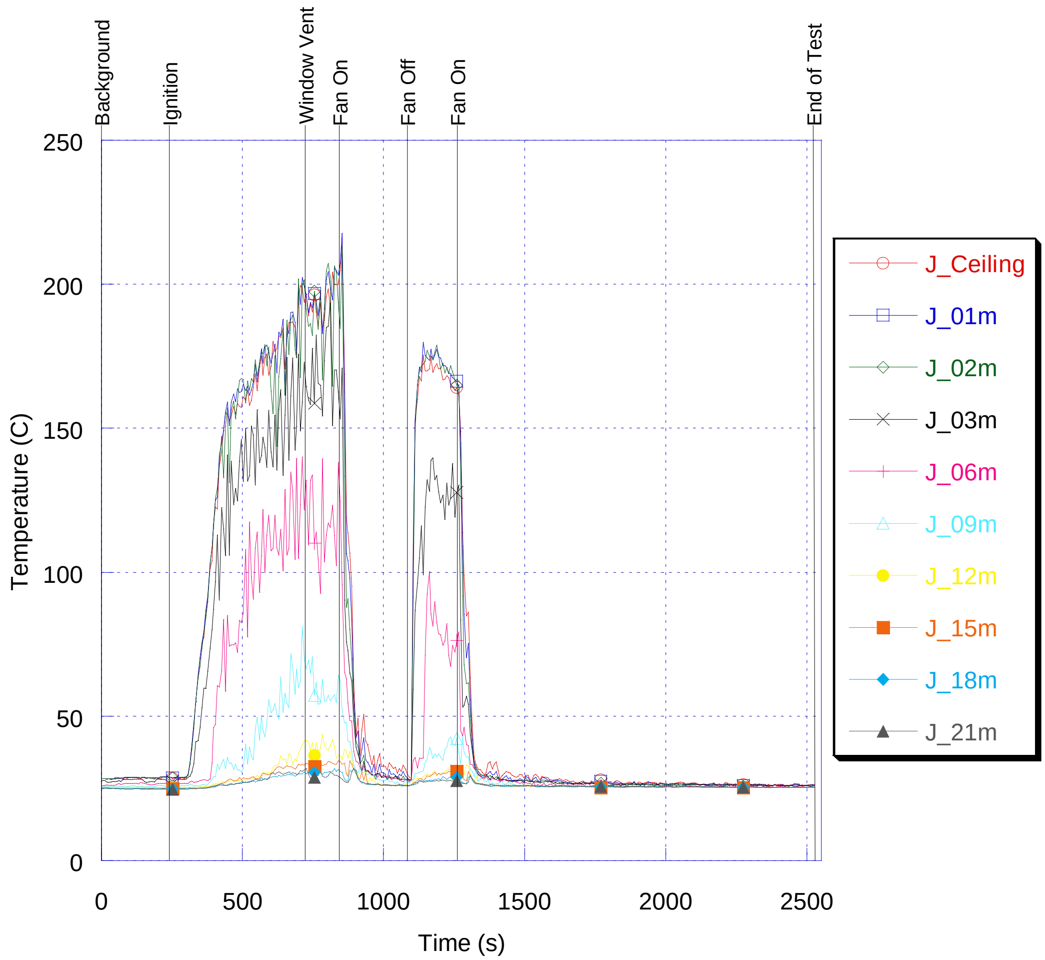

Figure 221. Experiment CF2 Temperature vs. Time for Location J

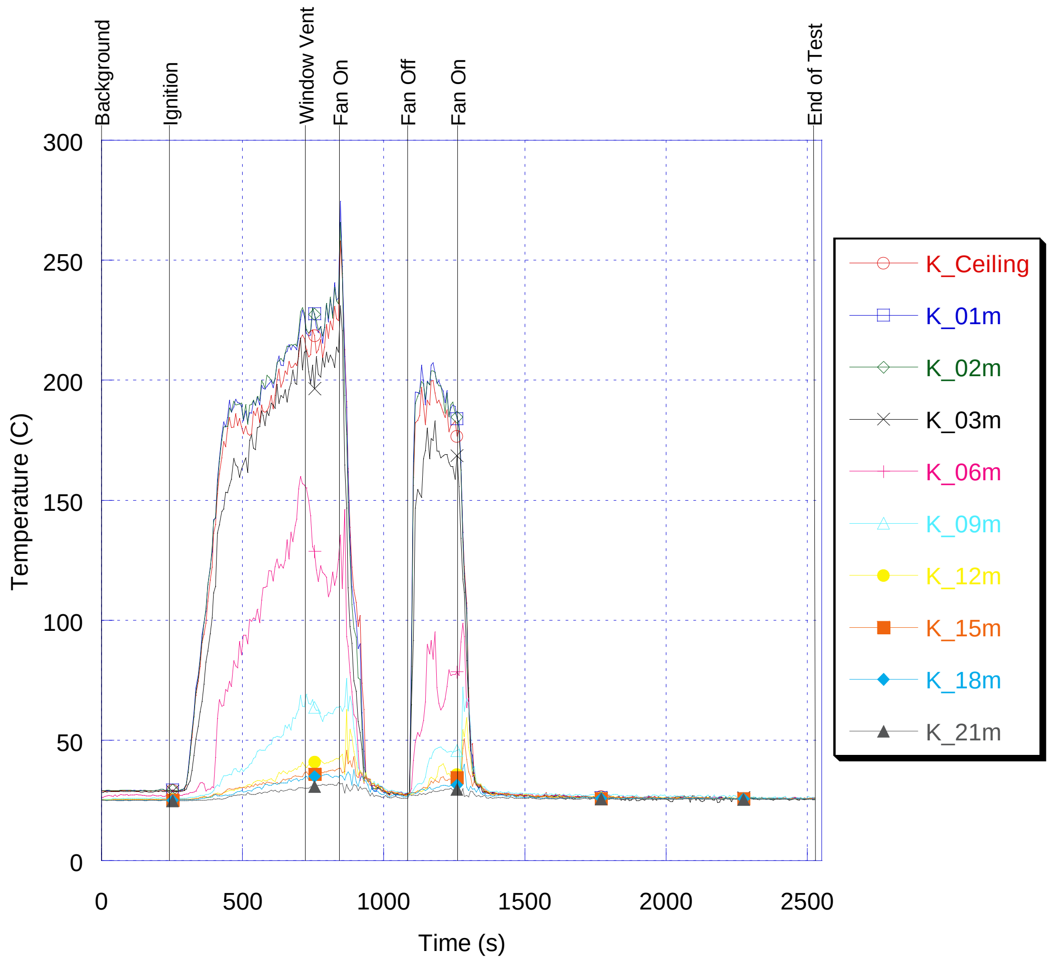

Figure 222. Experiment CF2 Temperature vs. Time for Location K

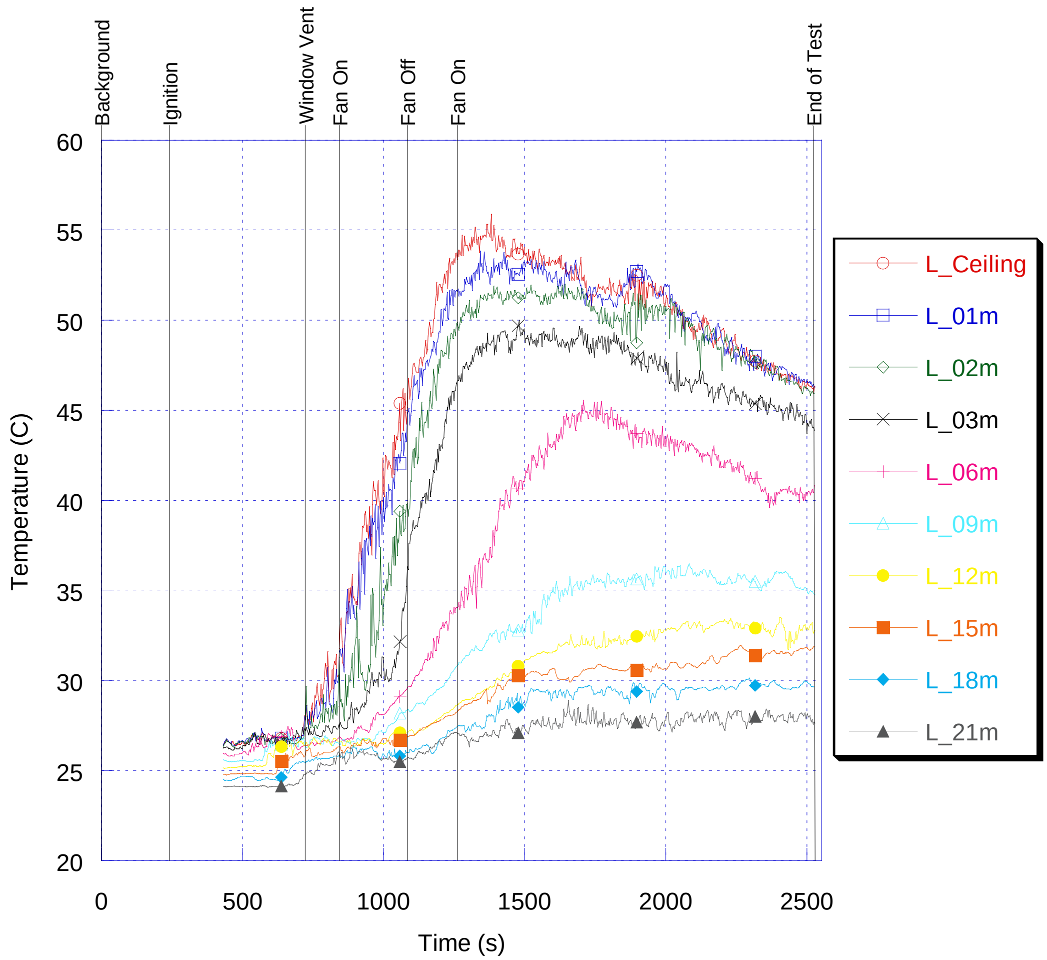

Figure 223. Experiment CF2 Temperature vs. Time for Location L

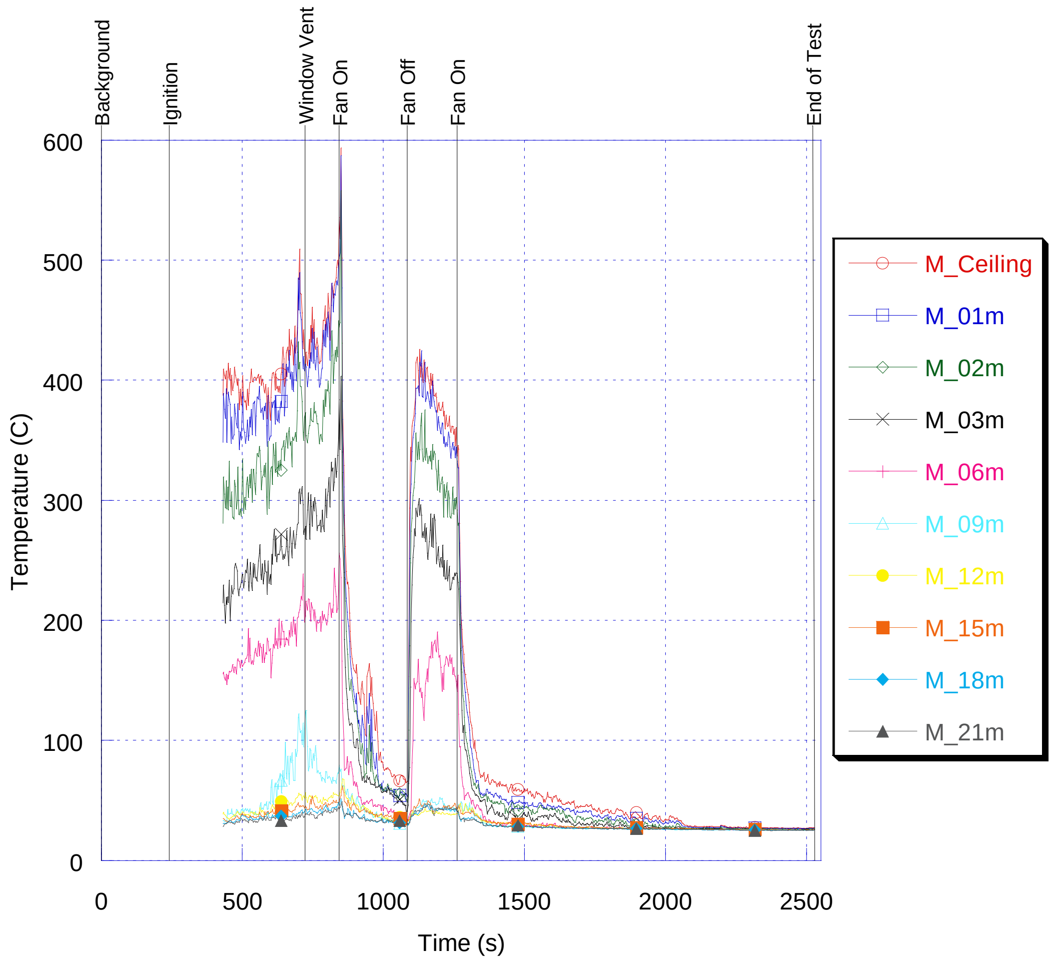

Figure 224. Experiment CF2 Temperature vs. Time for Location M

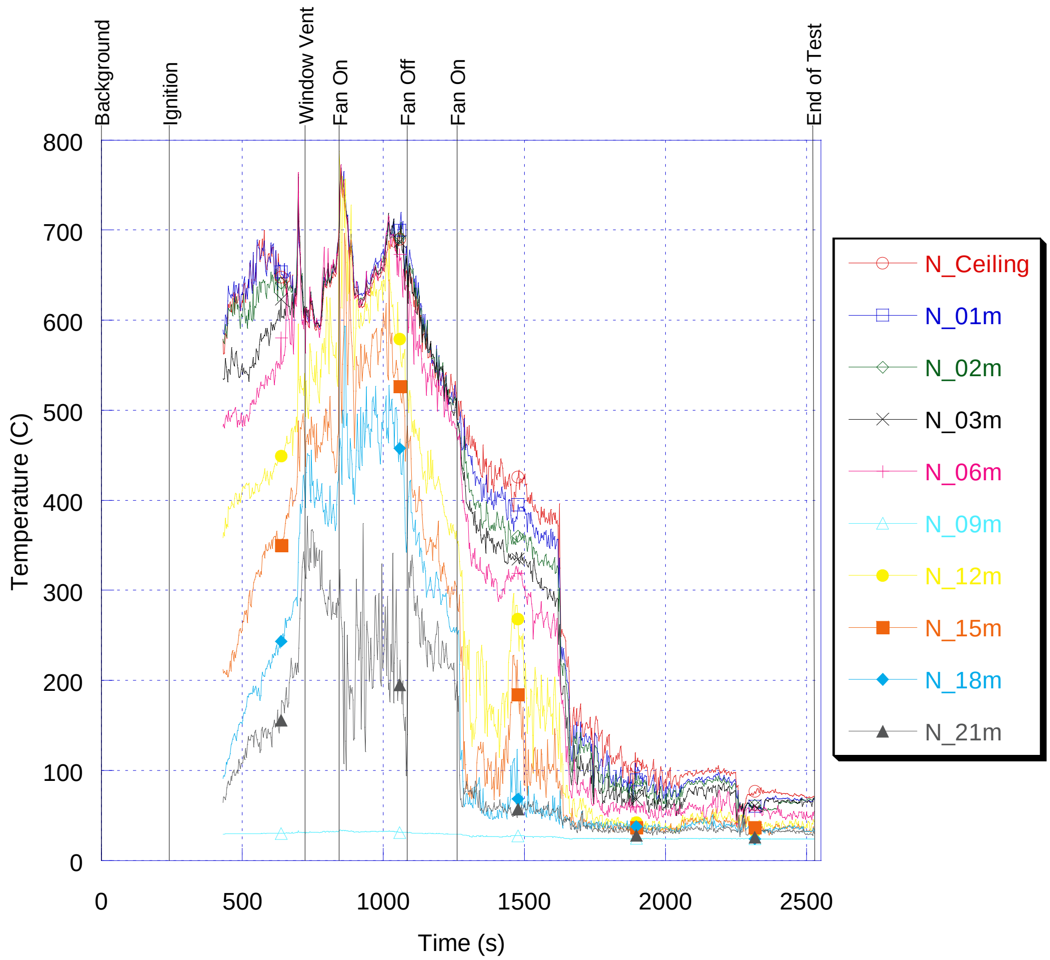

Figure 225. Experiment CF2 Temperature vs. Time for Location N

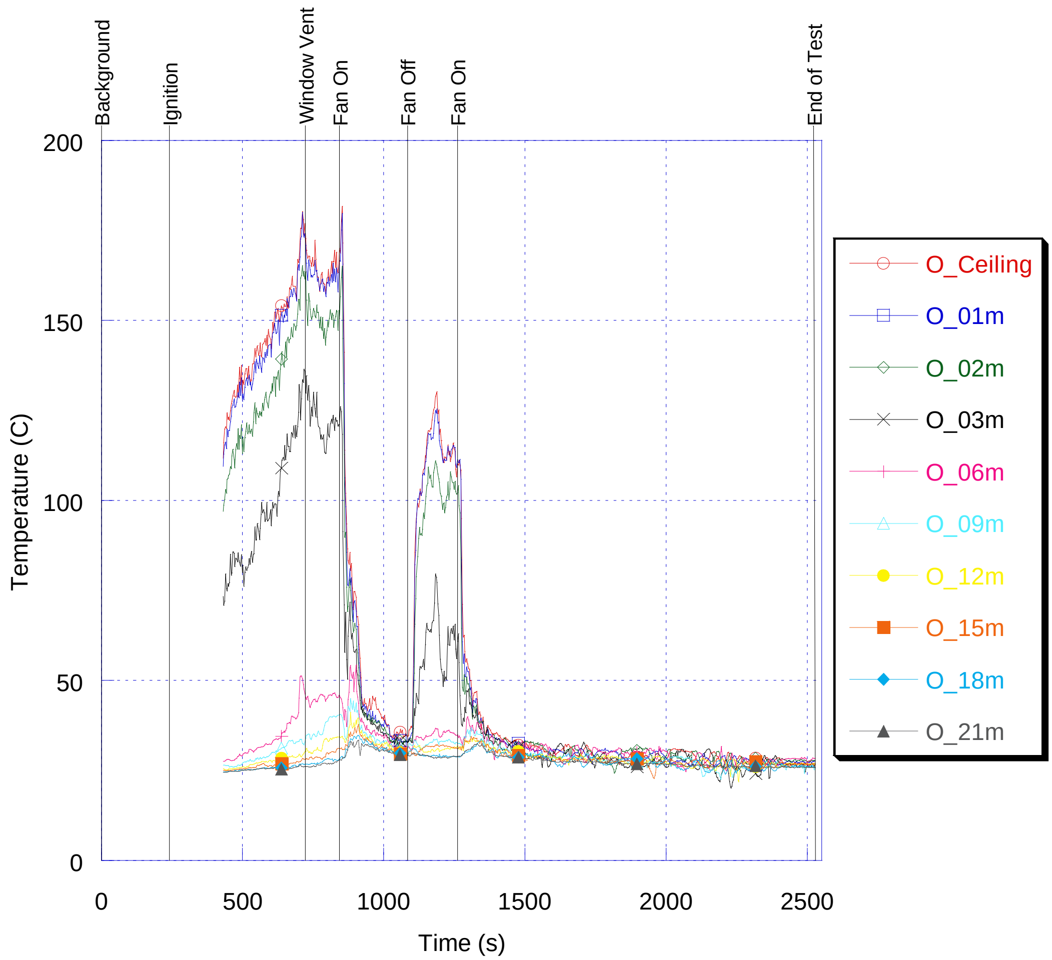

Figure 226. Experiment CF2 Temperature vs. Time for Location O

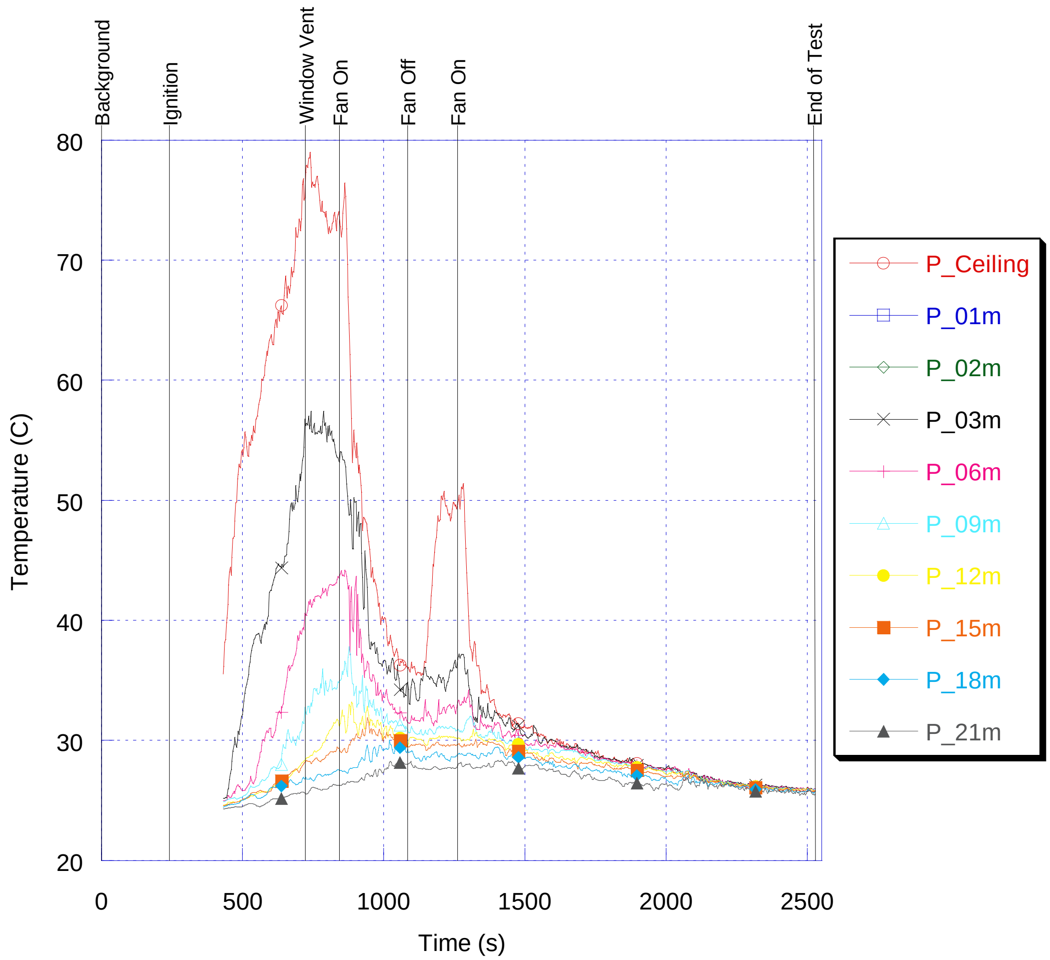

Figure 227. Experiment CF2 Temperature vs. Time for Location P

Experiment CF3

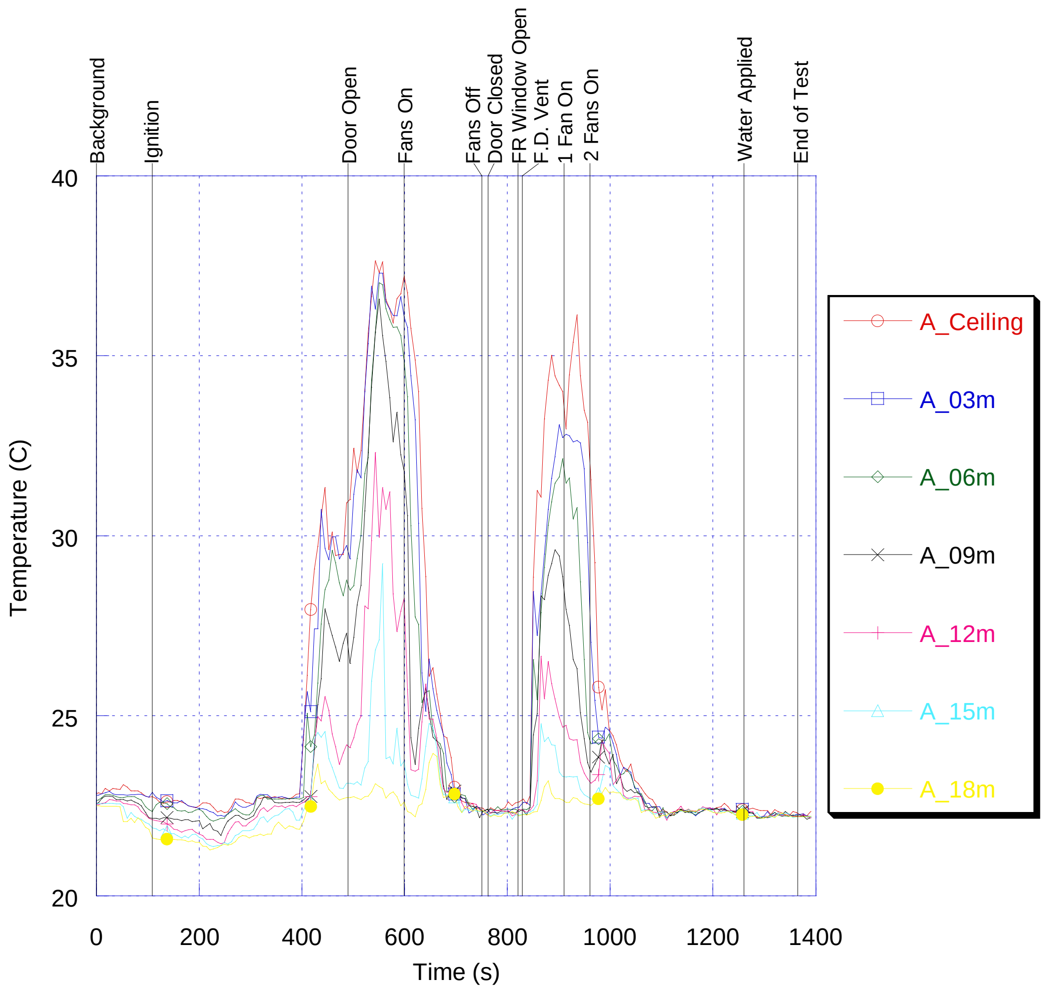

Figure 228. Experiment CF3 Temperature vs. Time for Location A

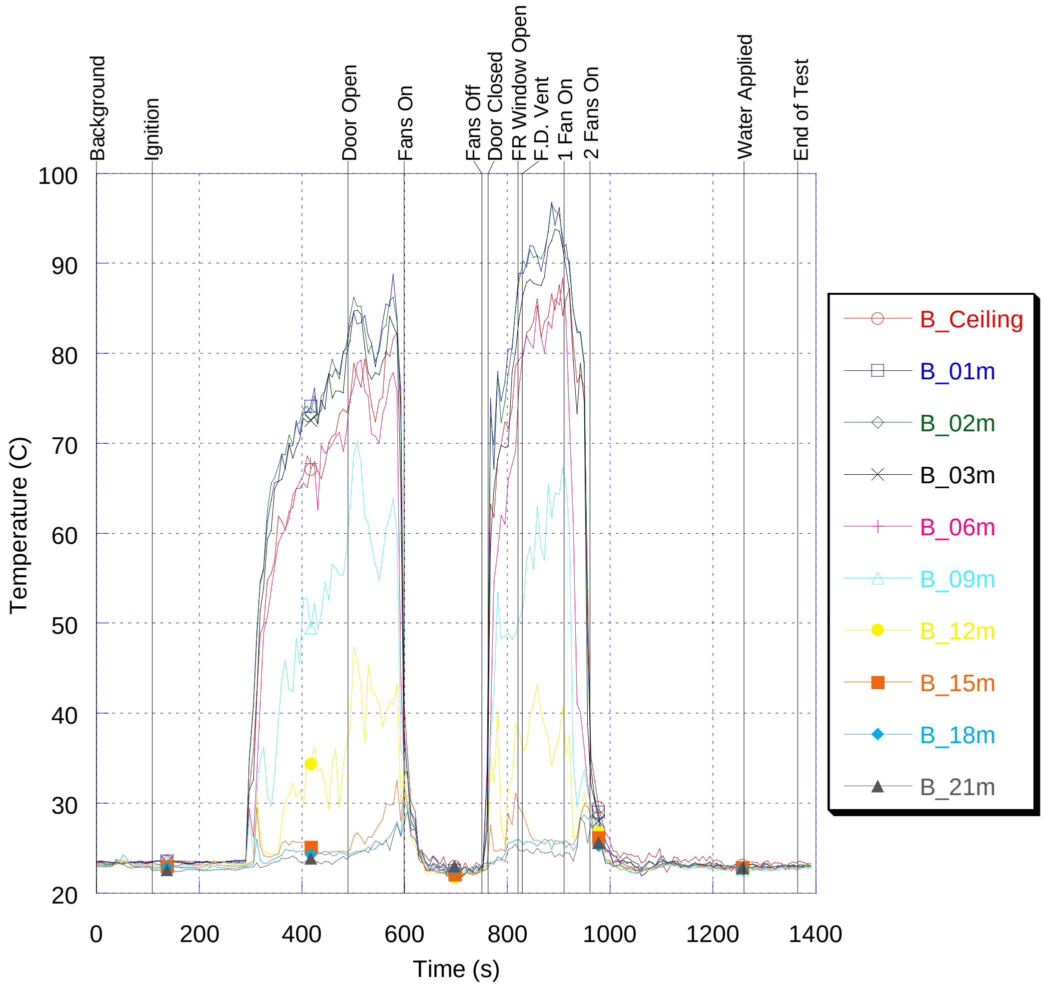

Figure 229. Experiment CF3 Temperature vs. Time for Location B

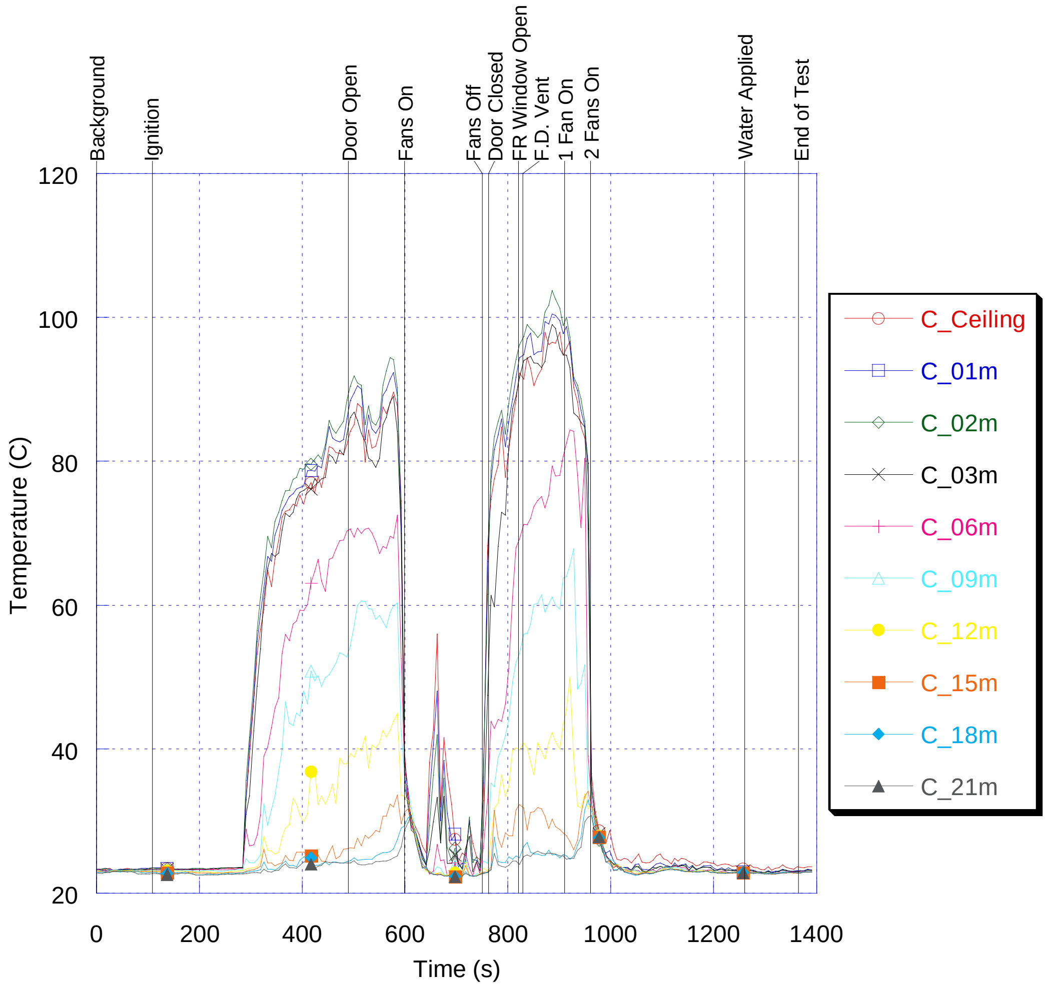

Figure 230. Experiment CF3 Temperature vs. Time for Location C

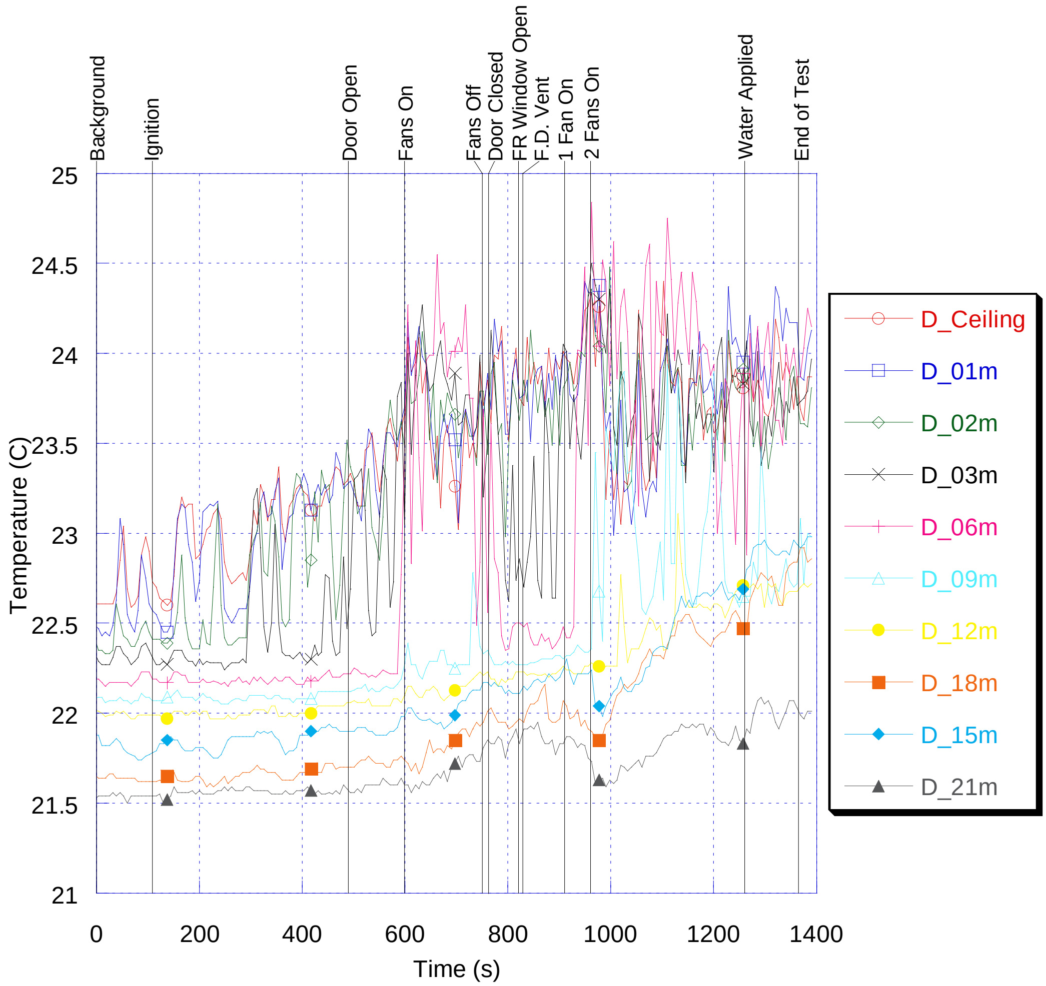

Figure 231. Experiment CF3 Temperature vs. Time for Location D

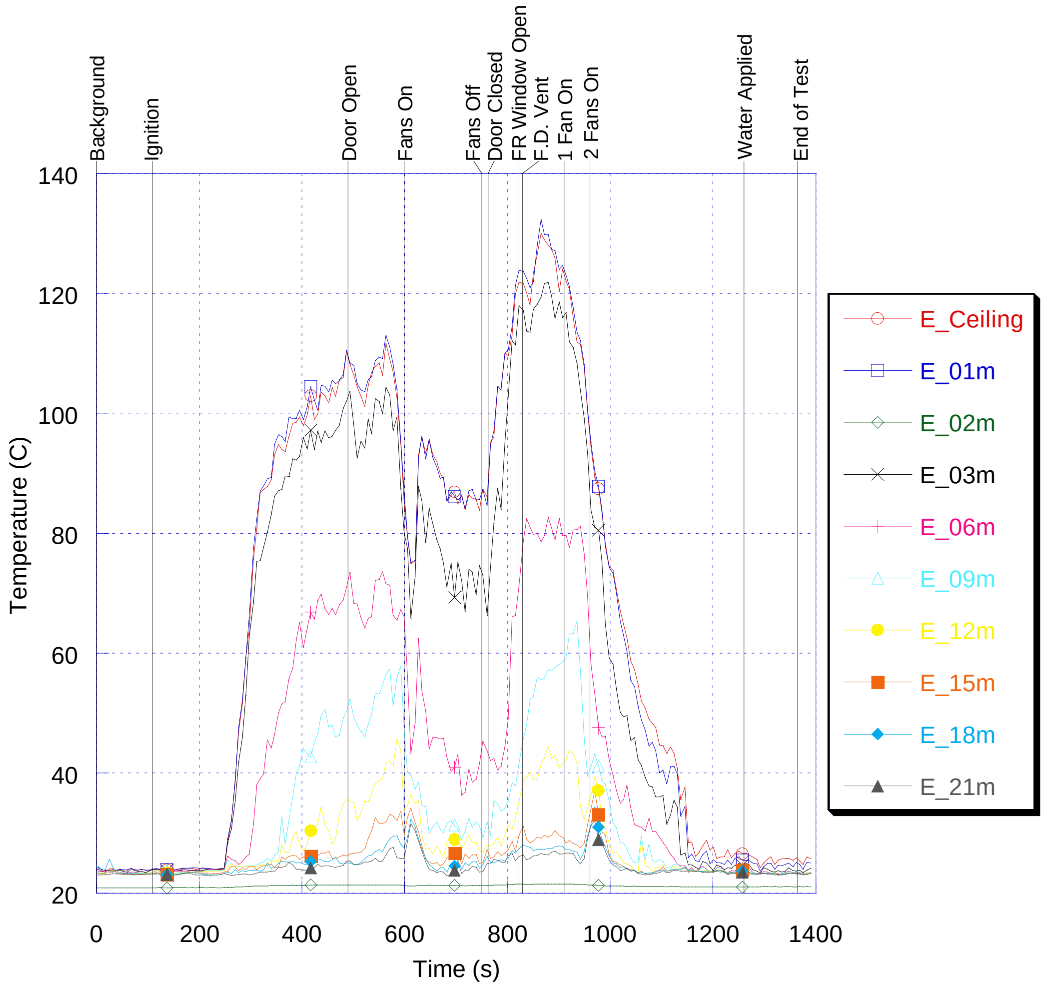

Figure 232. Experiment CF3 Temperature vs. Time for Location E

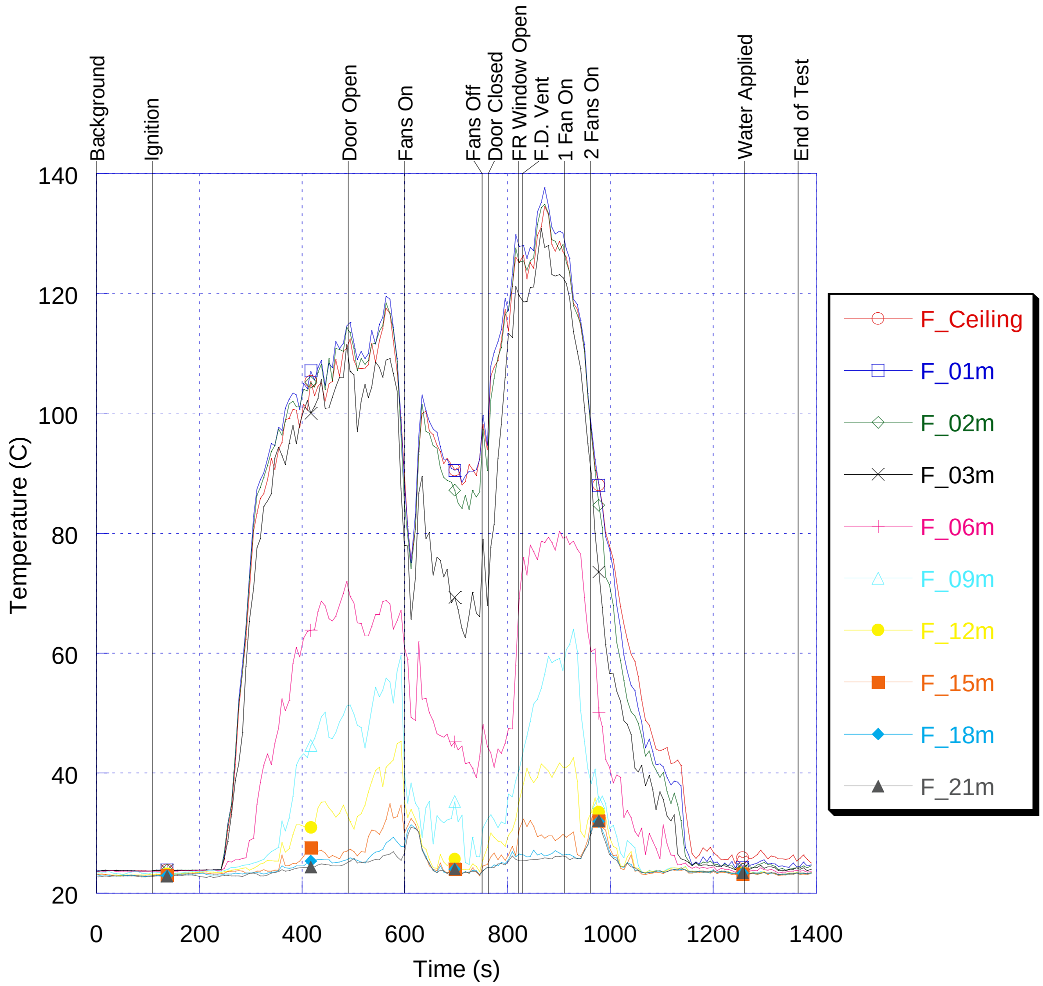

Figure 233. Experiment CF3 Temperature vs. Time for Location F

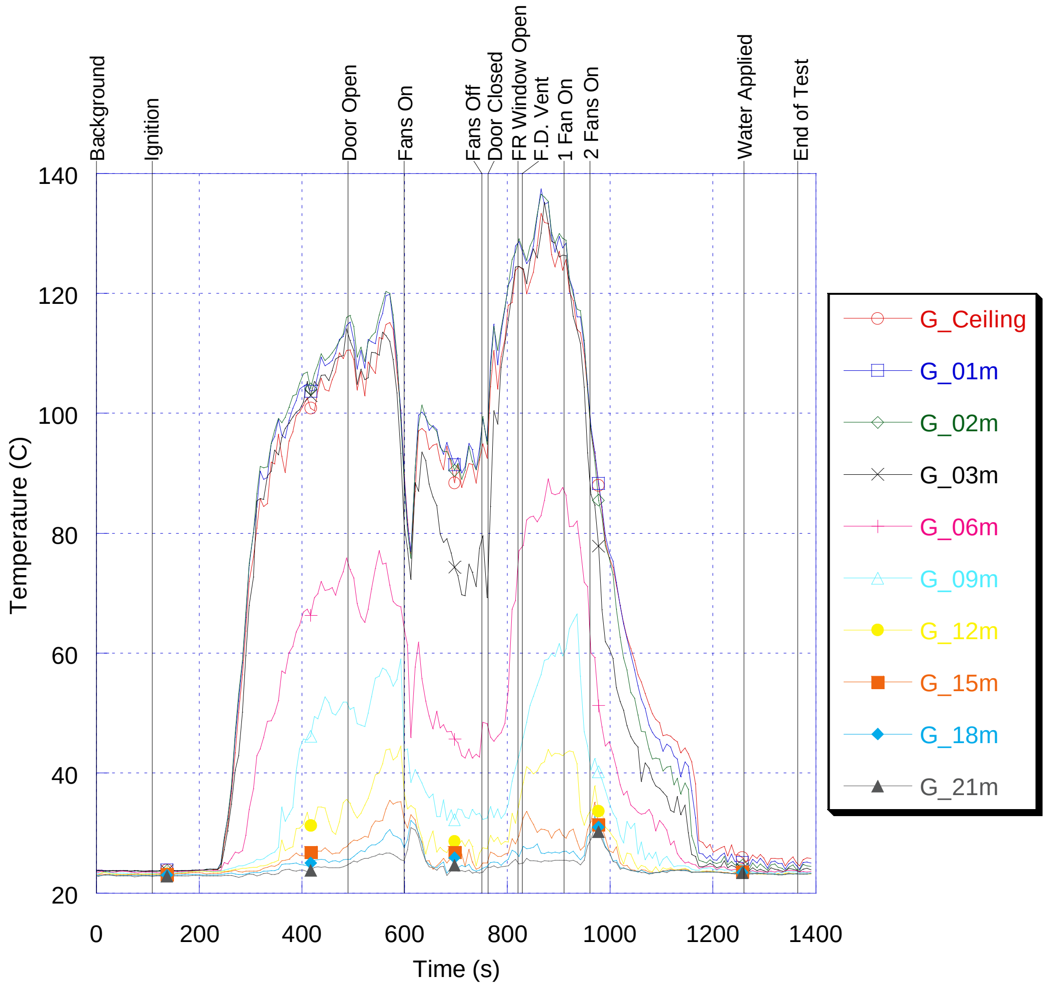

Figure 234. Experiment CF3 Temperature vs. Time for Location G

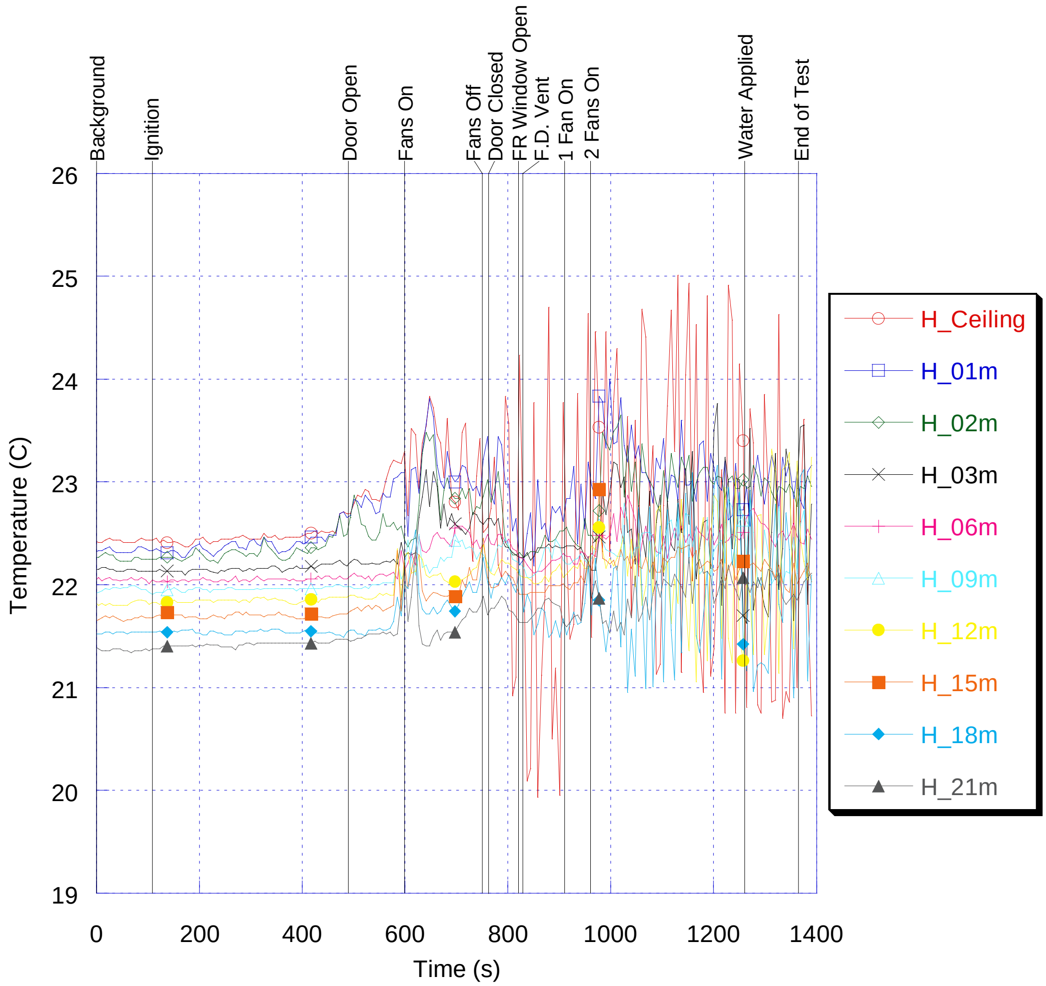

Figure 235. Experiment CF3 Temperature vs. Time for Location H

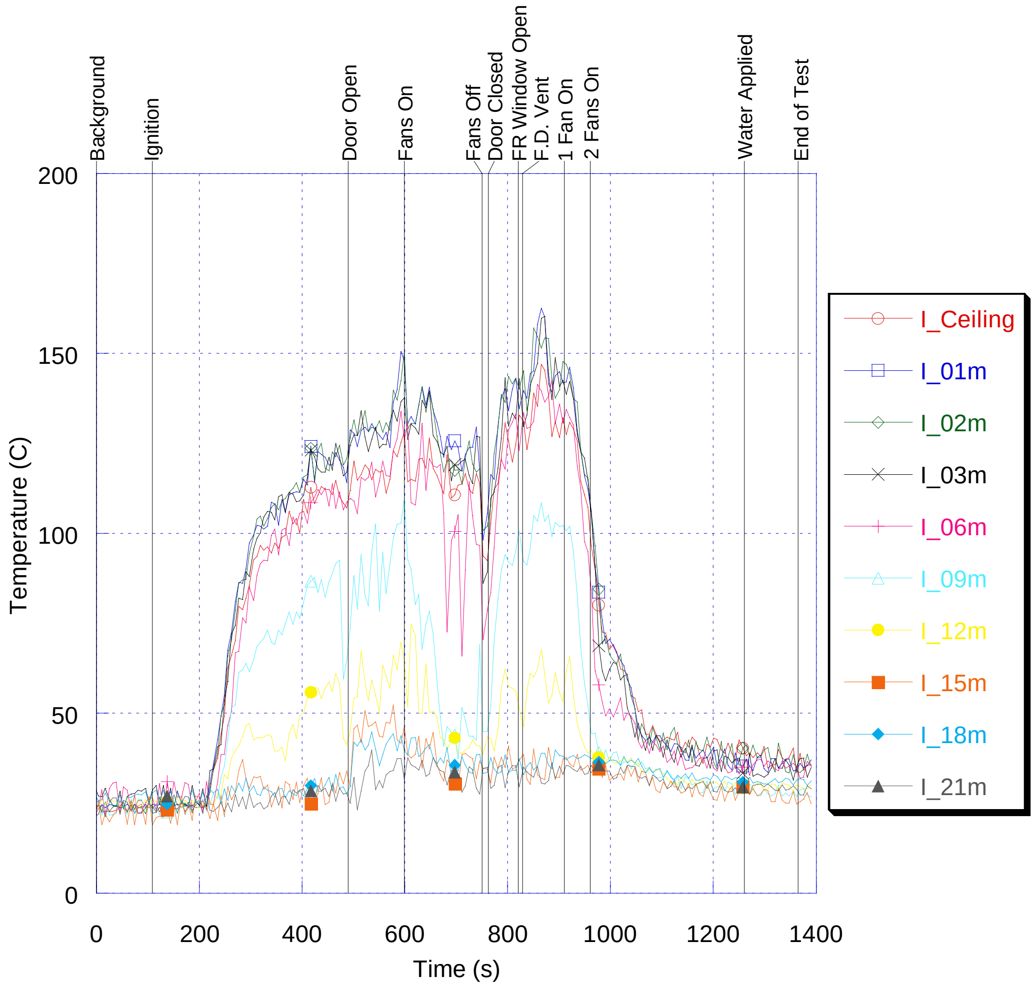

Figure 236. Experiment CF3 Temperature vs. Time for Location I

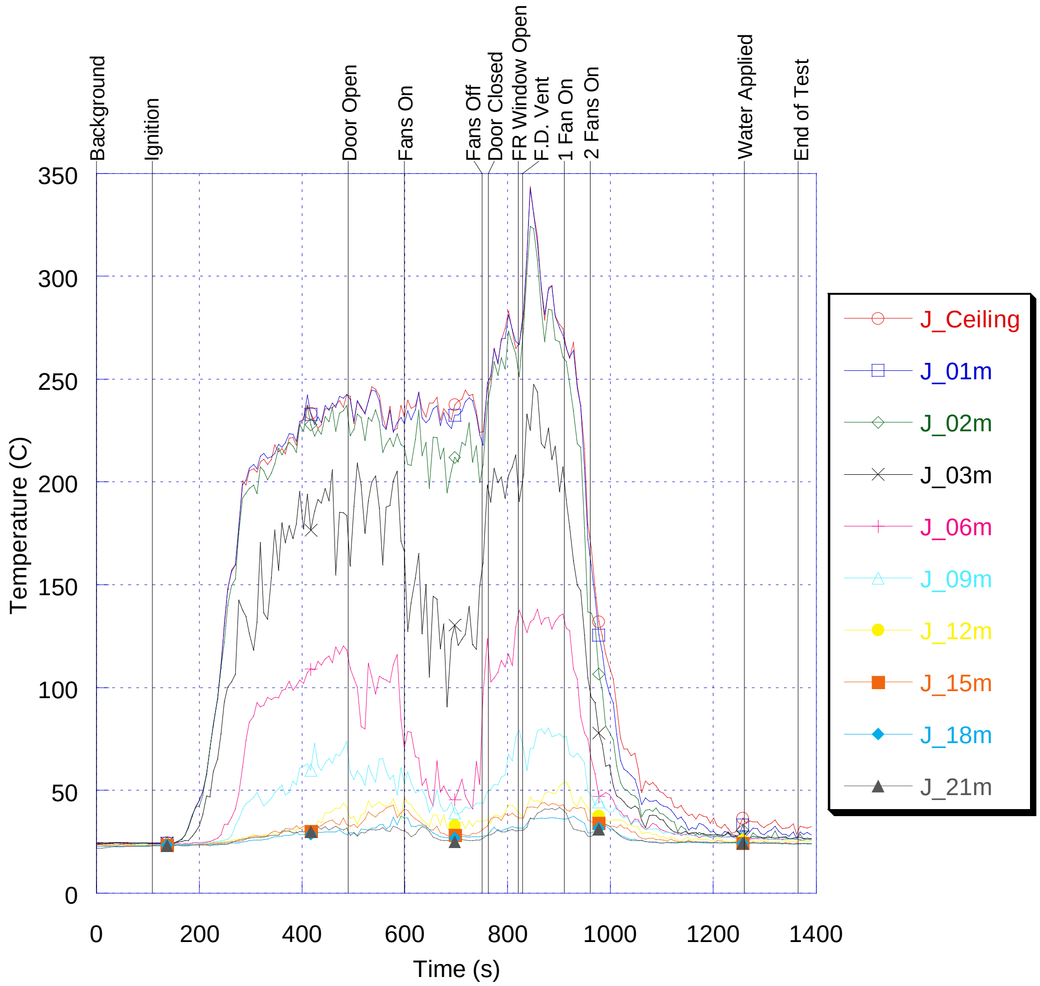

Figure 237. Experiment CF3 Temperature vs. Time for Location J

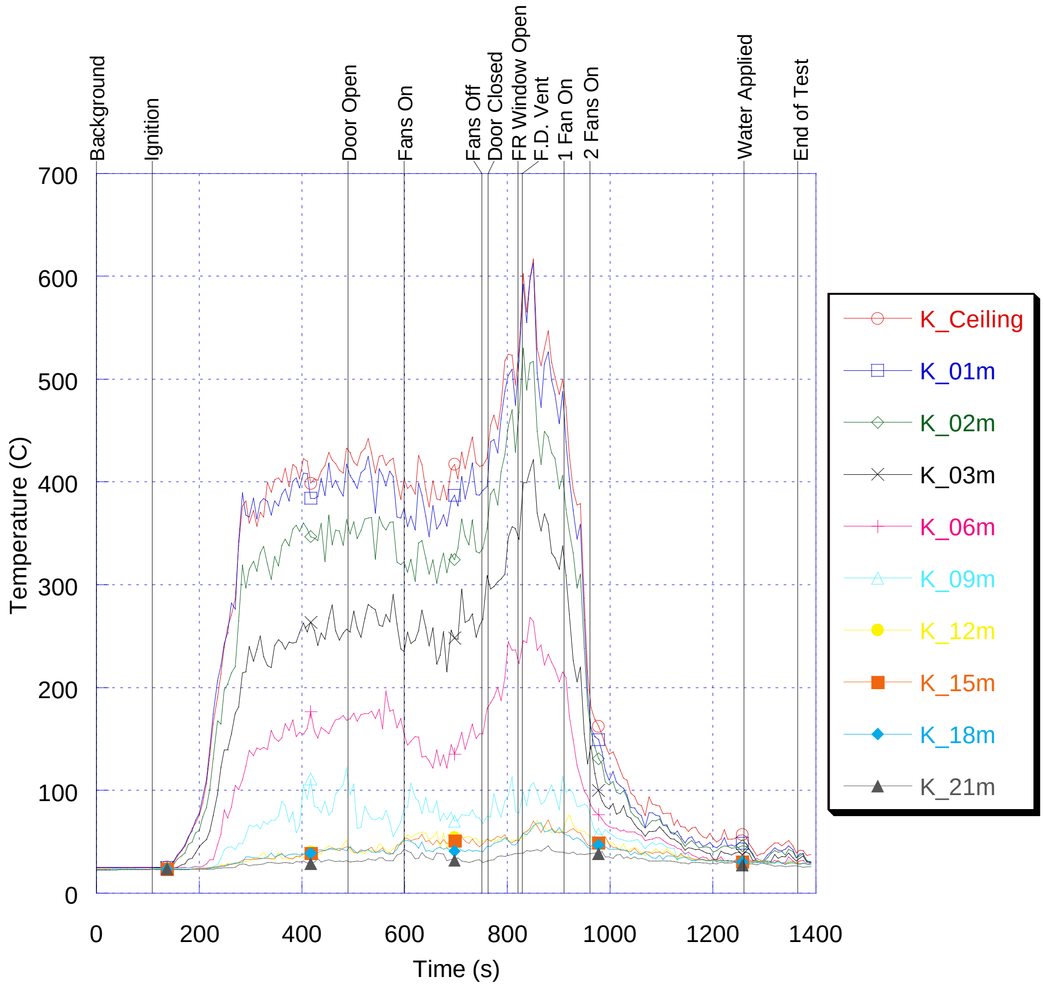

Figure 238. Experiment CF3 Temperature vs. Time for Location K

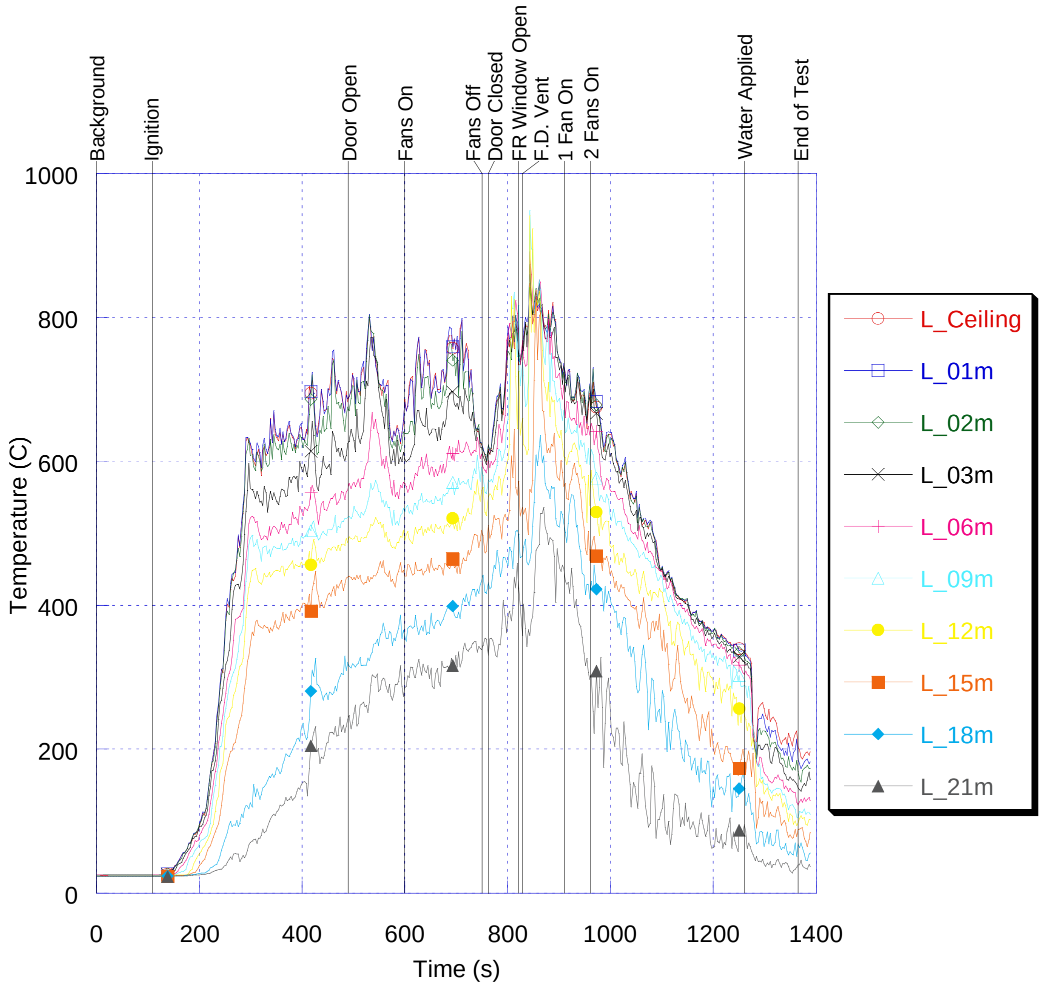

Figure 239. Experiment CF3 Temperature vs. Time for Location L

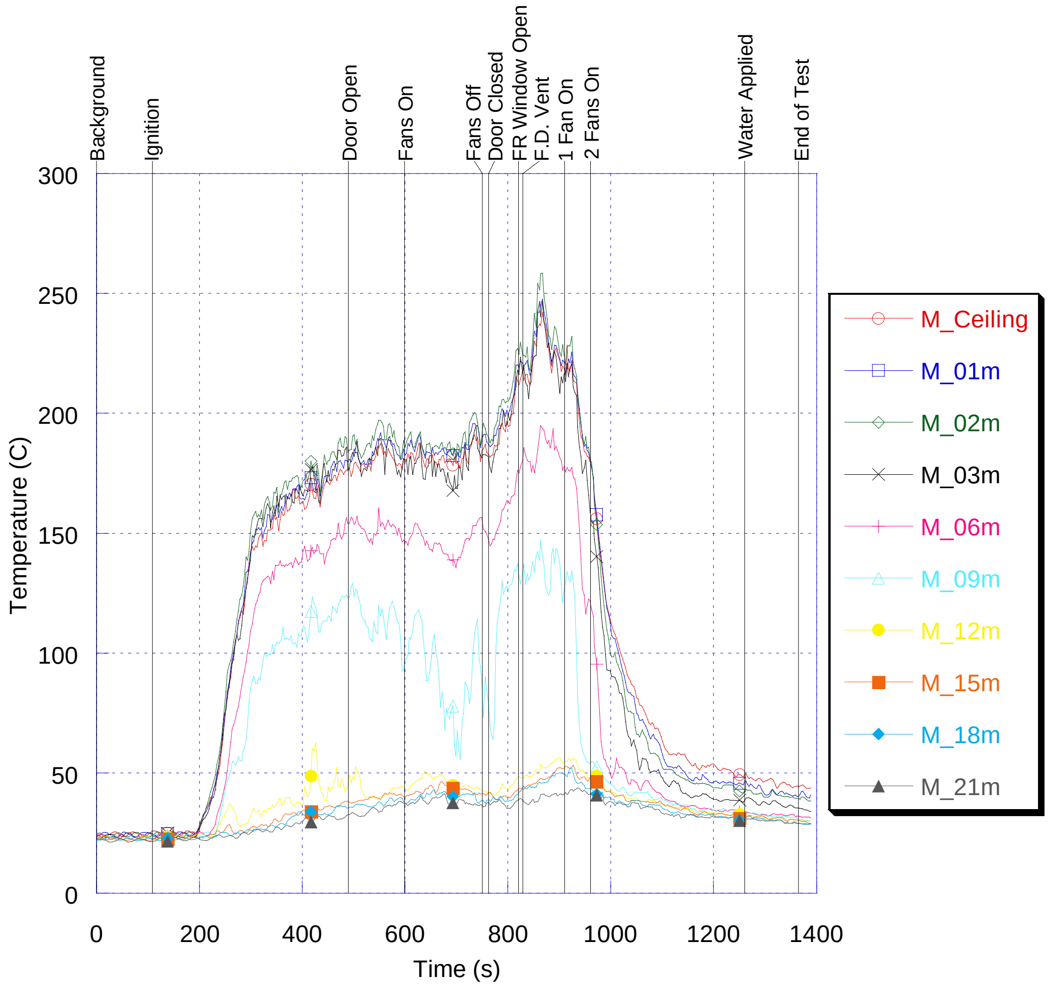

Figure 240. Experiment CF3 Temperature vs. Time for Location M

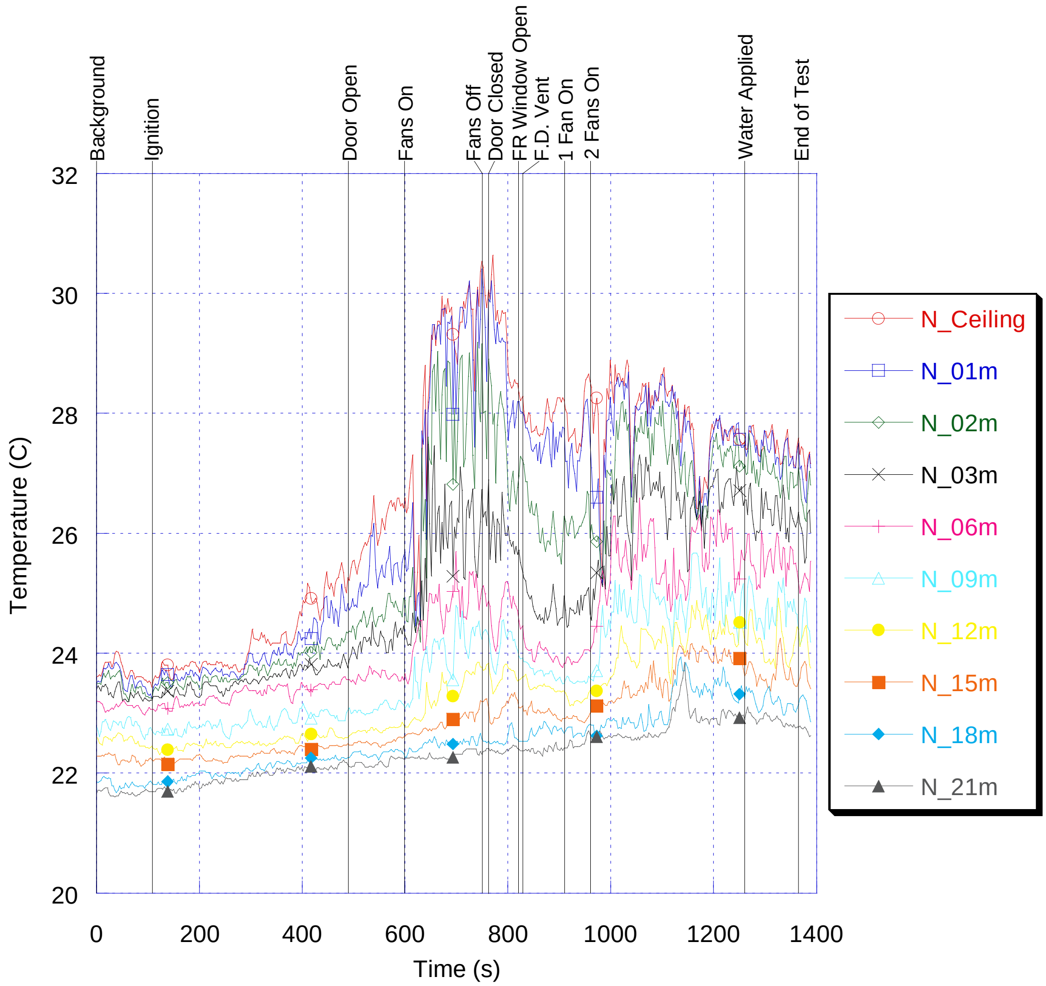

