5.5 Wind Control Devices with suppression WDF 5

The fifth experiment in the series was conducted to examine the impact of wind on the structure fire and quantify the impact of the small wind control device. It also examined the impact of a 30 gpm water flow to be applied in conjunction with the WCD deployment. The experimental preparations were made as described in Section 4. The fan speed used in this experiment was 1500 RPM, which provided a 3.0 m/s to 4.0 m/s (7 mph to 9 mph) wind speed at the window opening. A trash container fuel package was ignited remotely with and electric match to start the experiment at Time = 0 s. A time line of the experiment is presented in Table 5.5-1. The results for the experiment are presented in the following sections: observations, heat release rate, temperature, heat flux, pressure, velocity, and gas concentrations. An uncertainty range marker is included in each graph.

Table 5.5-1. Experiment 5 Timeline

Time (s)	Event
0	Ignition
90	Visible smoke layer
230	Window vented partially
233	Hot gas flow to floor in corridor IR
235	Window cleared
328	WCD on
392	Window sprinkler on
506	Fan off
513	WCD off
595	Sprinkler off
653	Test complete

5.5.1 Observations

The observations are presented as a series of images captured from eight camera locations, six were video cameras and two were thermal imaging cameras. The camera positions are shown in Figure 4.1.3-1.

Figure 5.5.1-1 through Figure 5.5.1-13, present sets of eight images one from each camera position, at a given time, from the time of ignition to 515 s after ignition. Each image view is labeled. The first four views at the top of each figure show the west wall and window of the structure and then follow a path through the interior of the structure with a view of the bed room, the living room and a view (looking west) through the open door to the corridor. The second set of four views, at the bottom of each figure, provides a video view of the north east portion of the corridor and a view of the inside of the target room door. The thermal imaging cameras provided a view of the east corridor, looking north, and a view of the inside of the target room.

Figure 5.5.1-1 shows the conditions at the time of ignition. At this point, the six video views are clear and unobstructed. However, the thermal images provide limited thermal contrast because the surfaces in the view were at nearly equal temperature.

The images in Figure 5.5.1-2 were captured 60 s after ignition. The fire from the trash container began to spread to the bed. There was very little smoke being produced and a layer has yet to develop. There was also no smoke or change in thermal condition in the living room, target room or corridor at this time.

The images in Figure 5.5.1-3 were recorded at 120 s after ignition. The fire had spread to the area between the bed and the upholstered chair with a flame height of approximately 1.2 m (4 ft) above the floor. The smoke layer was approximately 0.9 m (3 ft) thick throughout the bedroom. Smoke was beginning to spread through the hallway and into the living room. No smoke and heat had made it into the corridor at 120 s. The target room appears clear of smoke.

Figure 5.5.1-4 shows the images recorded at 180 s after ignition. The fire had spread across the left side of the bed and the smoke layer in the bedroom had descended to 0.9 m (3 ft) above the floor. The smoke layer in the hallway and living room had also dropped to 0.9 m (3 ft) above the floor. Smoke was flowing out of the doorway from the living room to the corridor and moving toward the vent.

Figure 5.5.1-5 shows the conditions at 240 s after ignition. The image shows the conditions just after the window was manually cleared. Flames are seen moving across the floor level in the bedroom and the camera views in the living room, hallway and corridor are obscured by smoke. The image from the corridor IR camera shows hot gases exiting the living room, filling the doorway top to bottom and impinging on the east wall of the corridor. Heat was flowing around the entire perimeter of the hall door into the target room, as shown in the thermal image of the target room.

Figure 5.5.1-6 was captured at 257 s after ignition. Flames were pulsing out of the top of the window opening. Flames can be seen in the bedroom at the floor level, coming through the hallway and into the living room. Flames are shown extending out through the doorway into the corridor from top to bottom. The metal door to the target room had flames coming from under of the door and a smoke layer was beginning to form in the target room.

Figure 5.5.1-7 shows the conditions at 300 s after ignition. Flames were pulsing out of the top of the window opening. Smoke was obscuring the views in the bedroom, living room and corridor. The amount of heat entering the hallway has caused the image from the corridor IR camera to deteriorate substantially. The visual image in the target room showed flames continuing to burn under the door. The visibility at the lower layer in the target room remained good.