Figure 241. Experiment CF3 Temperature vs. Time for Location N

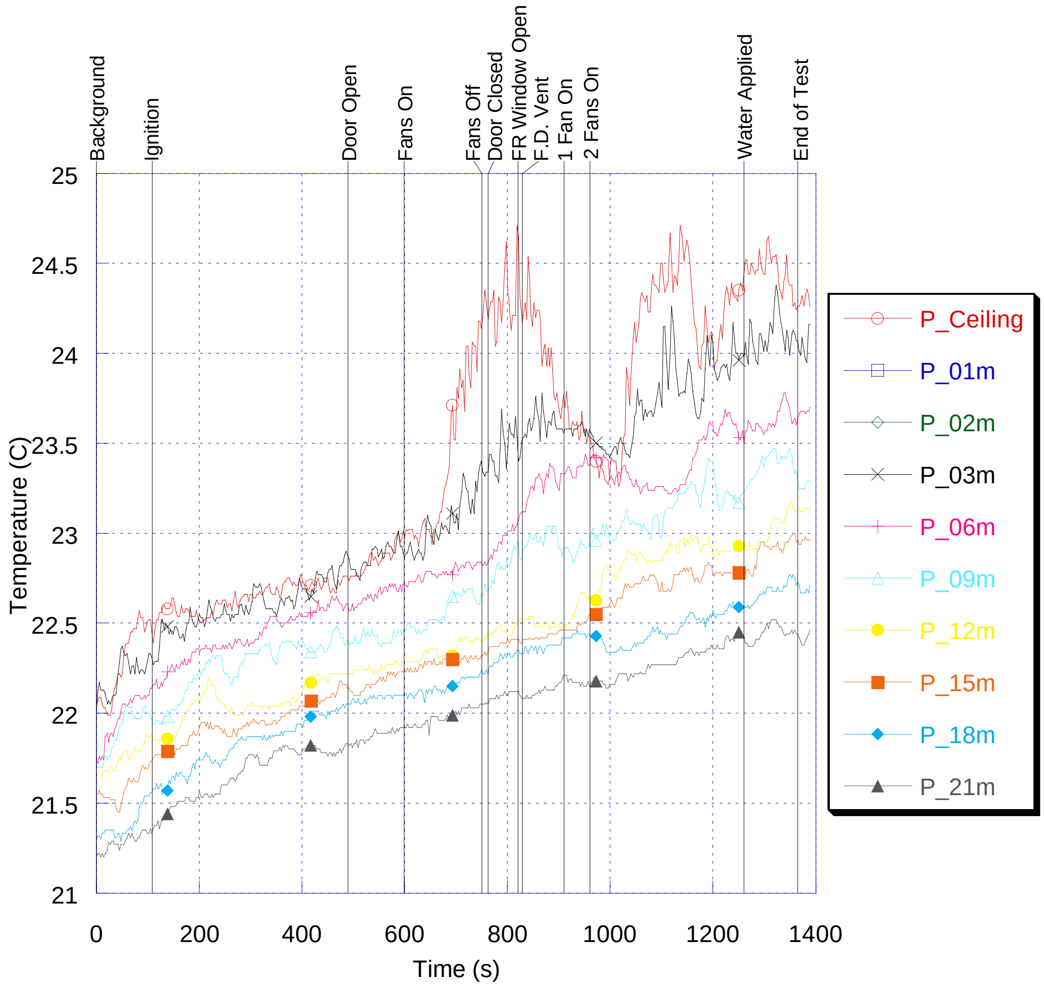

Figure 242. Experiment CF3 Temperature vs. Time for Location P

Experiment CF4

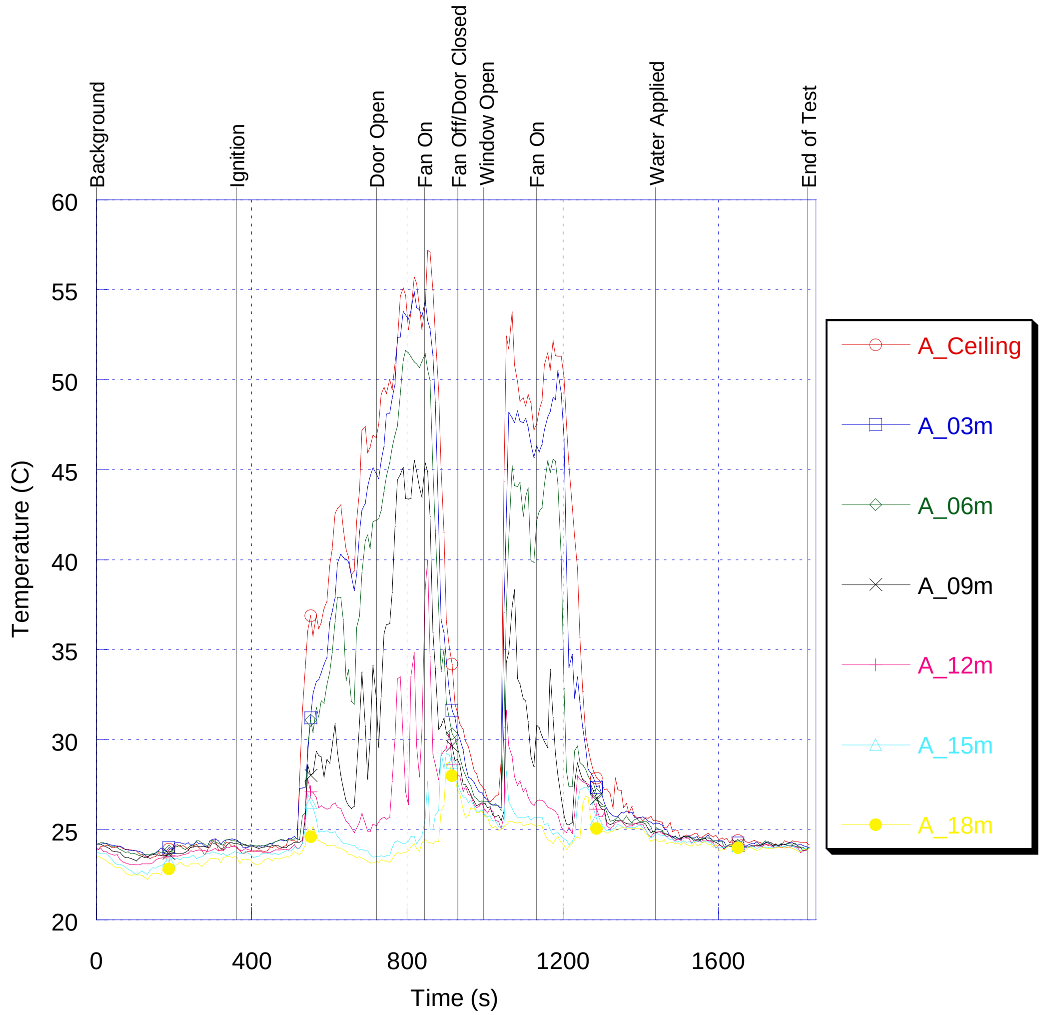

Figure 243. Experiment CF4 Temperature vs. Time for Location A

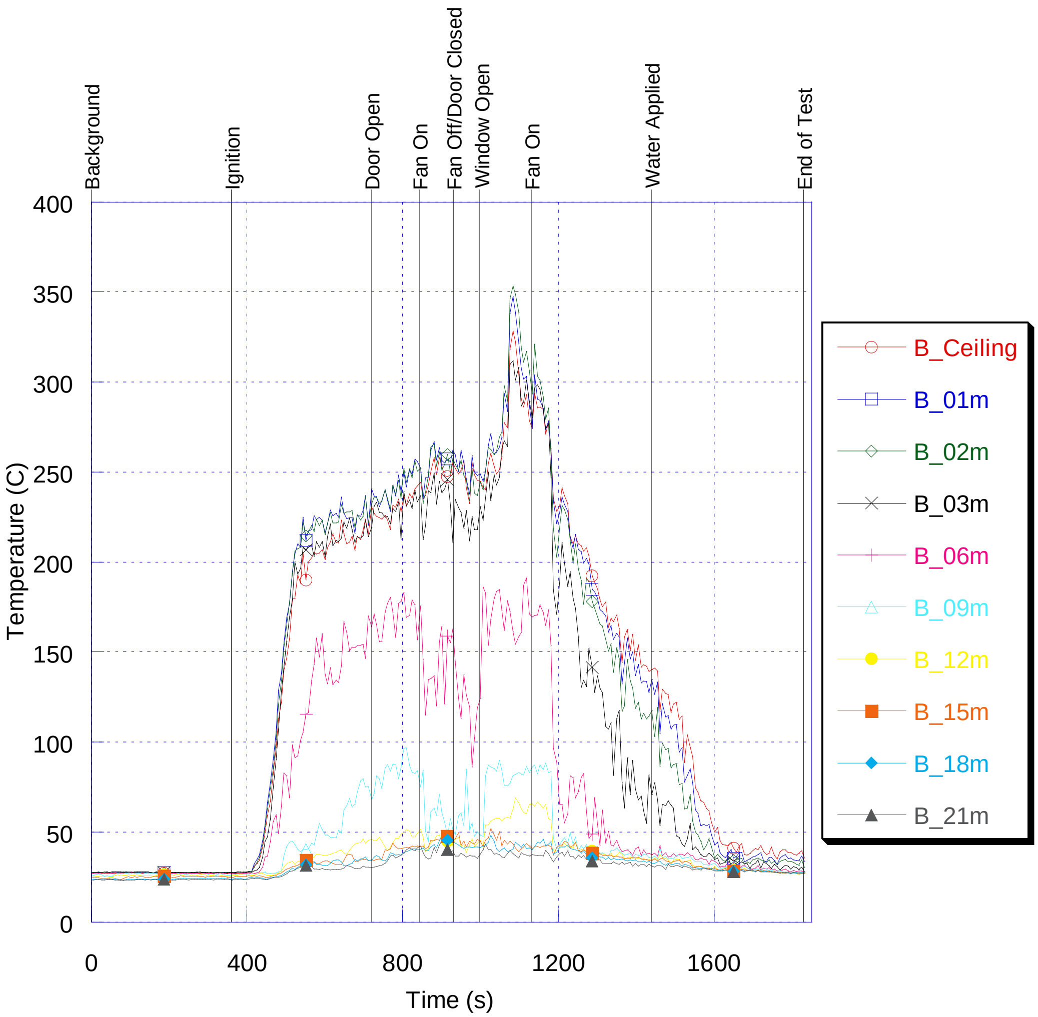

Figure 244. Experiment CF4 Temperature vs. Time for Location B

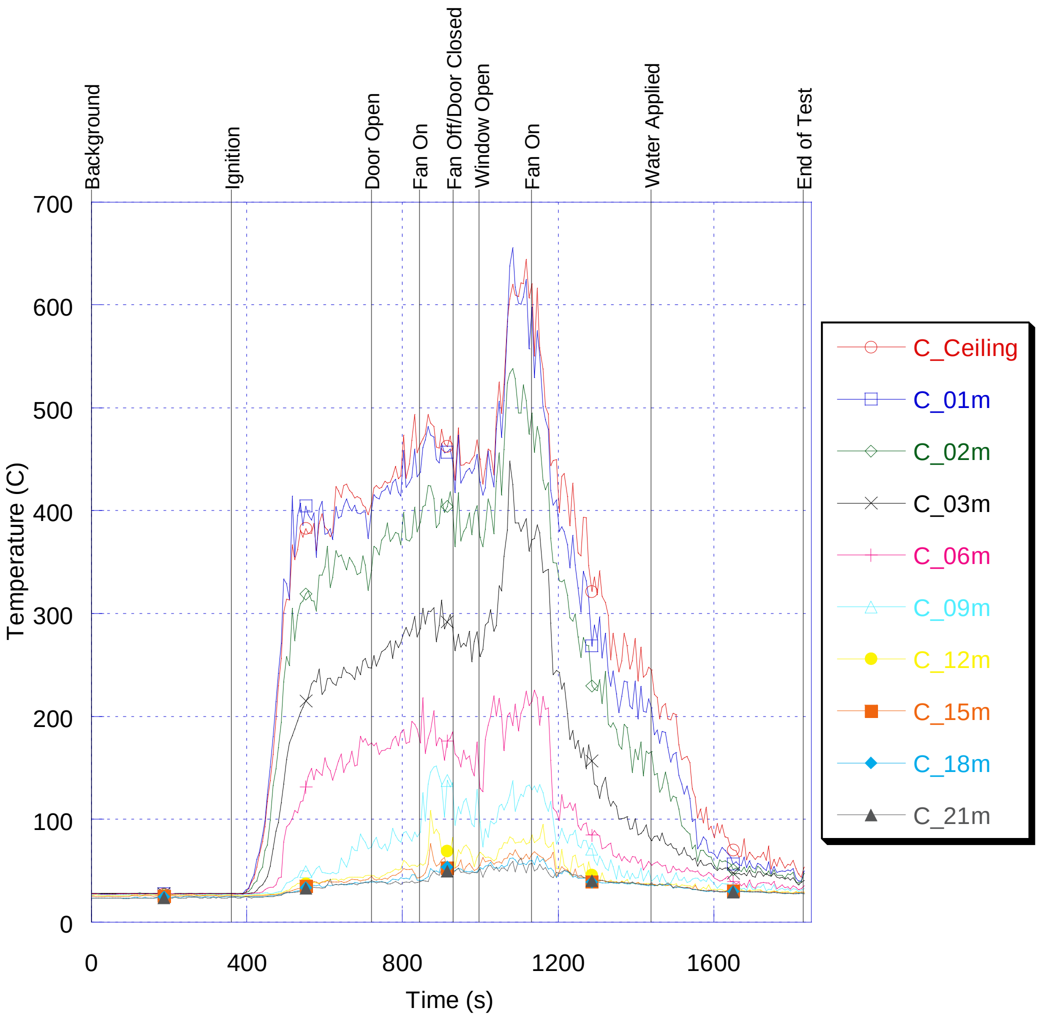

Figure 245. Experiment CF4 Temperature vs. Time for Location C

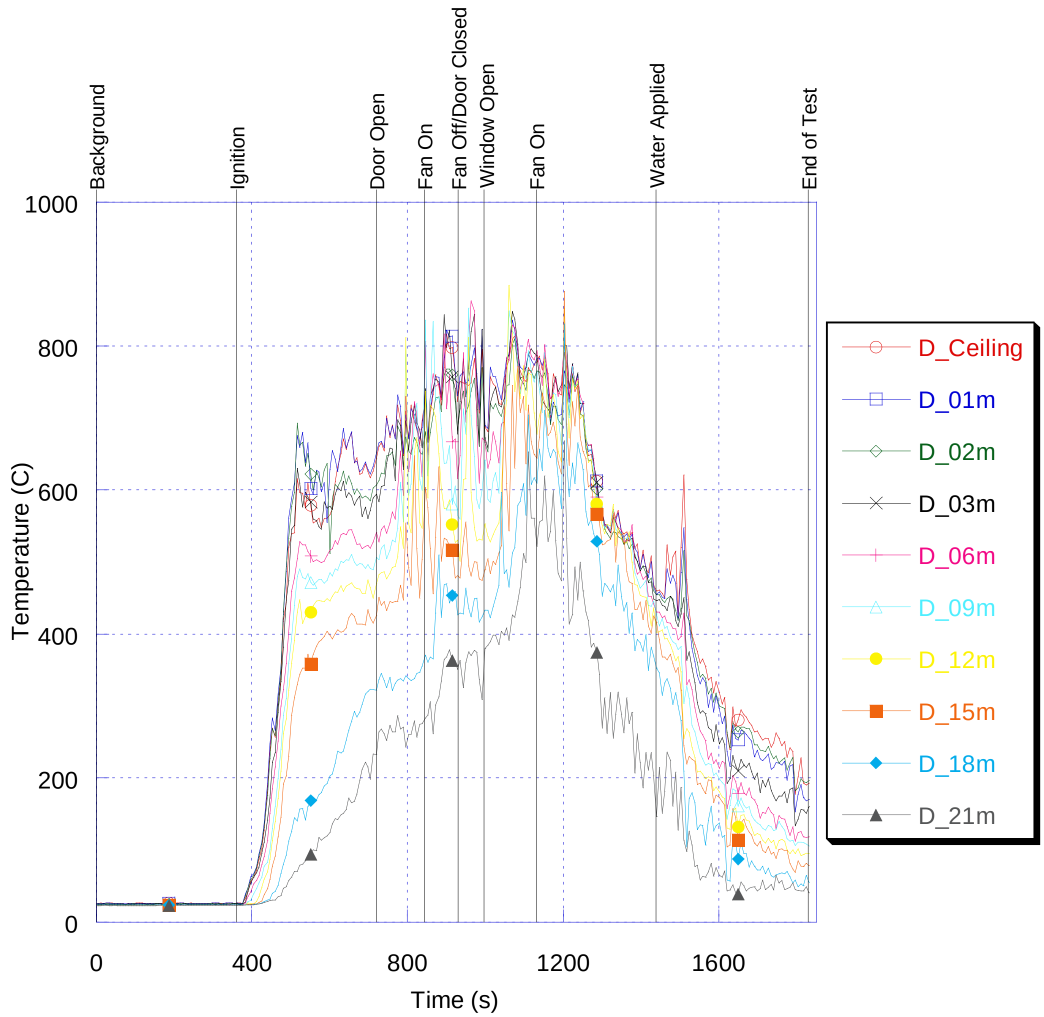

Figure 246. Experiment CF4 Temperature vs. Time for Location D

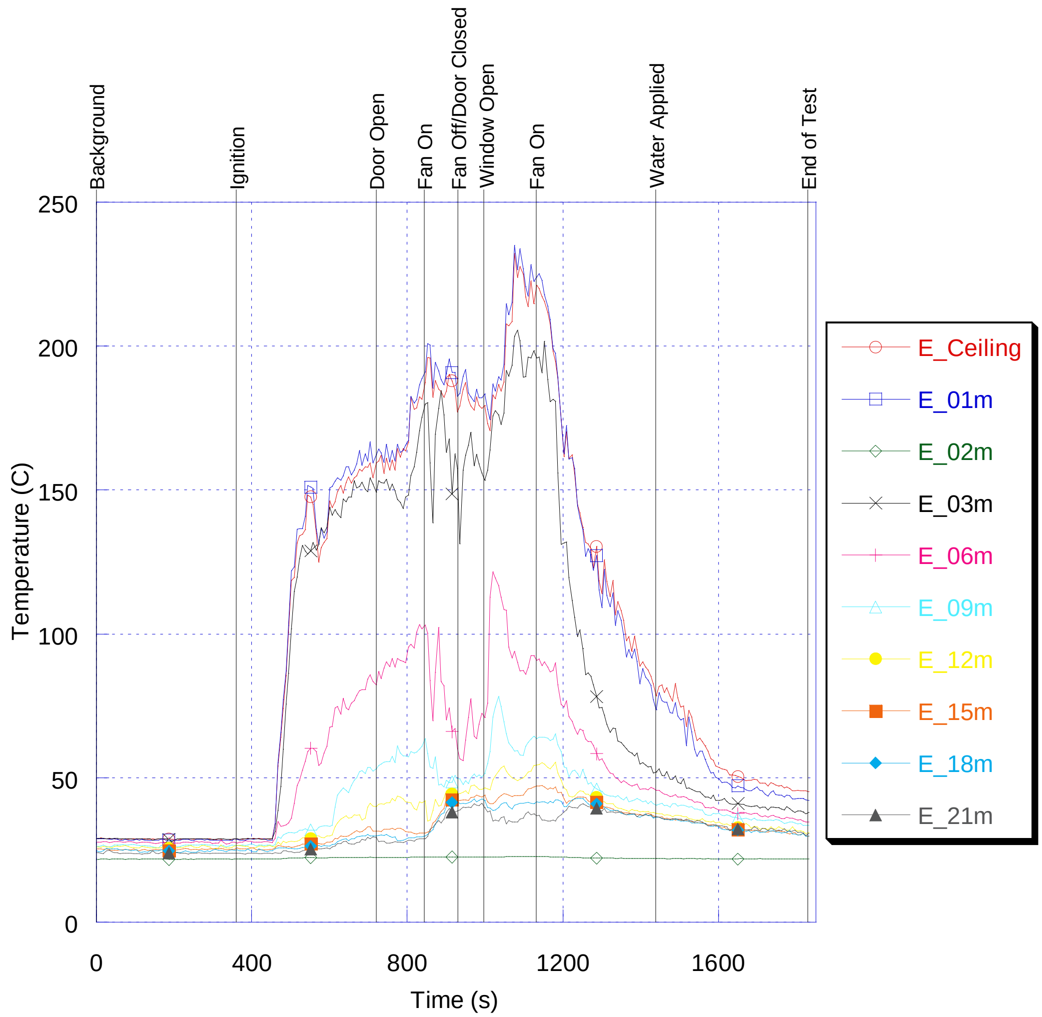

Figure 247. Experiment CF4 Temperature vs. Time for Location E

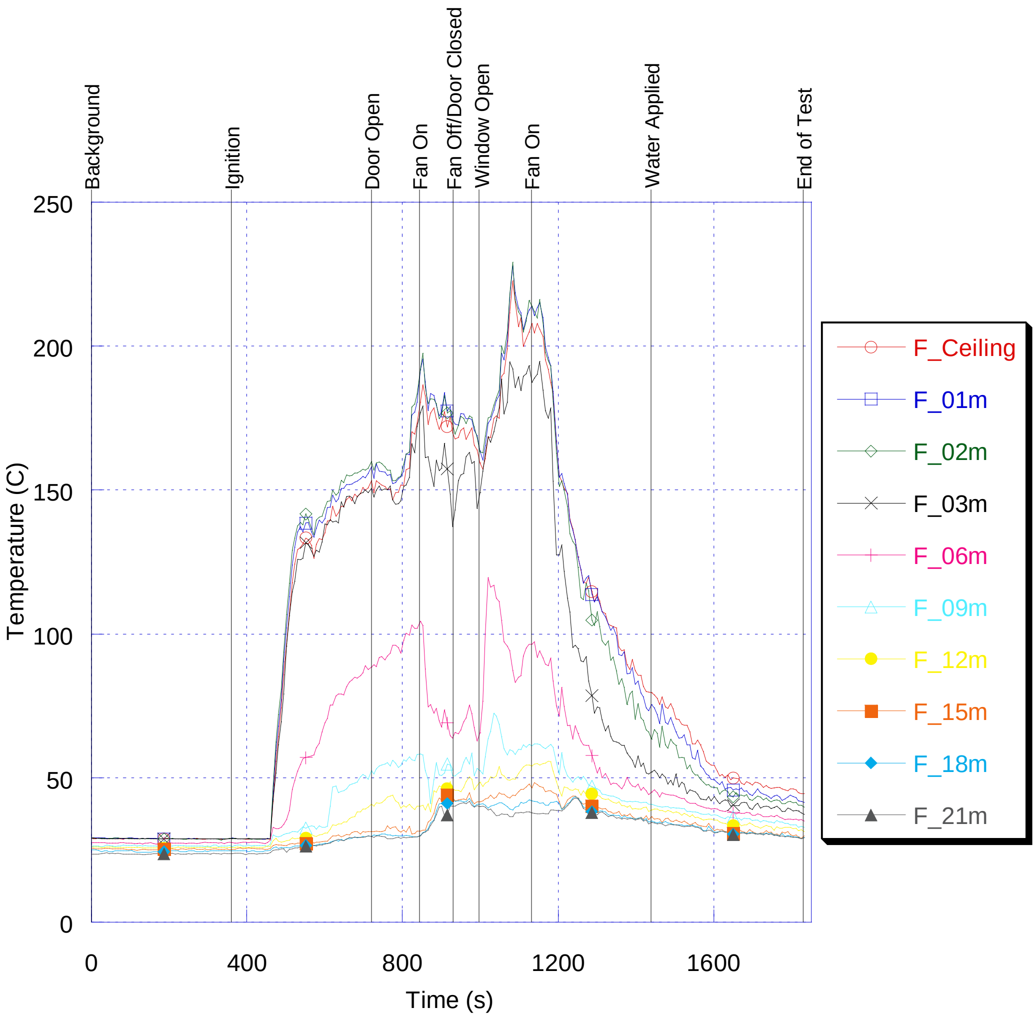

Figure 248. Experiment CF4 Temperature vs. Time for Location F

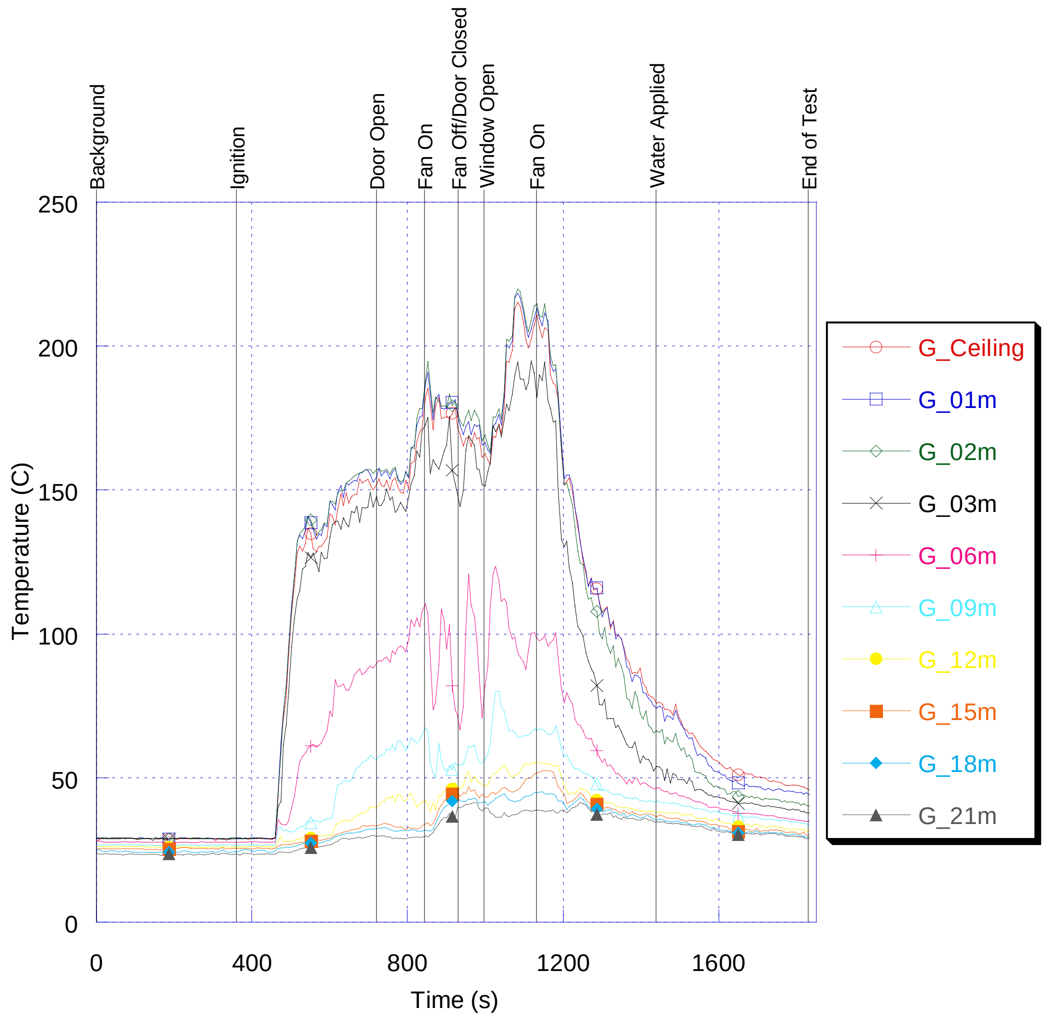

Figure 249. Experiment CF4 Temperature vs. Time for Location G

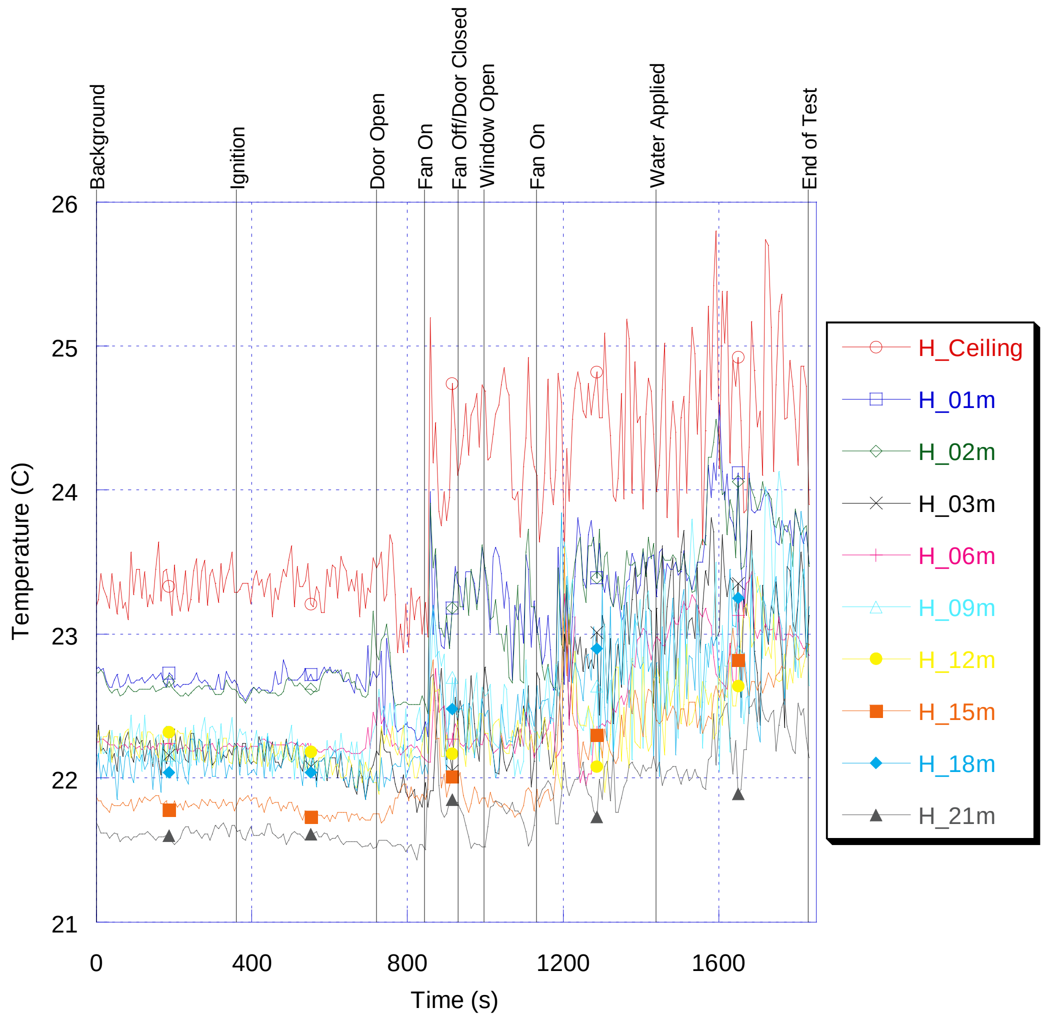

Figure 250. Experiment CF4 Temperature vs. Time for Location H

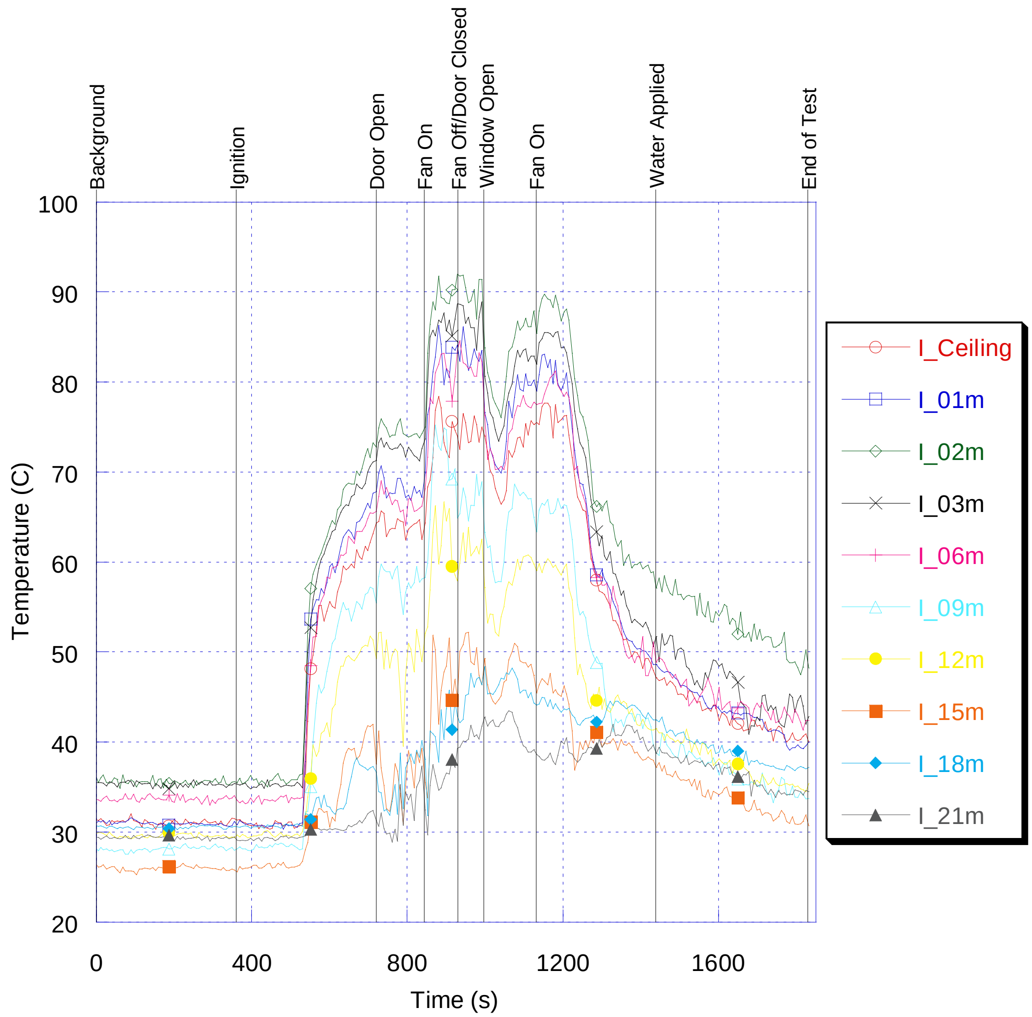

Figure 251. Experiment CF4 Temperature vs. Time for Location I

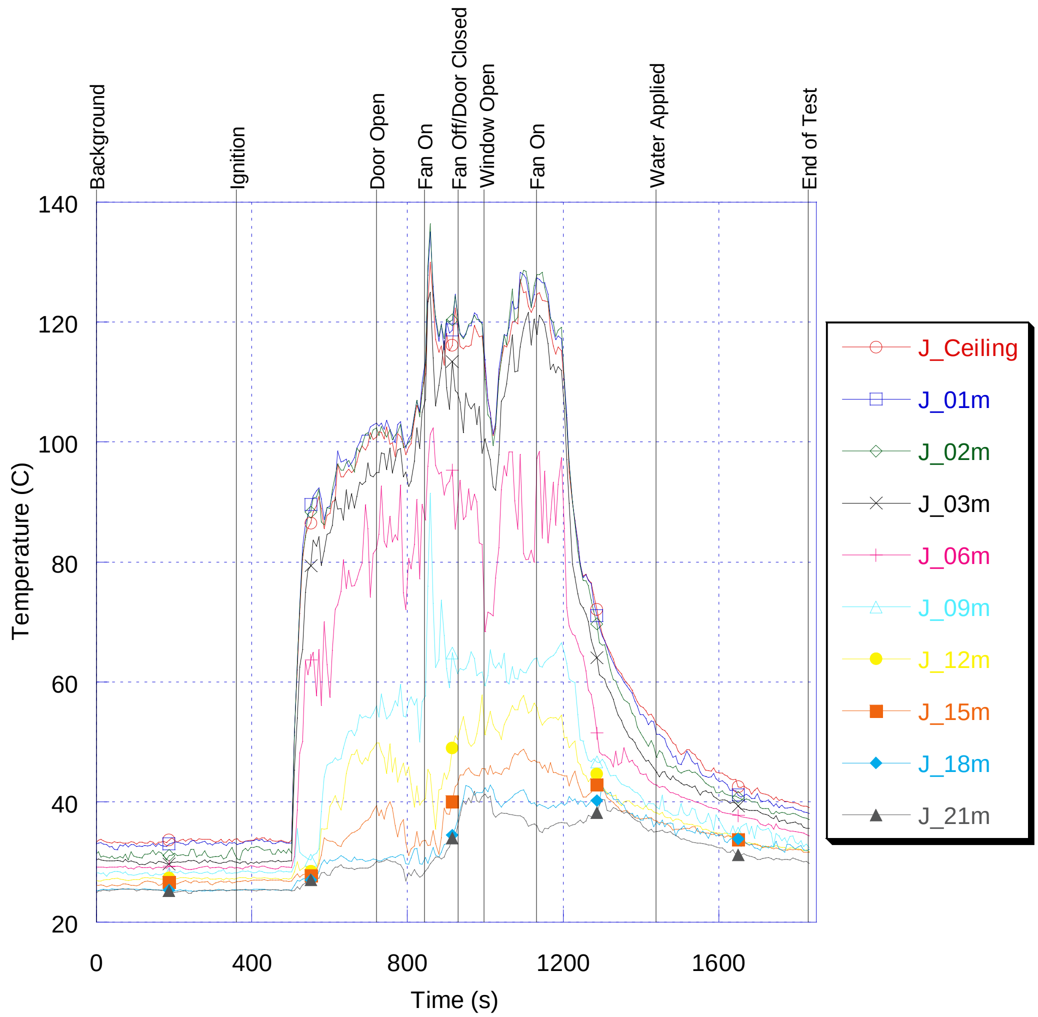

Figure 252. Experiment CF4 Temperature vs. Time for Location J

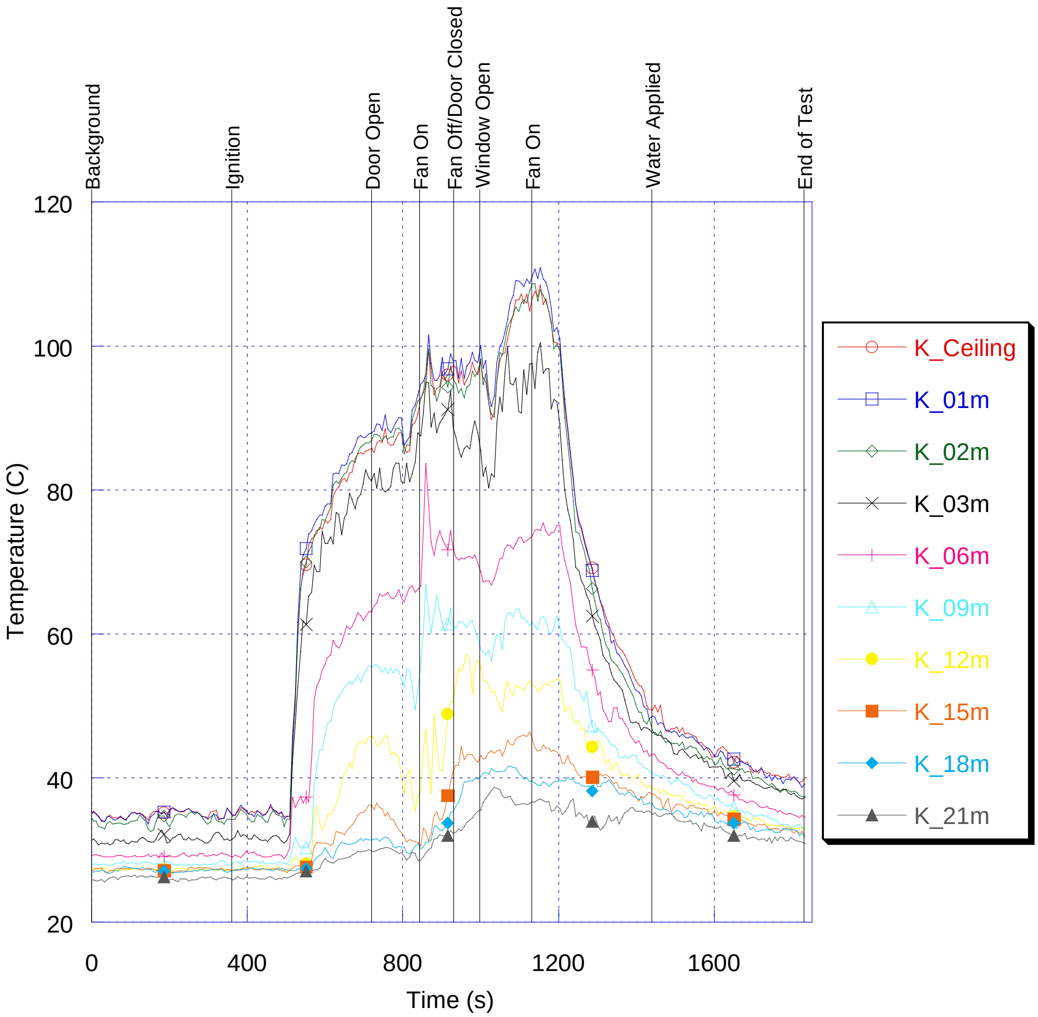

Figure 253. Experiment CF4 Temperature vs. Time for Location K

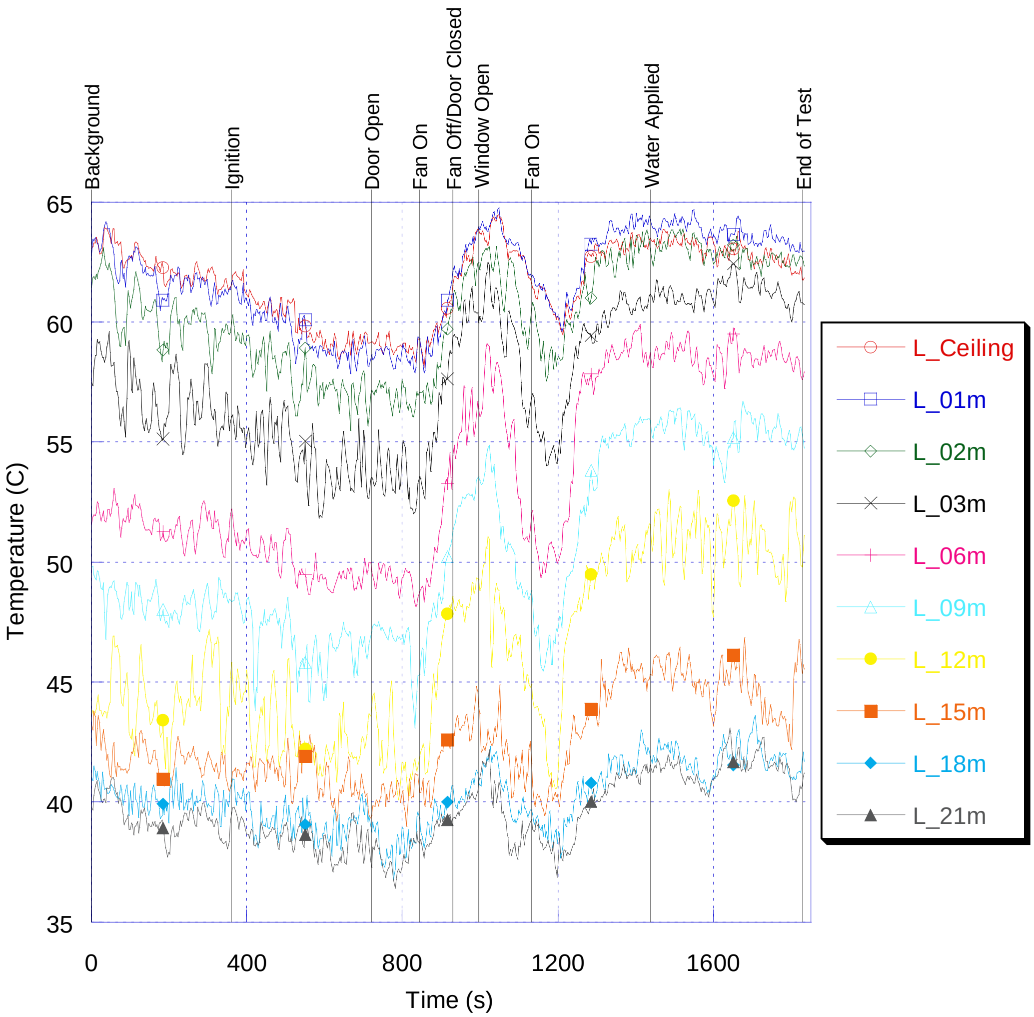

Figure 254. Experiment CF4 Temperature vs. Time for Location L

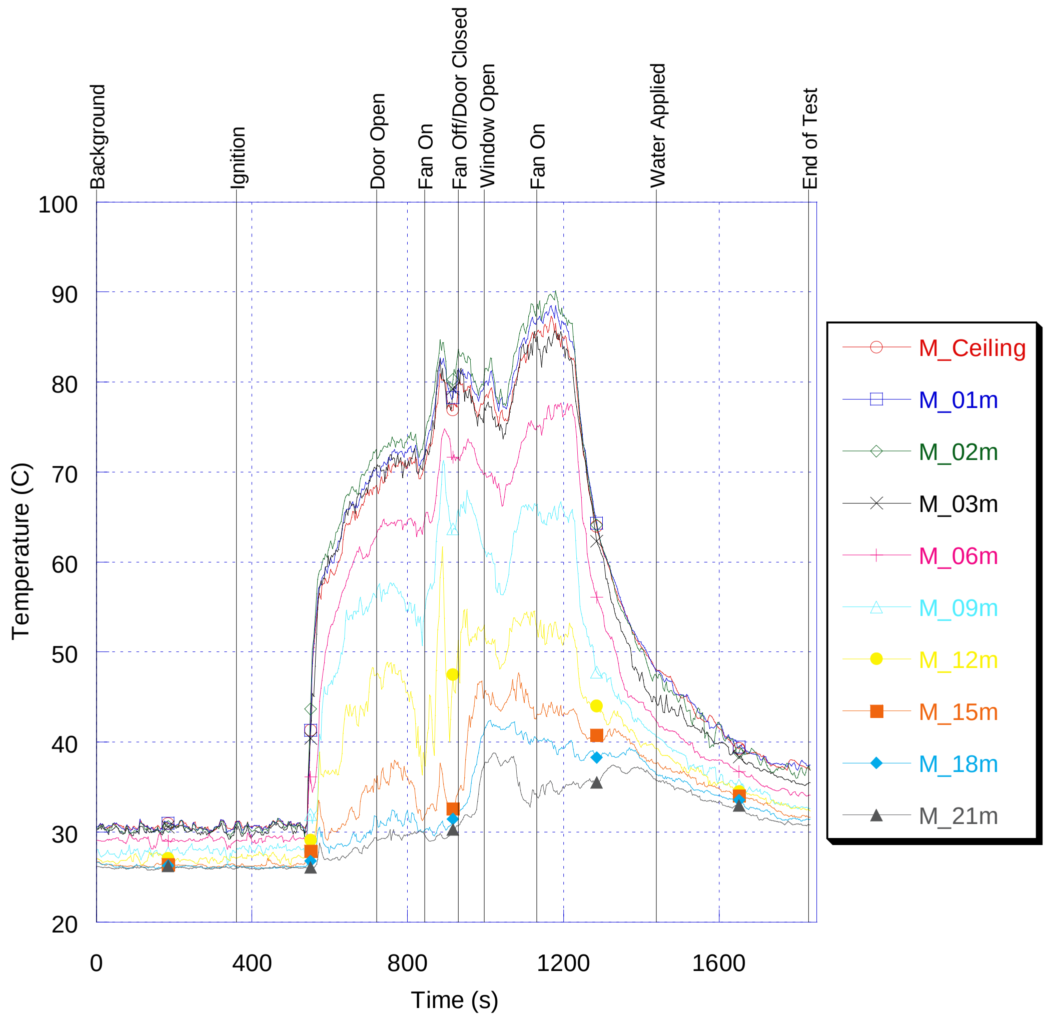

Figure 255. Experiment CF4 Temperature vs. Time for Location M

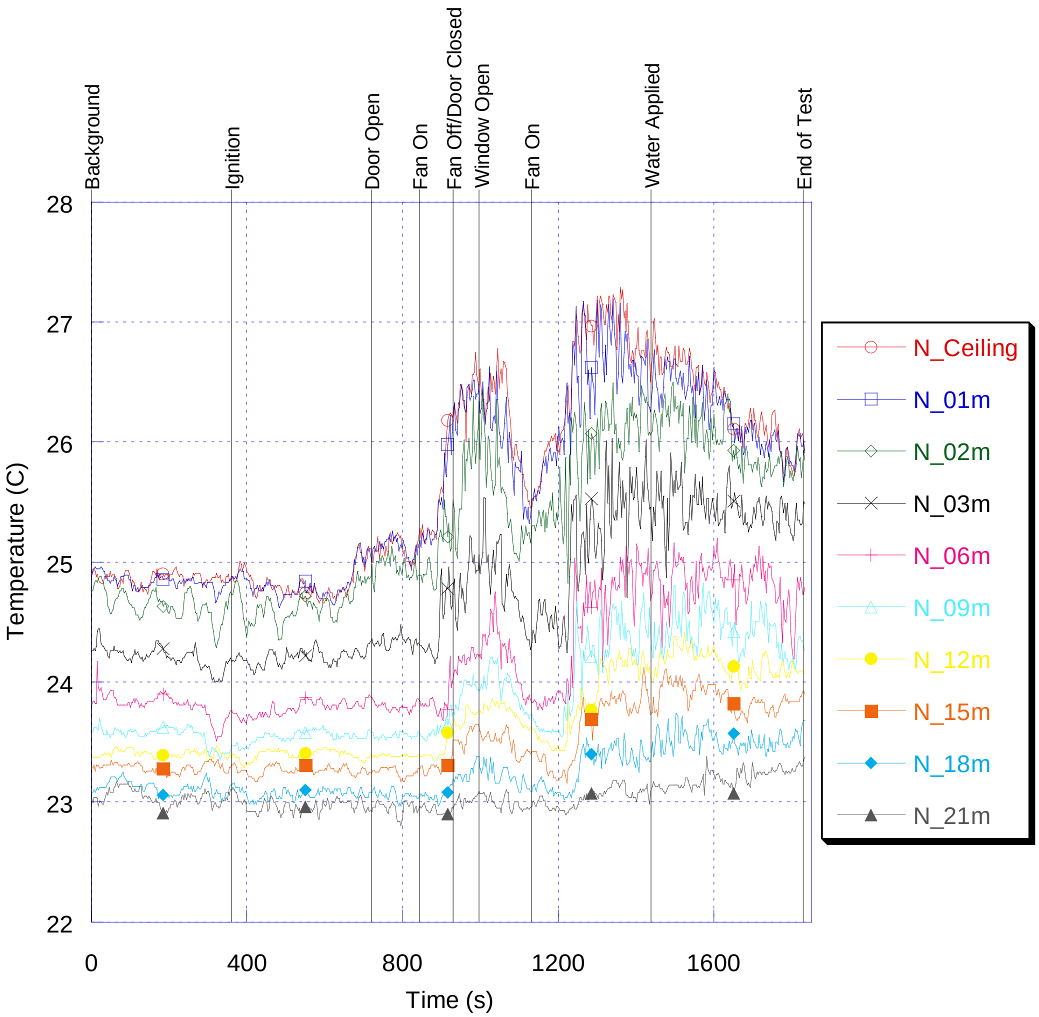

Figure 256. Experiment CF4 Temperature vs. Time for Location N

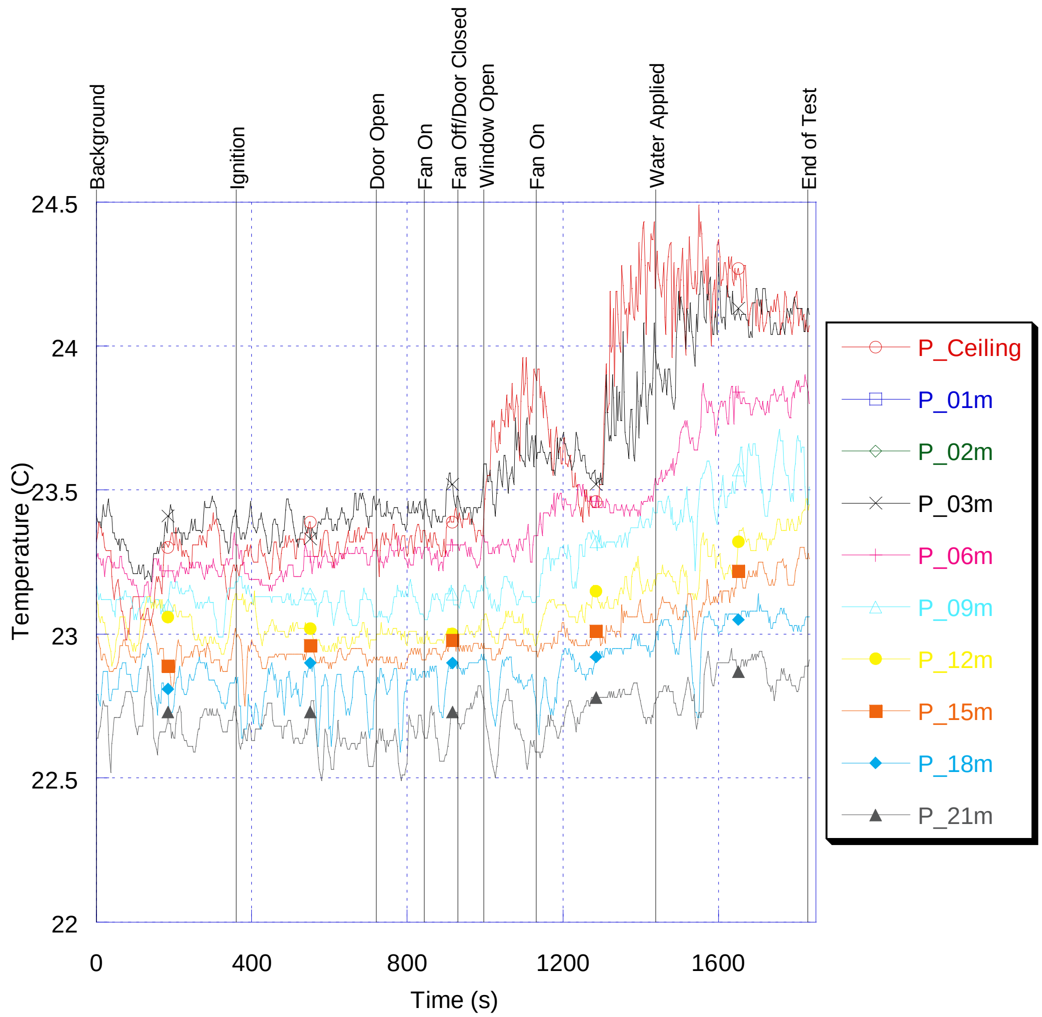

Figure 257. Experiment CF4 Temperature vs. Time for Location P

Experiment CF5

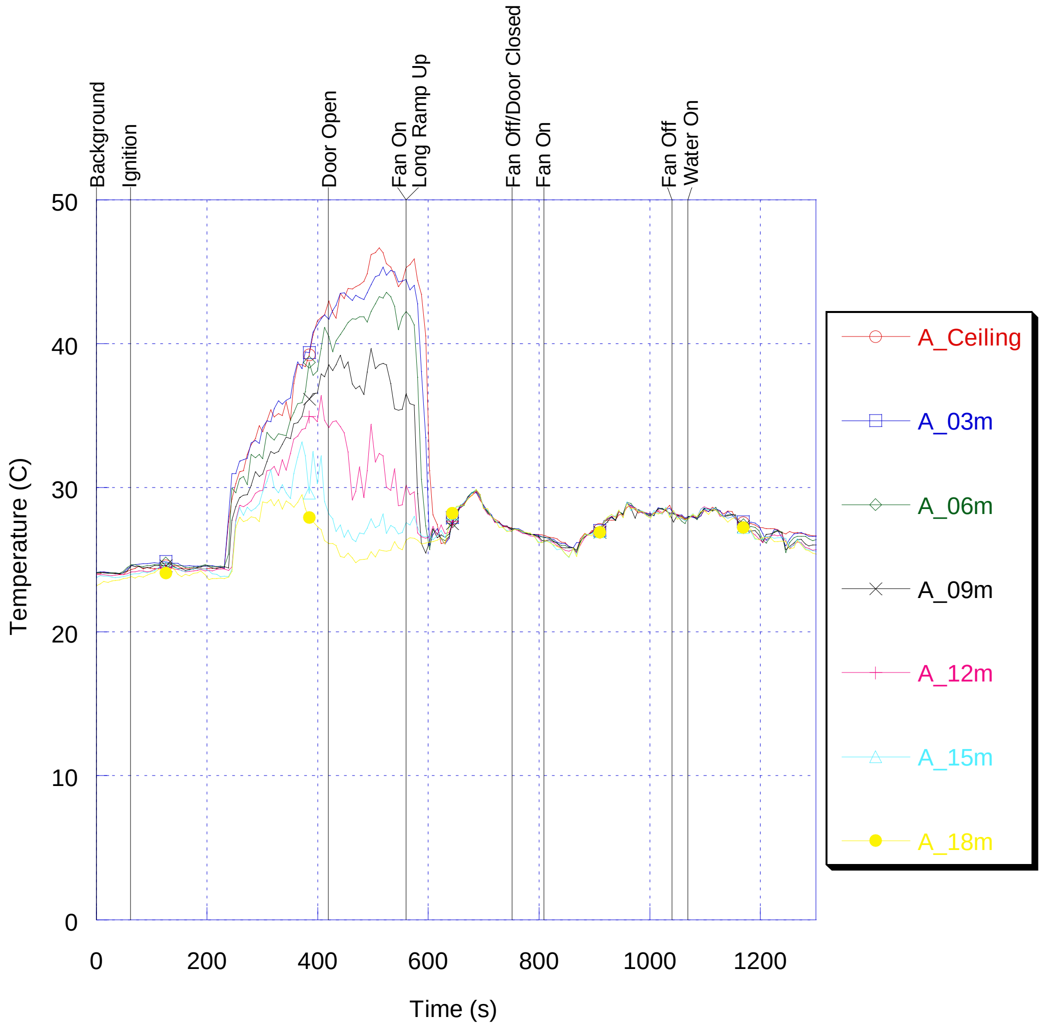

Figure 258. Experiment CF5 Temperature vs. Time for Location A

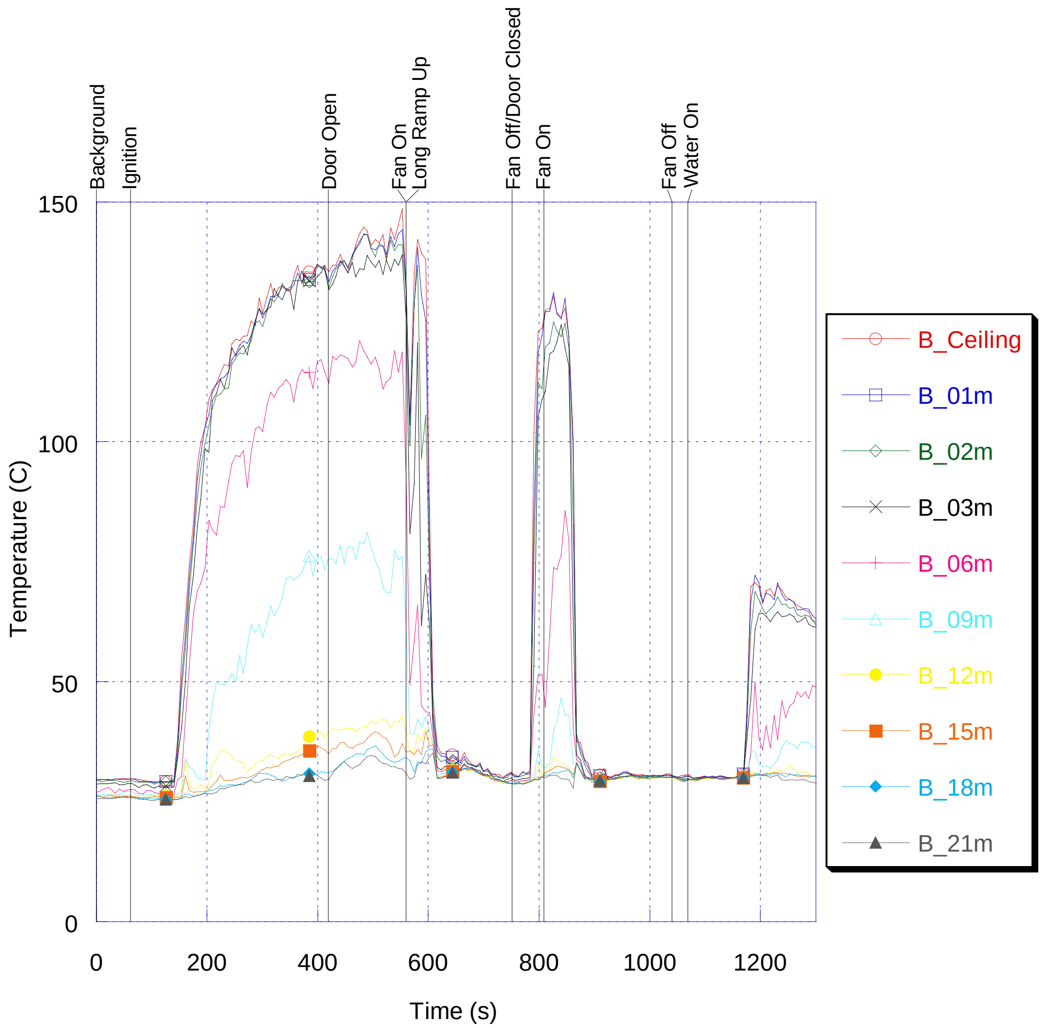

Figure 259. Experiment CF5 Temperature vs. Time for Location B

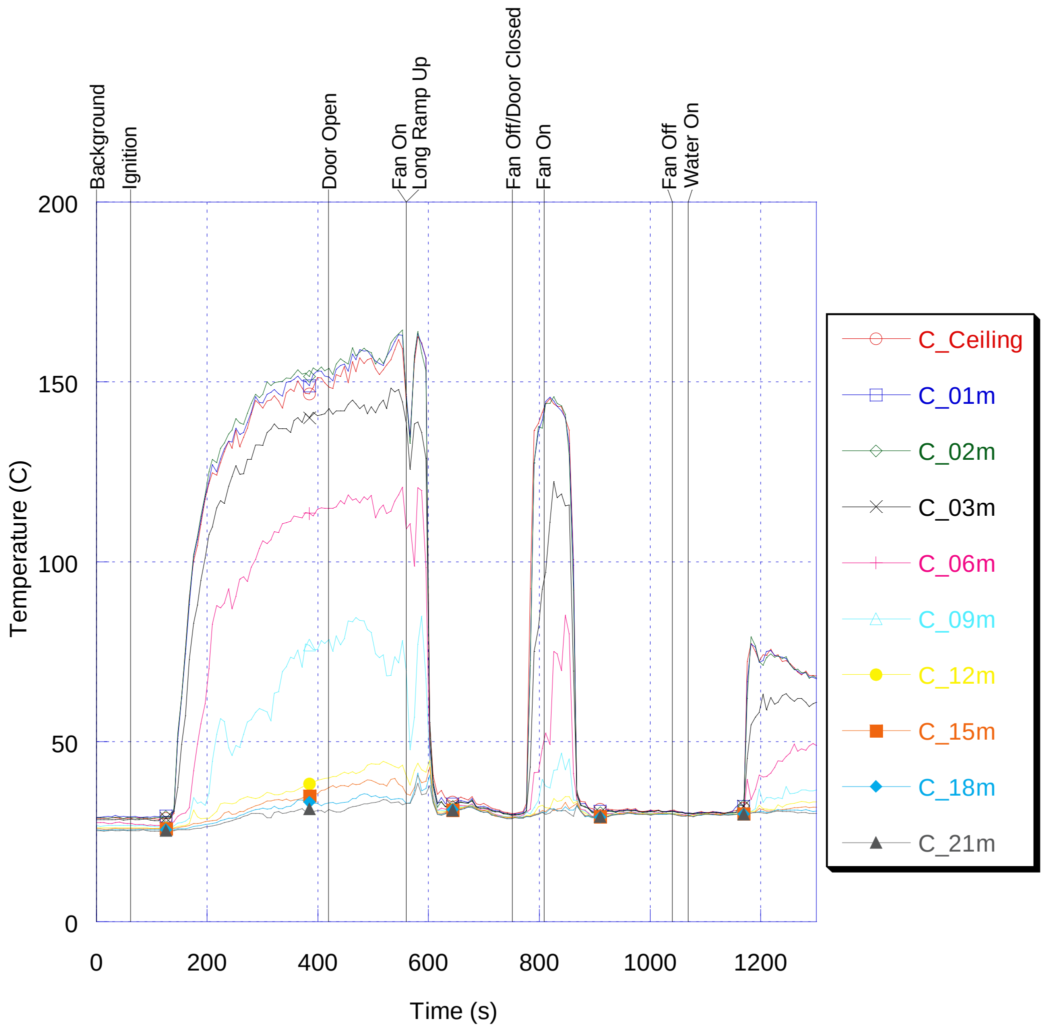

Figure 260. Experiment CF5 Temperature vs. Time for Location C

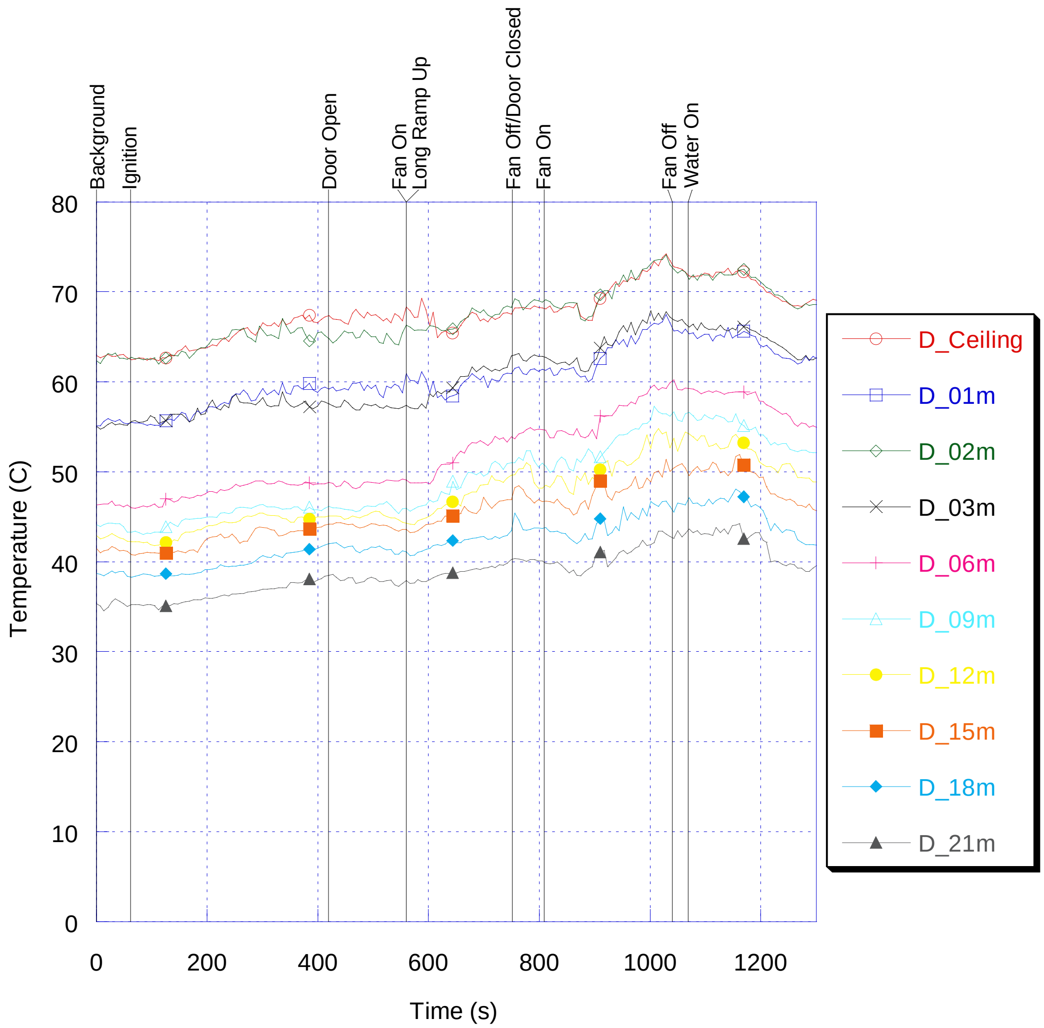

Figure 261. Experiment CF5 Temperature vs. Time for Location D

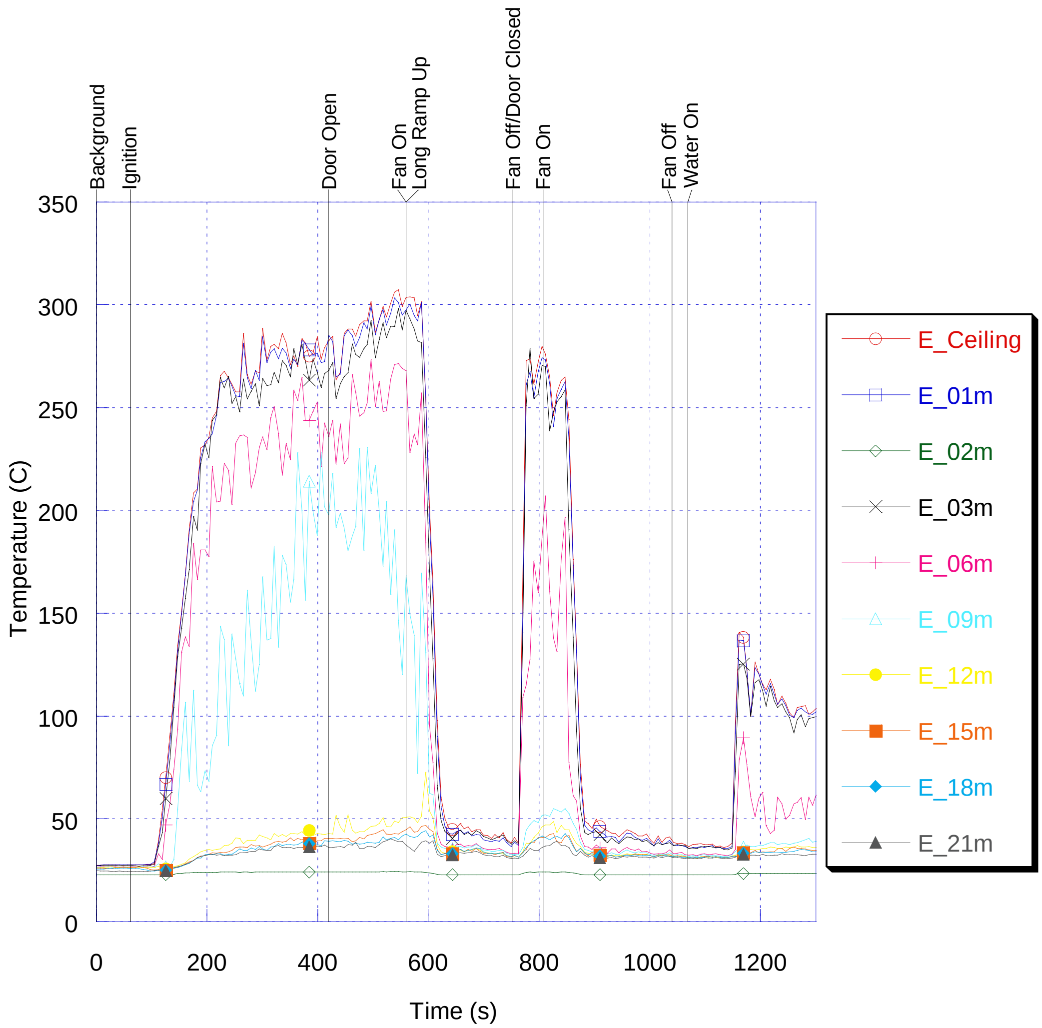

Figure 262. Experiment CF5 Temperature vs. Time for Location E

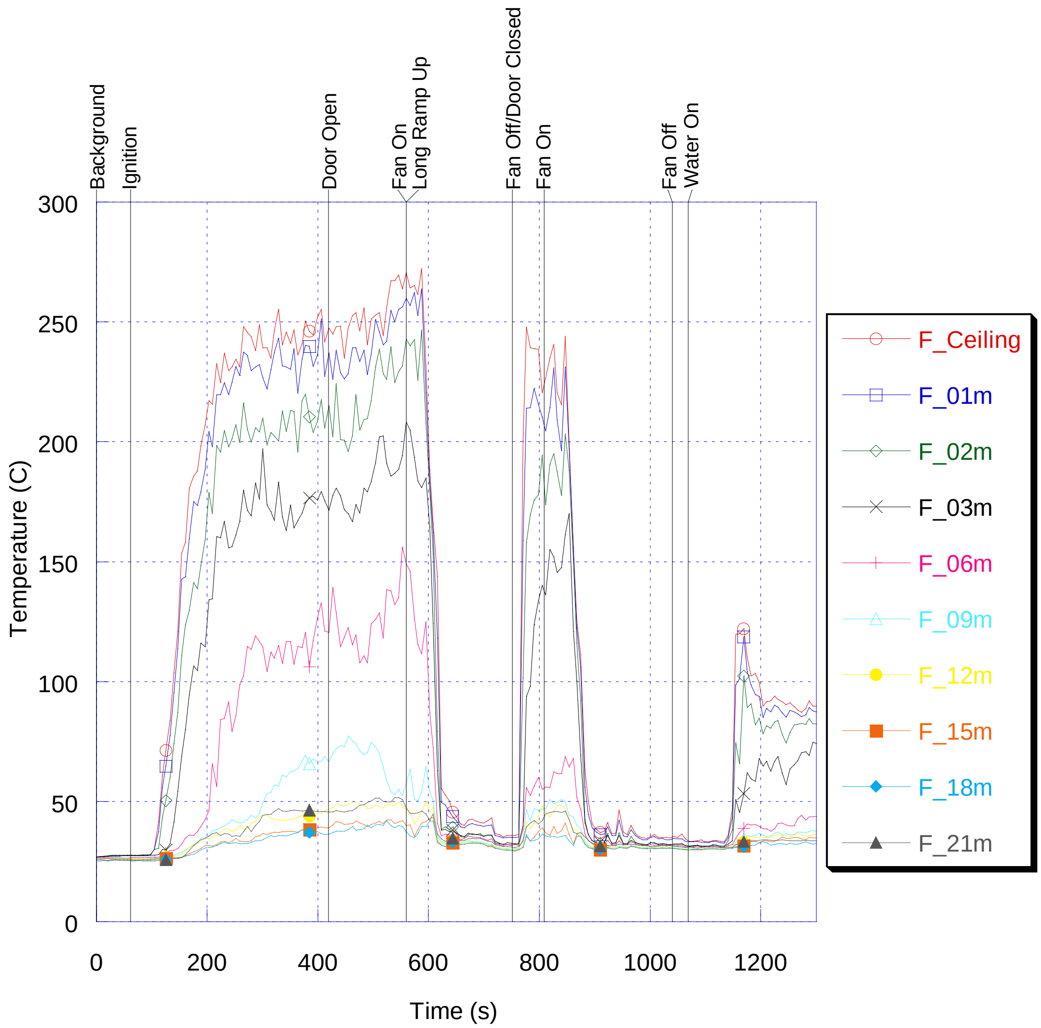

Figure 263. Experiment CF5 Temperature vs. Time for Location F

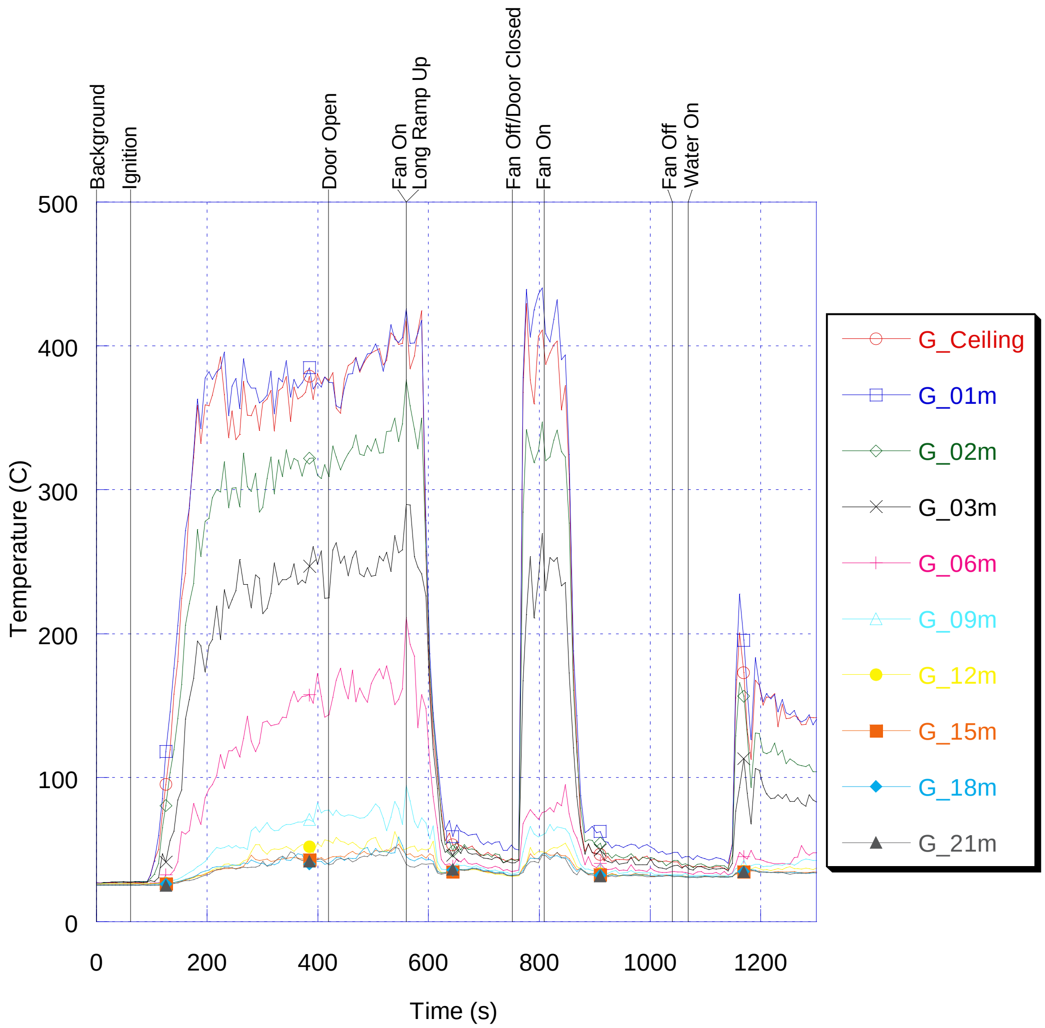

Figure 264. Experiment CF5 Temperature vs. Time for Location G

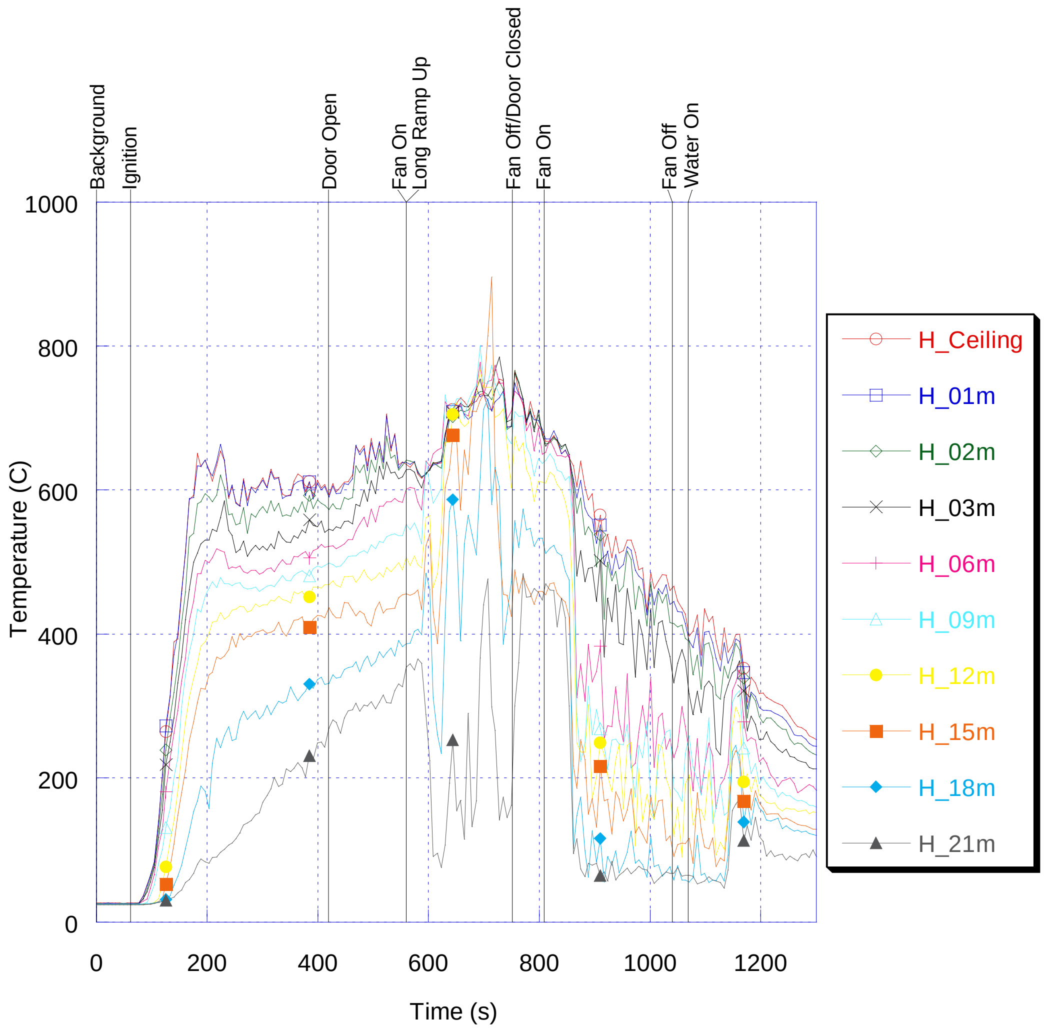

Figure 265. Experiment CF5 Temperature vs. Time for Location H

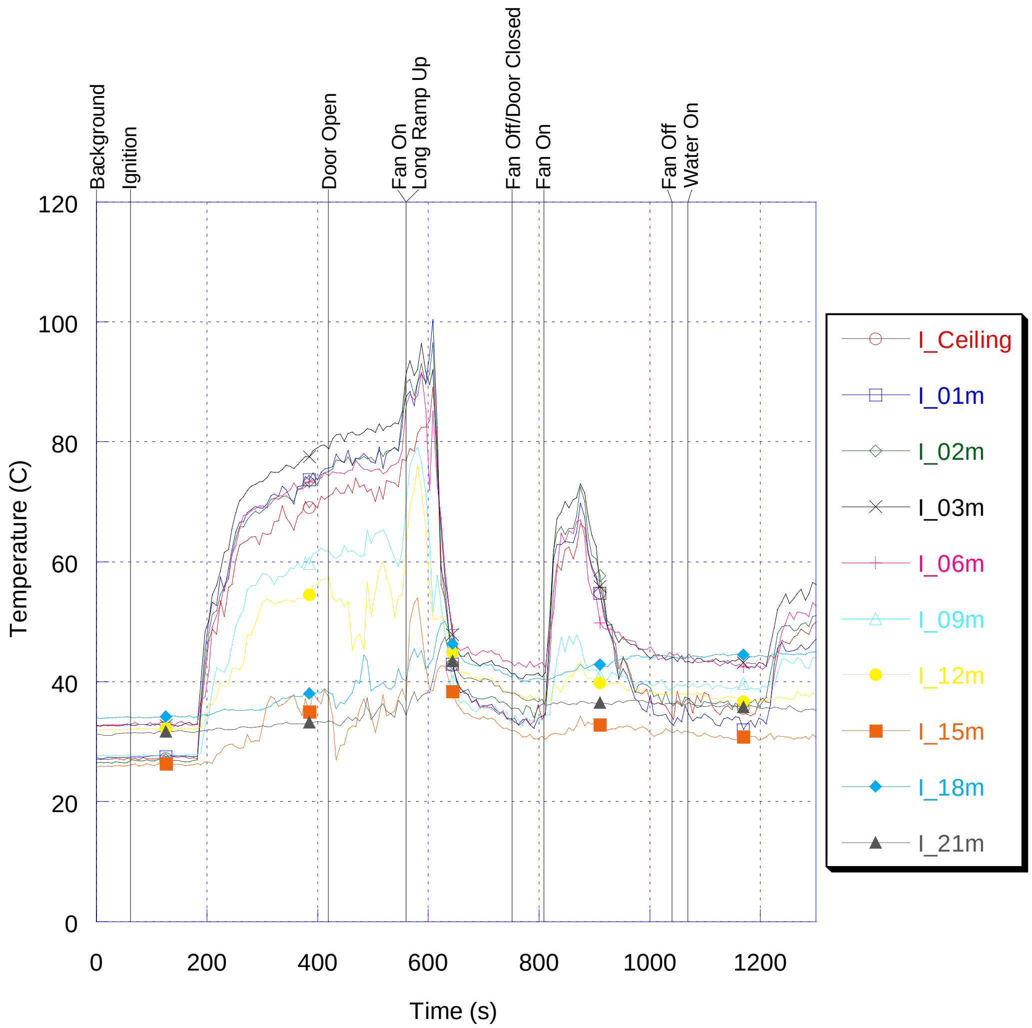

Figure 266. Experiment CF5 Temperature vs. Time for Location I

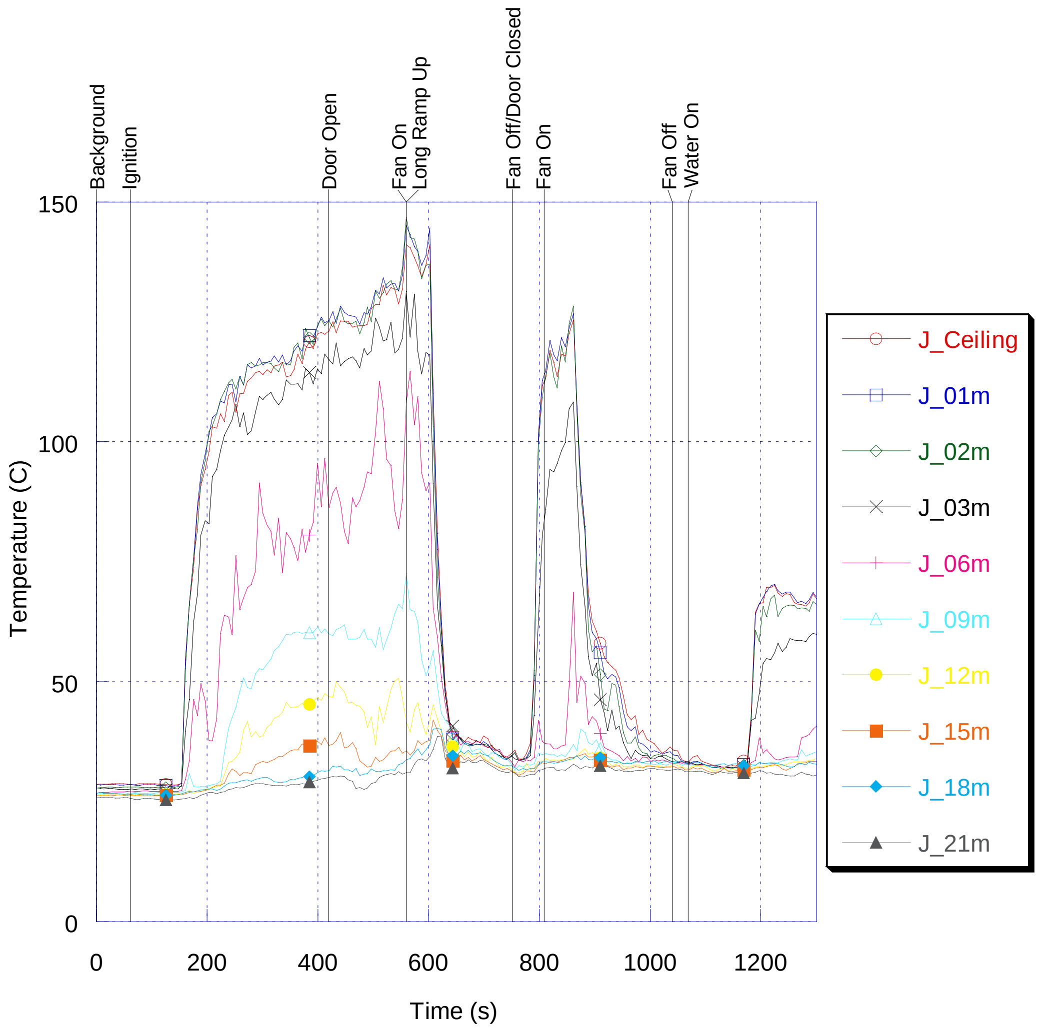

Figure 267. Experiment CF5 Temperature vs. Time for Location J

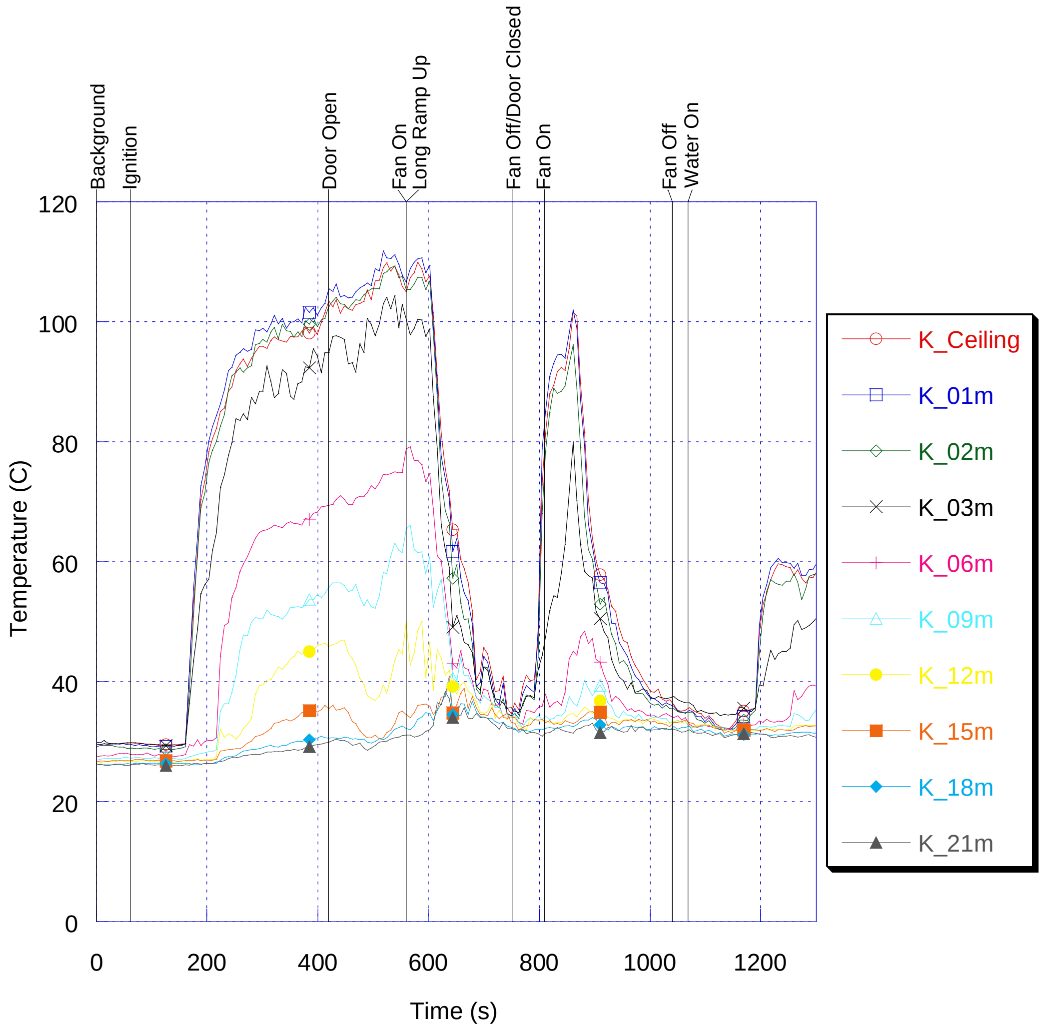

Figure 268. Experiment CF5 Temperature vs. Time for Location K

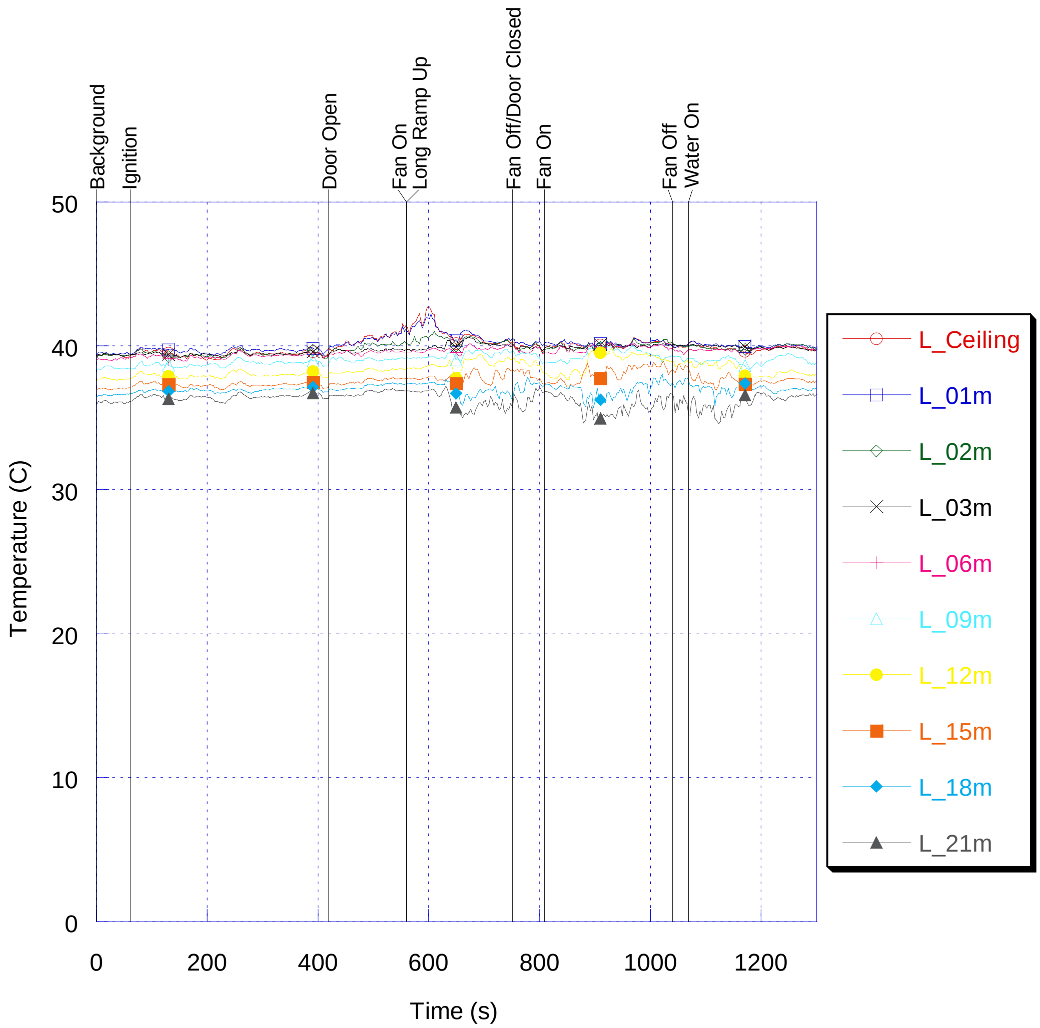

Figure 269. Experiment CF5 Temperature vs. Time for Location L

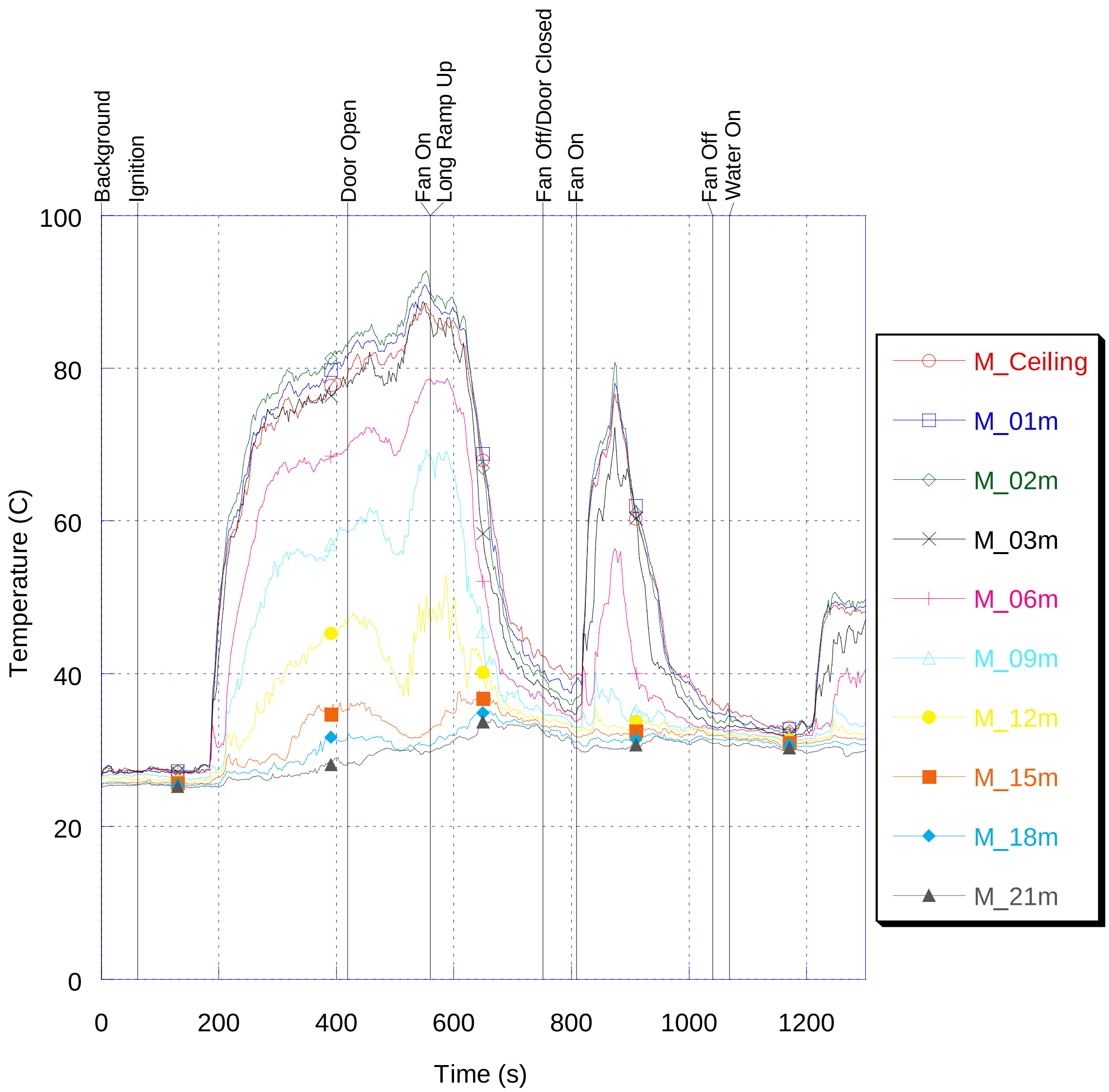

Figure 270. Experiment CF5 Temperature vs. Time for Location M

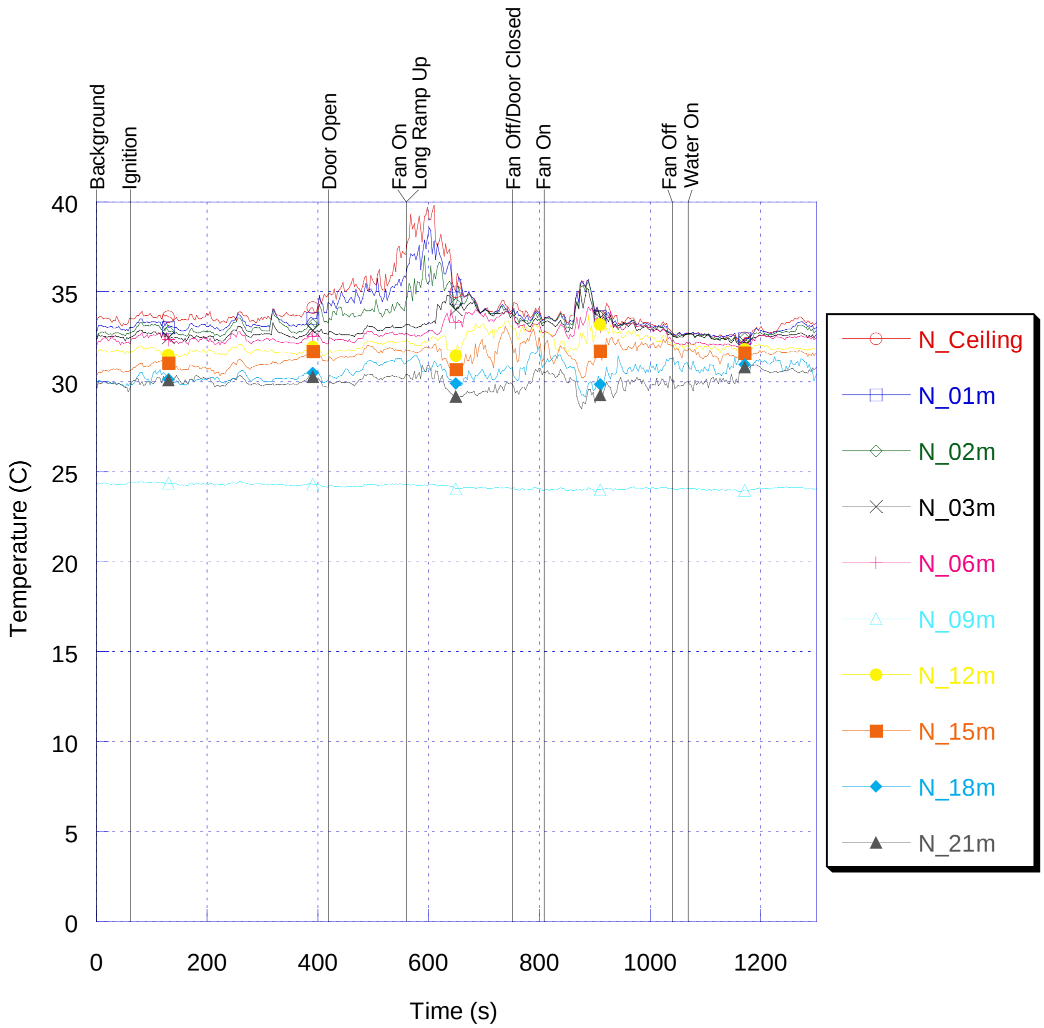

Figure 271. Experiment CF5 Temperature vs. Time for Location N

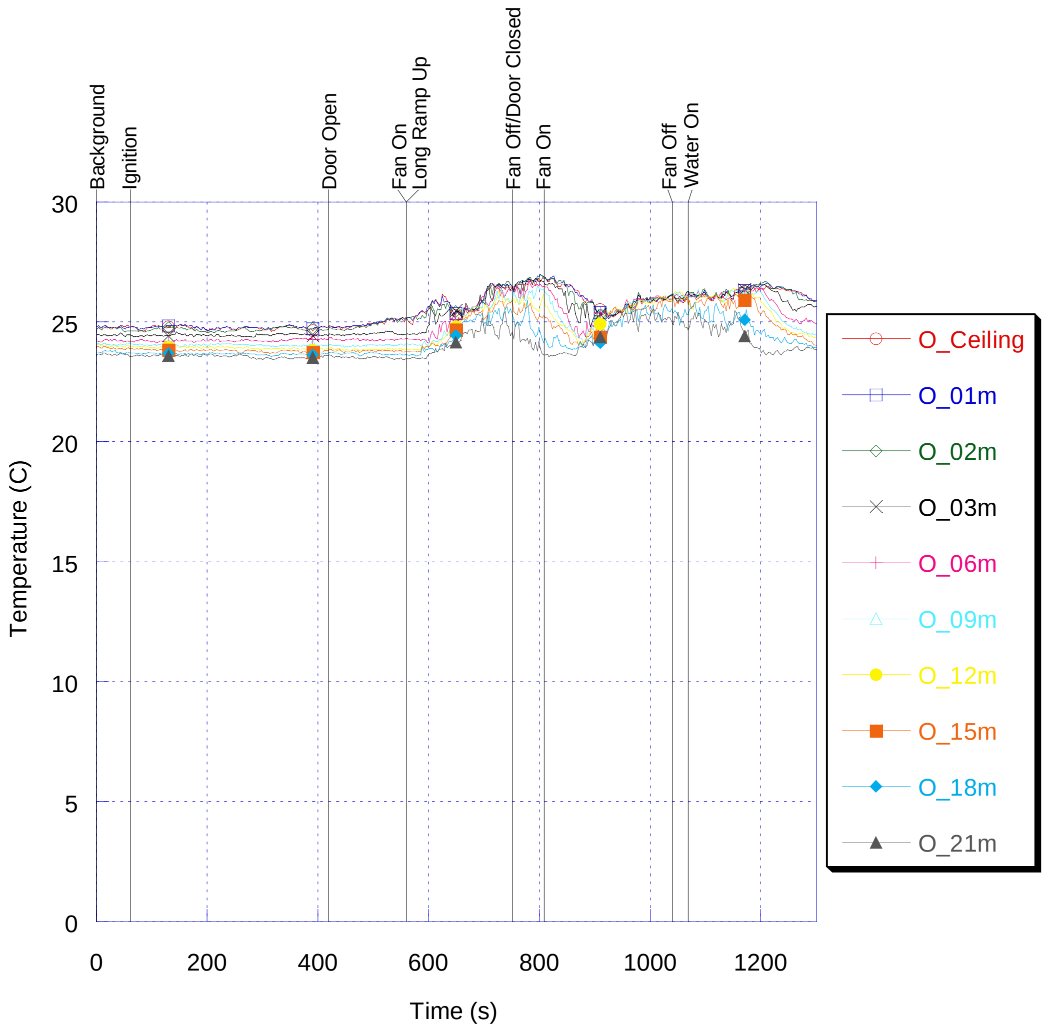

Figure 272. Experiment CF5 Temperature vs. Time for Location O

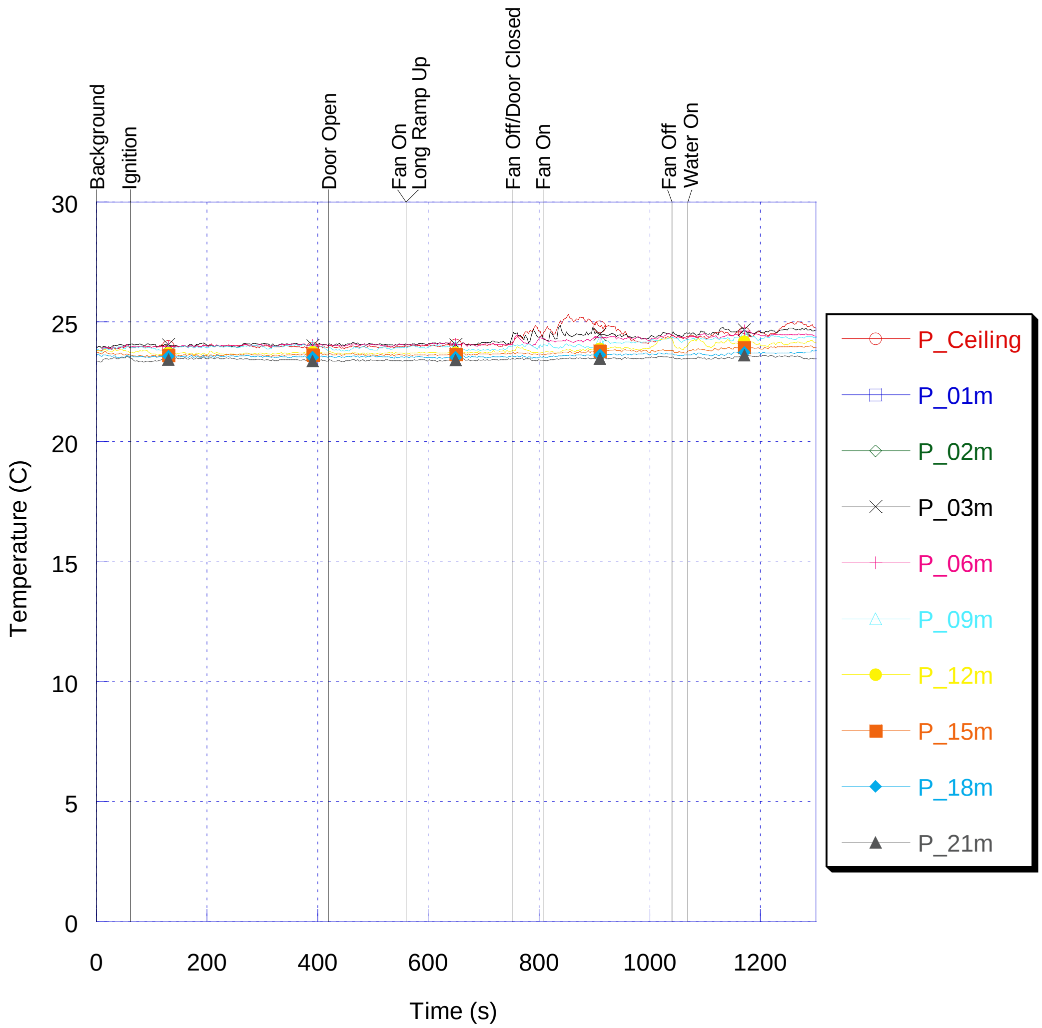

Figure 273. Experiment CF5 Temperature vs. Time for Location P

Experiment CF6

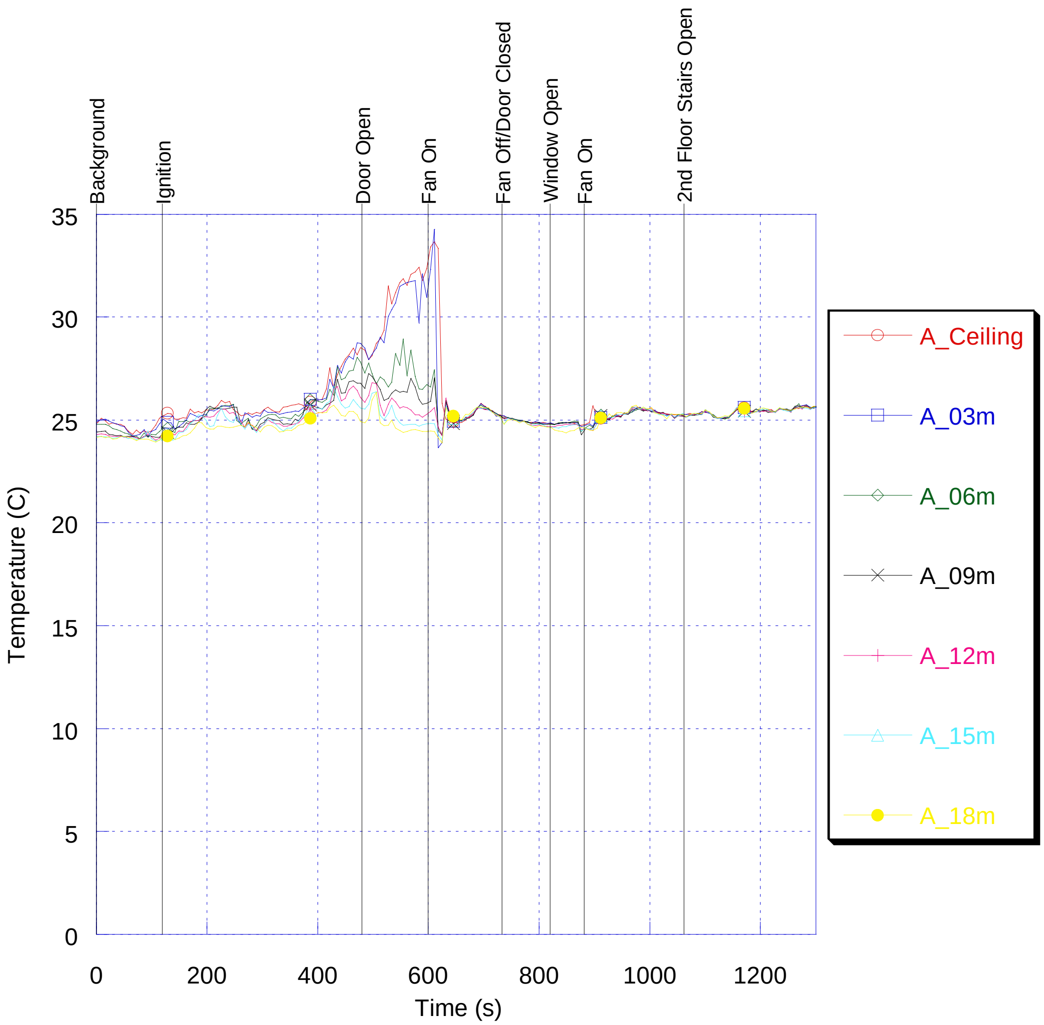

Figure 274. Experiment CF6 Temperature vs. Time for Location A

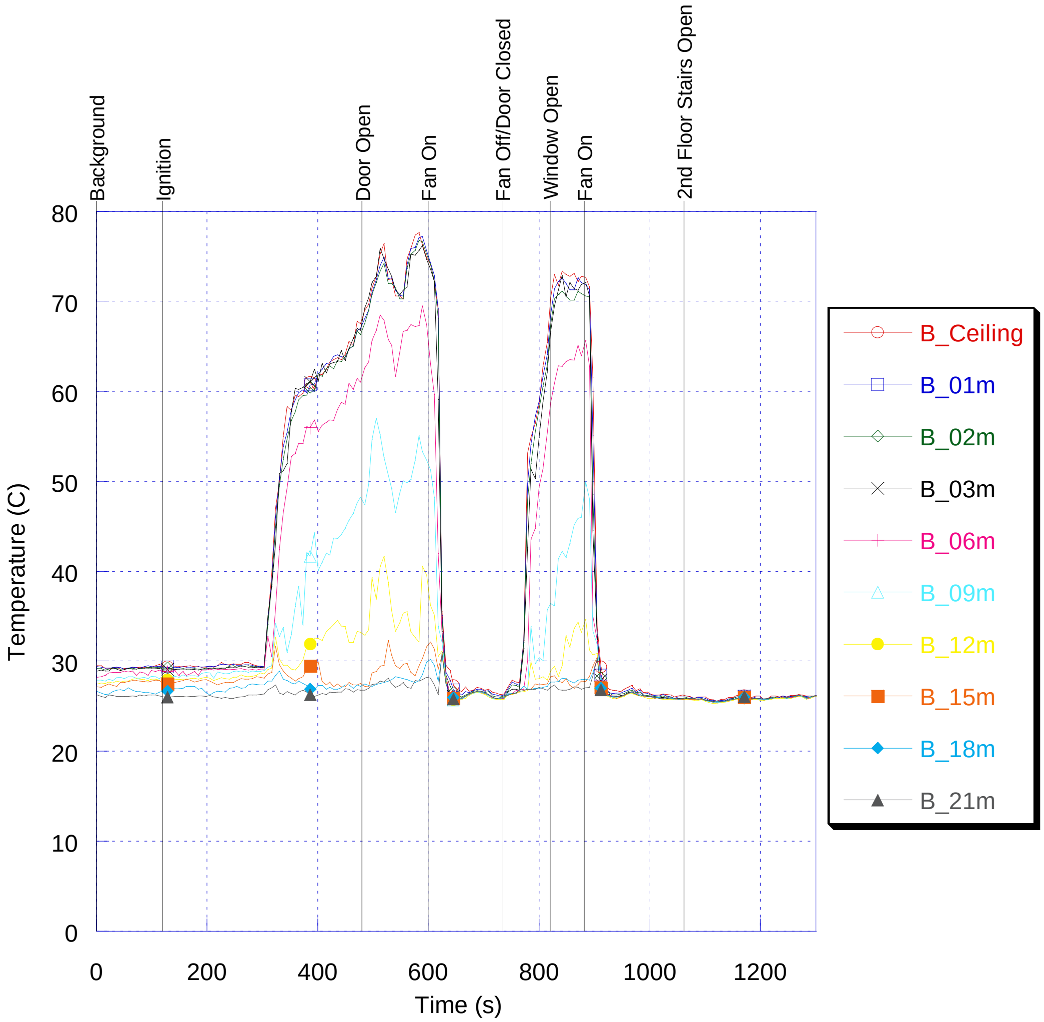

Figure 275. Experiment CF6 Temperature vs. Time for Location B

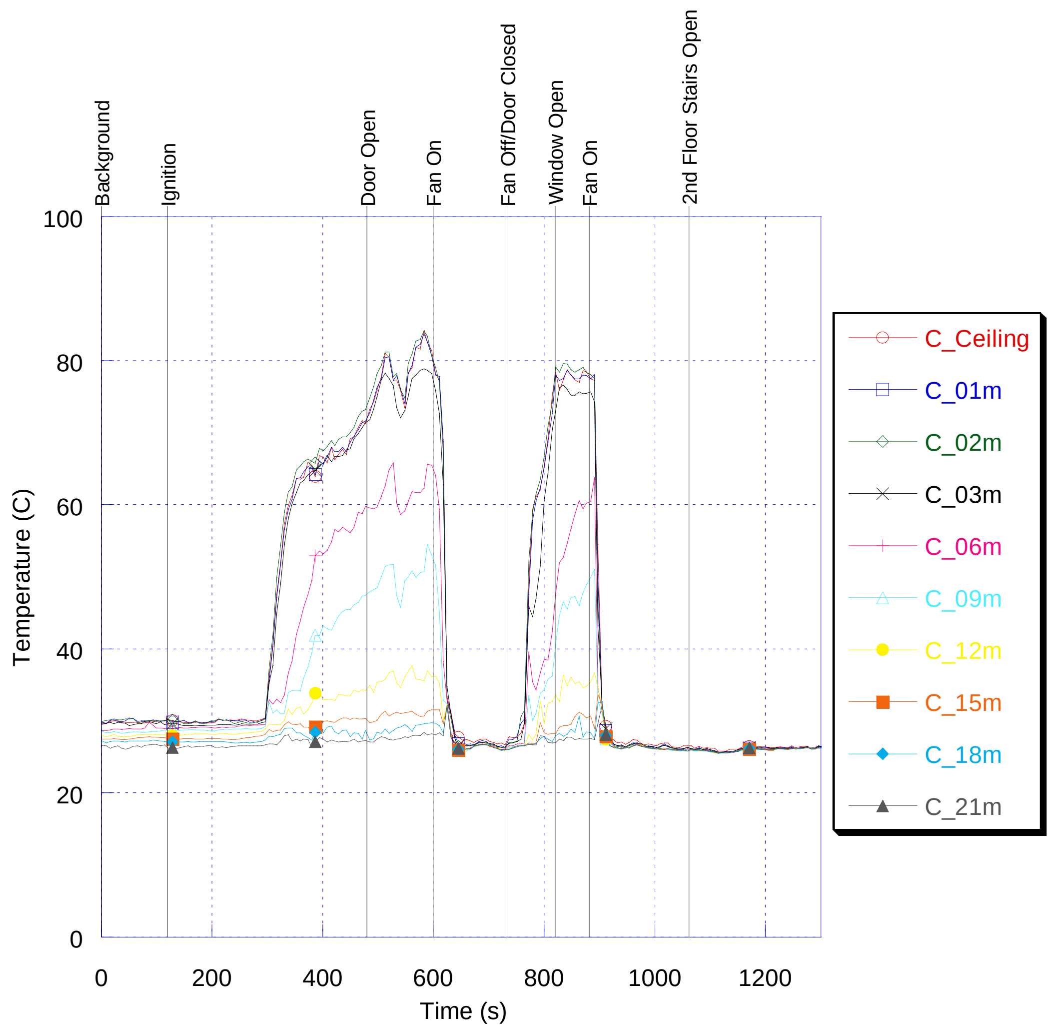

Figure 276. Experiment CF6 Temperature vs. Time for Location C

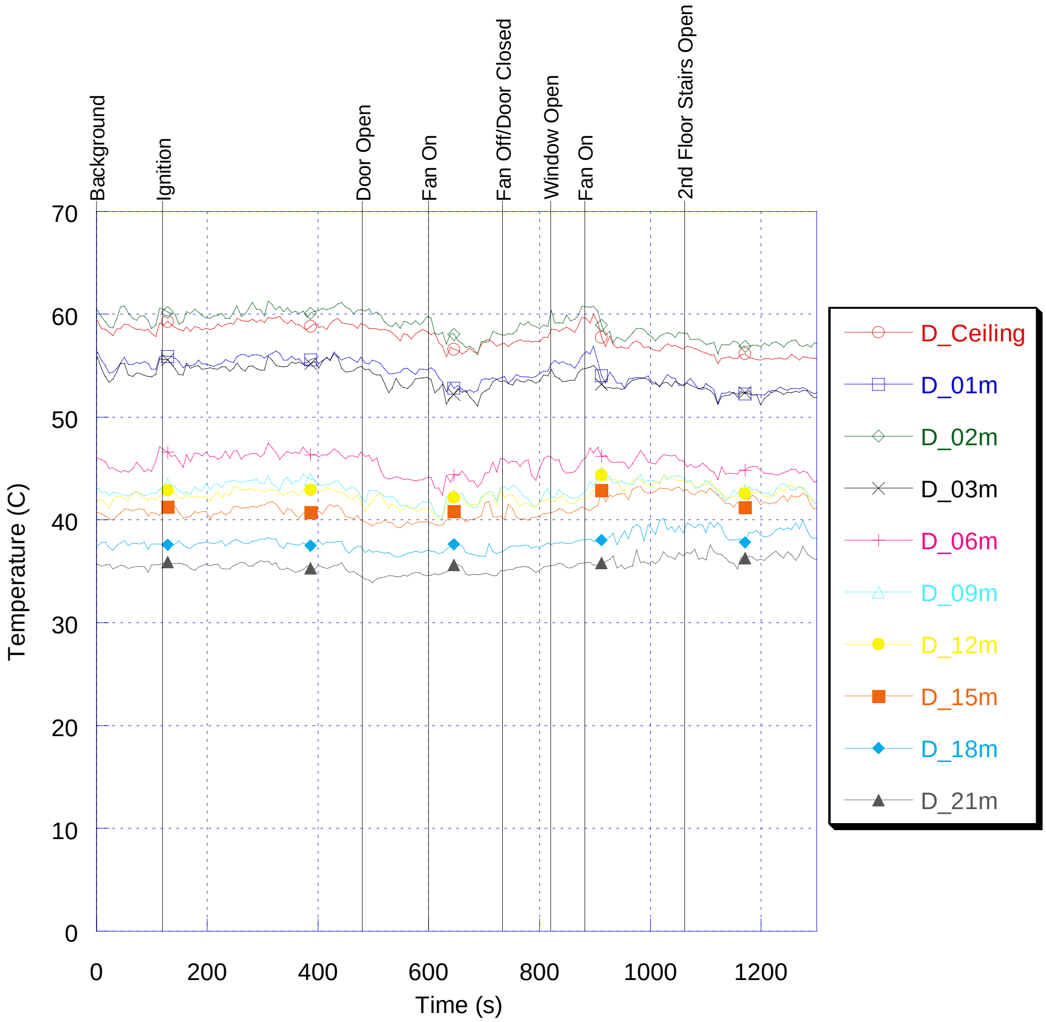

Figure 277. Experiment CF6 Temperature vs. Time for Location D

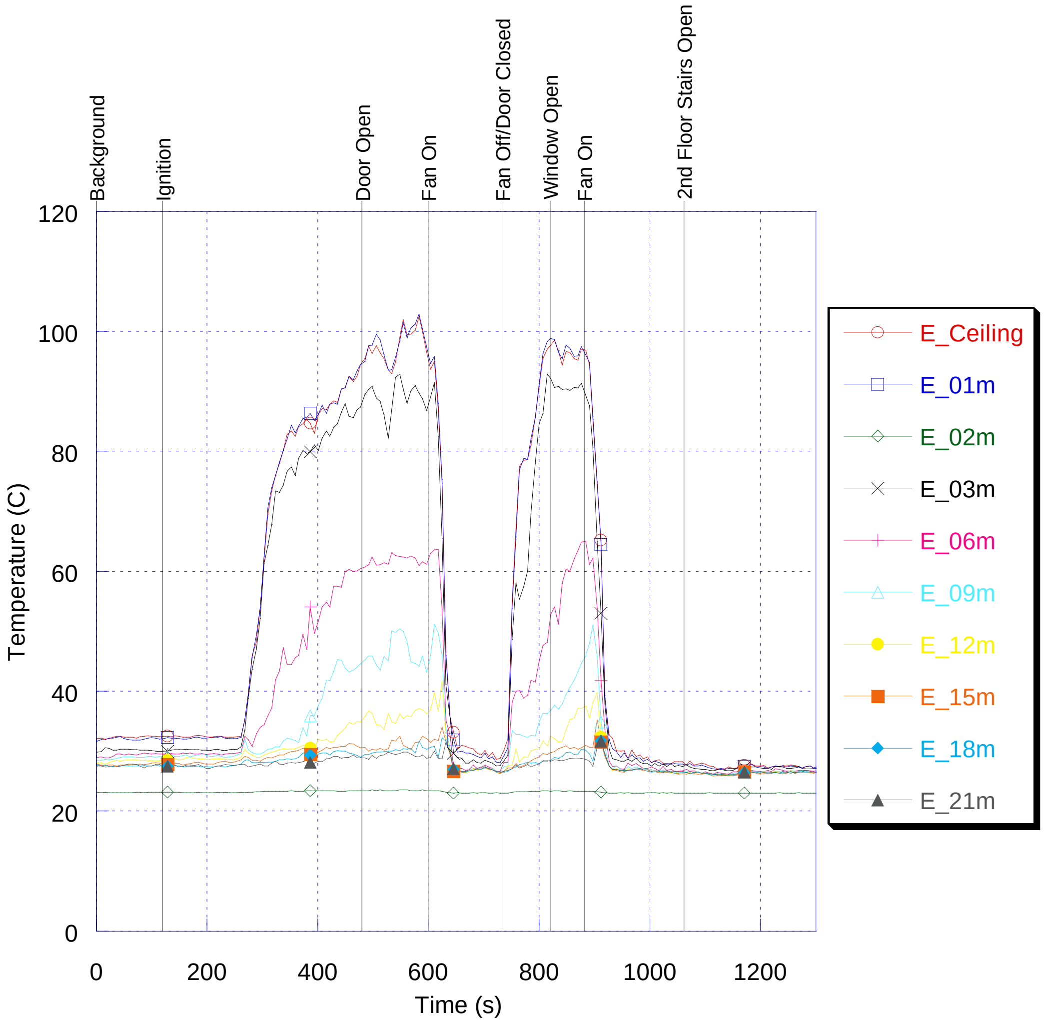

Figure 278. Experiment CF6 Temperature vs. Time for Location E

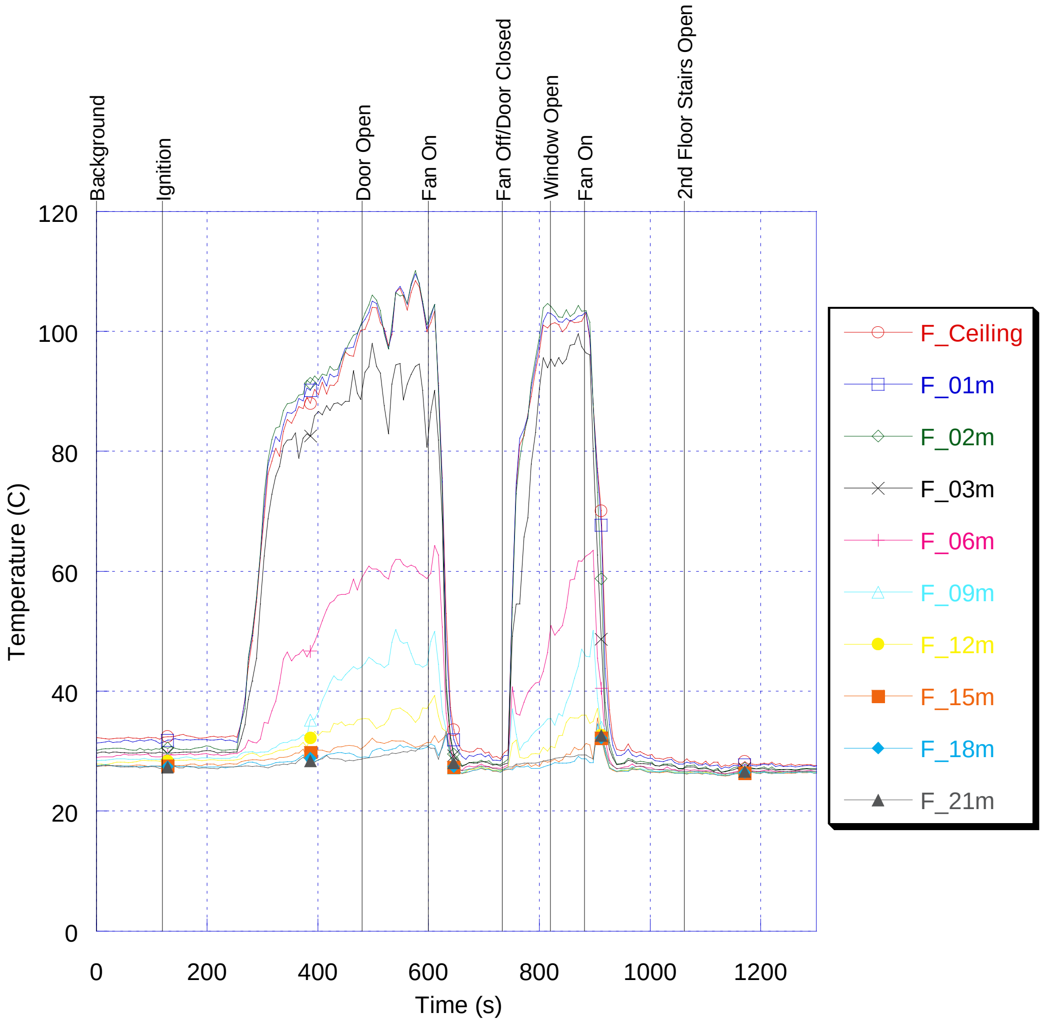

Figure 279. Experiment CF6 Temperature vs. Time for Location F

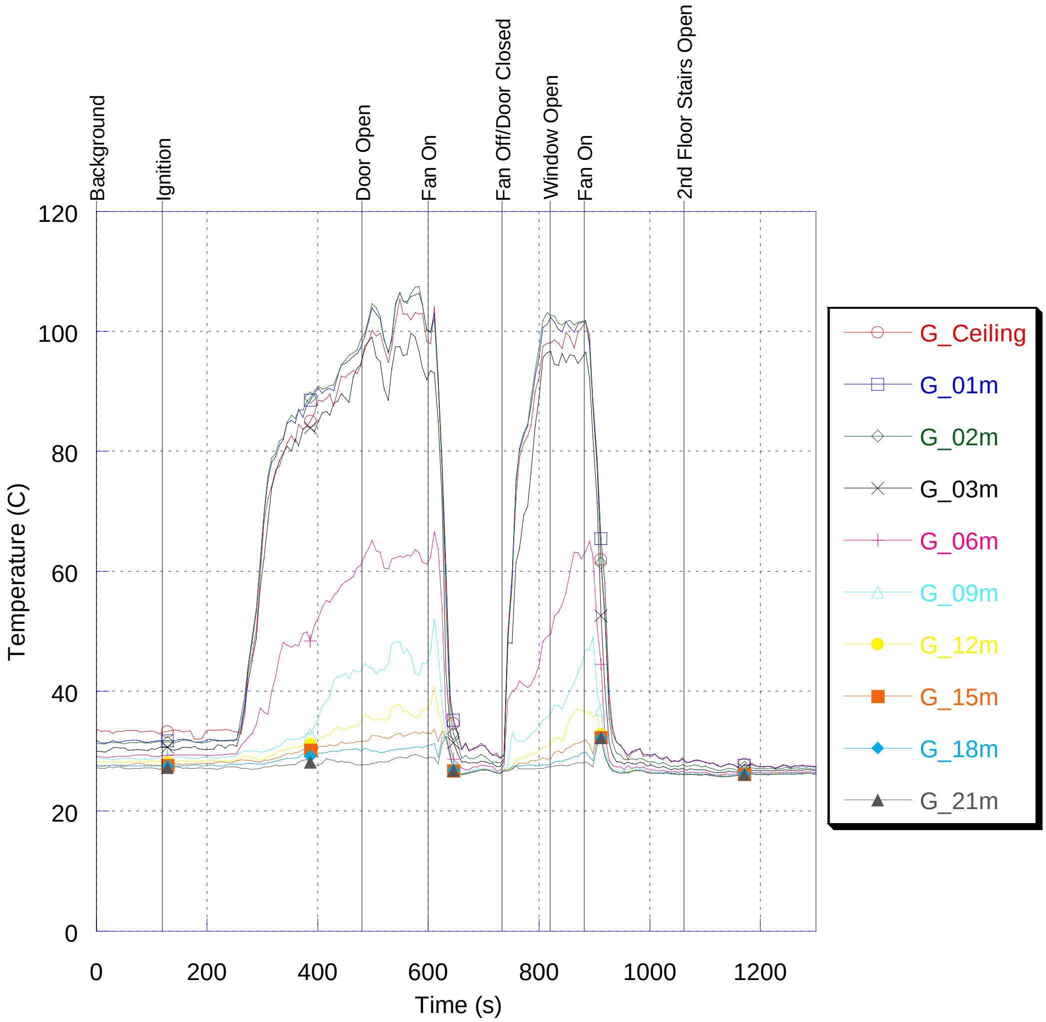

Figure 280. Experiment CF6 Temperature vs. Time for Location G

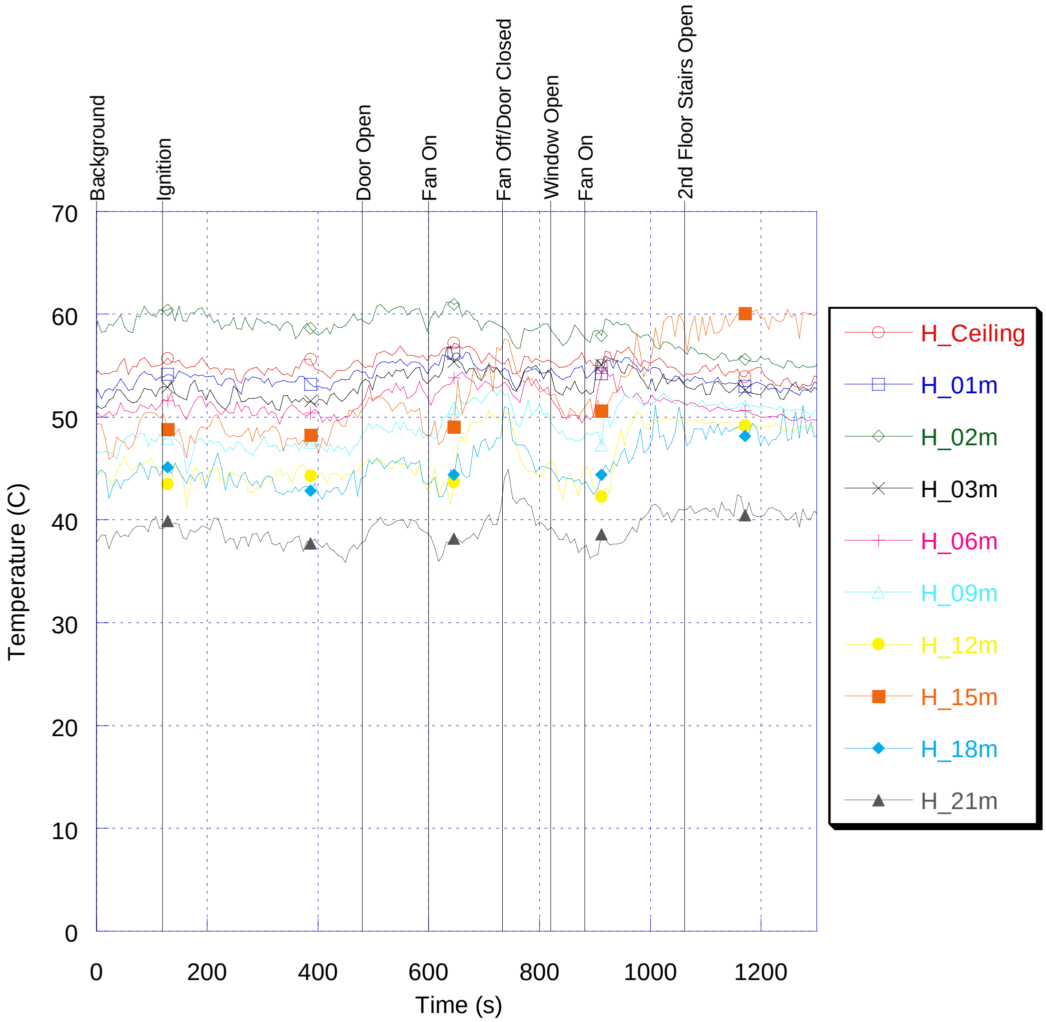