The images in Figure 5.5.1-8 were recorded at 327 s after ignition, just prior to the deployment of the small wind control device. Flames were flowing out of the window opening and visibility was worsening in the entire fire facility. The cameras from the bedroom and corridor were completely obscured by smoke, but the glow of flames was visible in the living room.   The thermal view of the corridor continued to show large quantities of heat but the ability to view any of the structure was lost. The target room video view continued to show flames around the bottom of the target room door. The thermal view shows the outlines of the metal door detail, as the door had increased in temperature.

At 335 s after ignition, the wind control device was deployed and in place as shown in the outside view of Figure 5.5.1-9. The interior video views were obscured by soot and a glow was still visible in the living room. The thermal view of the corridor no longer showed any hot gas flows, only a hot gas atmosphere. Conditions in the target room did not appear to have changed significantly but the flames pulled back under the door to the hallway.

Figure 5.5.1-10 shows the conditions at 360 s after ignition, or approximately 30 s since deployment of the wind control device. The interior video views were still obscured by soot. The thermal image from the corridor was still saturated with heat. In the target room the door continued to to heat up but remained fully intact. White smoke obscured the view in the target room.

Figure 5.5.1-11 shows the conditions at 420 s after ignition, which was about 30 s after the window sprinkler was activated. The interior video views were still obscured by soot. The target room thermal image shows the door is cooling down slightly.

The images in Figure 5.5.1-12 were recorded at 480 s after ignition, and 88 s after the window sprinkler was activated. There was very little change in any of the video or thermal images. Figure 5.5.1-13 shows the conditions just after the WCD was removed from the window after the experiment was terminated at 500 s. There were no flames coming out of the bedroom and the fire was knocked down significantly, but not completely extinguished.

Figure 5.5.1-1. Experiment 5, ignition.

Figure 5.5.1-2. Experiment 5, 60 s after ignition.

Figure 5.5.1-3. Experiment 5, 120 s after ignition.

Figure 5.5.1-4. Experiment 5, 180 s after ignition.

Figure 5.5.1-5. Experiment 5, 240 s after ignition.

Figure 5.5.1-6. Experiment 5, corridor flames, 257 s after ignition.

Figure 5.5.1-7. Experiment 5, 300 s after ignition.

Figure 5.5.1-8. Experiment 5, WCD deployed, 327 s after ignition.

Figure 5.5.1-9. Experiment 5, WCD in place, 335 s after ignition.

Figure 5.5.1-10. Experiment 5, 360 s after ignition.

Figure 5.5.1-11. Experiment 5, 420 s after ignition.

Figure 5.5.1-12. Experiment 5, 480 s after ignition.

Figure 5.5.1-13. Experiment 5, WCD removed, 515 s after ignition.

5.5.2 Heat Release Rate

Figure 5.5.2-1 shows the heat release rate time history for Experiment 5. The increase in measured heat release rate is delayed because for the first 100 s after ignition no heat or combustion products generated by the fire flowed out of the structure. After the window failed, at 230 s after ignition, the increase in heat release rate was clear. The heat release rate reached a peak of approximately 19 MW, 70 s after window failure. The small WCD was deployed and in place at 328 s after ignition. This resulted in a significant decrease in heat release rate. Within 10 s after the WCD was in place the heat release rate dropped from approximately 18 MW down to approximately 5 MW. Approximately 60 s after WCD deployment a low flow nozzle was turned on flowing 1.9 l/s (30 gpm) into the bedroom, behind the WCD. This caused the HRR to continue to decline for the duration of the experiment.