Figure 281. Experiment CF6 Temperature vs. Time for Location H

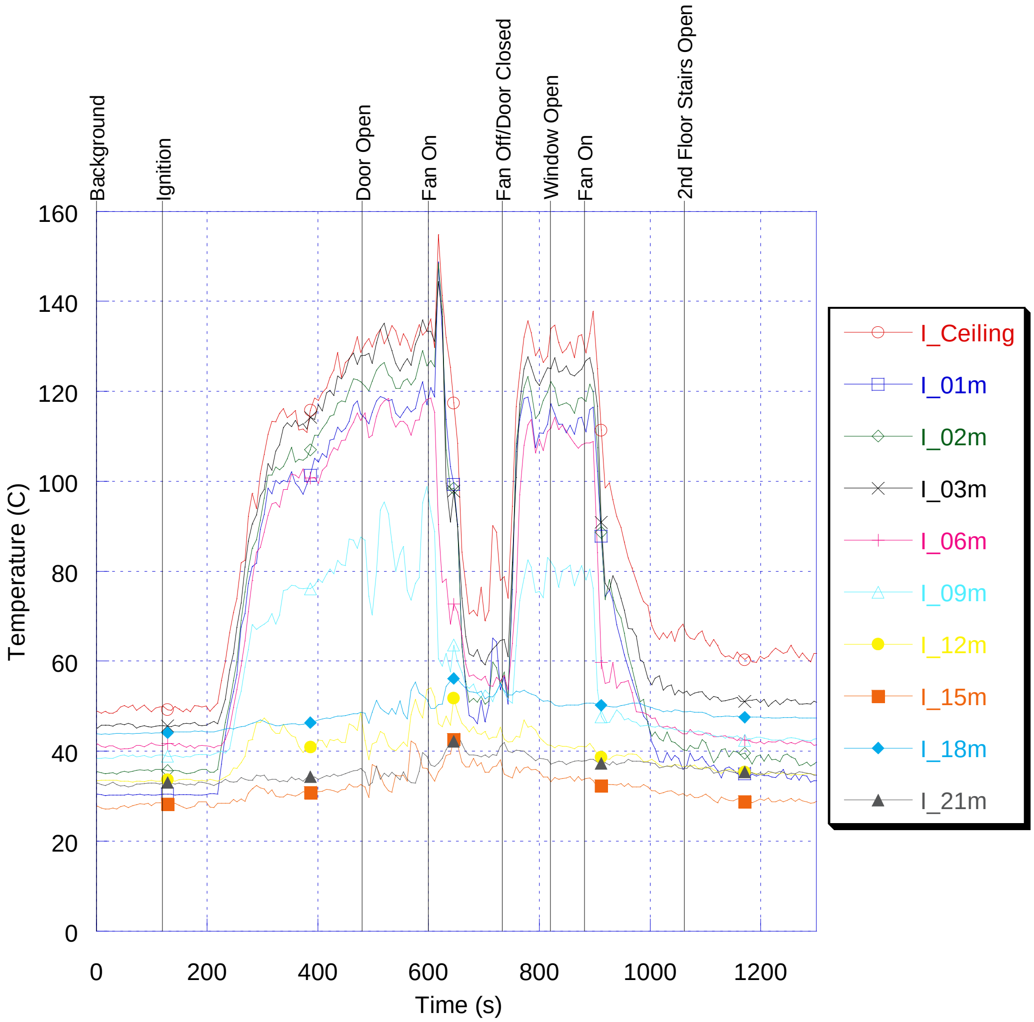

Figure 282. Experiment CF6 Temperature vs. Time for Location I

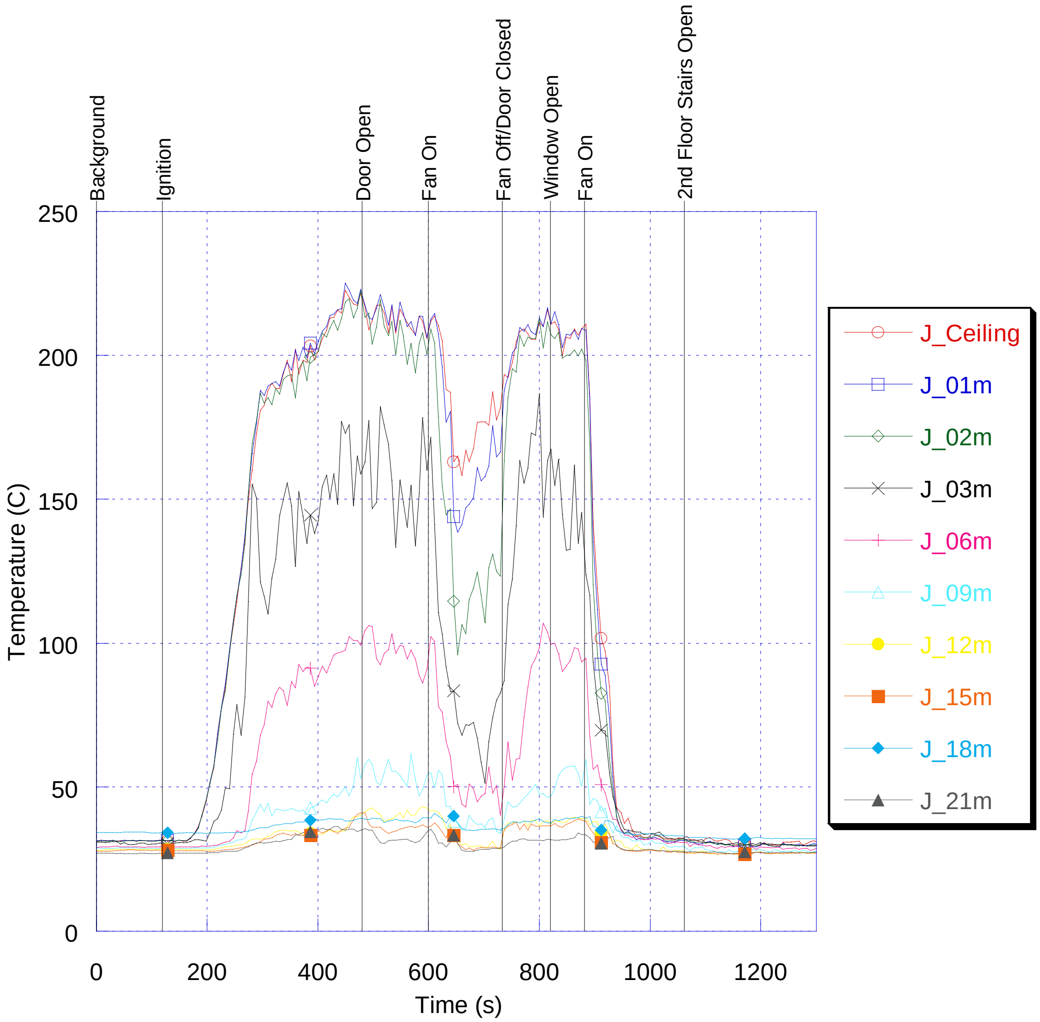

Figure 283. Experiment CF6 Temperature vs. Time for Location J

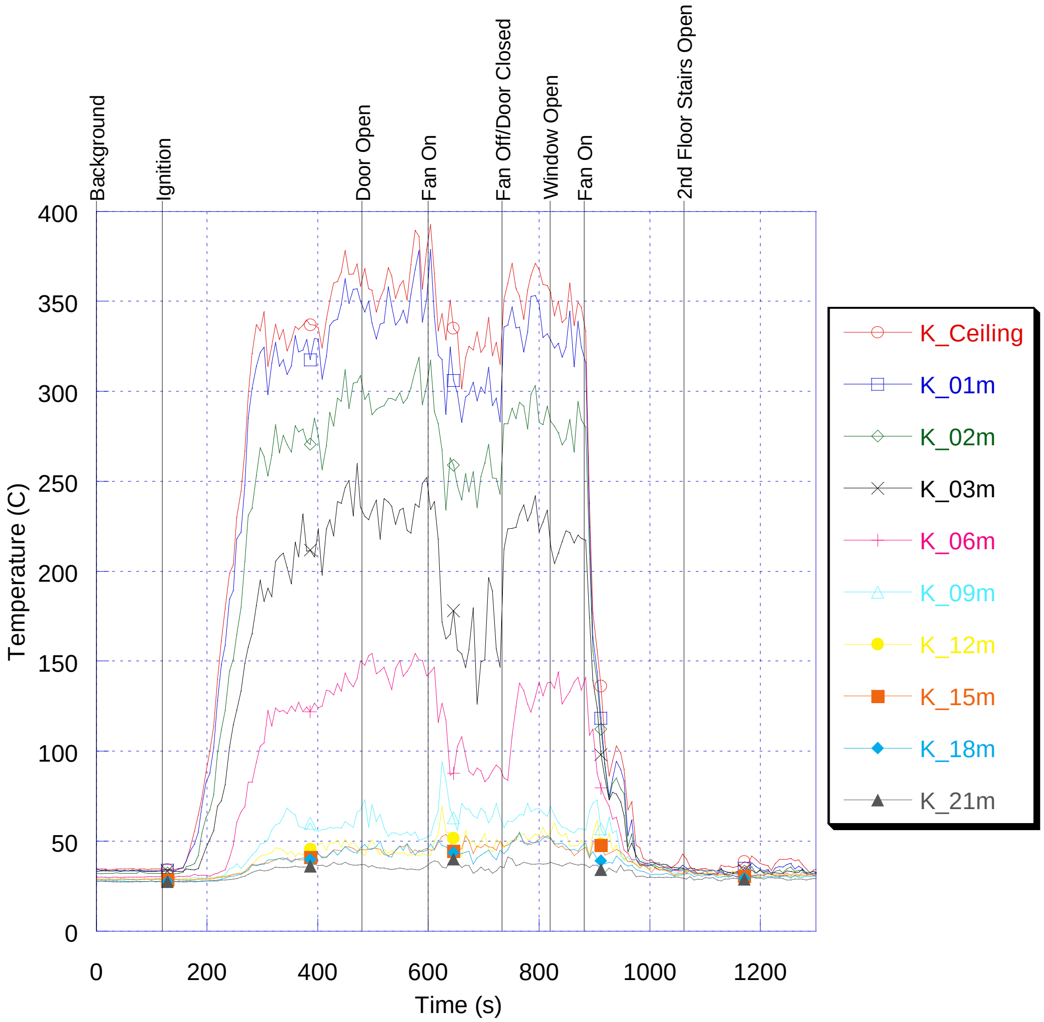

Figure 284. Experiment CF6 Temperature vs. Time for Location K

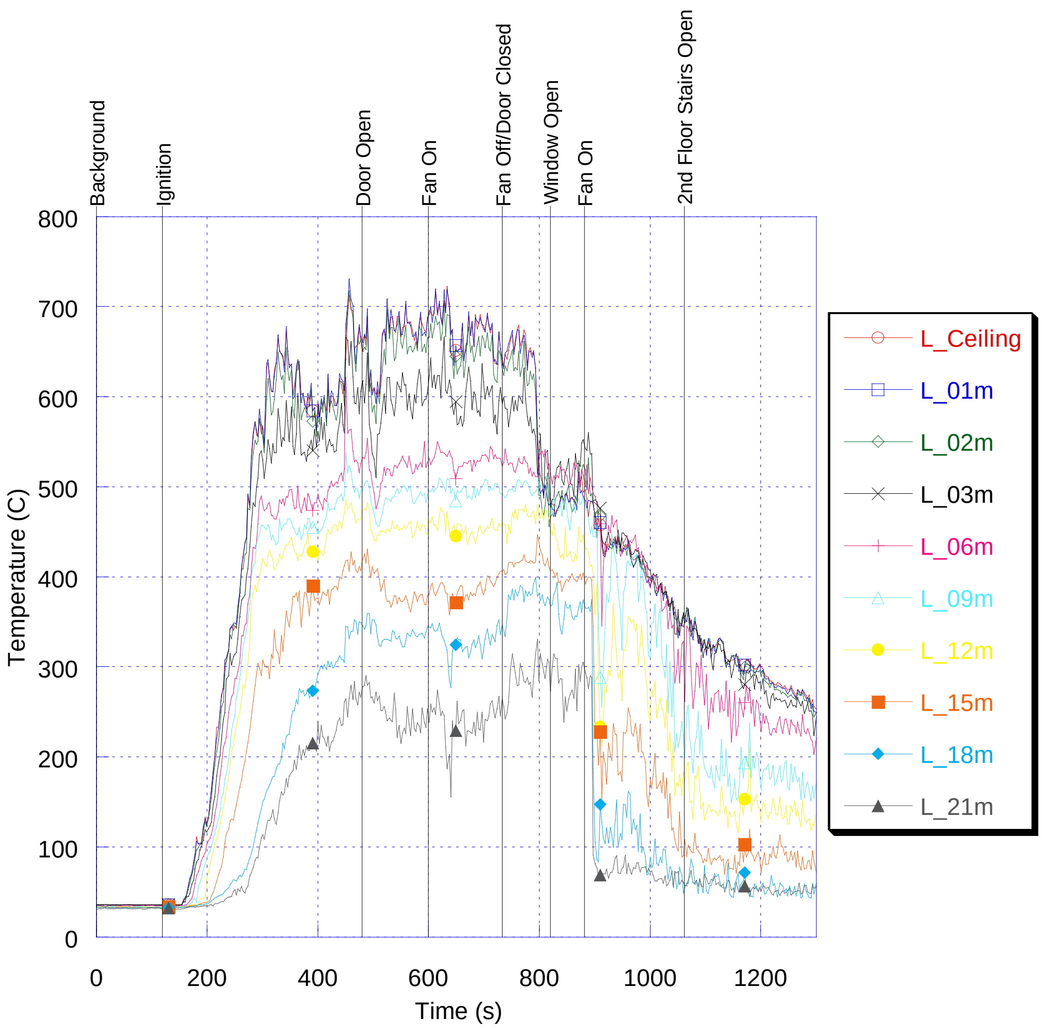

Figure 285. Experiment CF6 Temperature vs. Time for Location L

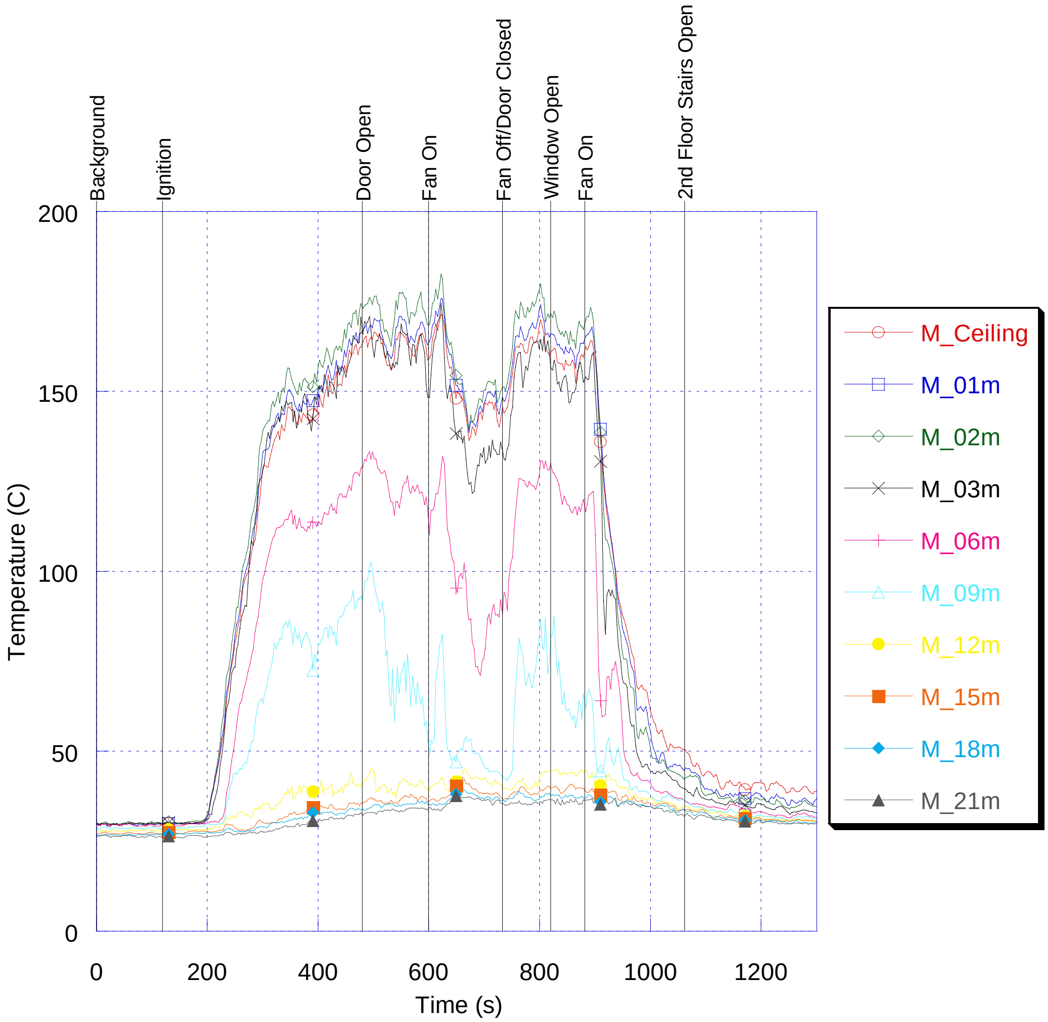

Figure 286. Experiment CF6 Temperature vs. Time for Location M

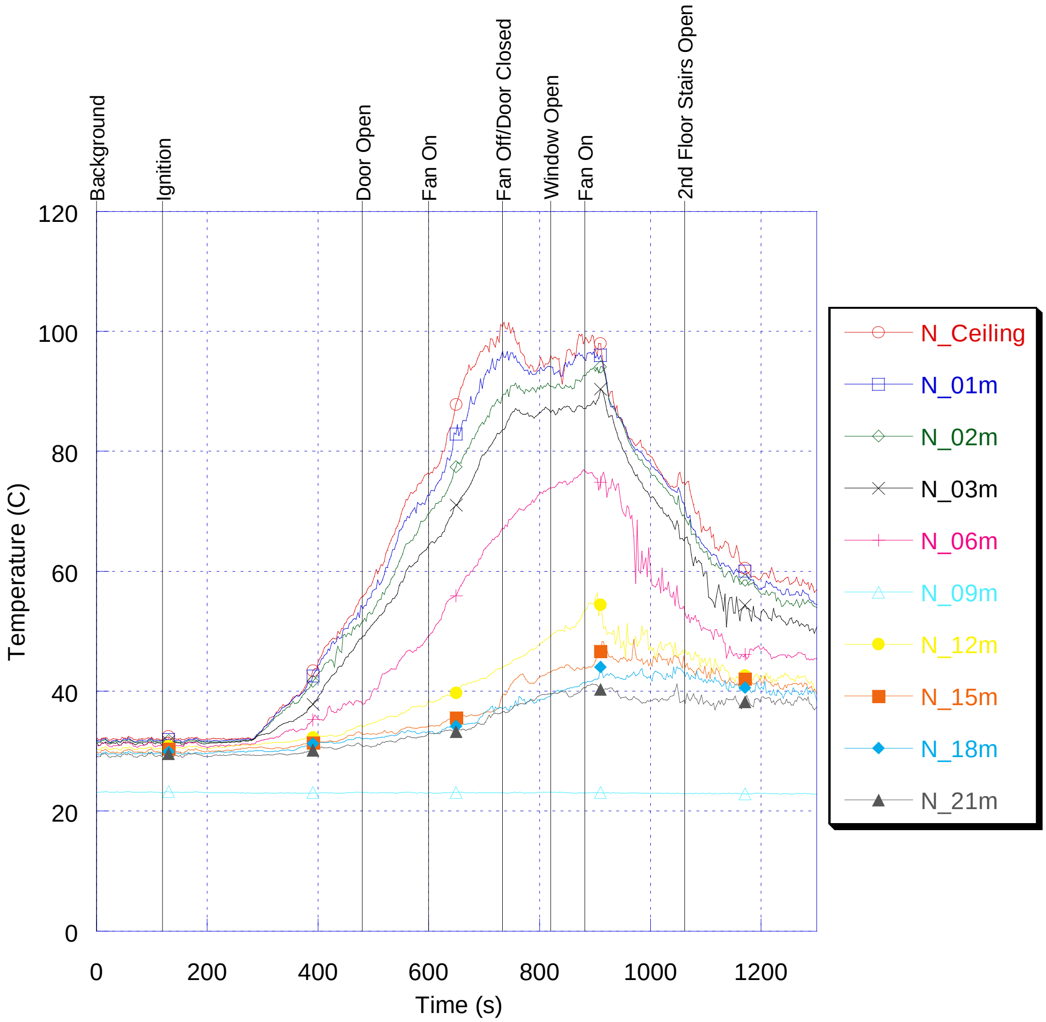

Figure 287. Experiment CF6 Temperature vs. Time for Location N

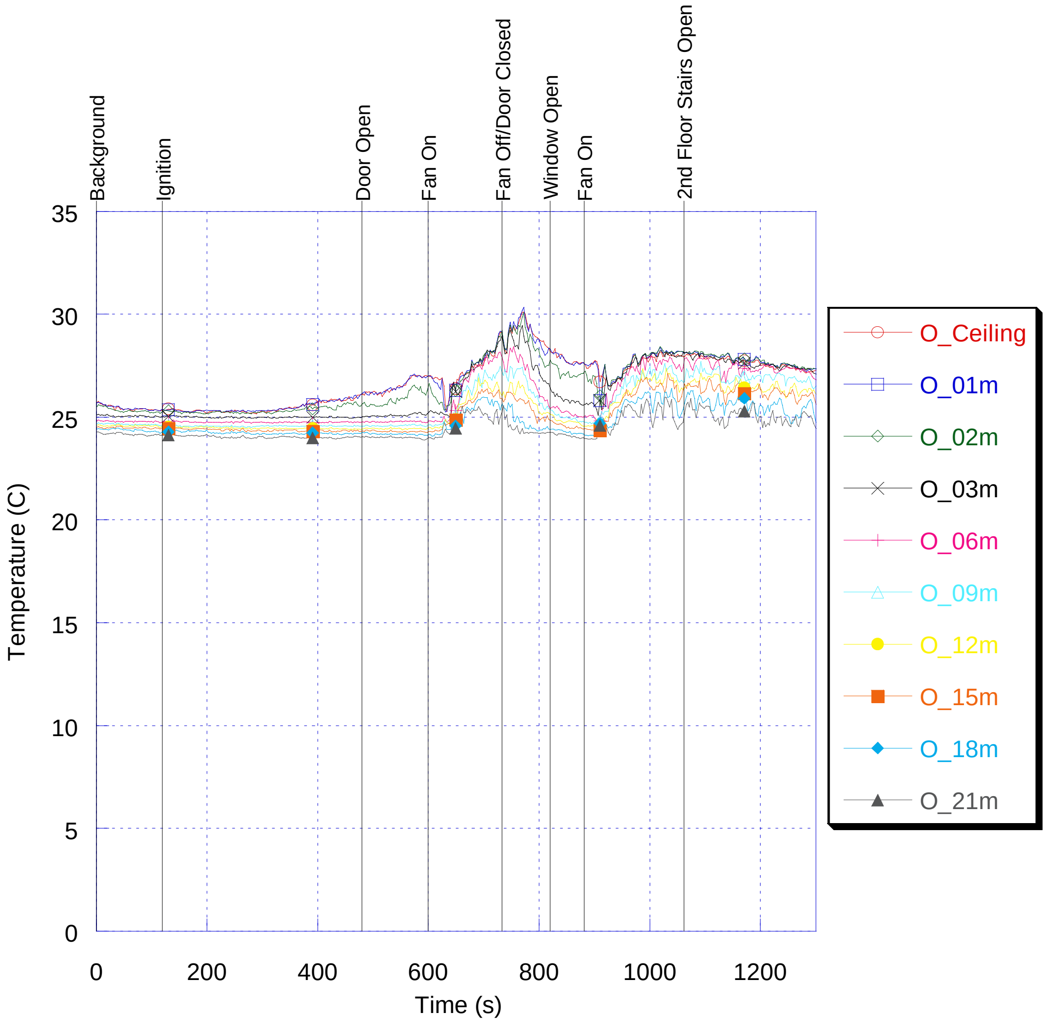

Figure 288. Experiment CF6 Temperature vs. Time for Location O

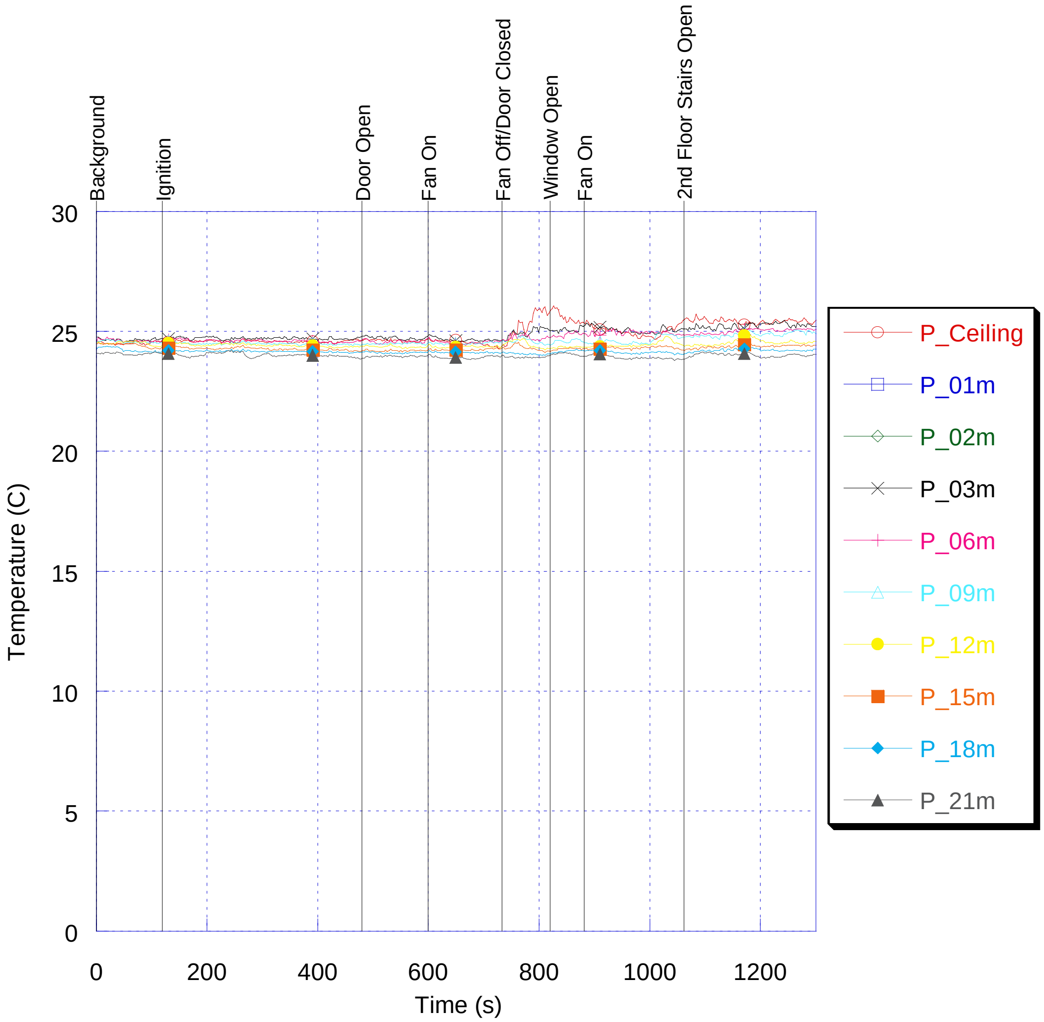

Figure 289. Experiment CF6 Temperature vs. Time for Location P

APPENDIX D – Pressure versus time for experiments GF7 through GF12

Timelines of the experimental configuration changes

Experiment GF7

Time	Event
(s)	
0	Background
120	Ignition
960	24 in. Fan On
1080	Rear Door 1 Open
1500	Fan Off (Move Inside)
1620	Fan On
2056	Fan Off
2146	SVU to 2000 rpm
2265	SVU to 4000 rpm
2500	End of Data

Experiment GF8

Time	Event
(s)	
0	Background
120	Ignition
840	27 in. Fan On
960	Rear Door 1 Open
1260	Fan Off (Move Inside)
1380	Fan On
1810	Fan Off
1960	SVU 4000 rpm
2300	End of Data

Experiment GF9

Time	Event
(s)	
0	Background
660	Ignition
1272	Roof Vent
1440	SVU On
1600	SVU Off
1770	MVU On
1770	Rear Door 1, 2 Open
2160	Suppression
2300	End of Data

Experiment GF10

Time	Event
(s)	
0	Background
120	Ignition
720	Rear Door 1 Open
870	2 – 27 in. Fans On
1020	Rear Door 2 Open
1260	Rear Doors 3, 4 Open
1260	Suppression
1575	Rear Doors 3, 4 Closed
1800	Fans Off (Move Inside)
1860	Fans On
2000	End of Data

Experiment GF11

Time	Event
(s)	
0	Background
120	Ignition
720	Rear doors 1, 2 Open
840	MVU On
973	Rear doors 3, 4 Open
1200	Suppression
1250	End of Data

Experiment GF12

Time	Event
(s)	
0	Background
120	Ignition
660	Rear doors 1, 2 Open
720	Rear doors 3, 4 Open
780	MVU On
842	Roof Open
887	Suppression
1000	End of Data

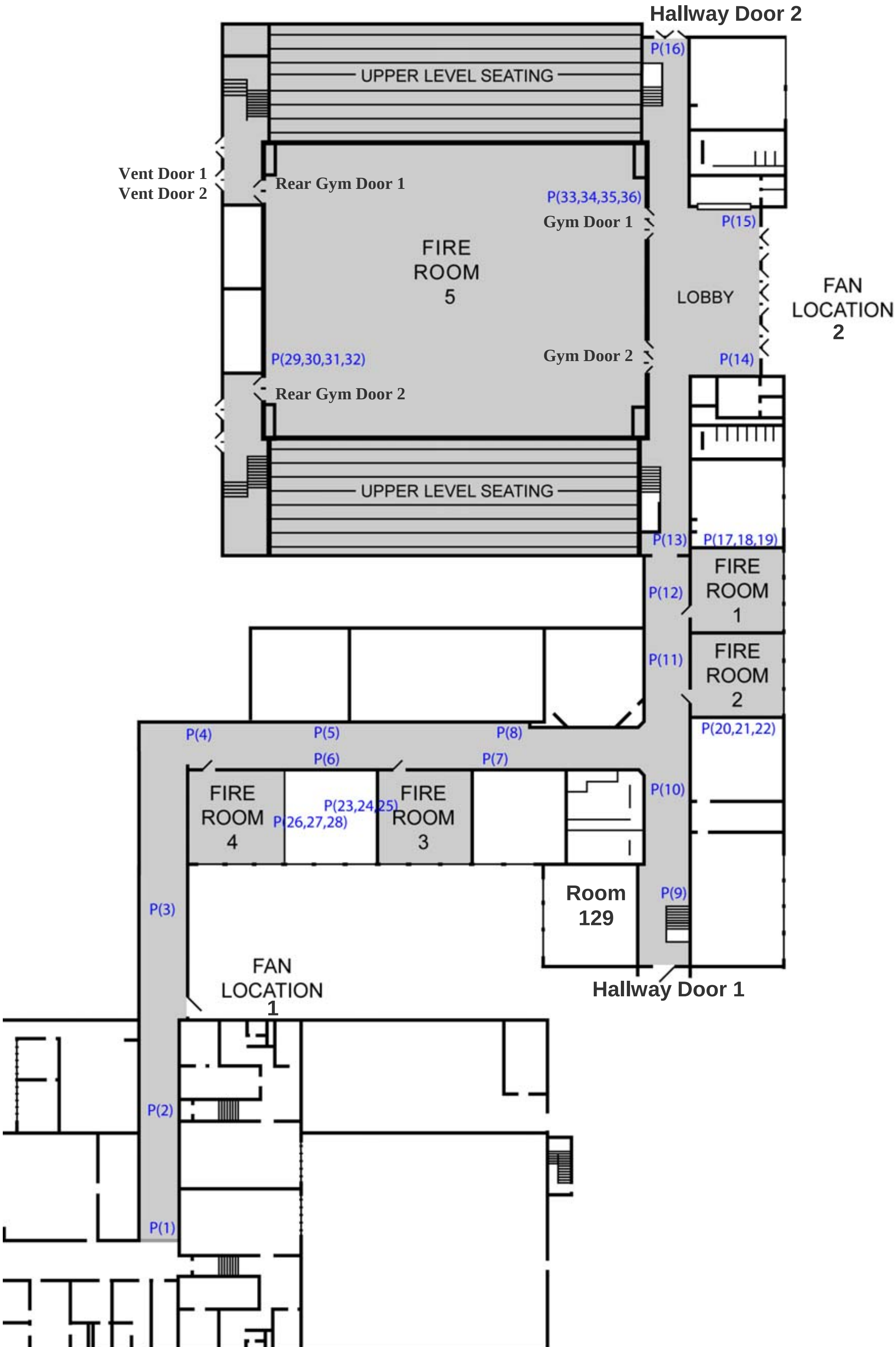

Figure 290. Pressure Transducer Locations

Experiment GF7

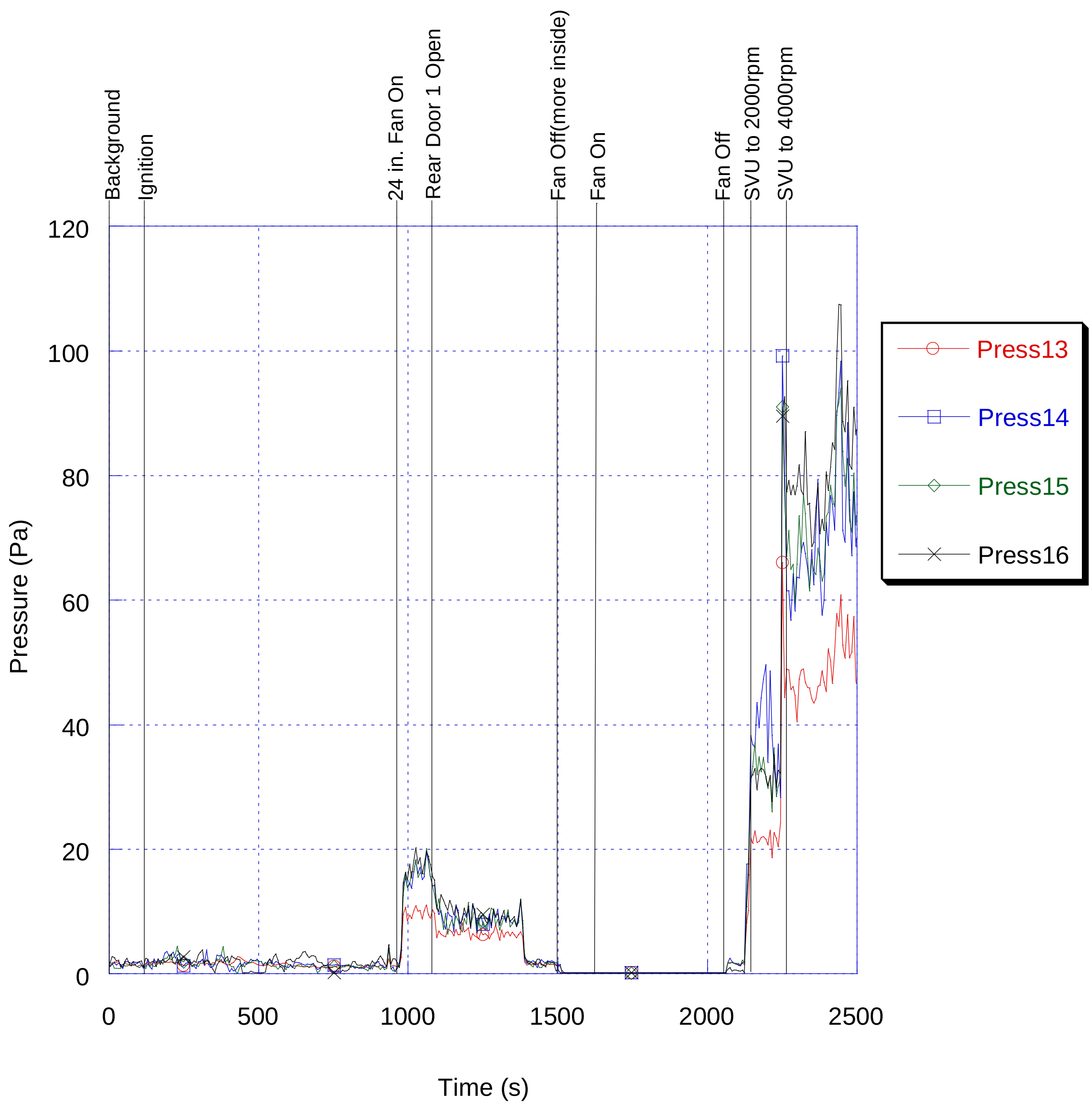

Figure 291. Experiment GF7 Pressure vs. Time for transducers 13-16

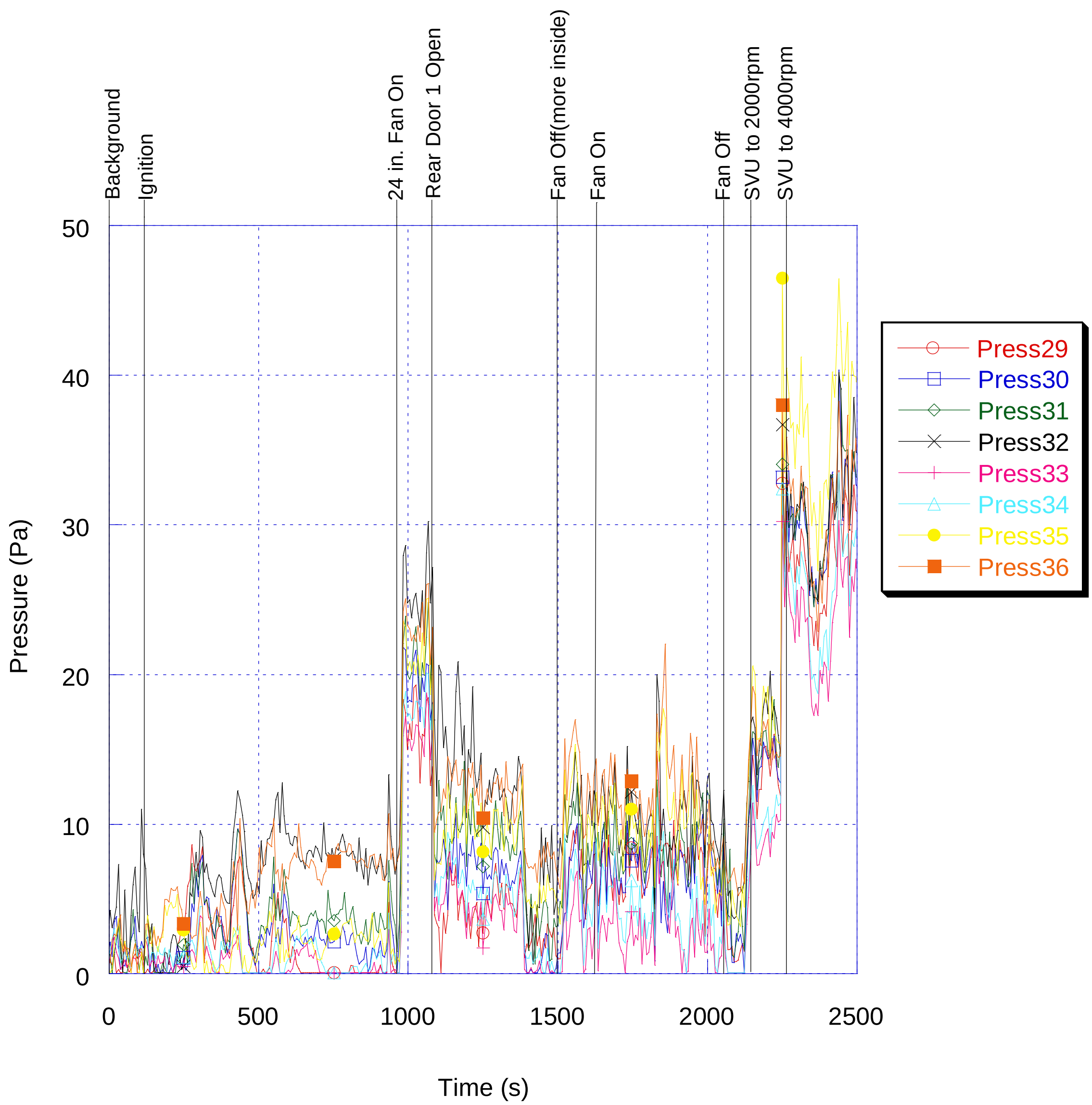

Figure 292. Experiment GF7 Pressure vs. Time for transducers 29-36

Experiment GF8

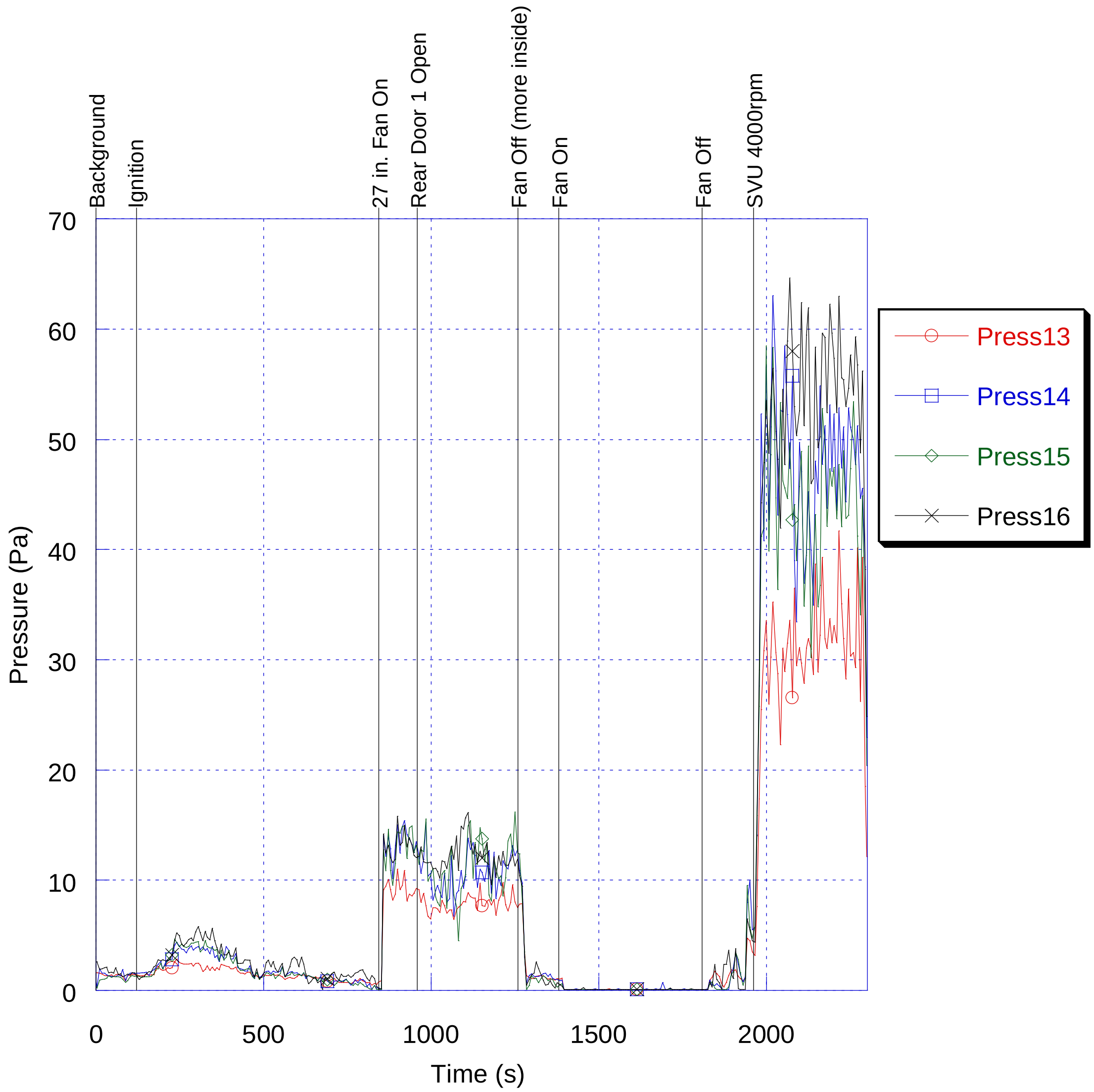

Figure 293. Experiment GF8 Pressure vs. Time for transducers 13-16

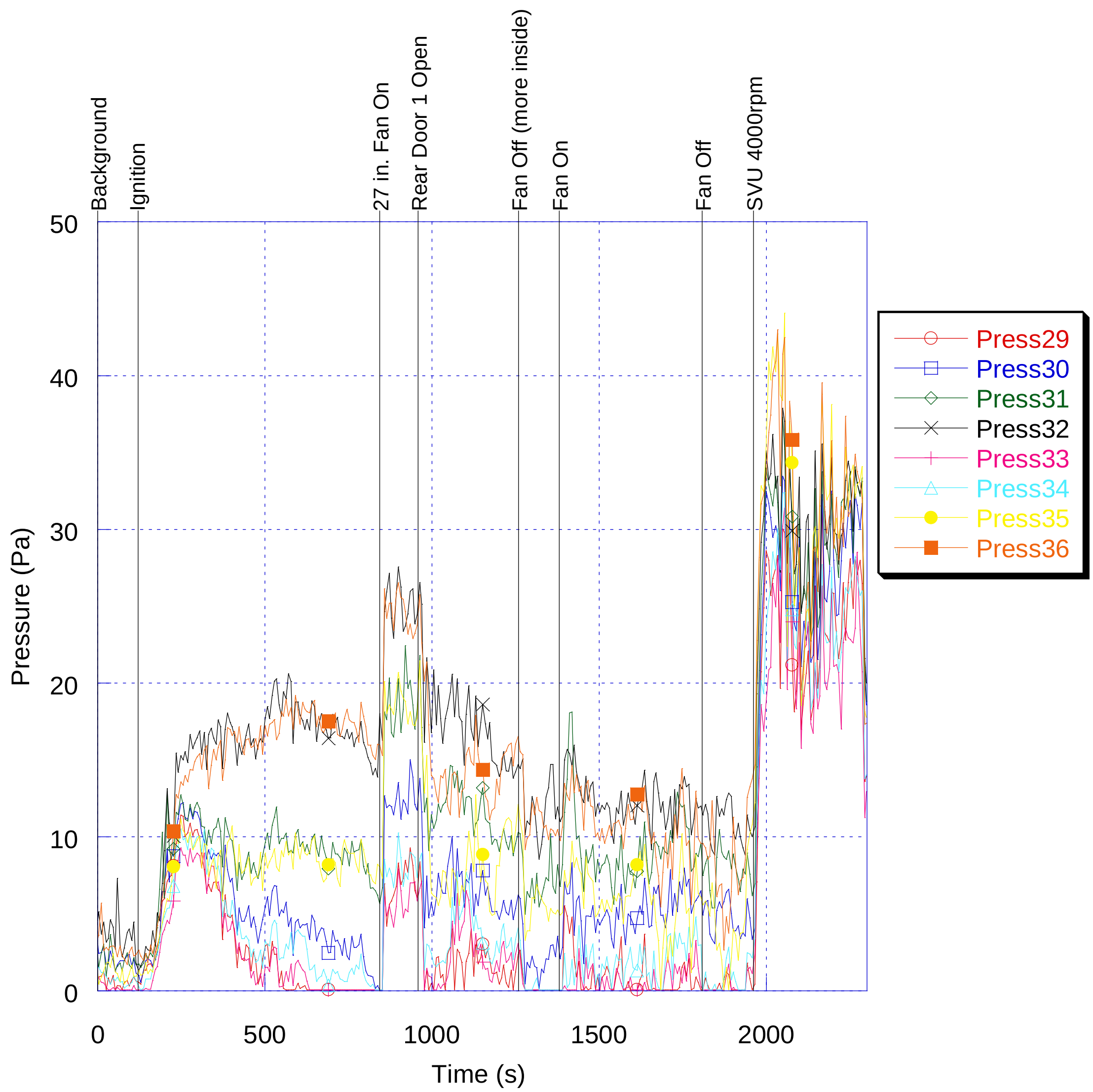

Figure 294. Experiment GF8 Pressure vs. Time for transducers 29-36

Experiment GF9

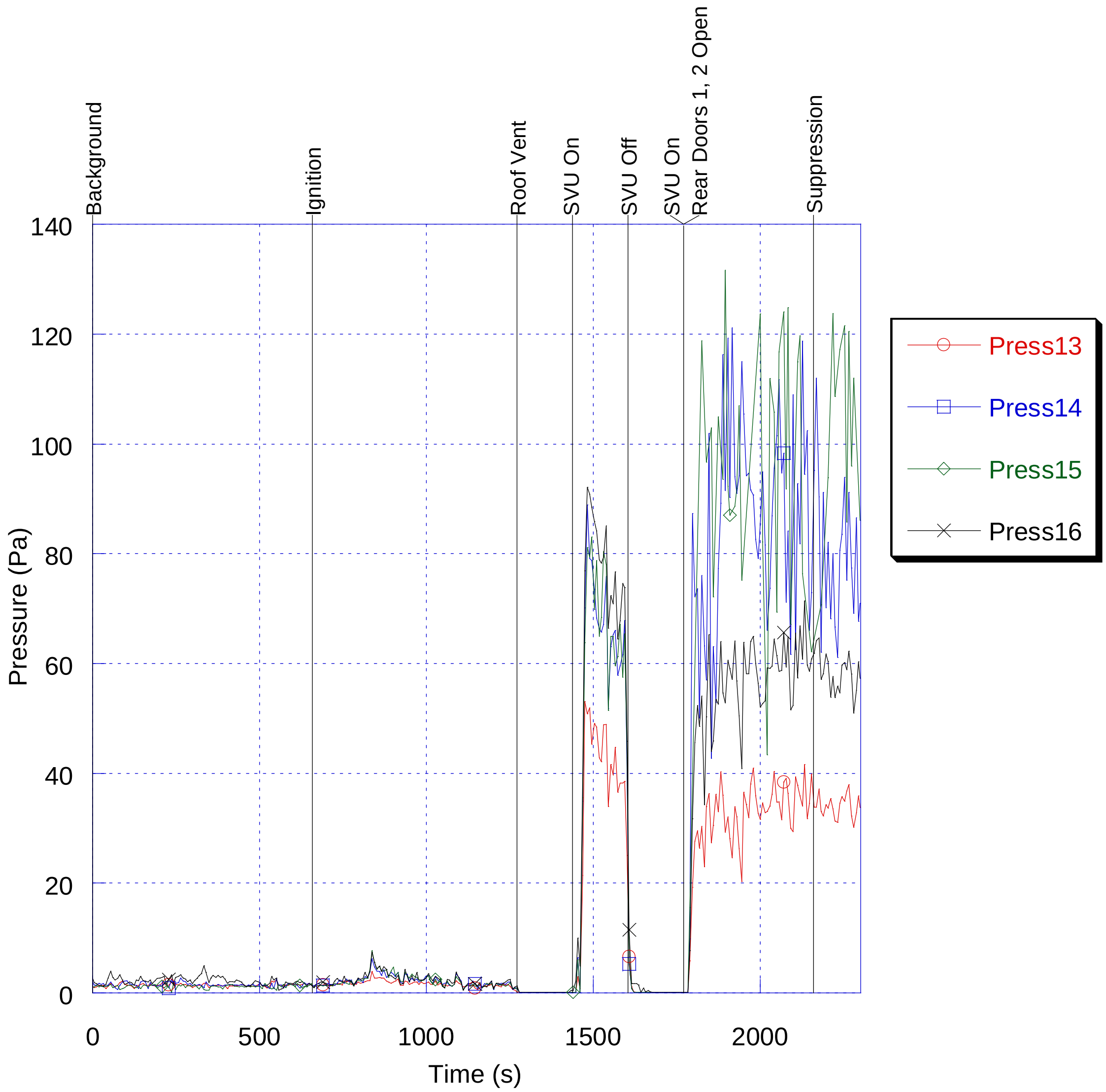

Figure 295. Experiment GF9 Pressure vs. Time for transducers 13-16

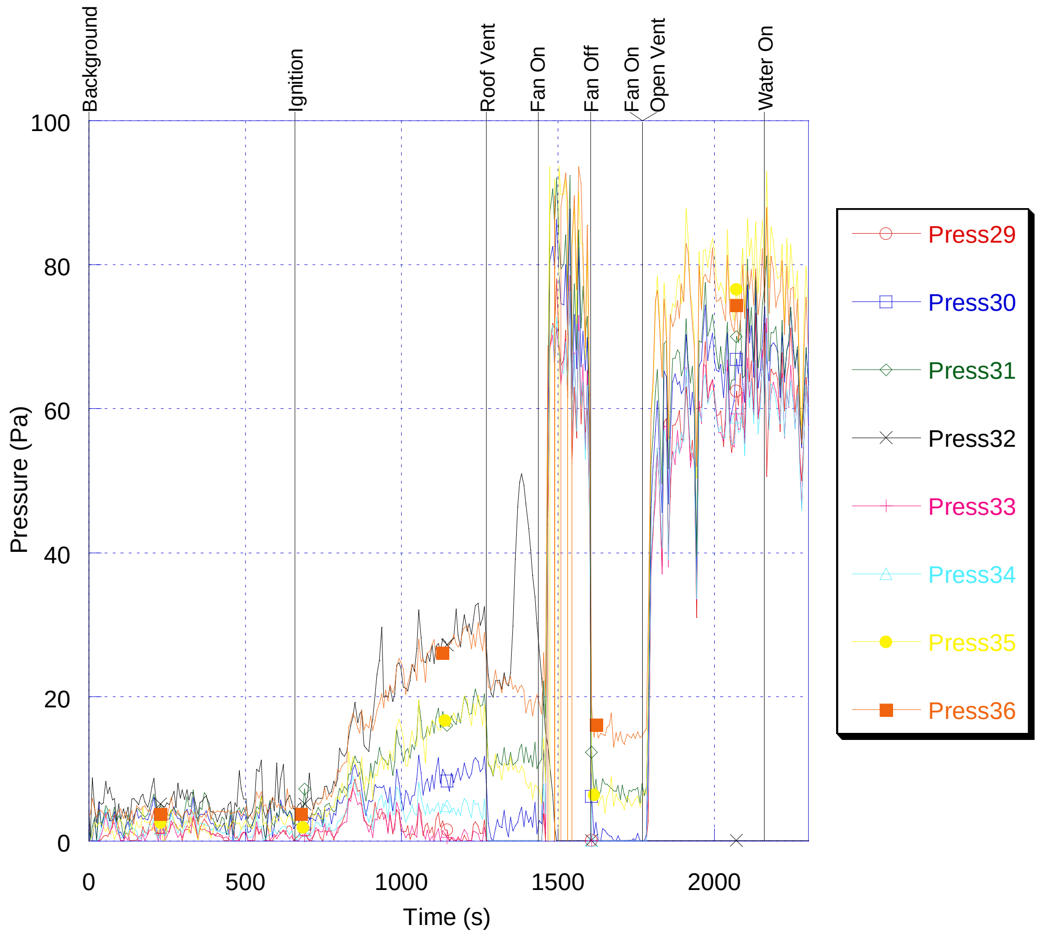

Figure 296. Experiment GF9 Pressure vs. Time for transducers 29-36

Experiment GF10

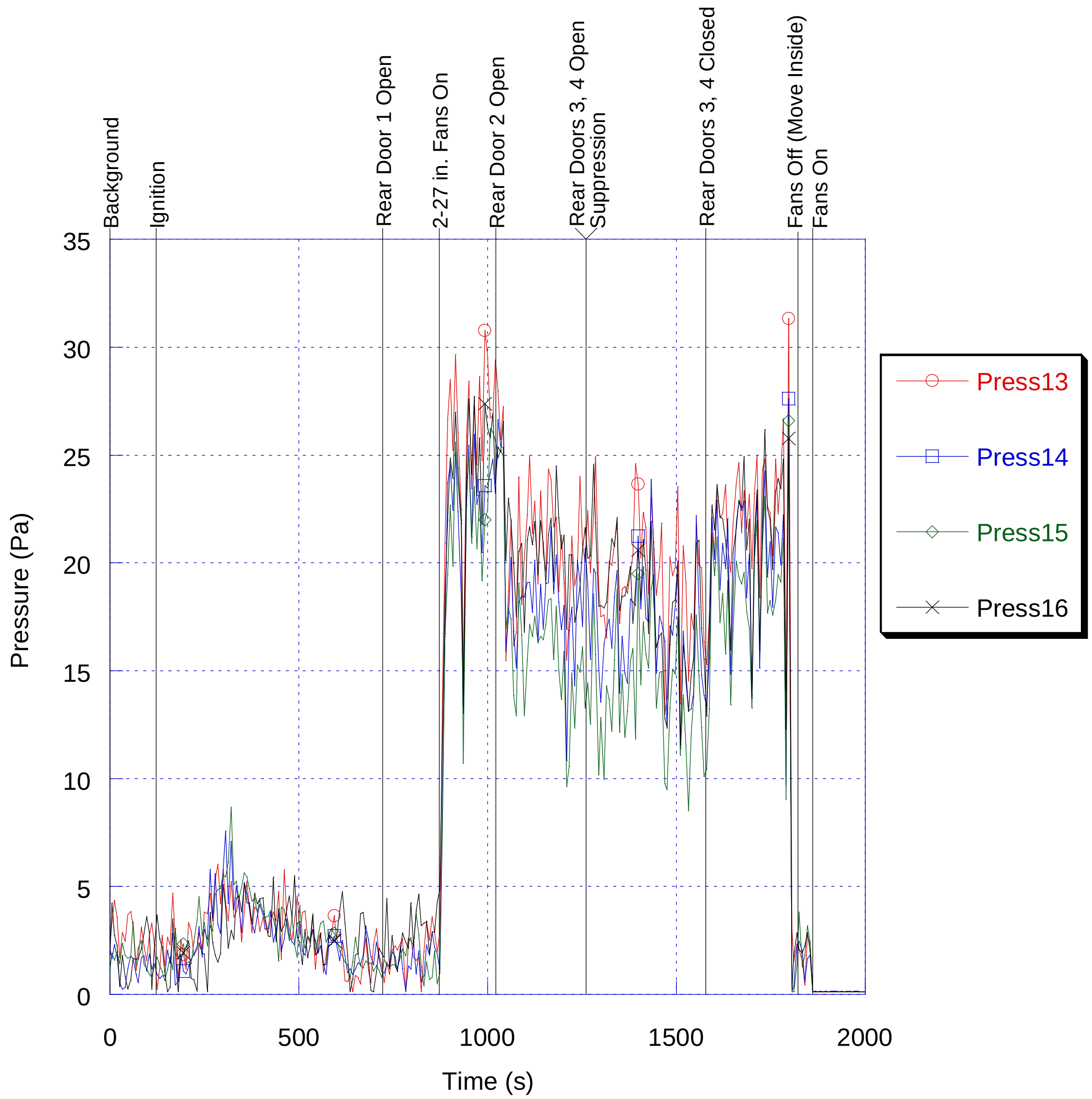

Figure 297. Experiment GF10 Pressure vs. Time for transducers 13-16

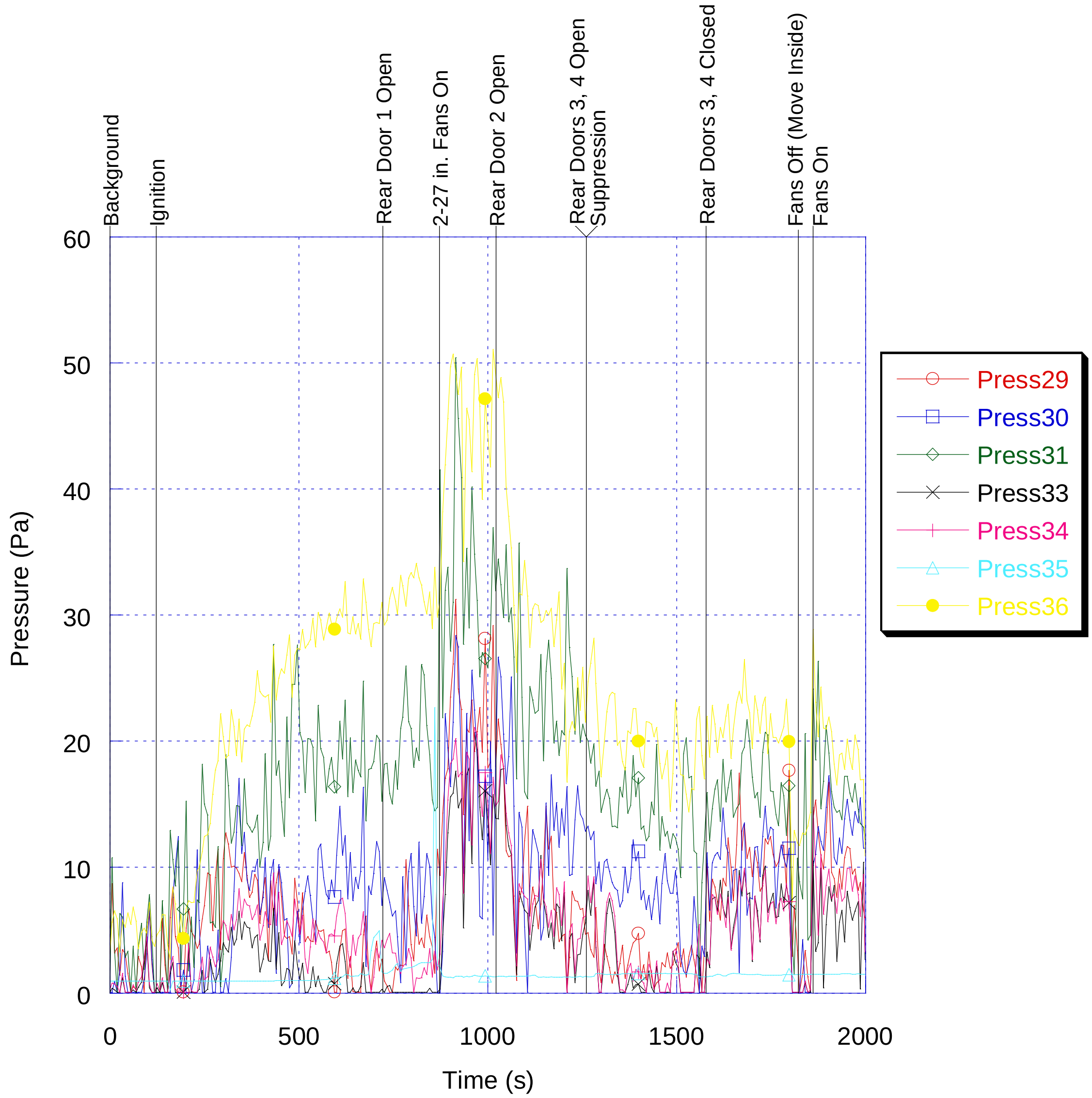

Figure 298. Experiment GF10 Pressure vs. Time for transducers 29-36

Experiment GF11

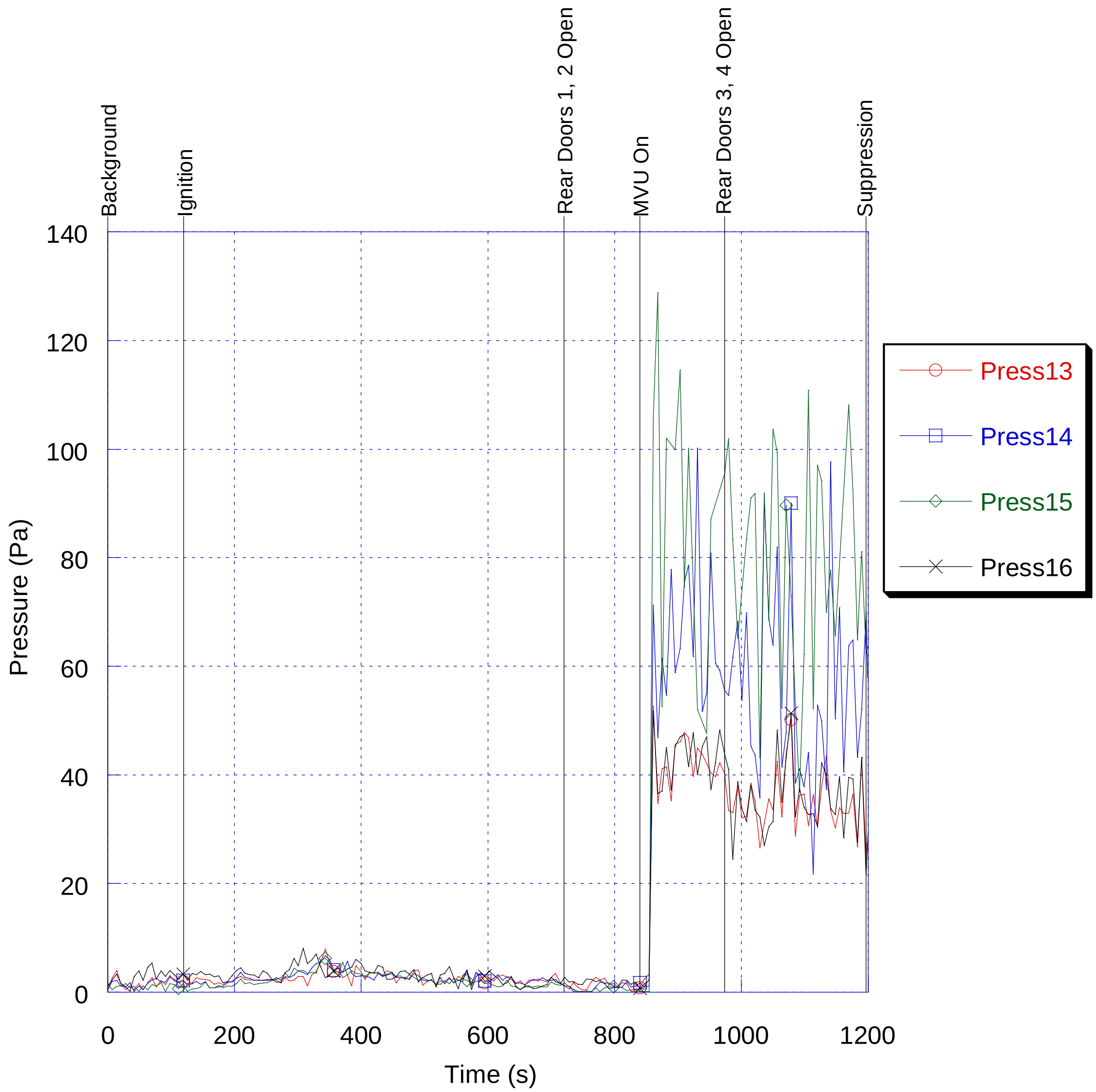

Figure 299. Experiment GF11 Pressure vs. Time for transducers 13-16

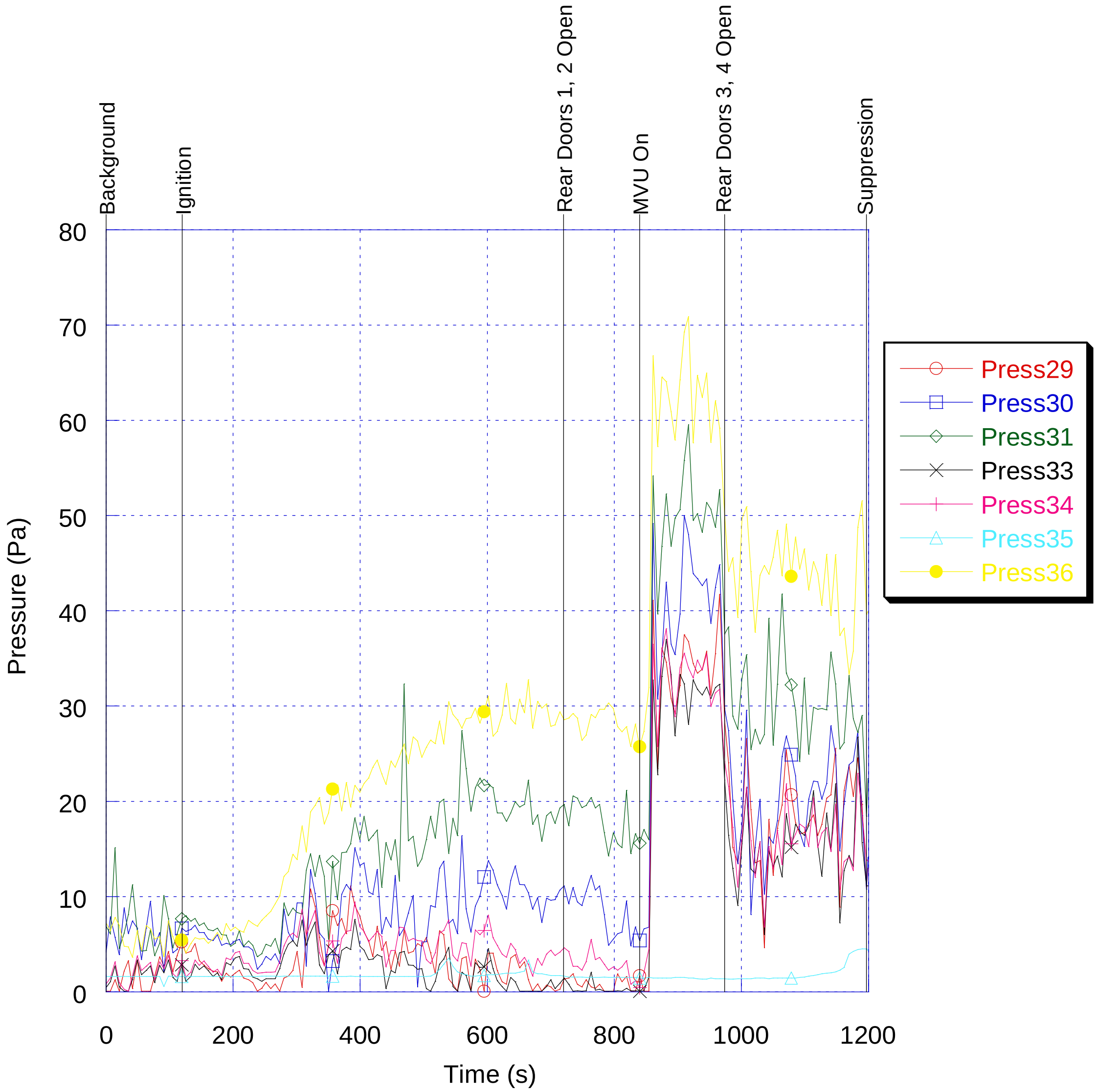

Figure 300. Experiment GF11 Pressure vs. Time for transducers 29-36

Experiment GF12

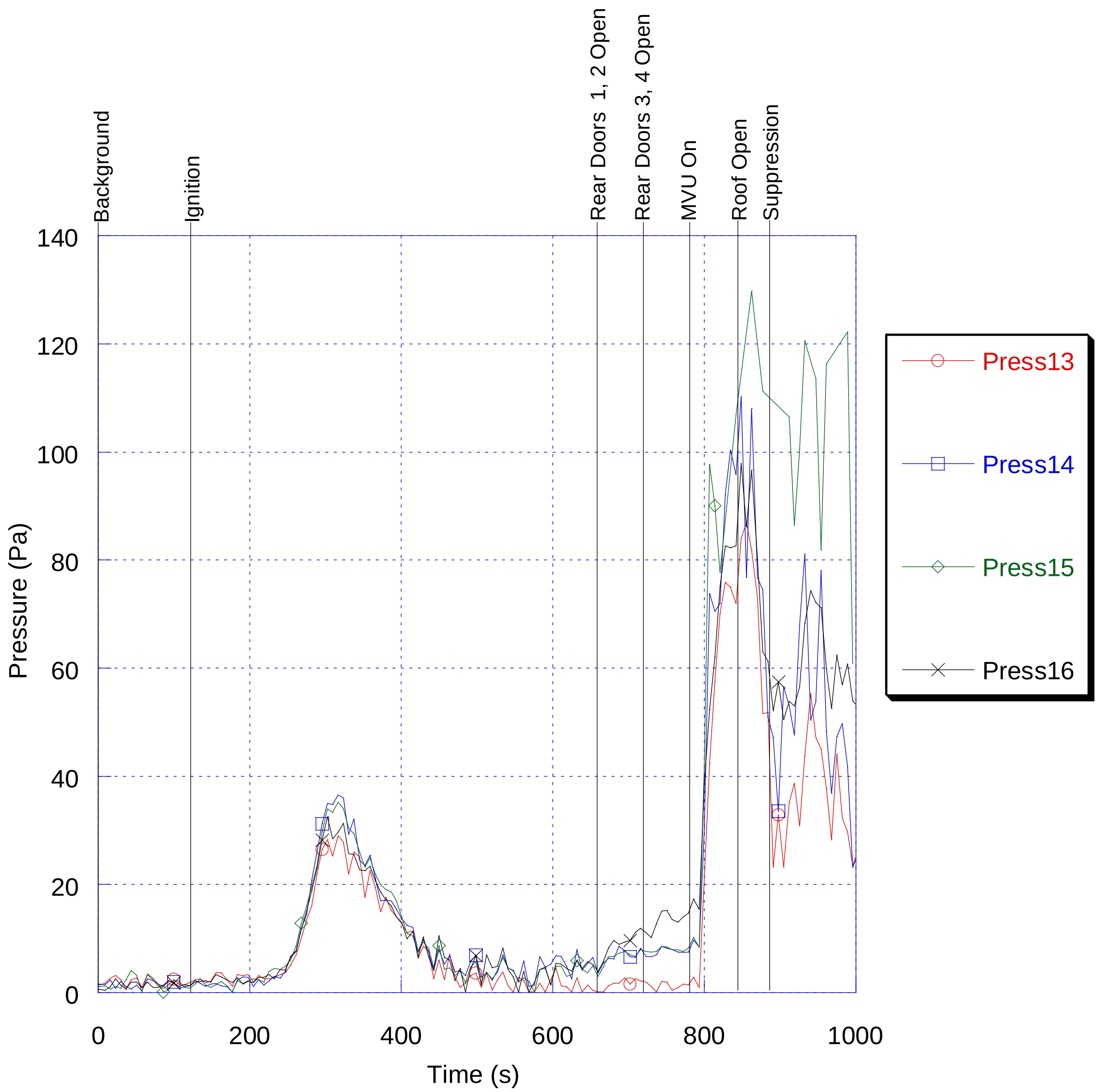

Figure 301. Experiment GF12 Pressure vs. Time for transducers 13-16

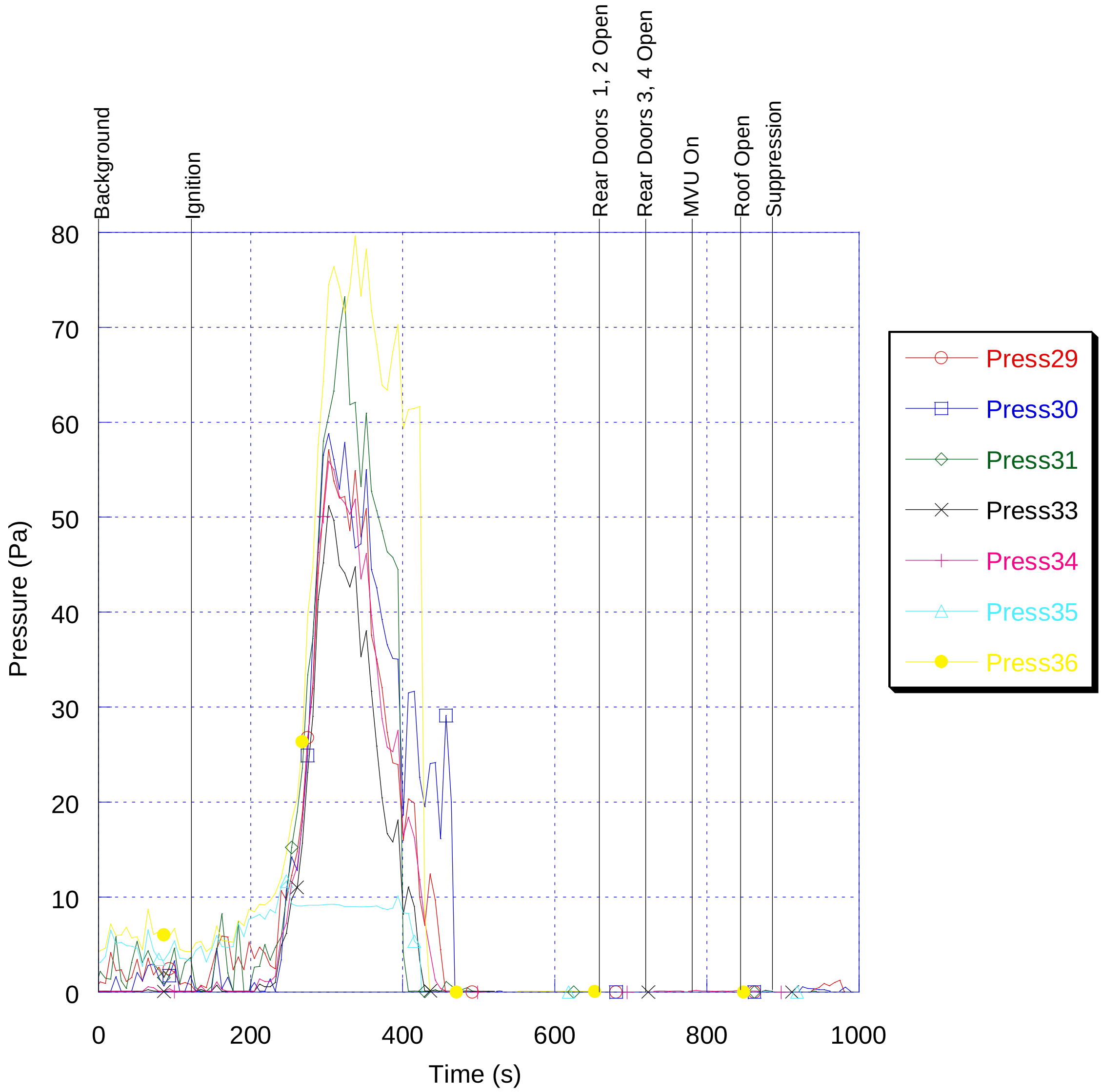

Figure 302. Experiment GF12 Pressure vs. Time for transducers 29-36