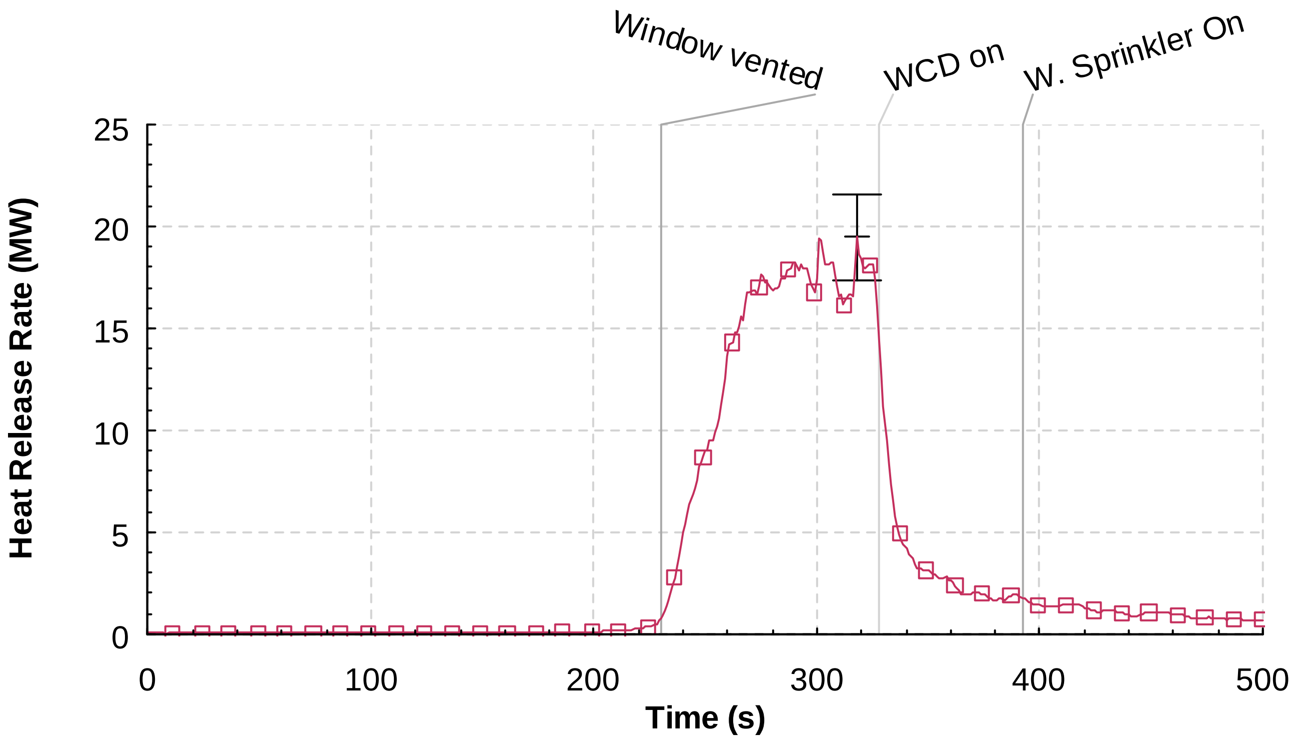

Figure 5.5.2-1. Heat release rate versus time, Experiment 5.

5.5.3 Temperatures

Figure 5.5.3-1 through Figure 5.5.3-11 provides the temperature measurements from the thermocouple arrays shown in Figure 4.1.3-1. The figures are given in order from the western most measurement point, the bed room window opening, and moving through the structure toward the east; bedroom, hall, living room, corridor, south and southwest portions of the corridor (closed end) and then to the north section of the corridor and ending with the exhaust vent. The last two temperature graphs have temperatures associated with the target room.

The three thermocouples located in the window opening, shown in Figure 5.5.3-1, provide insight into the ventilation conditions at the window. After window failure at 230 s temperatures fluctuate as the flames are pulsing out of the window and wind is blowing into the window. The highest temperatures are located in the top of the window opening. Once the WCD was deployed, the temperatures steadied, and ranged from 500 ºC (932 ºF) at the top to 200 ºC (392 ºF) at the bottom of the window. The temperatures then declined substantially after the activation of the low flow nozzle.

The measurements from the thermocouple array located in the center of the bedroom are given in Figure 5.5.3-2. Prior to the window failure, the temperatures in the bedroom increased from ambient conditions to a peak of approximately 750 ºC (1382 ºF) near the ceiling. At the same time, the temperatures, 2.13 m (7.00 ft) below the ceiling, were almost 100 ºC (212 ºF). After the window vented, the wind mixed and slightly cooled the gases in the room. This condition only lasted about 10 s, and then the temperatures from the ceiling down to 1.52 m (5.00 ft) below the ceiling began to increase and stratify again. Flashover conditions were reached, based on temperatures from ceiling to floor being in excess of 600 ºC (1112 ºF), at approximately 250 s after ignition and 20 s after window failure. The WCD was deployed at 328 s. Within 50 s of deployment temperatures had decreased from in excess of 800 ºC (1472 ºF) to less than 500 ºC (932 ºF). At 392 s the low flow nozzle was activated and the temperatures in the room stratified. The ceiling temperature increased to 550 ºC (1022 ºF) and the lower layer temperatures decreased to less than 200 ºC (392 ºF).