APPENDIX E – Temperature versus time for experiments GF7 through GF12

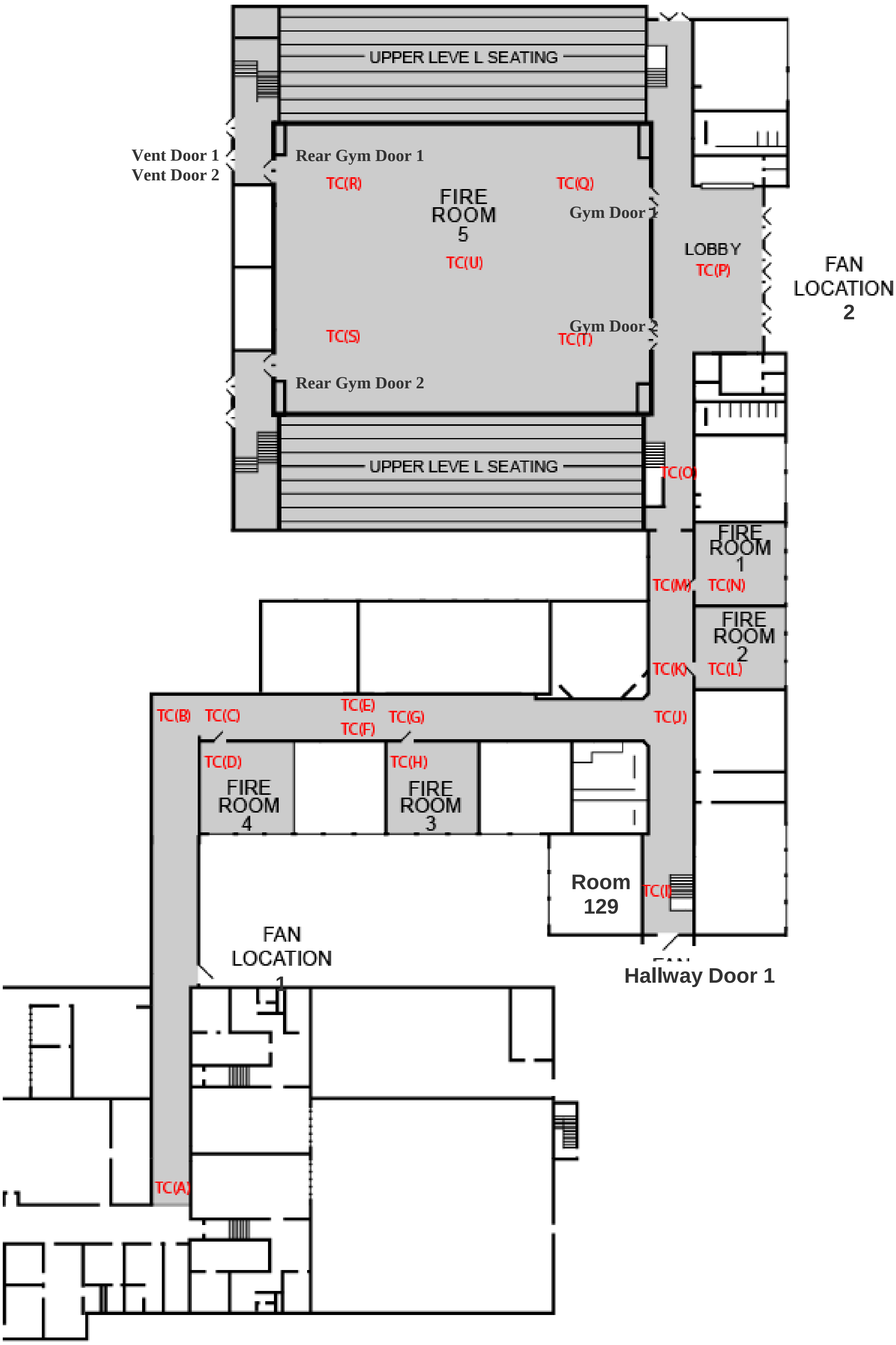

Figure 303. Temperature Measurement Locations

Experiment GF7

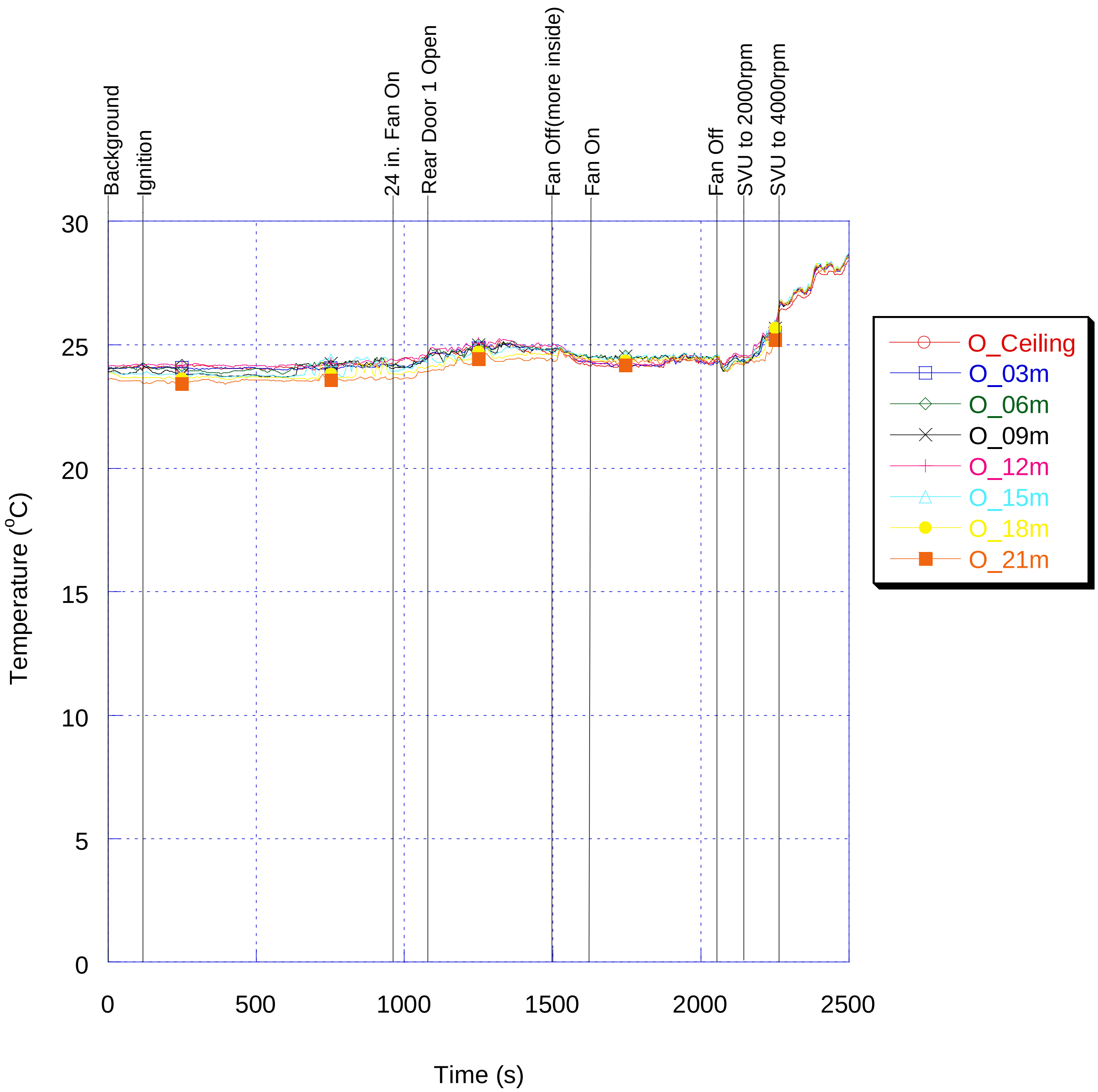

Figure 304. Experiment GF7 Temperature vs. Time for Location O

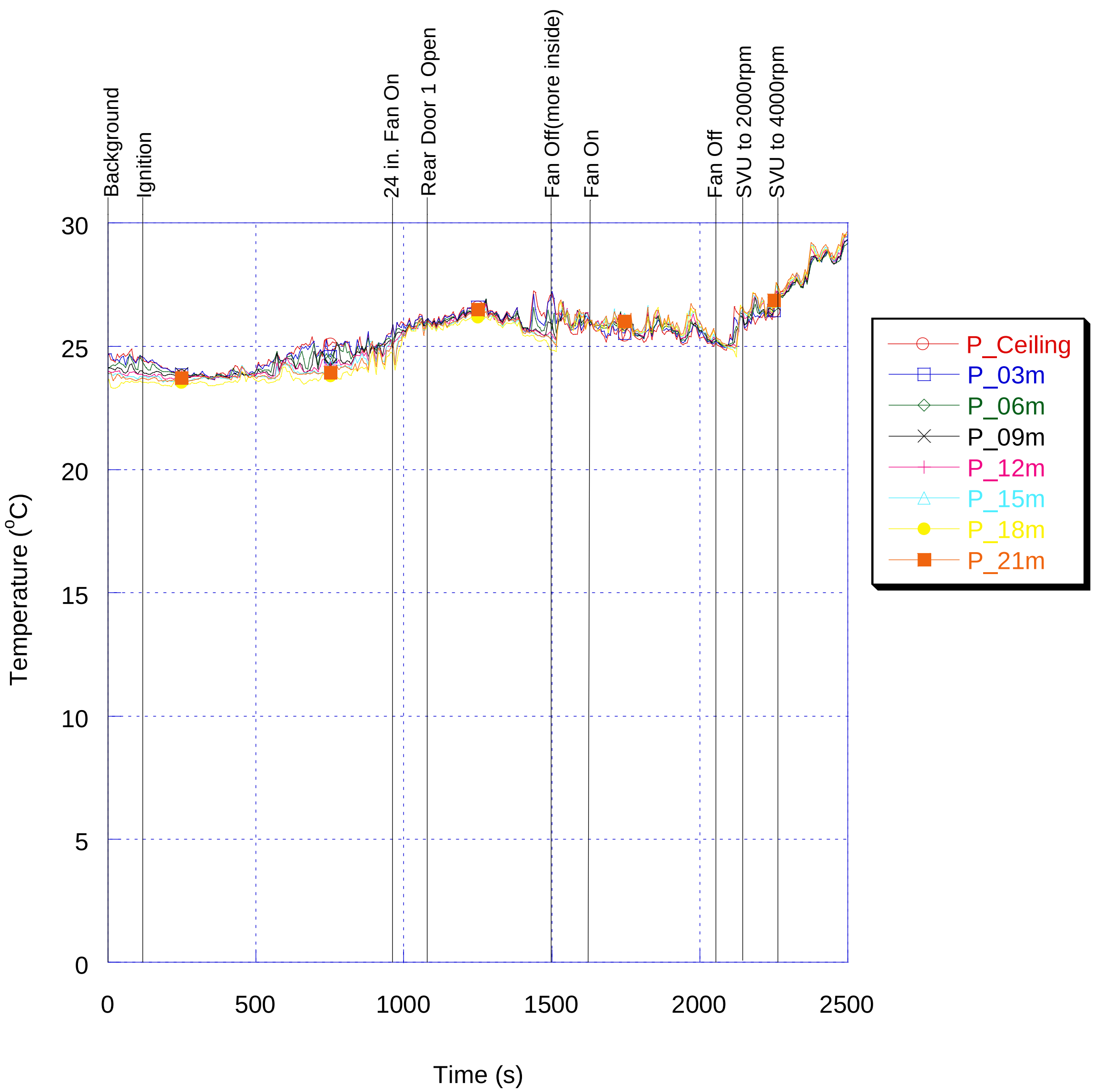

Figure 305. Experiment GF7 Temperature vs. Time for Location P

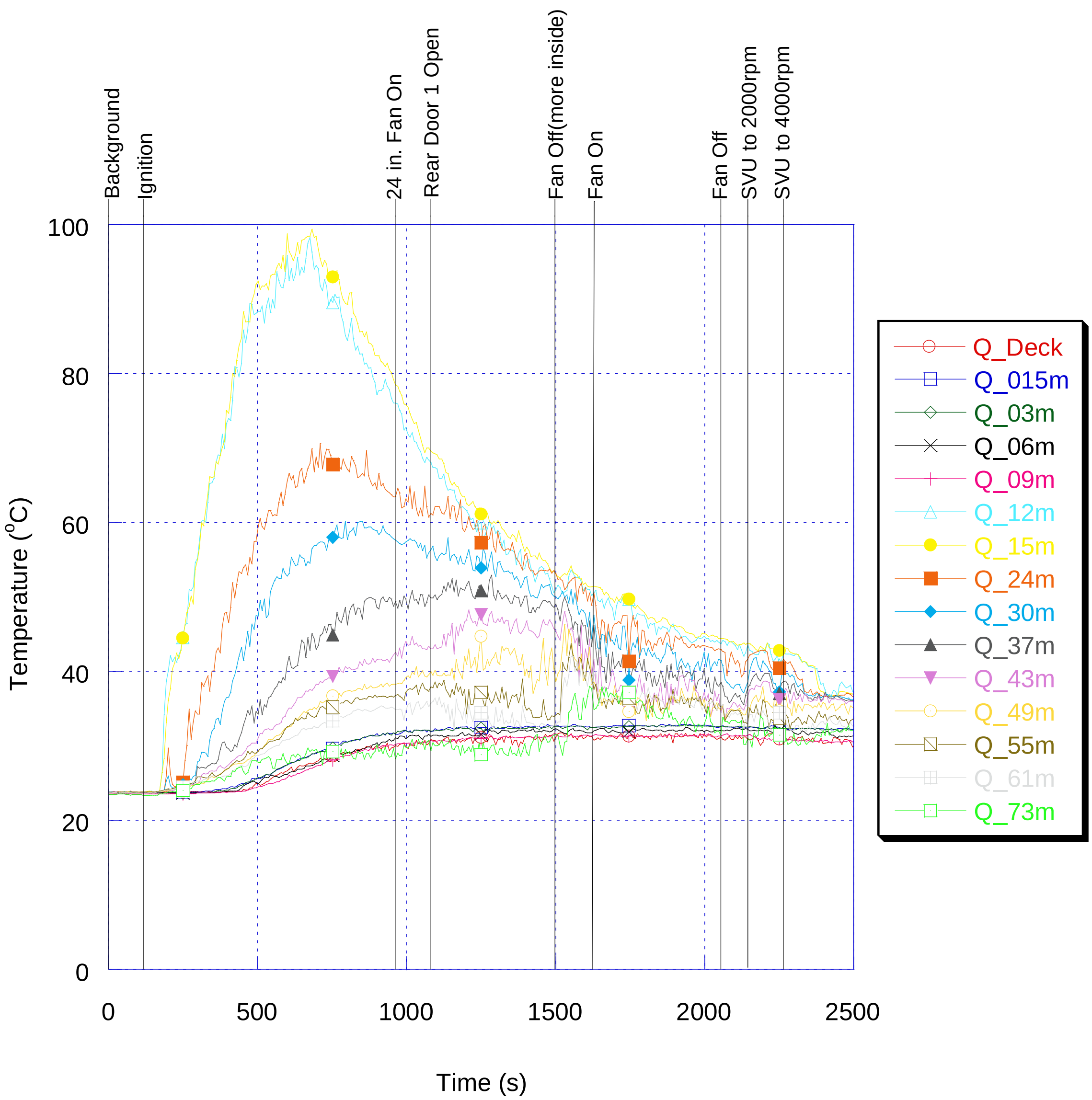

Figure 306. Experiment GF7 Temperature vs. Time for Location Q

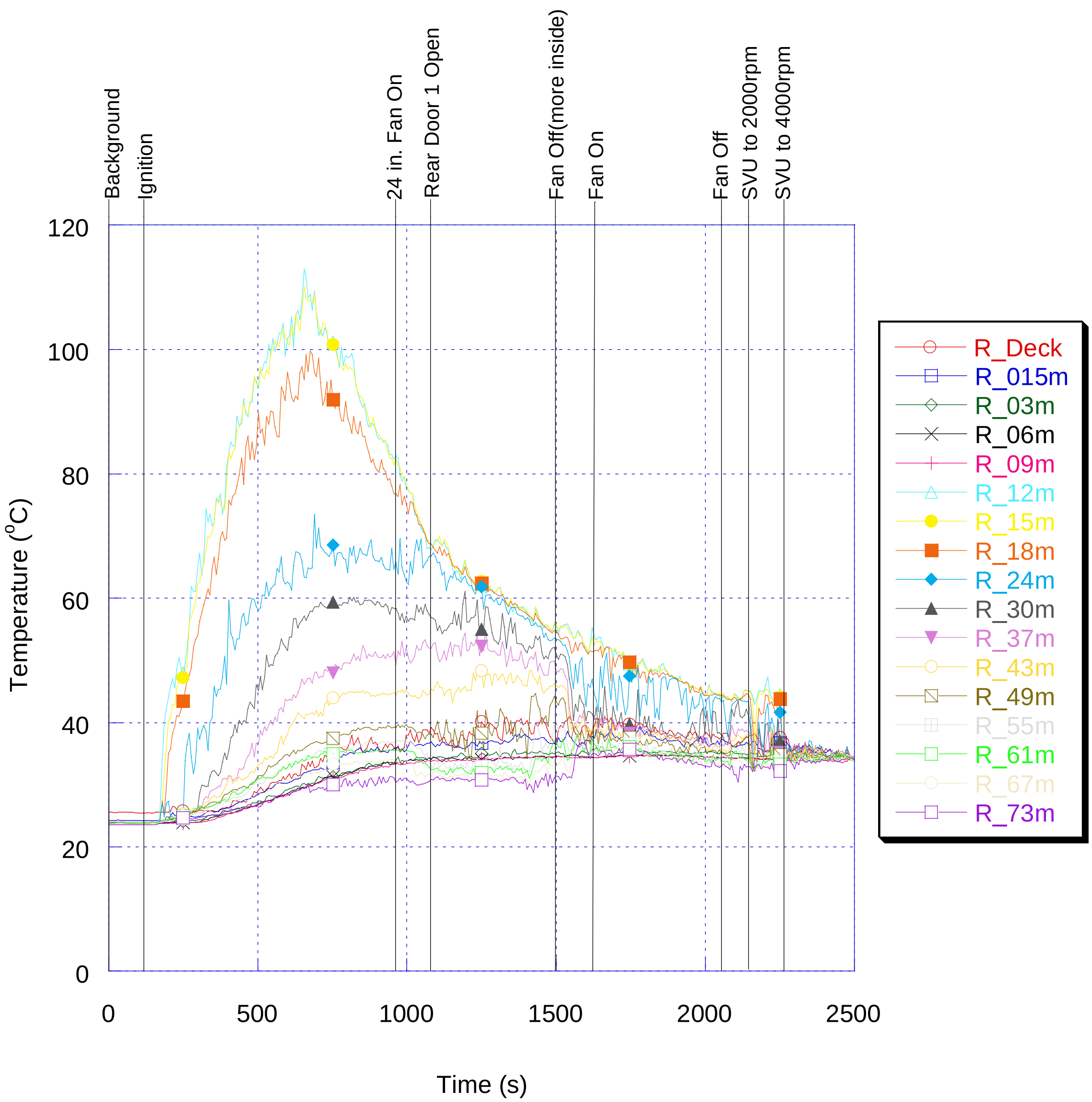

Figure 307. Experiment GF7 Temperature vs. Time for Location R

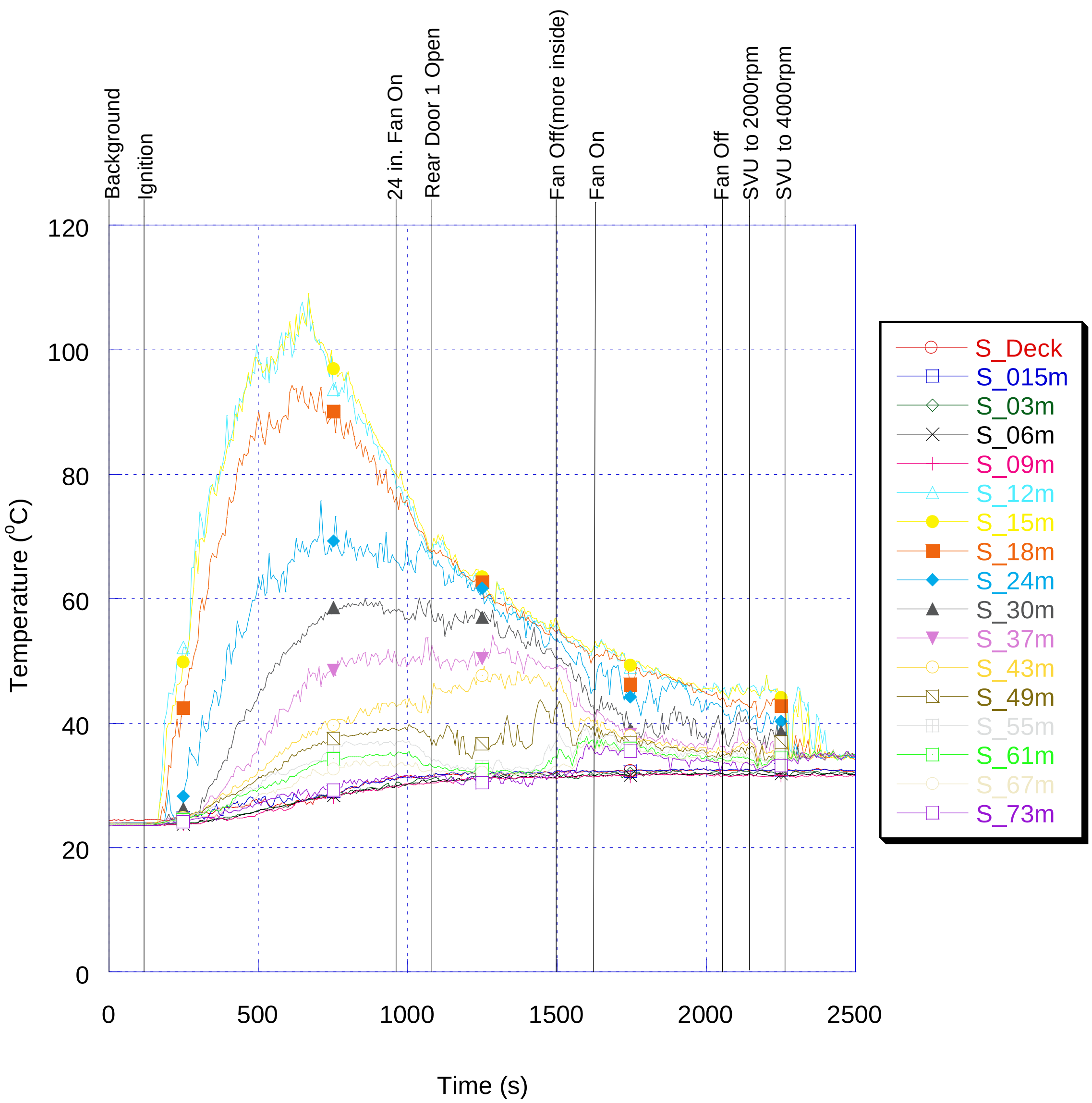

Figure 308. Experiment GF7 Temperature vs. Time for Location S

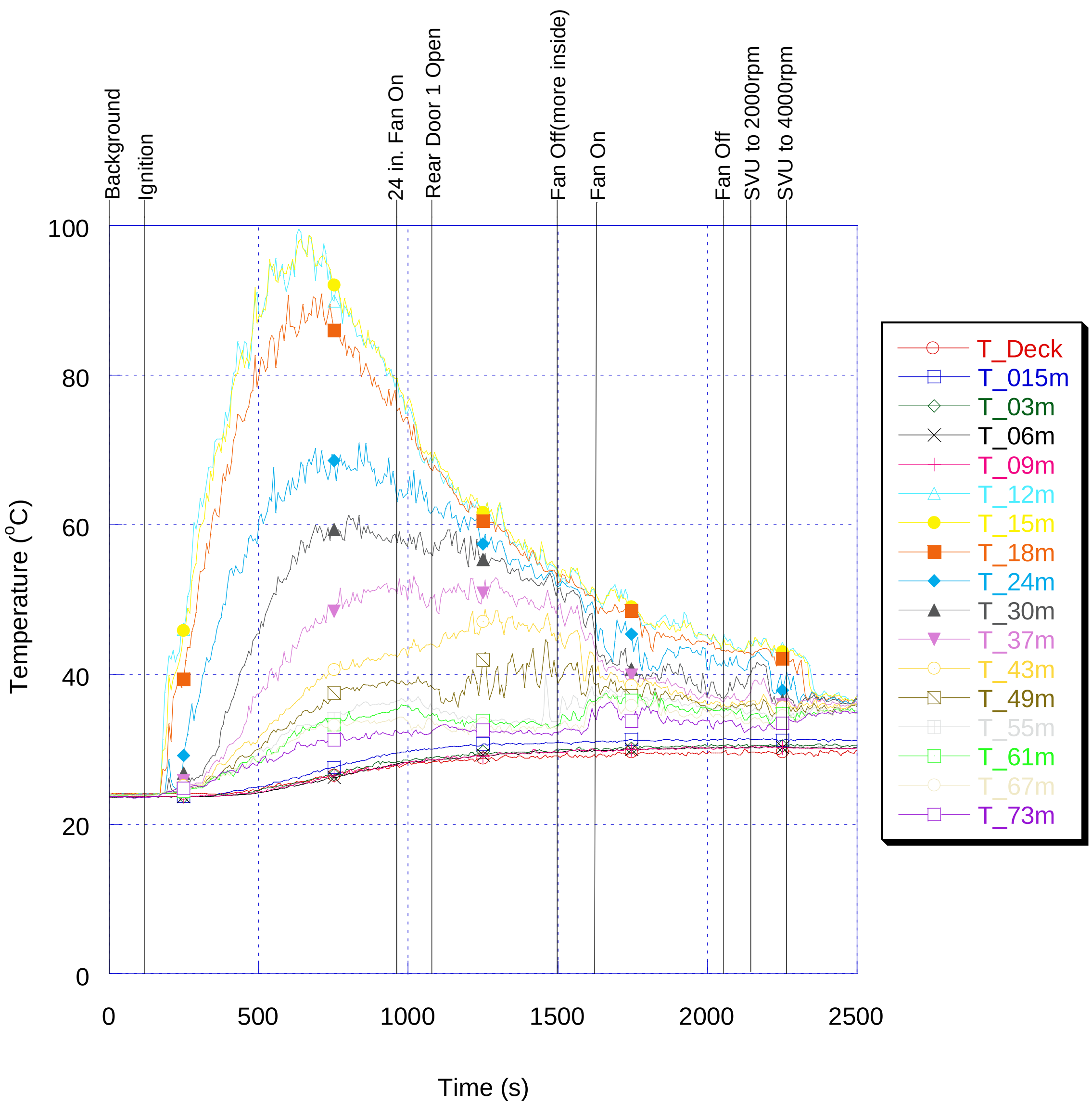

Figure 309. Experiment GF7 Temperature vs. Time for Location T

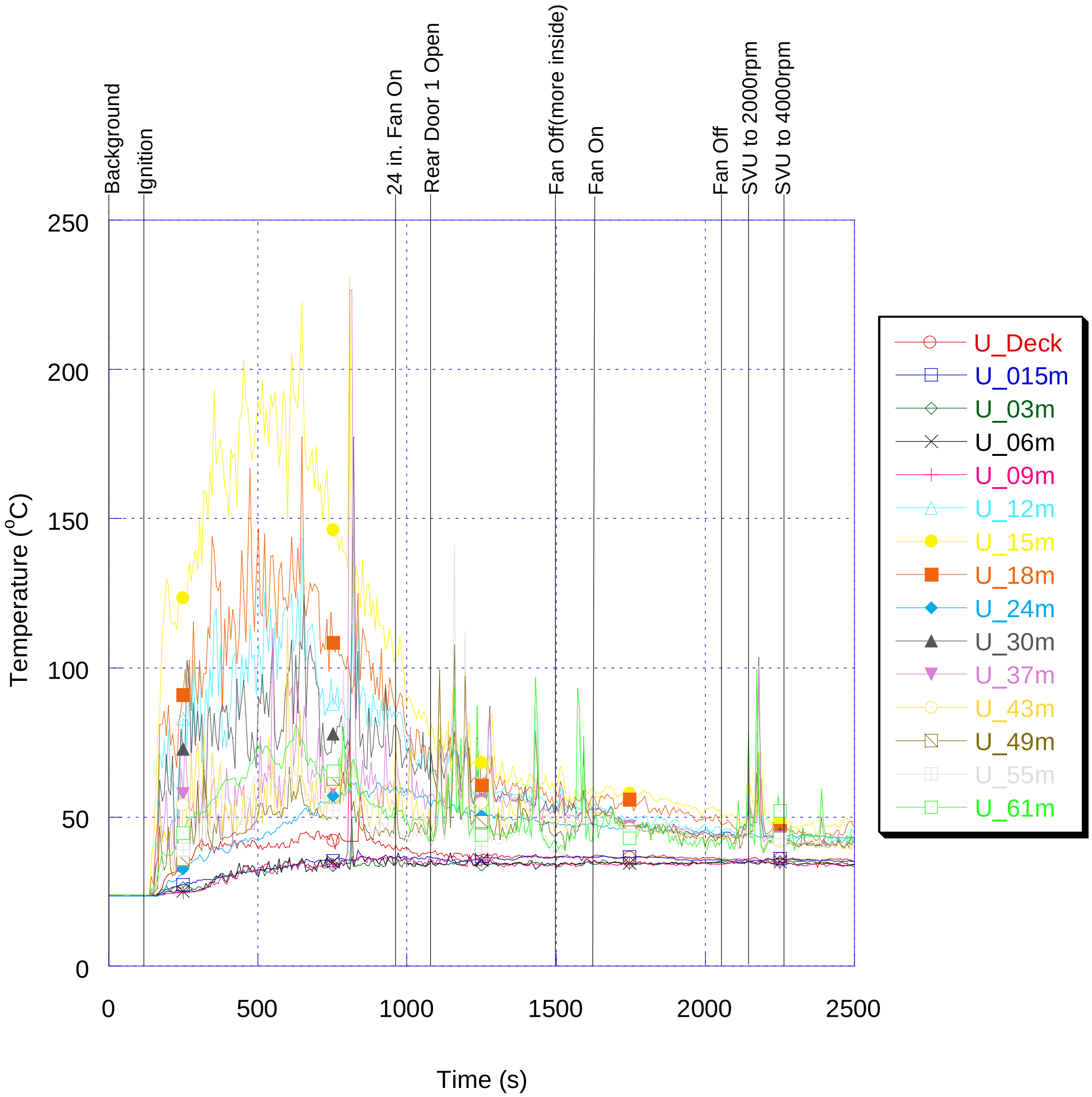

Figure 310. Experiment GF7 Temperature vs. Time for Location U

Experiment GF8

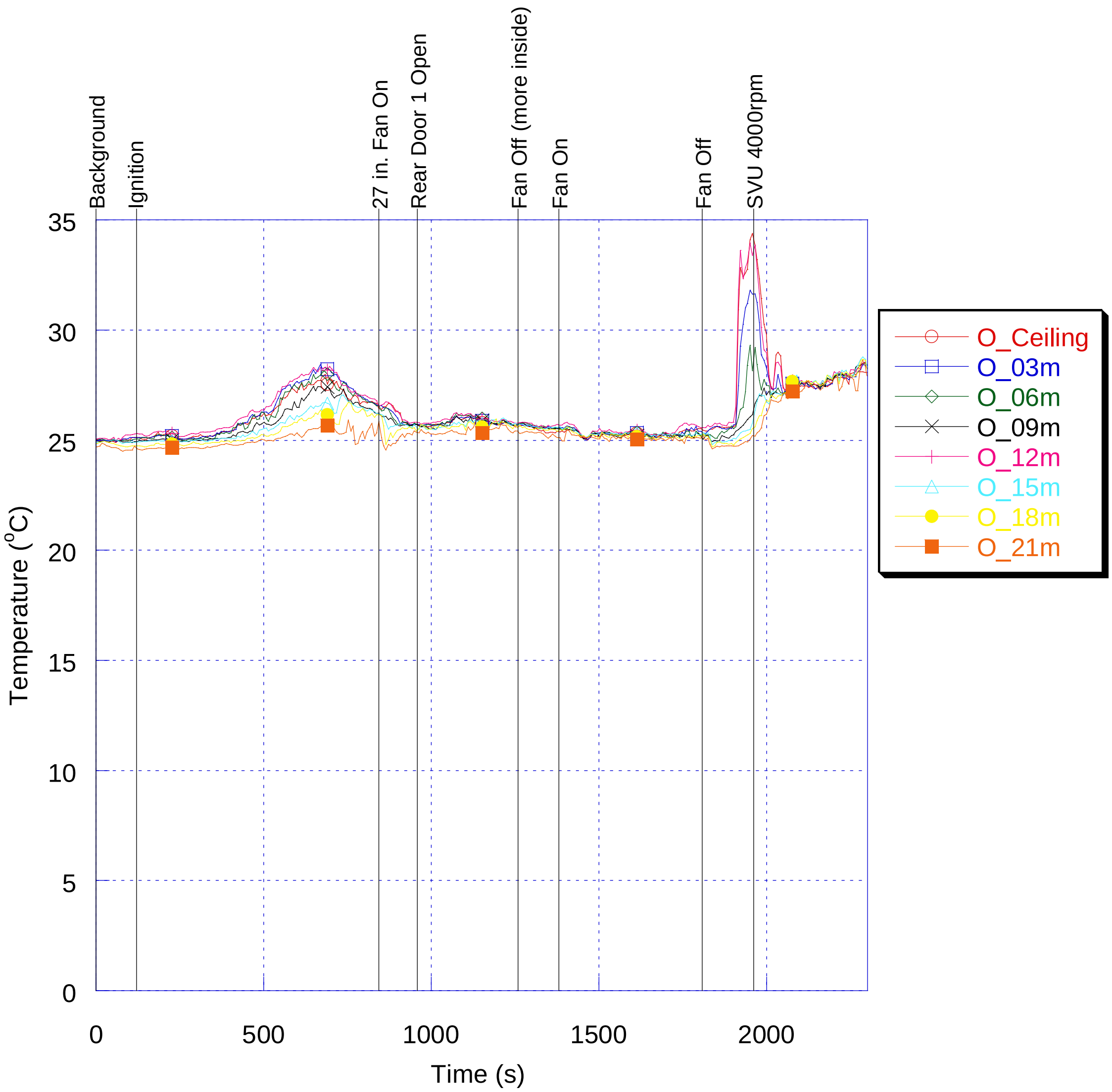

Figure 311. Experiment GF8 Temperature vs. Time for Location O

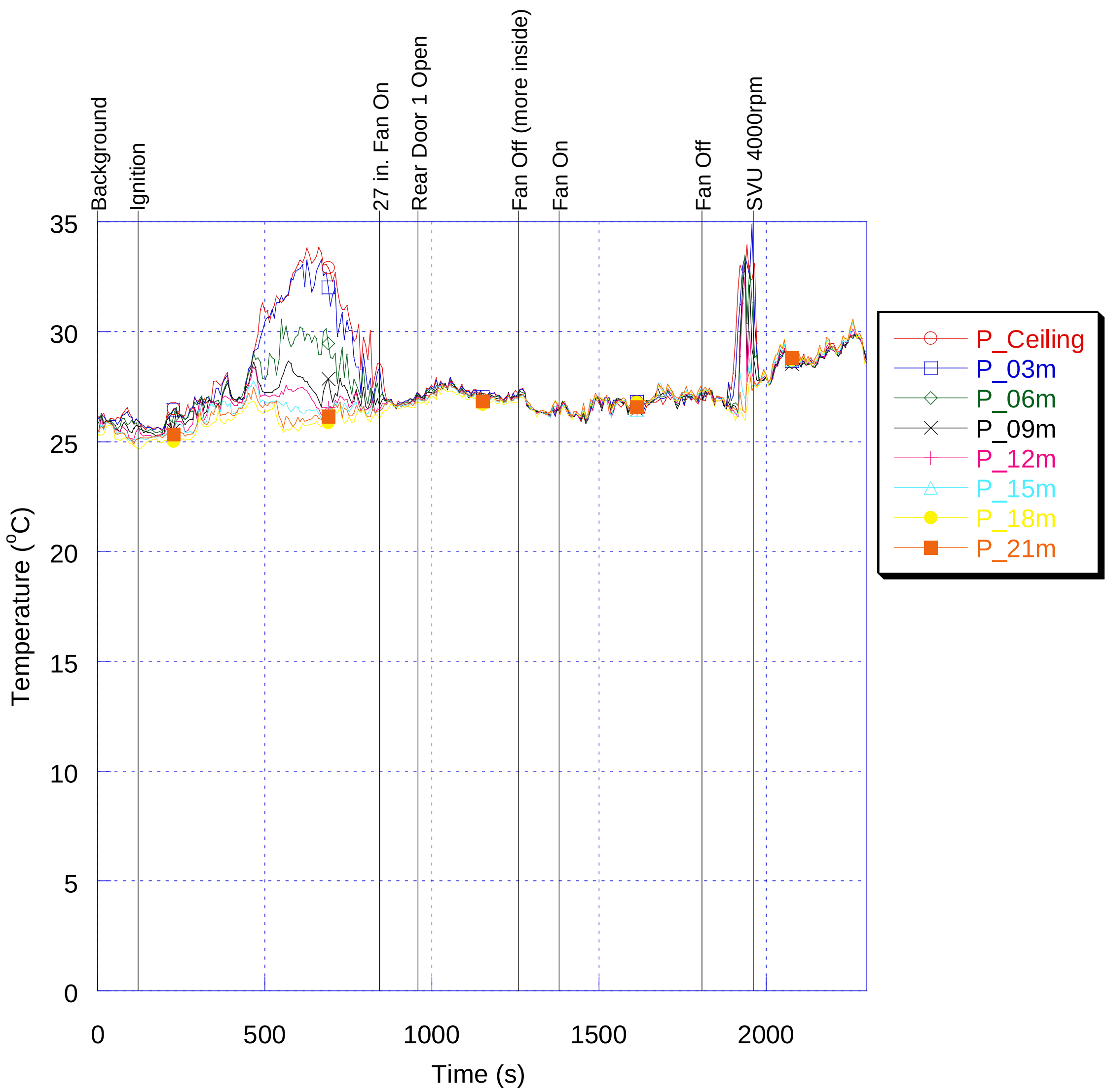

Figure 312. Experiment GF8 Temperature vs. Time for Location P

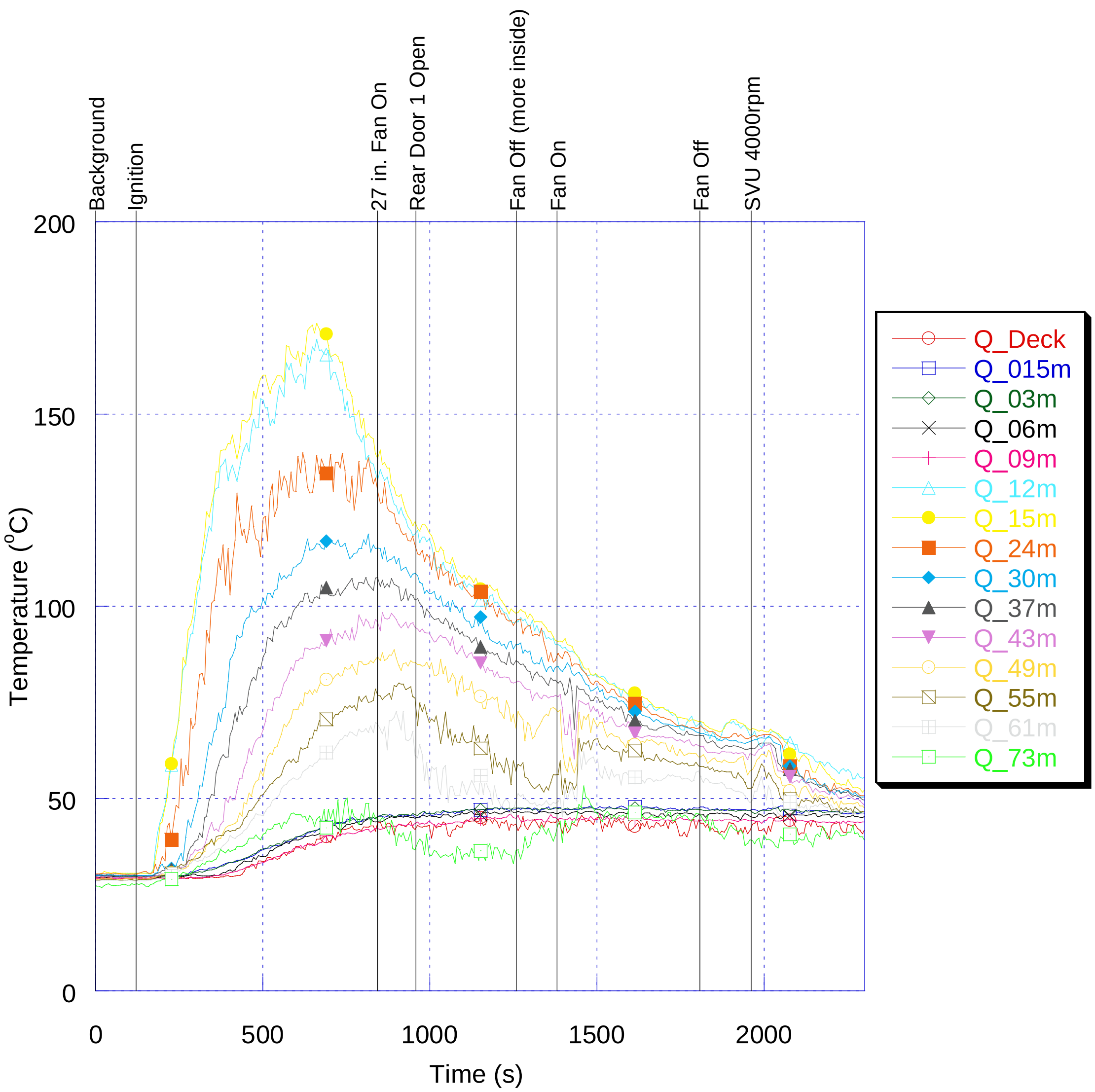

Figure 313. Experiment GF8 Temperature vs. Time for Location Q

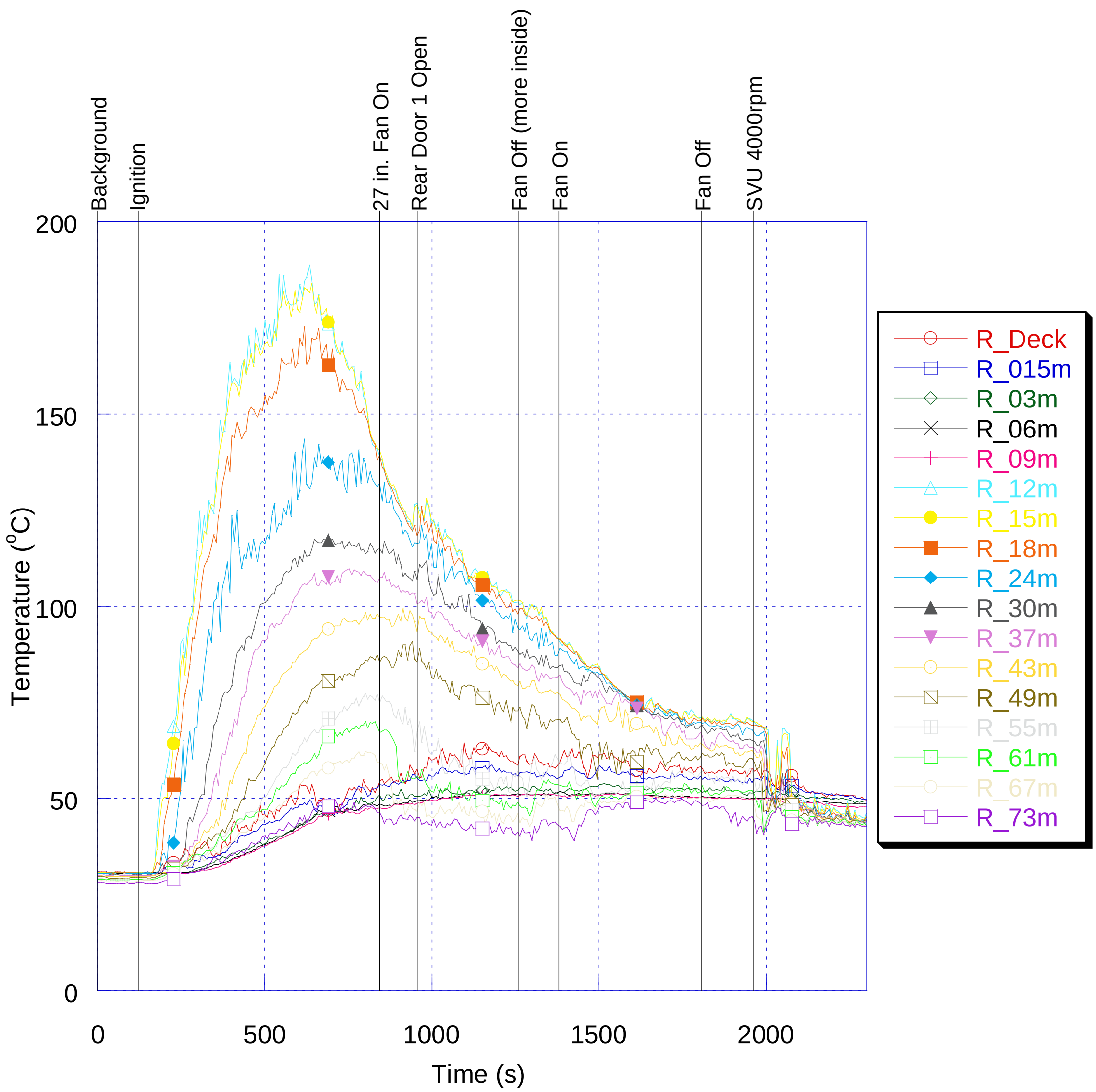

Figure 314. Experiment GF8 Temperature vs. Time for Location R

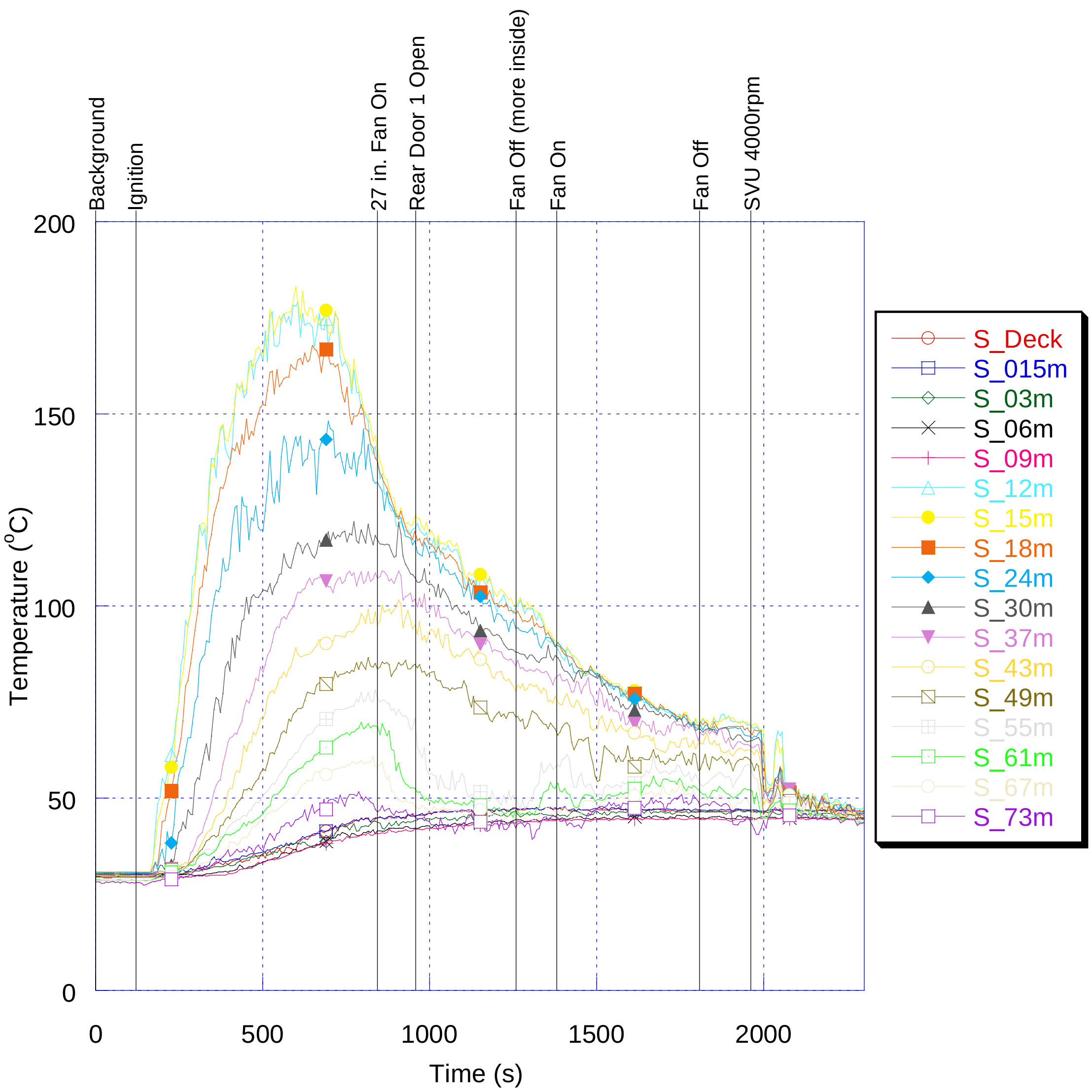

Figure 315. Experiment GF8 Temperature vs. Time for Location S

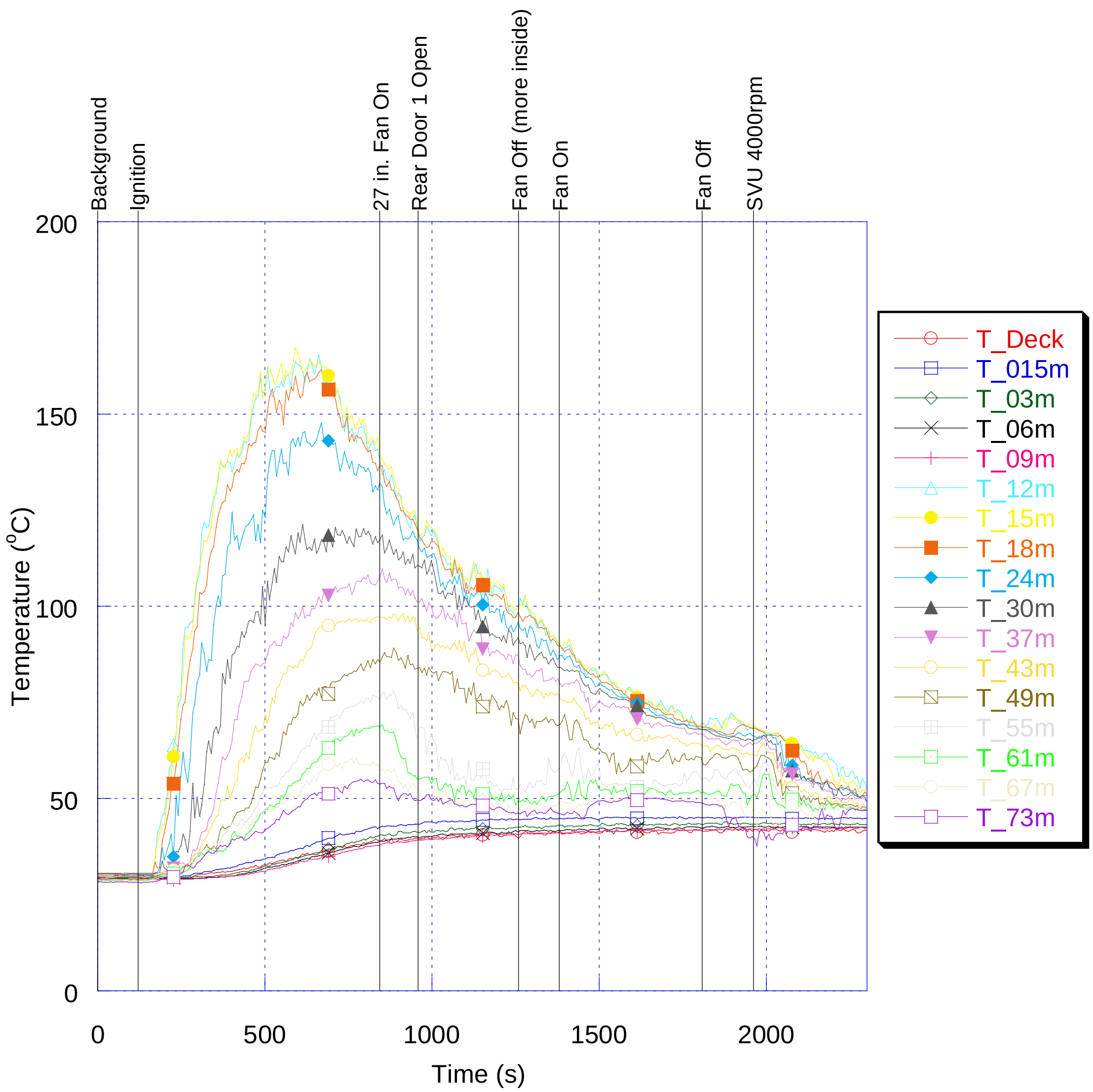

Figure 316. Experiment GF8 Temperature vs. Time for Location T

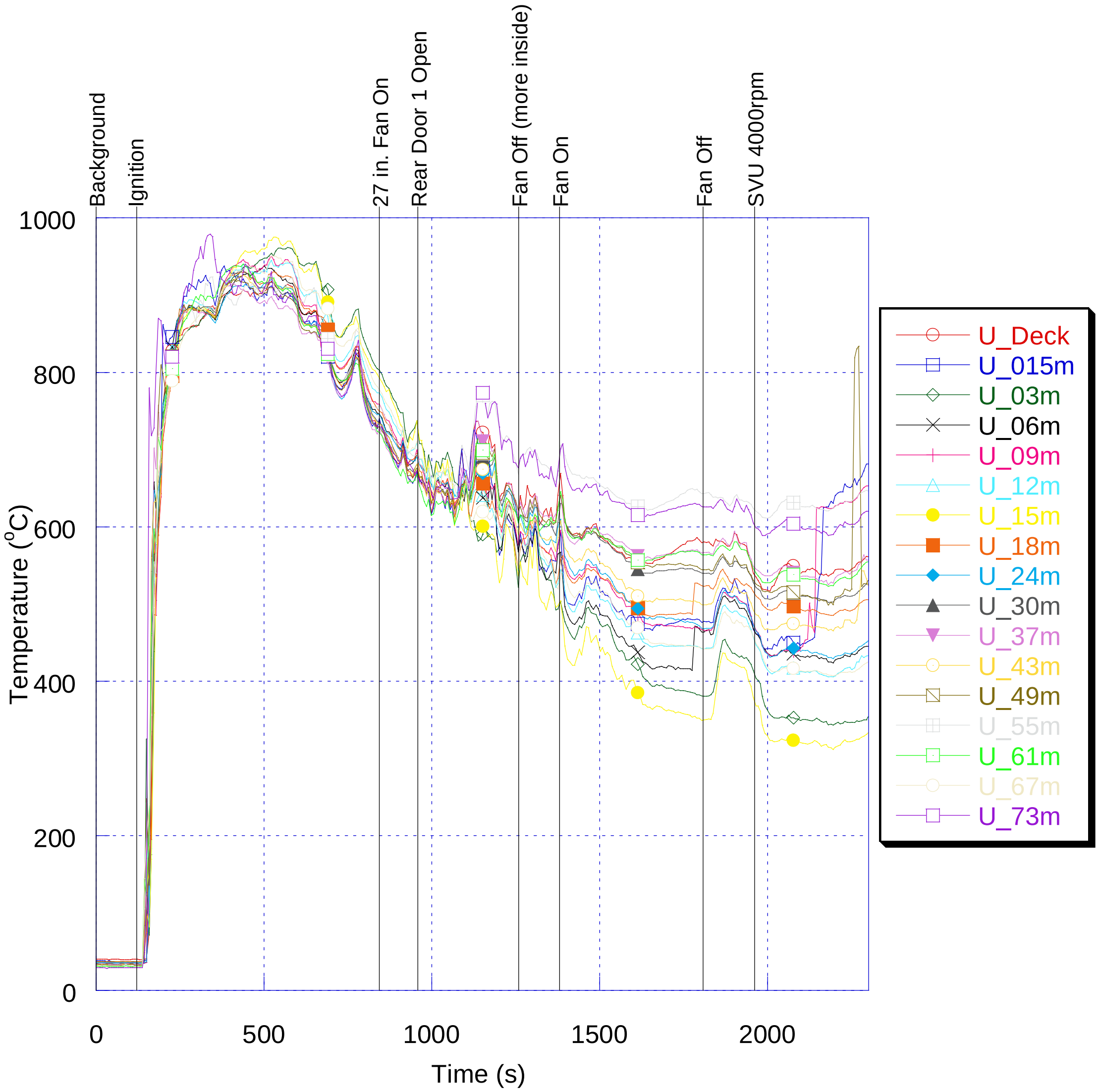

Figure 317. Experiment GF8 Temperature vs. Time for Location U

Experiment GF9

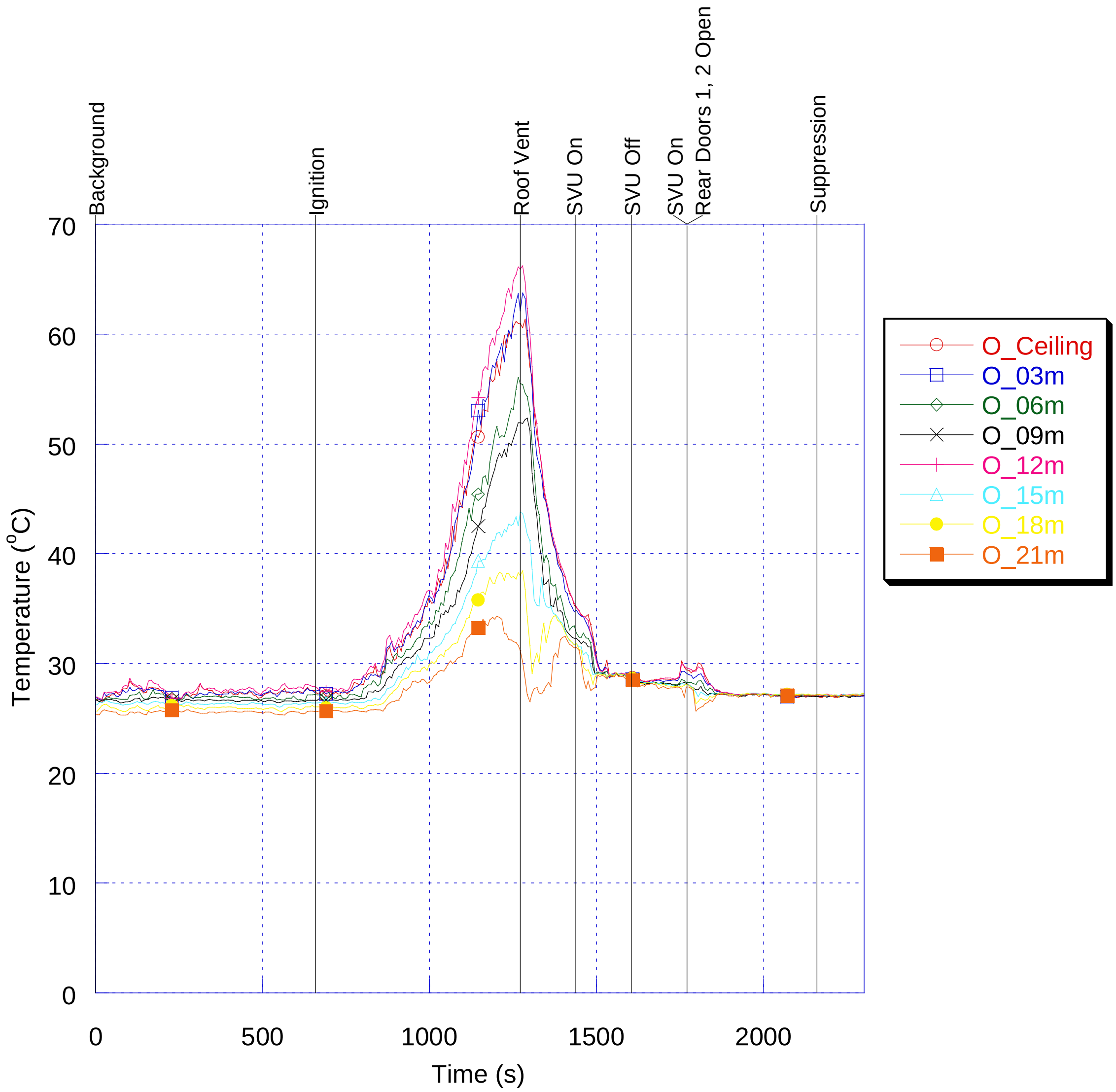

Figure 318. Experiment GF9 Temperature vs. Time for Location O

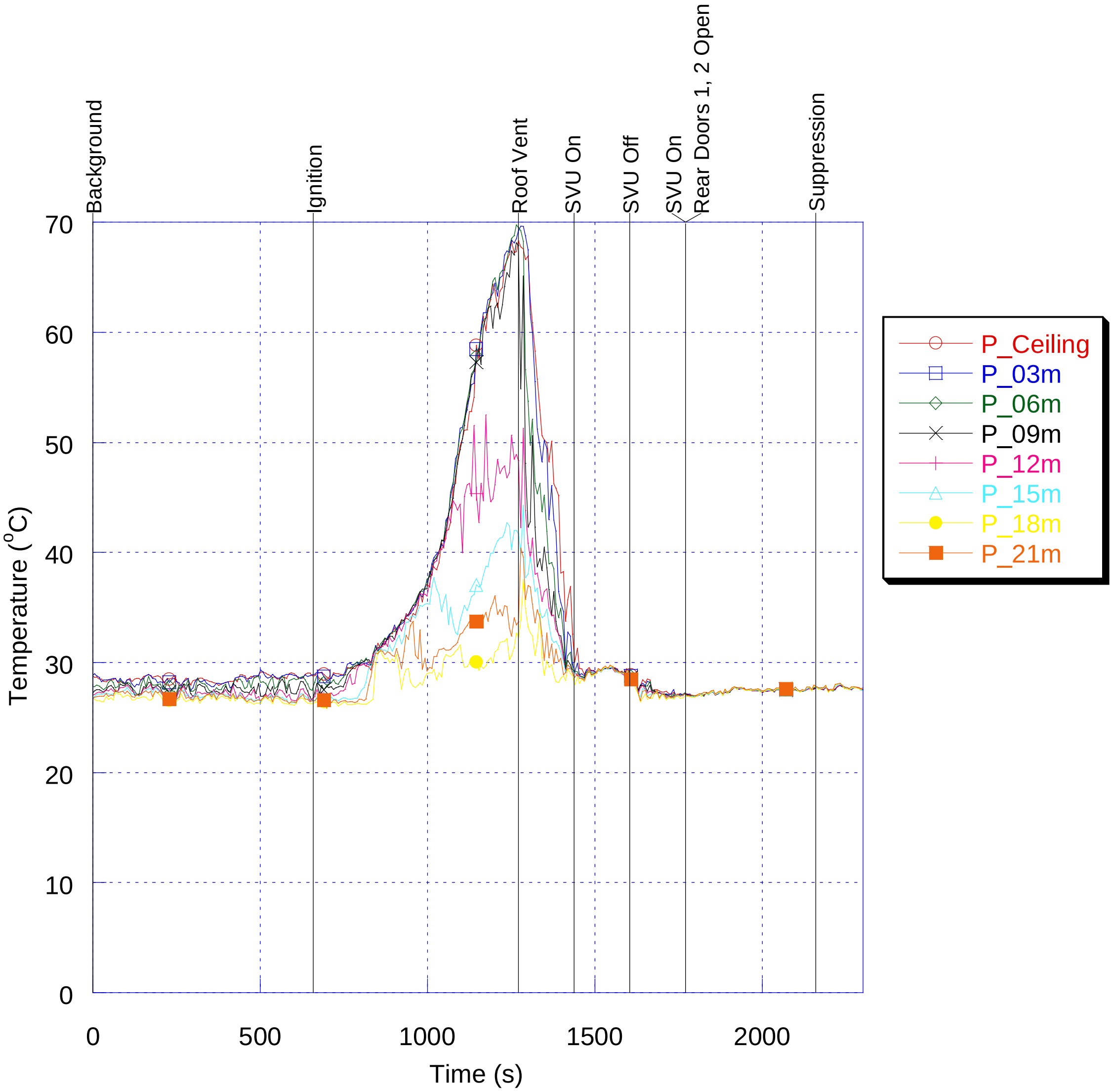

Figure 319. Experiment GF9 Temperature vs. Time for Location P

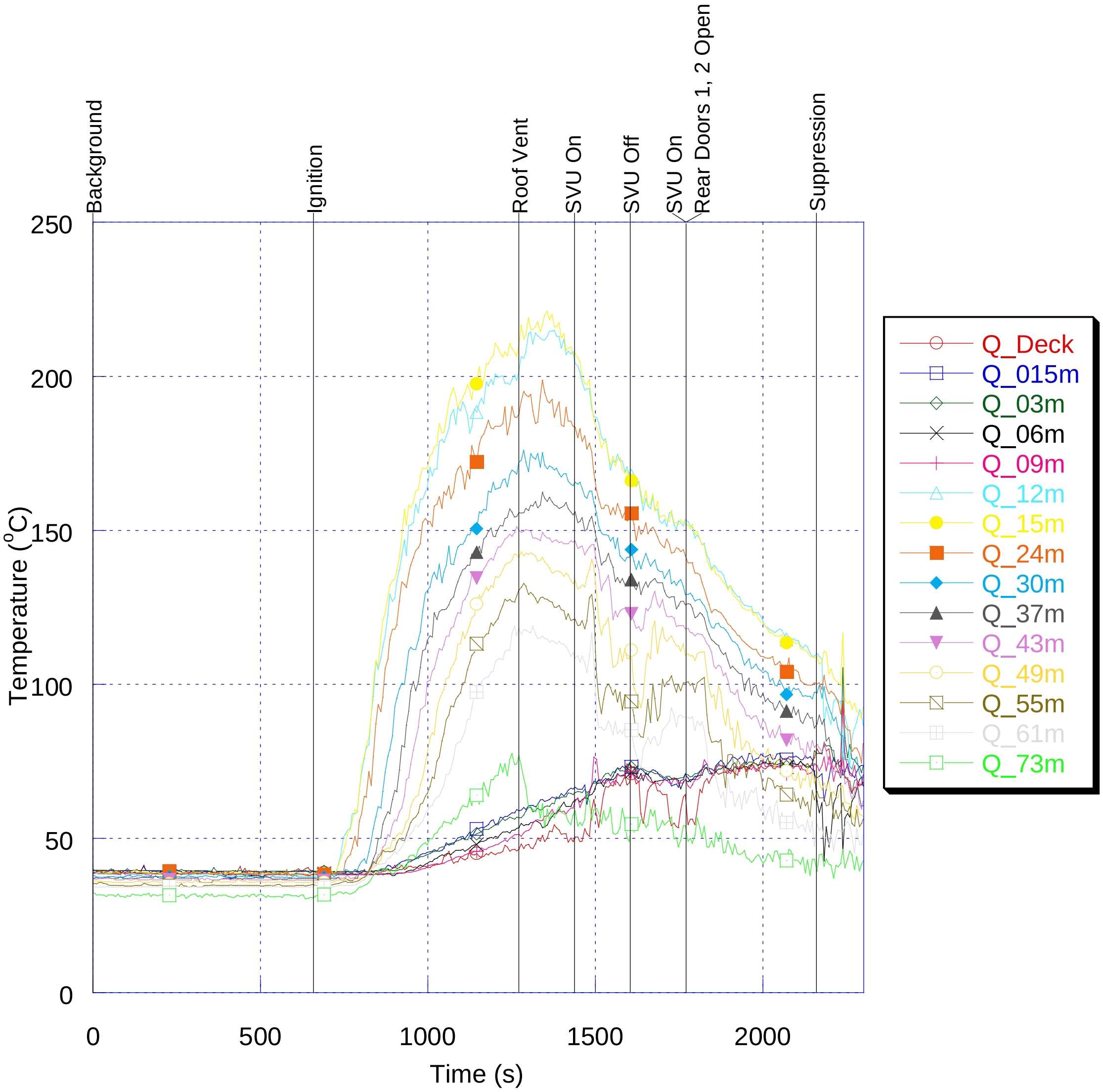

Figure 320. Experiment GF9 Temperature vs. Time for Location Q

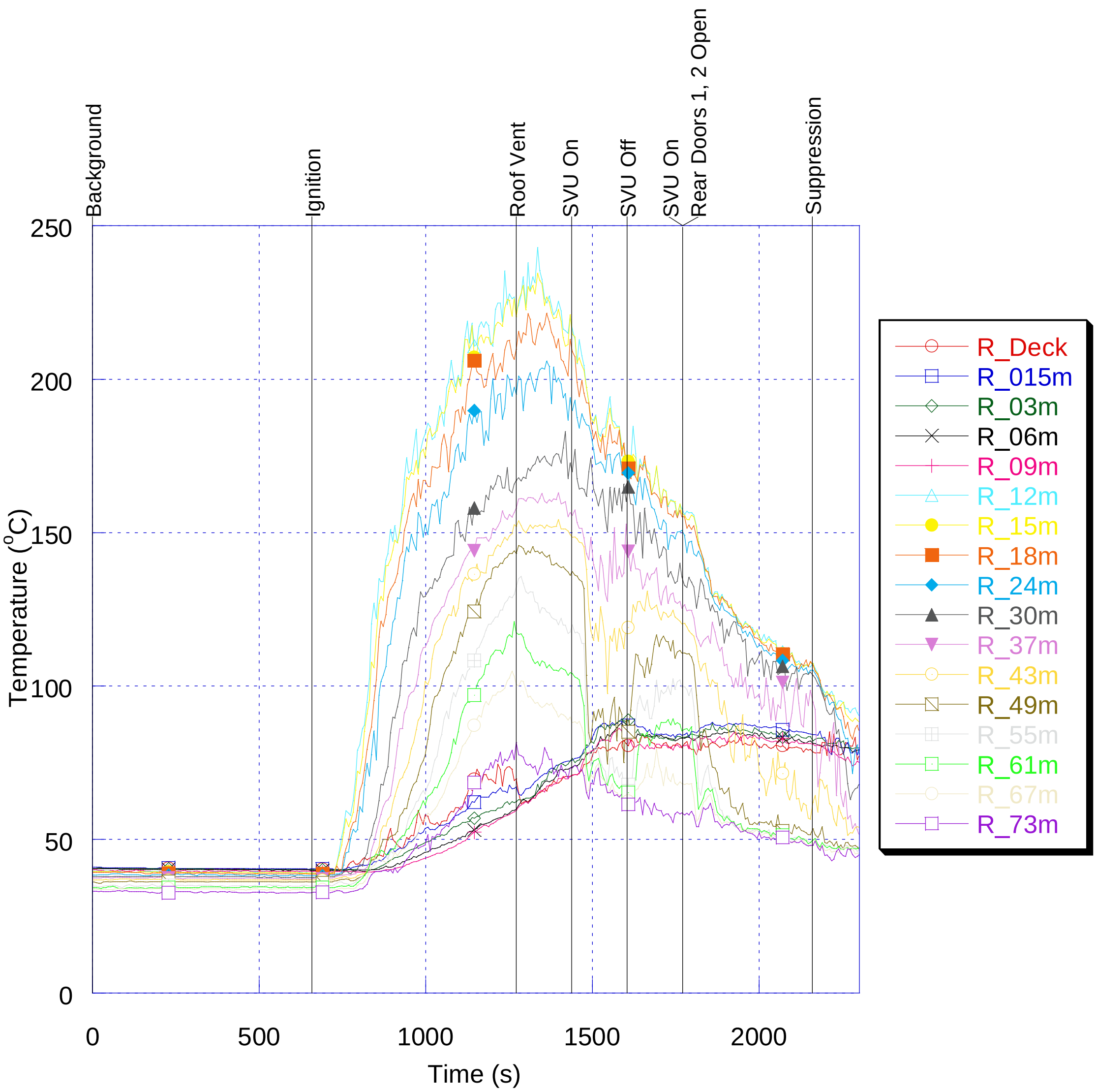

Figure 321. Experiment GF9 Temperature vs. Time for Location R

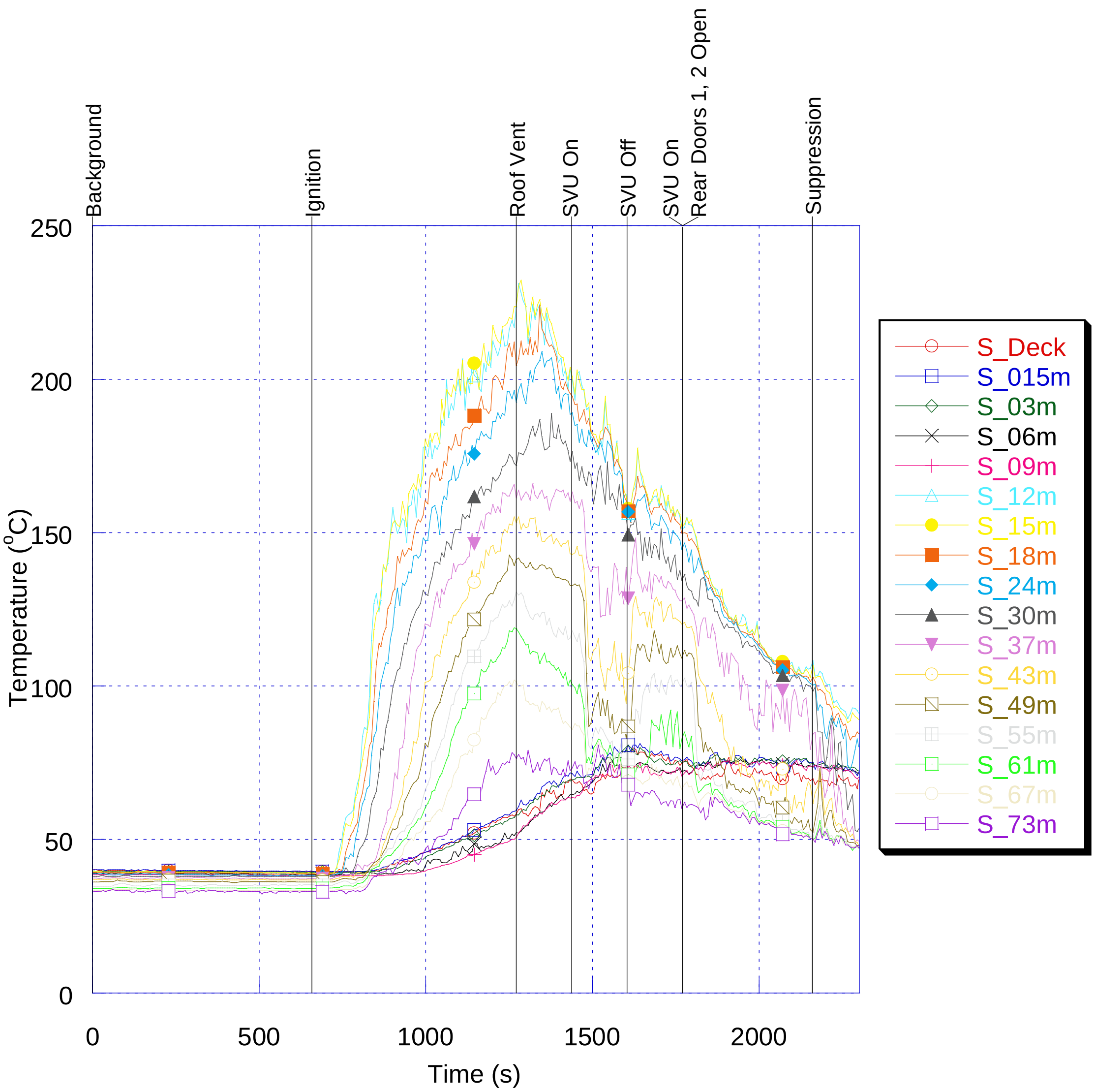

Figure 322. Experiment GF9 Temperature vs. Time for Location S

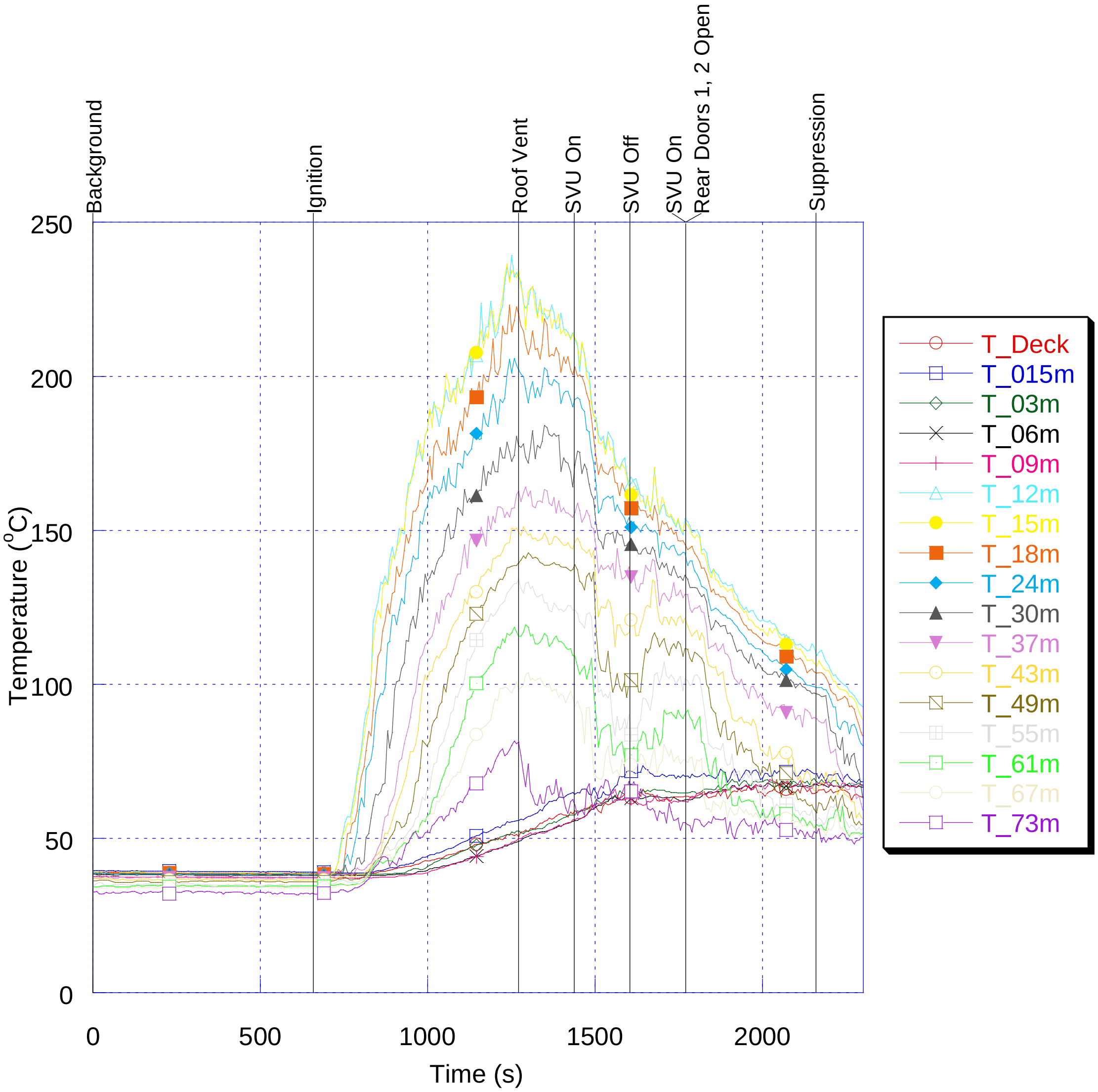

Figure 323. Experiment GF9 Temperature vs. Time for Location T

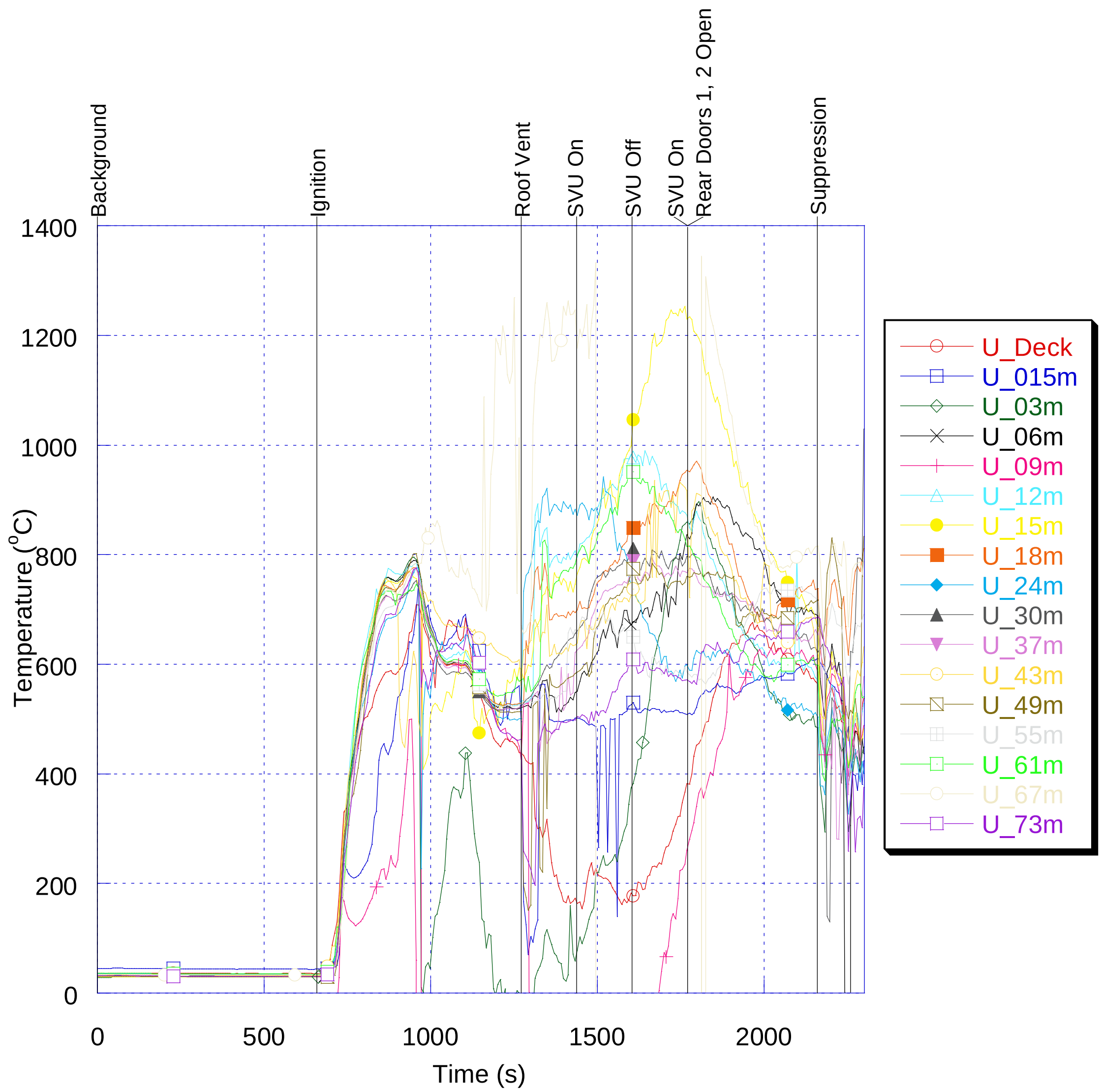

Figure 324. Experiment GF9 Temperature vs. Time for Location U

Experiment GF10

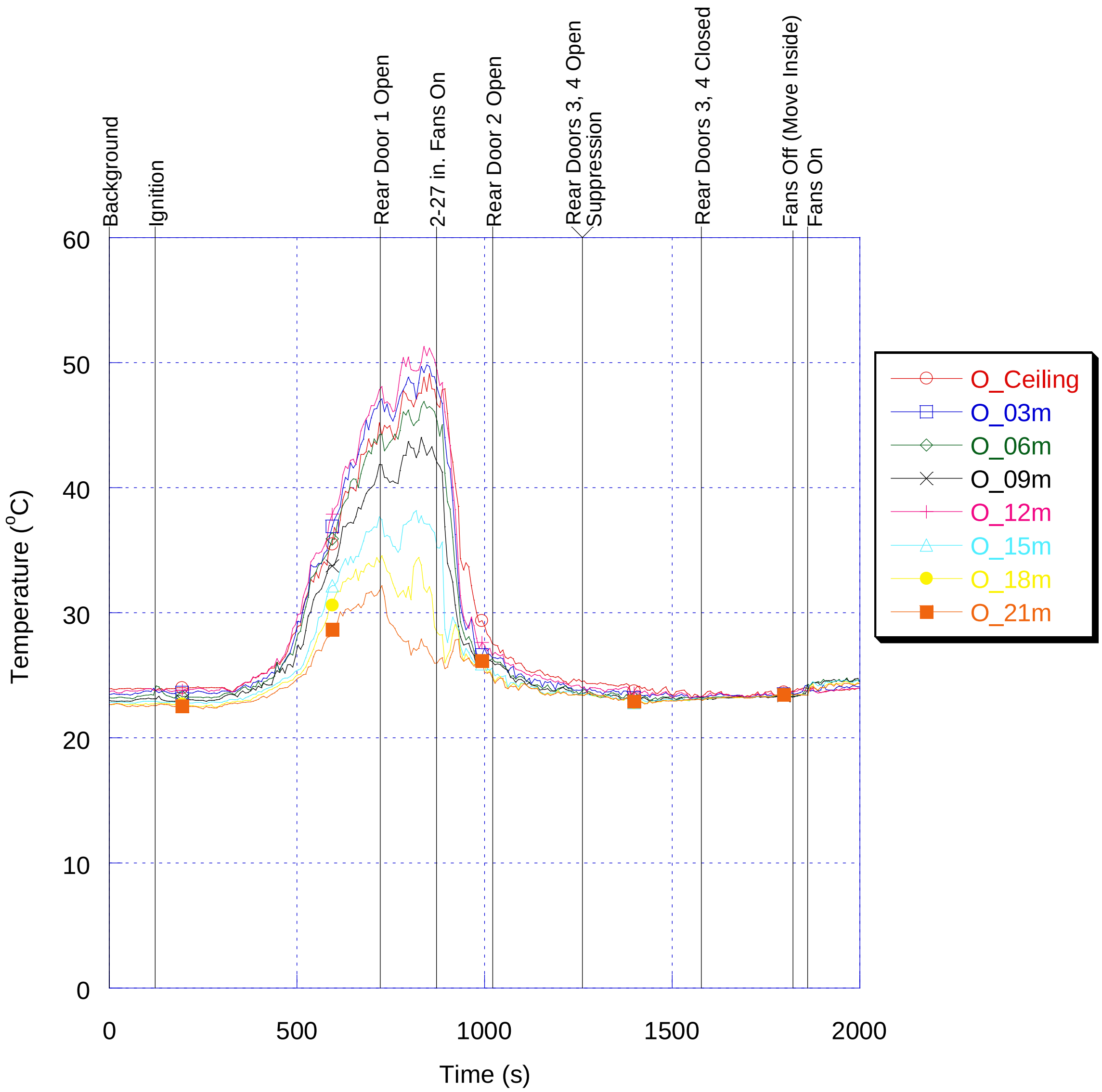

Figure 325. Experiment GF10 Temperature vs. Time for Location O

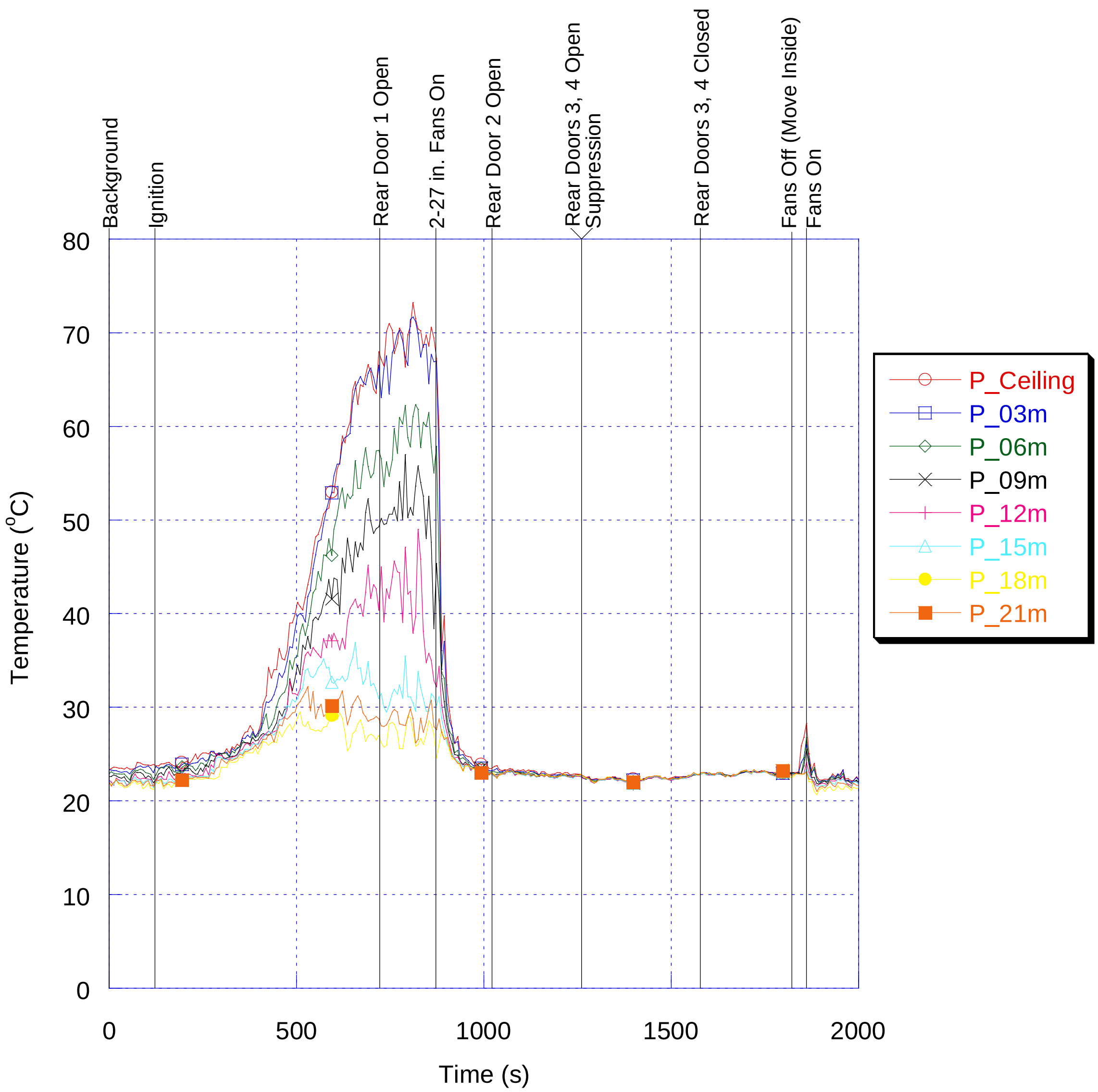

Figure 326. Experiment GF10 Temperature vs. Time for Location P

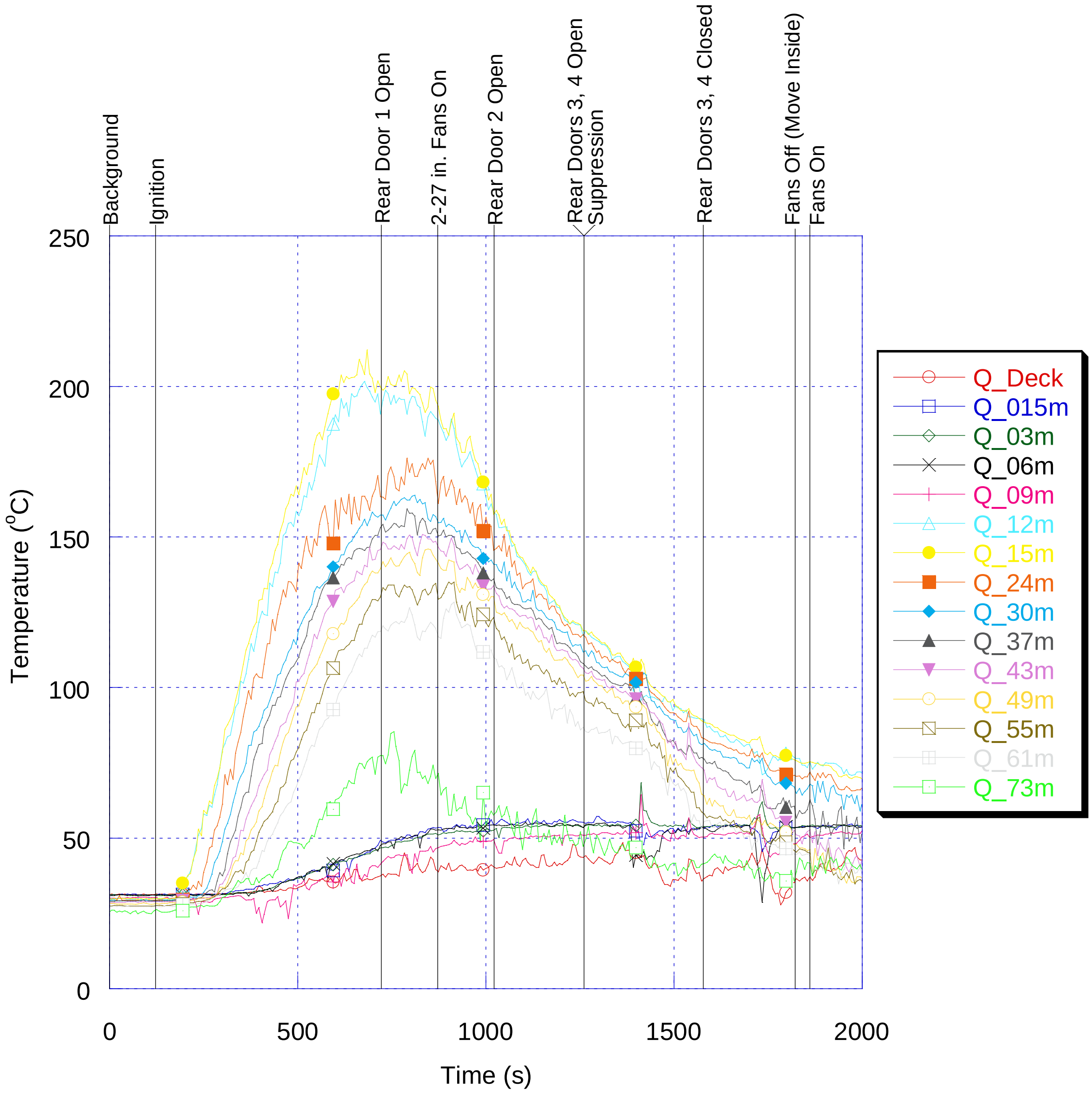

Figure 327. Experiment GF10 Temperature vs. Time for Location Q

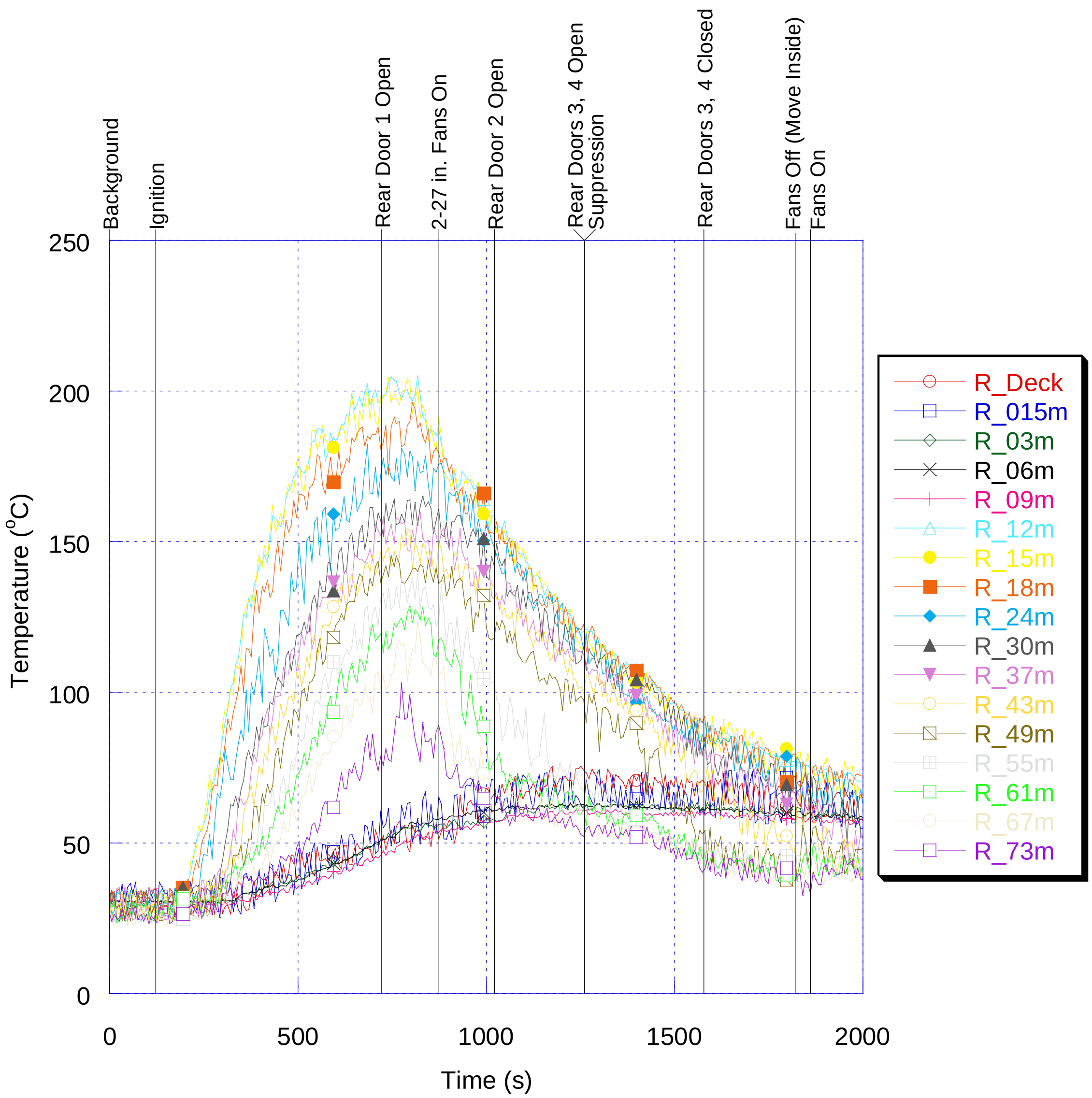

Figure 328. Experiment GF10 Temperature vs. Time for Location R

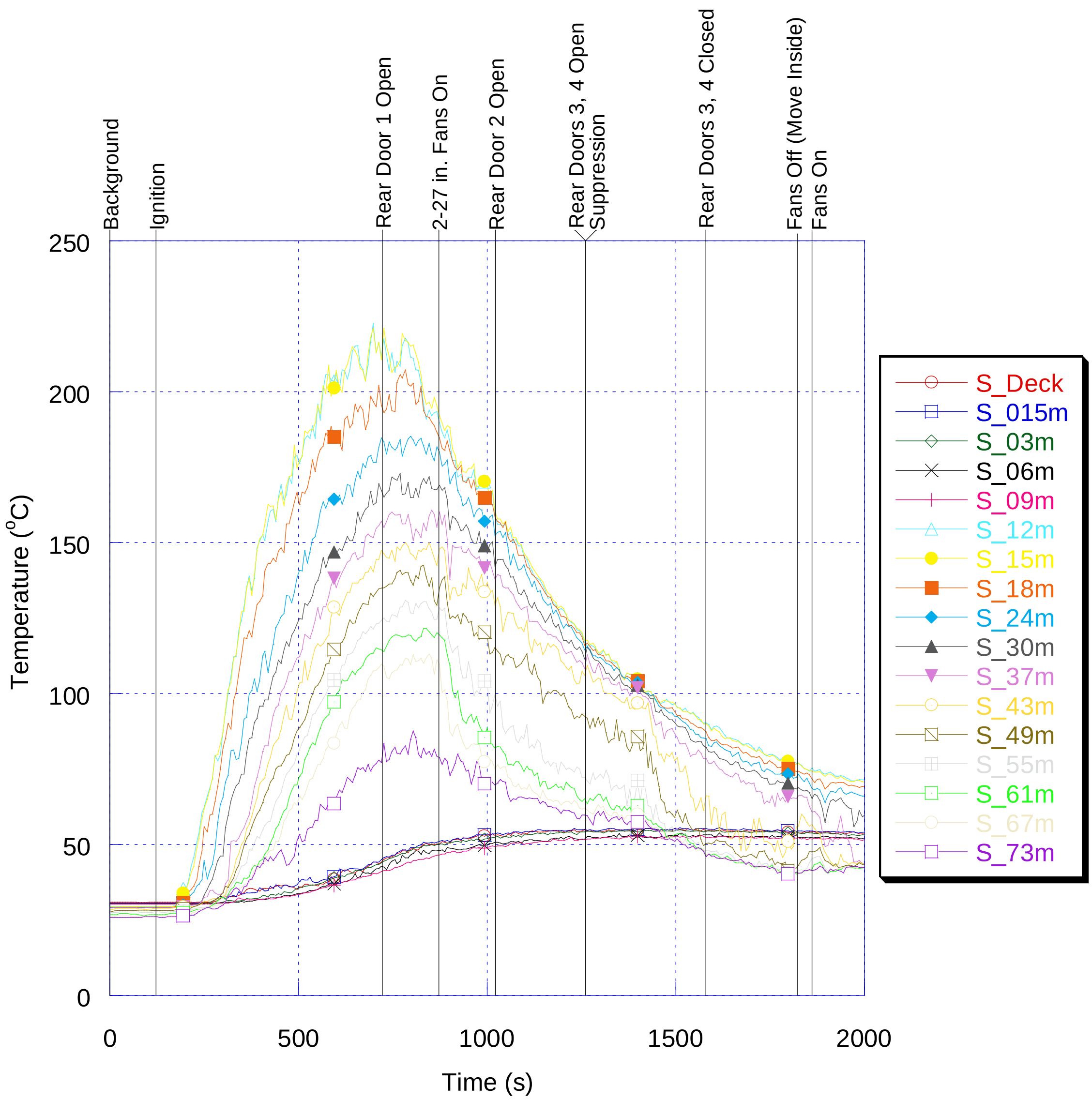

Figure 329. Experiment GF10 Temperature vs. Time for Location S

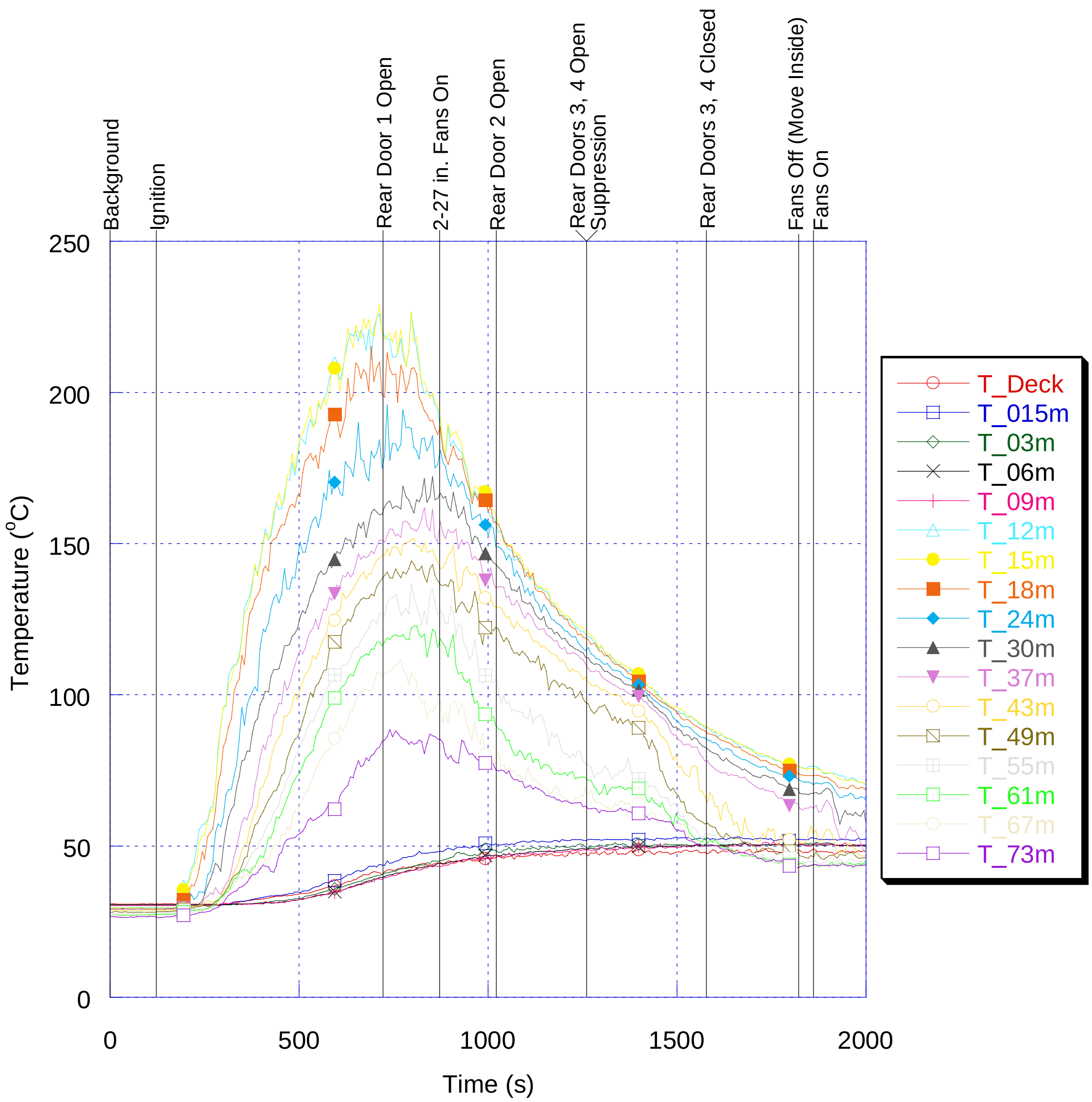

Figure 330. Experiment GF10 Temperature vs. Time for Location T

Experiment GF11

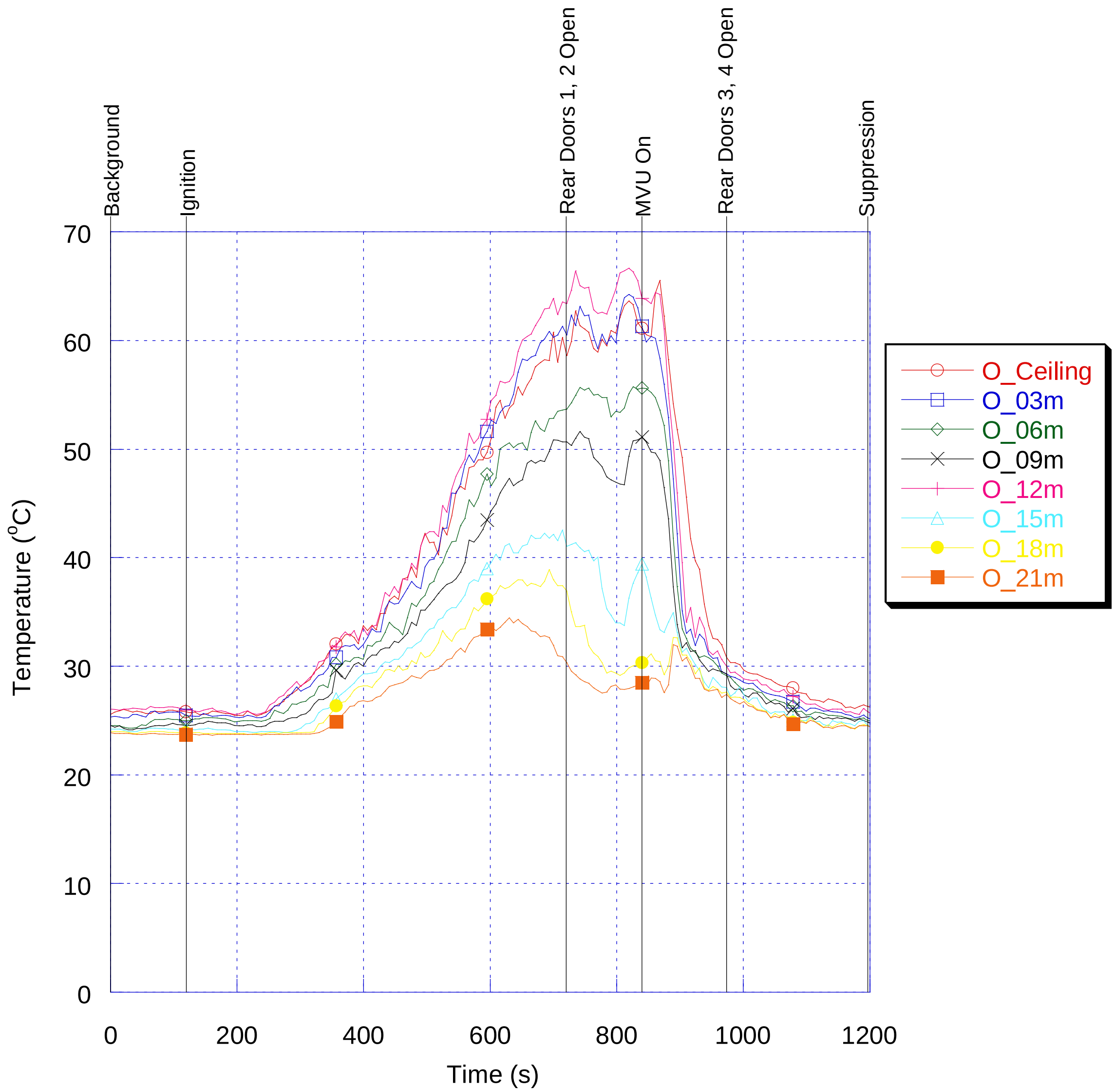

Figure 331. Experiment GF11 Temperature vs. Time for Location O

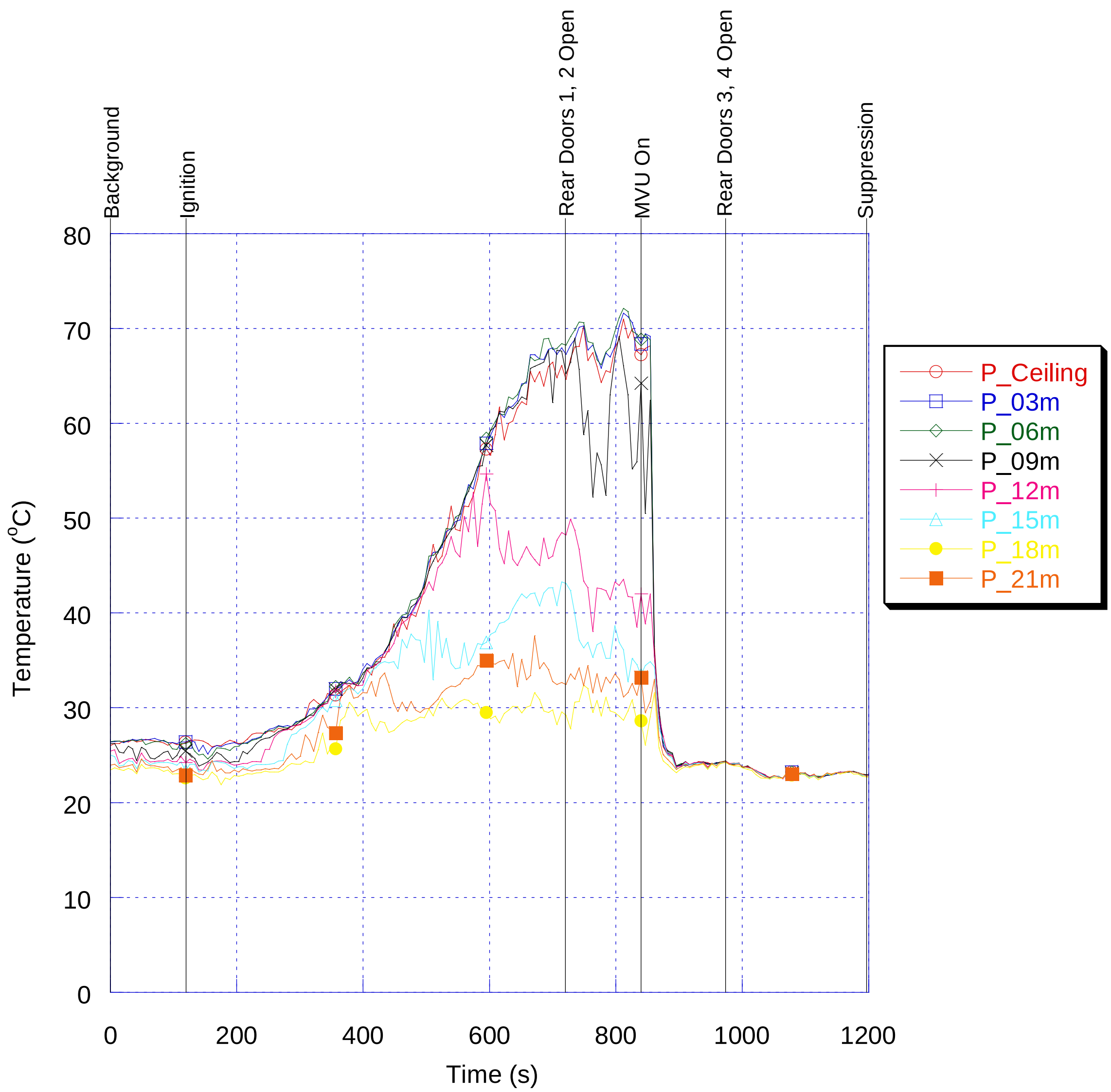

Figure 332. Experiment GF11 Temperature vs. Time for Location P

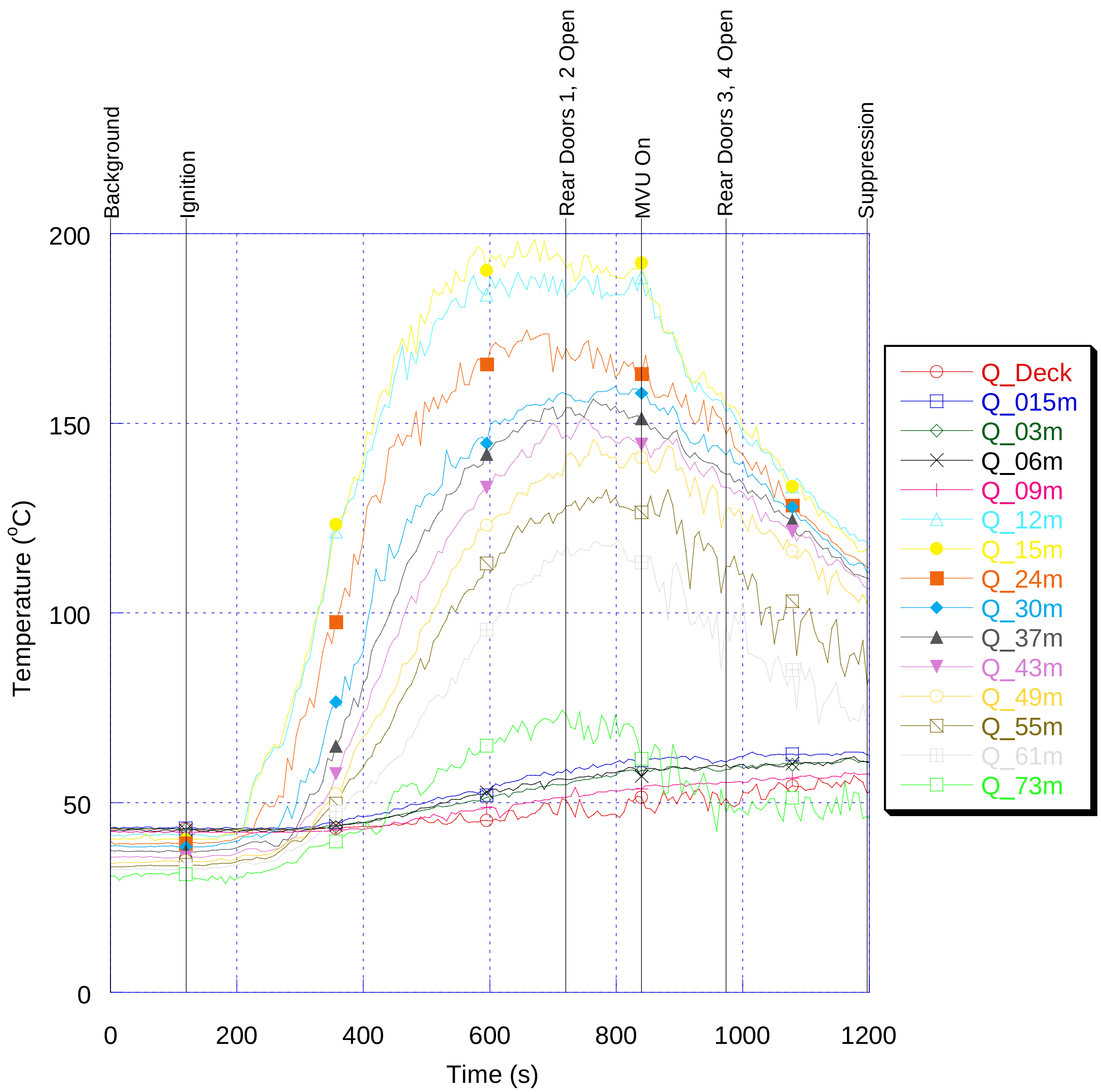

Figure 333. Experiment GF11 Temperature vs. Time for Location Q

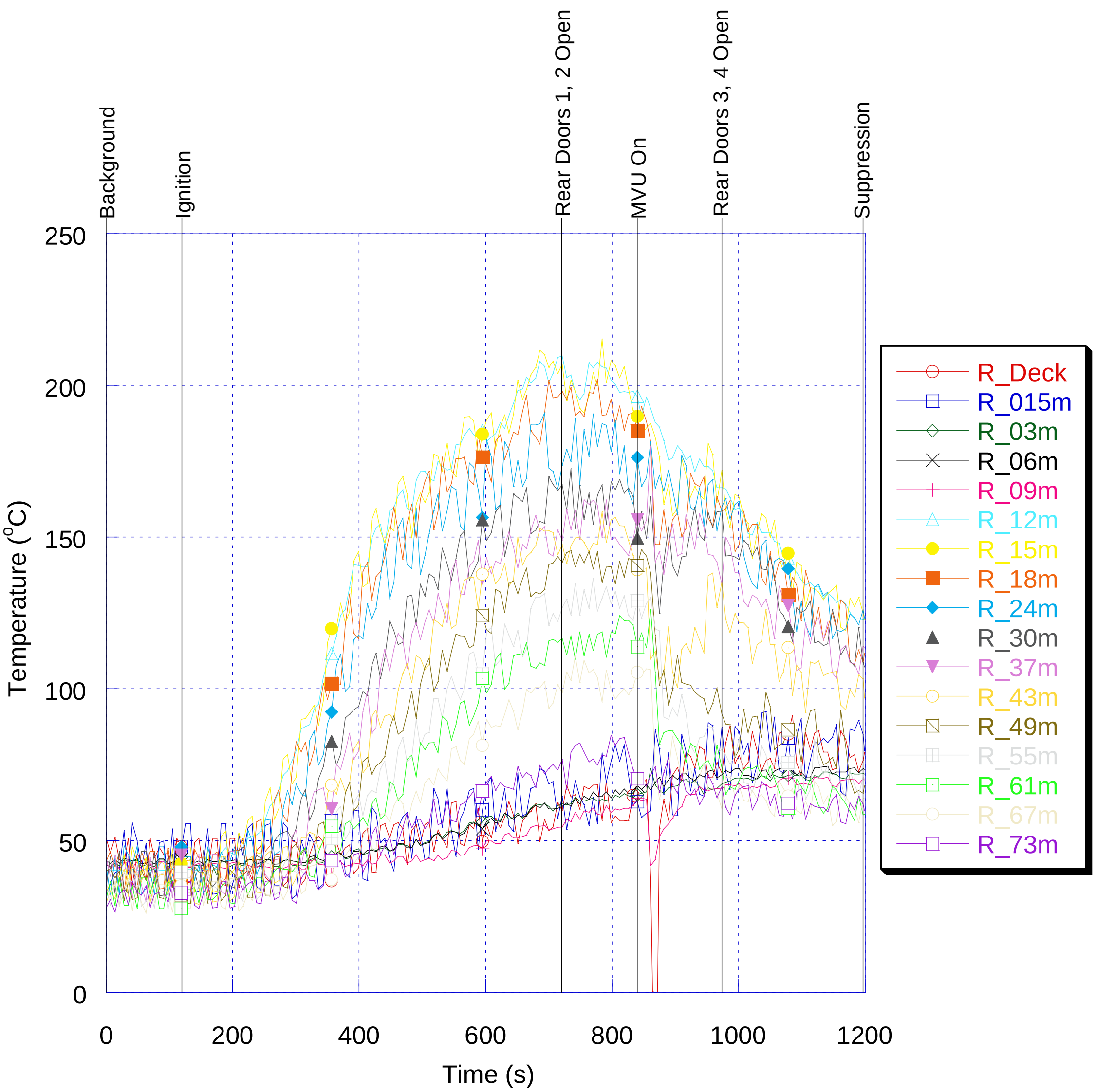

Figure 334. Experiment GF11 Temperature vs. Time for Location R

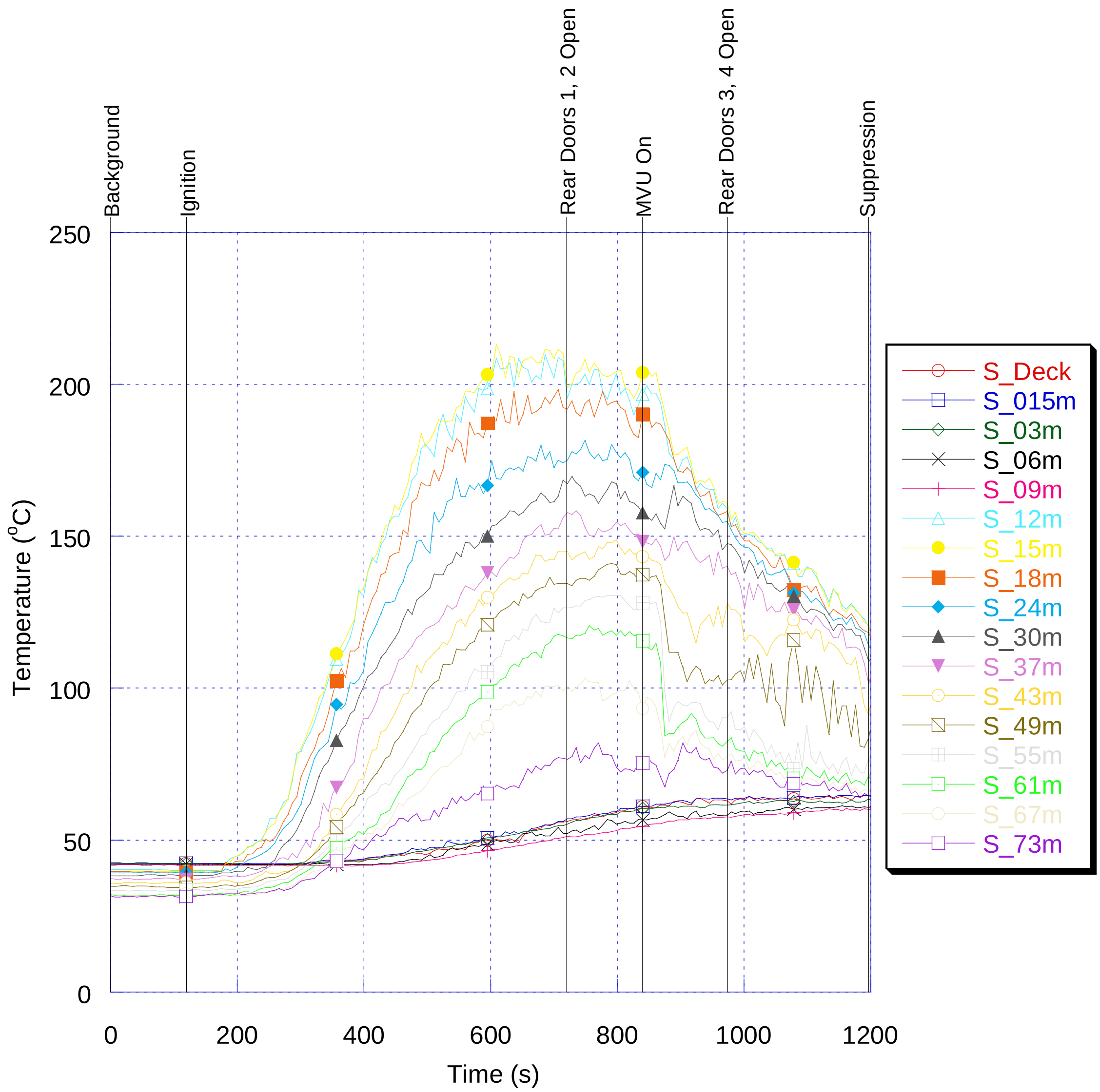

Figure 335. Experiment GF11 Temperature vs. Time for Location S

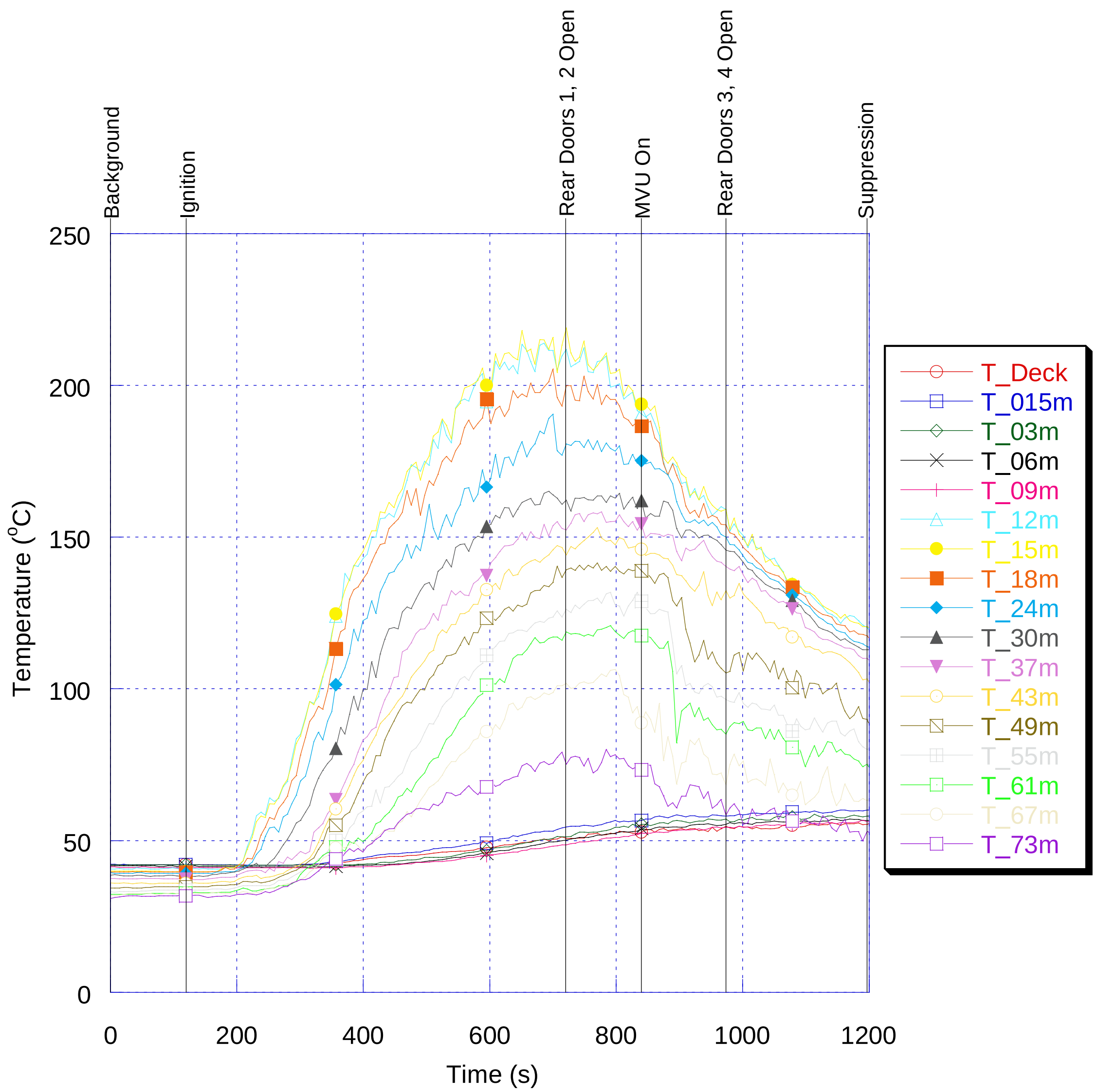

Figure 336. Experiment GF11 Temperature vs. Time for Location T

Experiment GF12

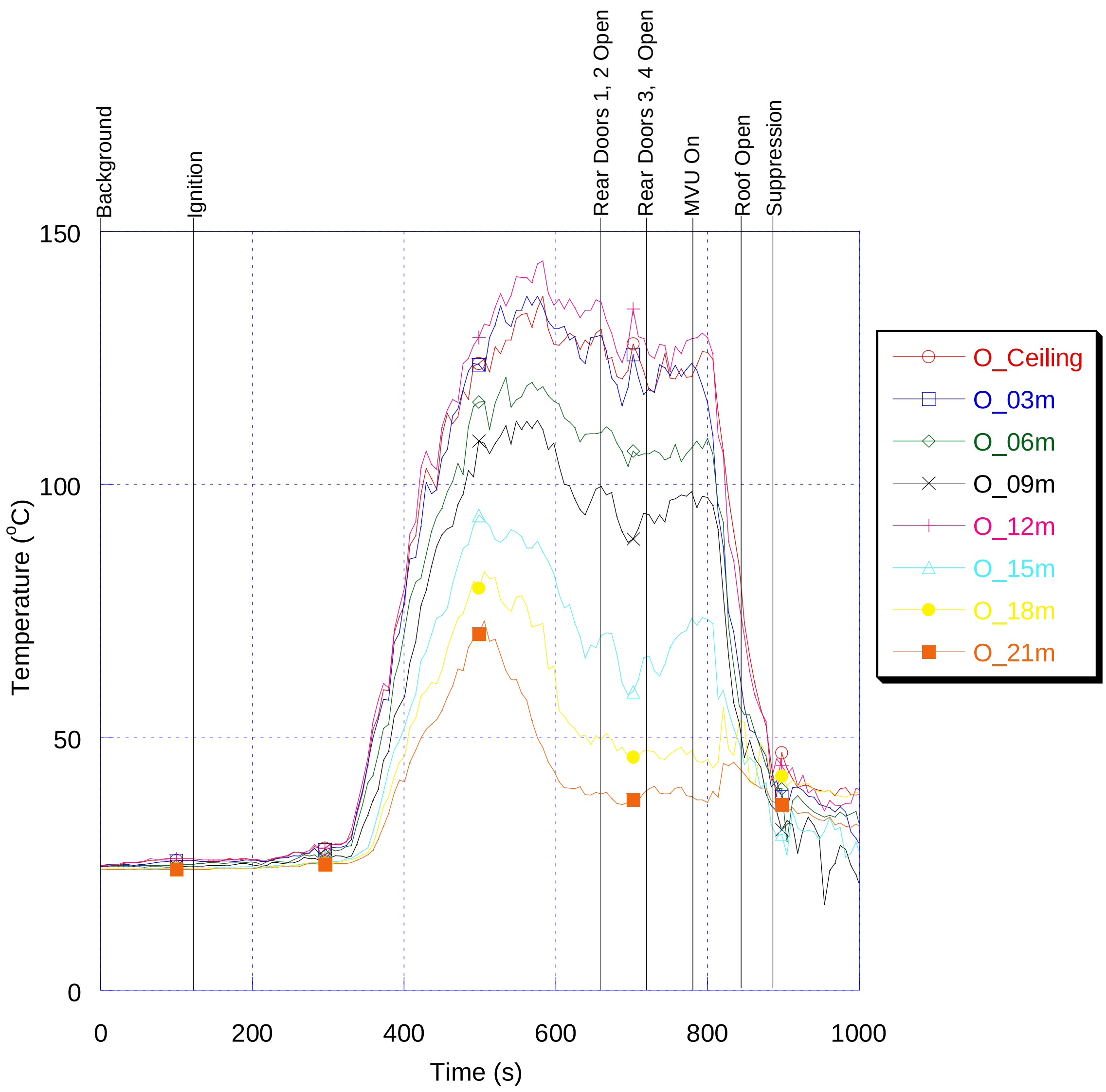

Figure 337. Experiment GF12 Temperature vs. Time for Location O

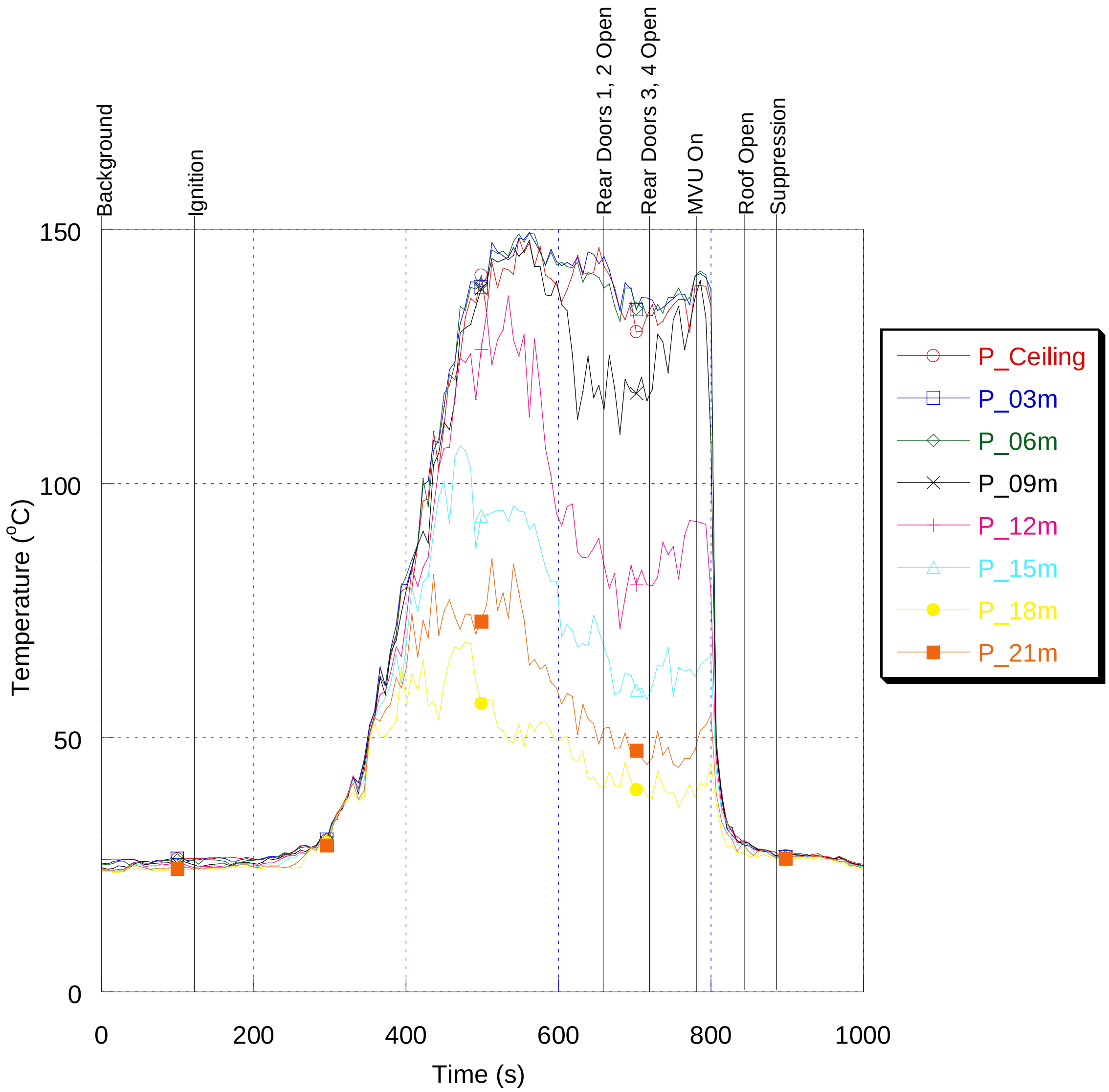

Figure 338. Experiment GF12 Temperature vs. Time for Location P

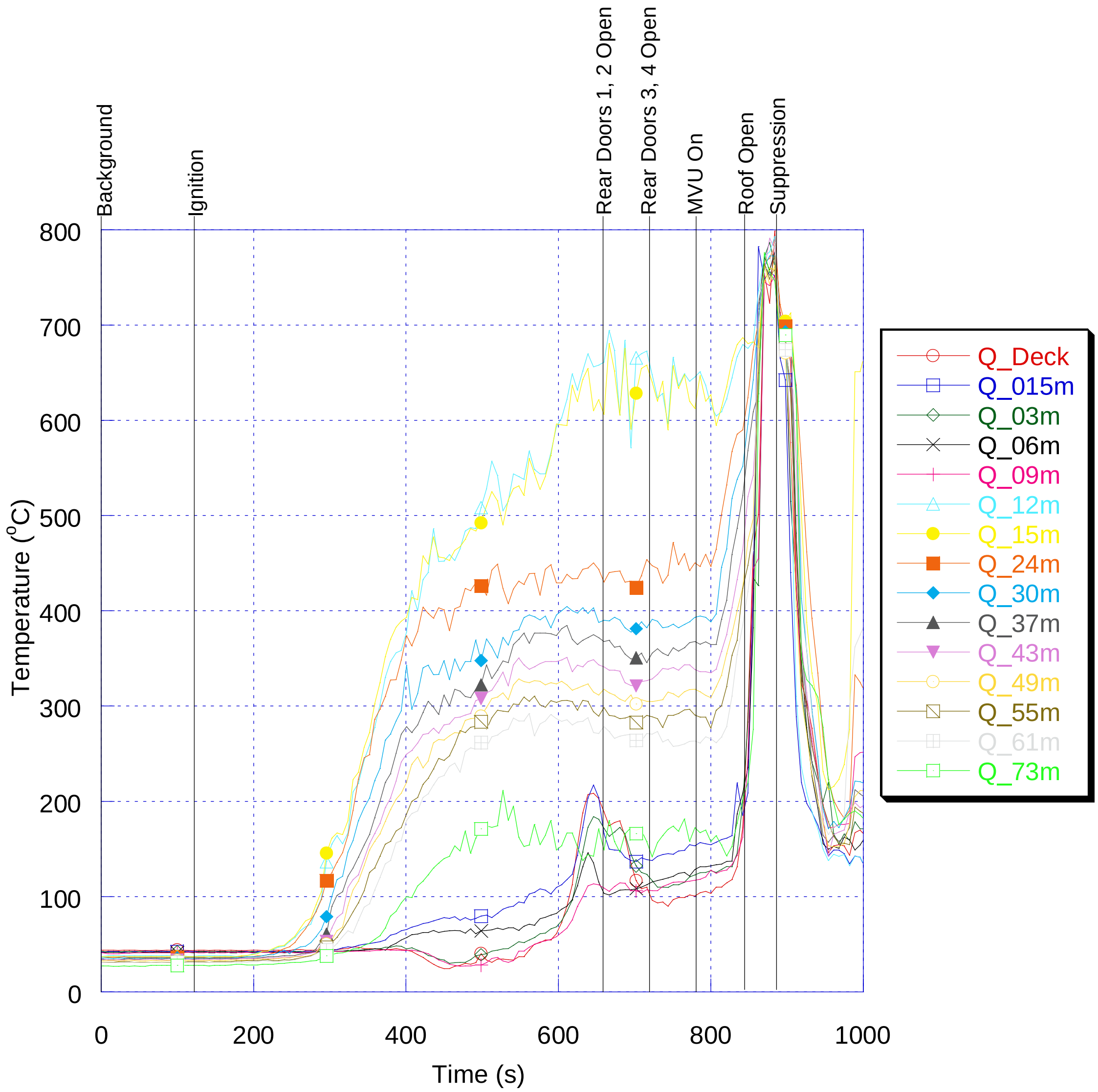

Figure 339. Experiment GF12 Temperature vs. Time for Location Q

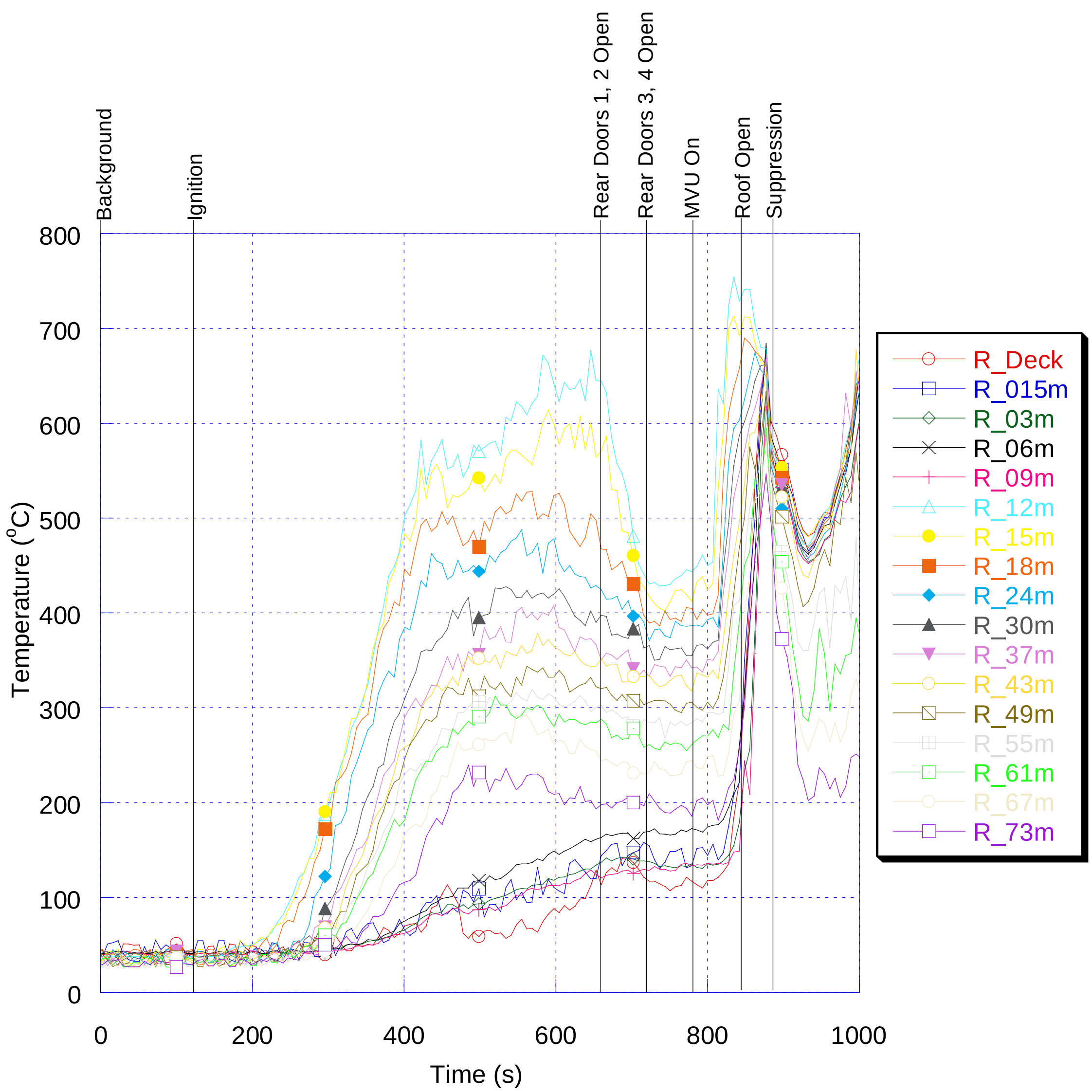

Figure 340. Experiment GF12 Temperature vs. Time for Location R

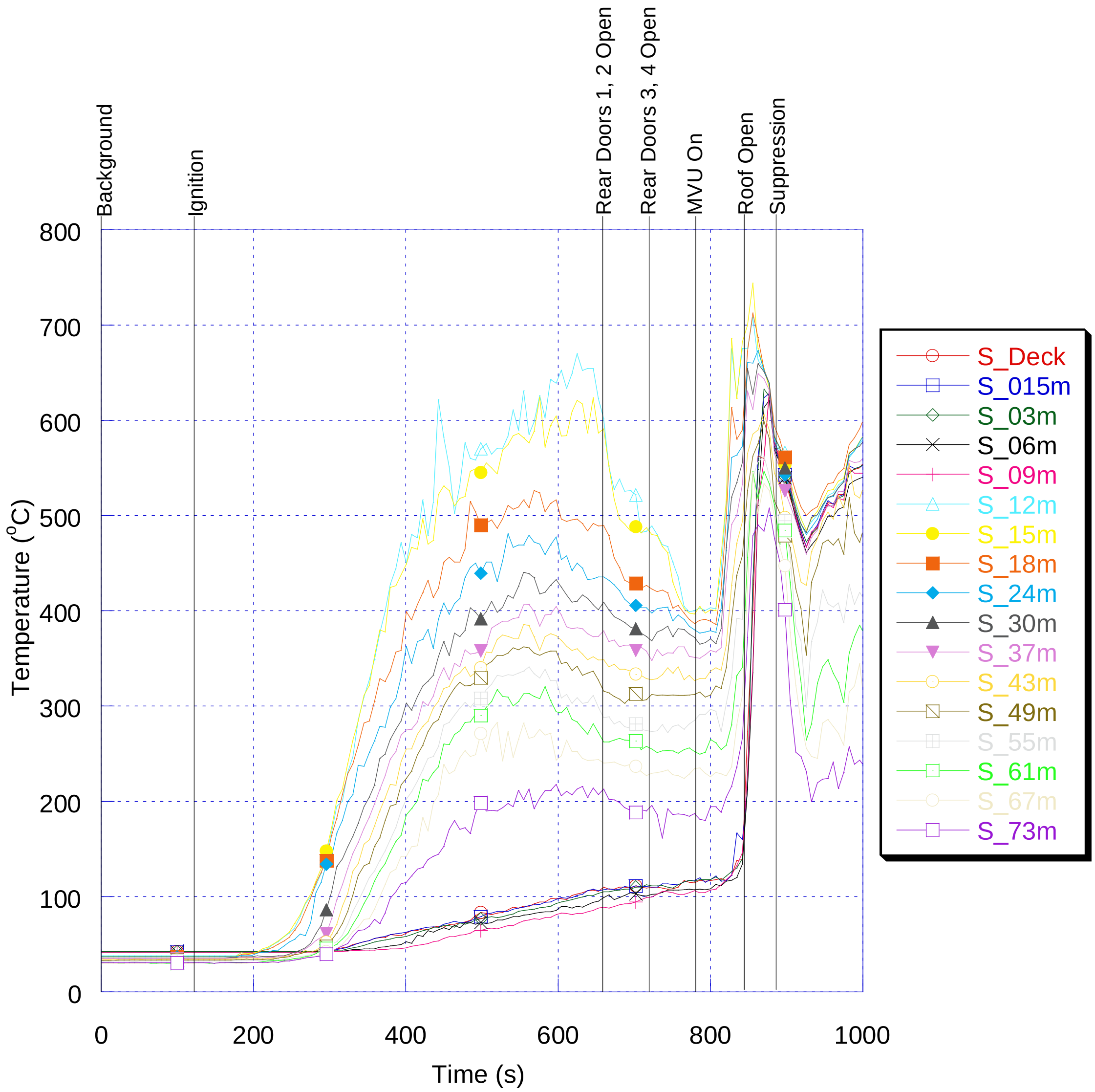

Figure 341. Experiment GF12 Temperature vs. Time for Location S

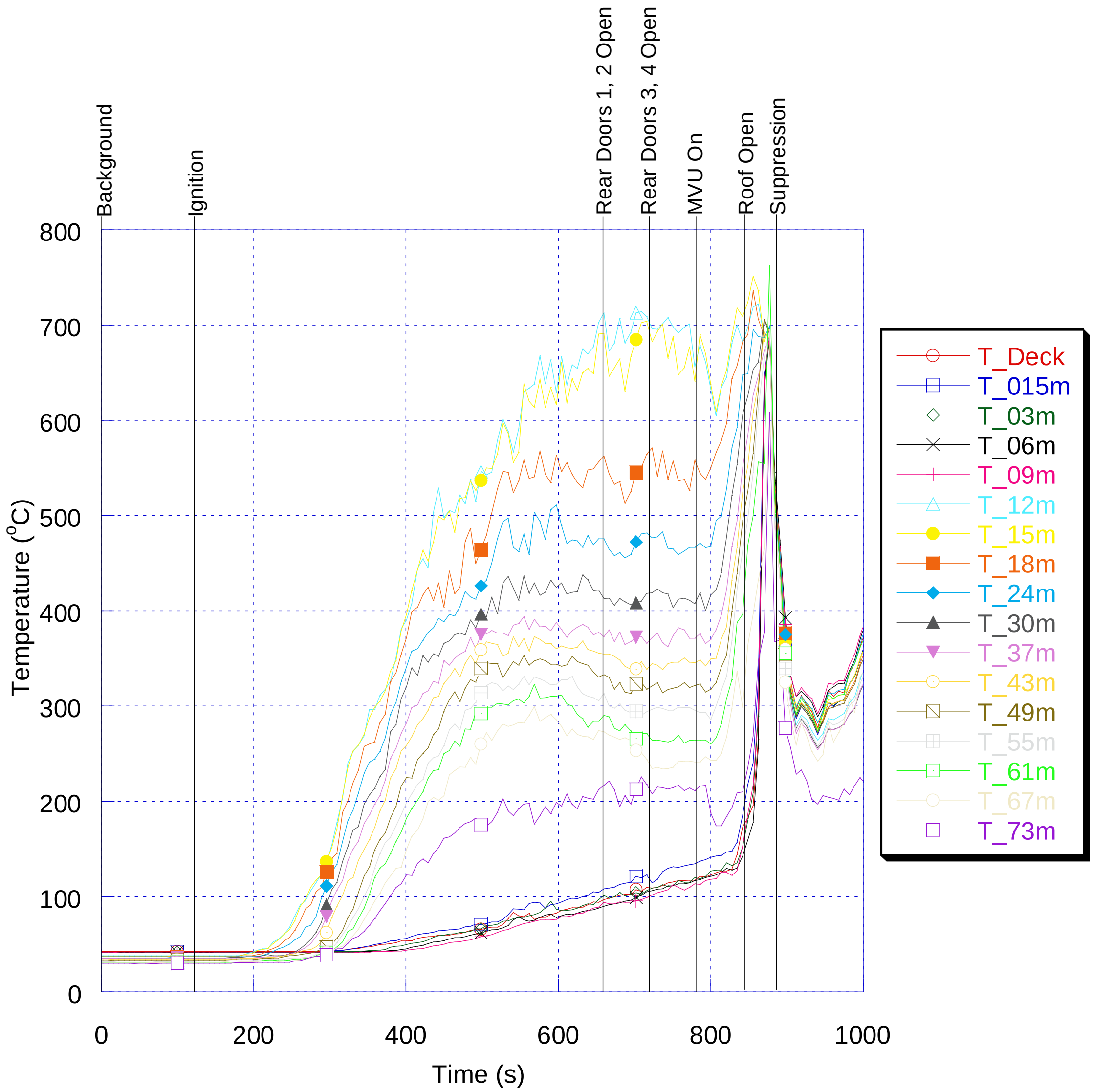

Figure 342. Experiment GF12 Temperature vs. Time for Location T