The data from the hall thermocouple array is presented in Figure 5.5.3-3. The temperatures slowly increased as the fire in the bedroom developed. The ceiling temperature in the hallway reached approximately 400 ºC (752 ºF), while the temperature 2.13 m (7.00 ft) below the ceiling was still ambient. At 260 s, 30 s after window failure the temperatures from floor to ceiling were in excess of 800 ºC (1472 ºF). Temperatures remained above 600 ºC (1112 ºF) until the WCD was deployed at 328 s. The temperatures were uniform at 1100 ºC (2012 ºF) from the floor to the ceiling just before blanket deployment and decreased to below 500 ºC (932 ºF) in 60 s. The hallway temperatures continued to decrease after the activation of the low flow nozzle into the bedroom.

The data from the living room corner thermocouple array is shown in Figure 5.5.3-4. At 230 s, after window failure, the temperatures from floor to ceiling were in excess of 600 ºC (1112 ºF) after 20 s. Temperatures remained above 550 ºC (1022 ºF) until the WCD was deployed at 328 s. The temperatures continually decreased to below 450 ºC (842 ºF) until the low flow nozzle was activated. After the low flow nozzle was activated at 392 s the temperatures continually declined to below 250 ºC (482 ºF) at the termination of the experiment. This suggests that the combination of a WCD and water application into the bedroom does not allow for burning in the living room.

The temperatures from the center of the living room are shown in Figure 5.5.3-5 for the time history of the experiment. Again there was a dramatic temperature increase seconds after the window failure. As the hot gases were forced through the living room the temperatures elevated from 300 ºC (572 ºF) at the ceiling and ambient at the floor to over 800 ºC (1472 ºF) from floor to ceiling. The temperature became steady and then there was an unknown thermocouple array failure that occurred at 280 s. Temperature data beyond that time was not used for analysis.

Temperature conditions in the corridor are given in Figure 5.5.3-6 through Figure 5.5.3-9. The three thermocouple arrays located just outside the doorway from the living room all elevated very quickly after the failure of the window. Temperatures in this area all exceeded 700 ºC (1292 ºF) at 260 s, 30 s after window failure. Temperatures were lower and there was a vertical temperature gradient in the southwest corner of the corridor, or the dead end, because it was out of the flow path of the products of combustion. Once the WCD was deployed the temperatures throughout the corridor decreased to below 400 ºC (752 ºF), with the lowest temperatures in the southwest corner. The temperature 2.13 m (7 ft) below the ceiling in the southwest corner remained below 300 ºC (572 ºF) for the duration of the experiment. After the introduction of water into the bedroom the temperatures throughout the corridor slowly declined to less than 200 ºC (392 ºF).

The temperatures at the exhaust vent are given in Figure 5.5.3-10. These thermocouples are at the same elevation located 2.44 m (8 ft) above the ceiling of the corridor. The three thermocouples are spaced 0.51 m (1.67 ft) apart along the east-west centerline of the vent. These temperatures increased from less than 100 ºC (212 ºF) to greater than 600 ºC (1112 ºF) in about 30 s following window failure. With the WCD in place these temperatures all dropped below 300 ºC (572 ºF). These lower temperatures suggest there was some mixing of fresh air in the stack with the WCD in place. Similar to the rest of the structure, after water application, the temperatures continued to decline until the termination of the experiment.

The final temperature graph displays the temperature time history for the target room (Figure 5.5.3-11). All of the temperatures remained near ambient until the window failed. After window failure, the temperature in the center of the room continually increased as heat entered the room from the hallway around the metal door. The metal door remained intact and the ceiling temperature peaked at 175 ºC (347 ºF) while the temperature 2.13 m (7 ft) from the ceiling remained below 60 ºC (140 ºF). After WCD deployment the temperatures began to converge to between 80 ºC (176 ºF) and 140 ºC (284 ºF). After water application, the temperatures all continued to decrease and were all below 100 ºC (212 ºF) at the termination of the experiment.

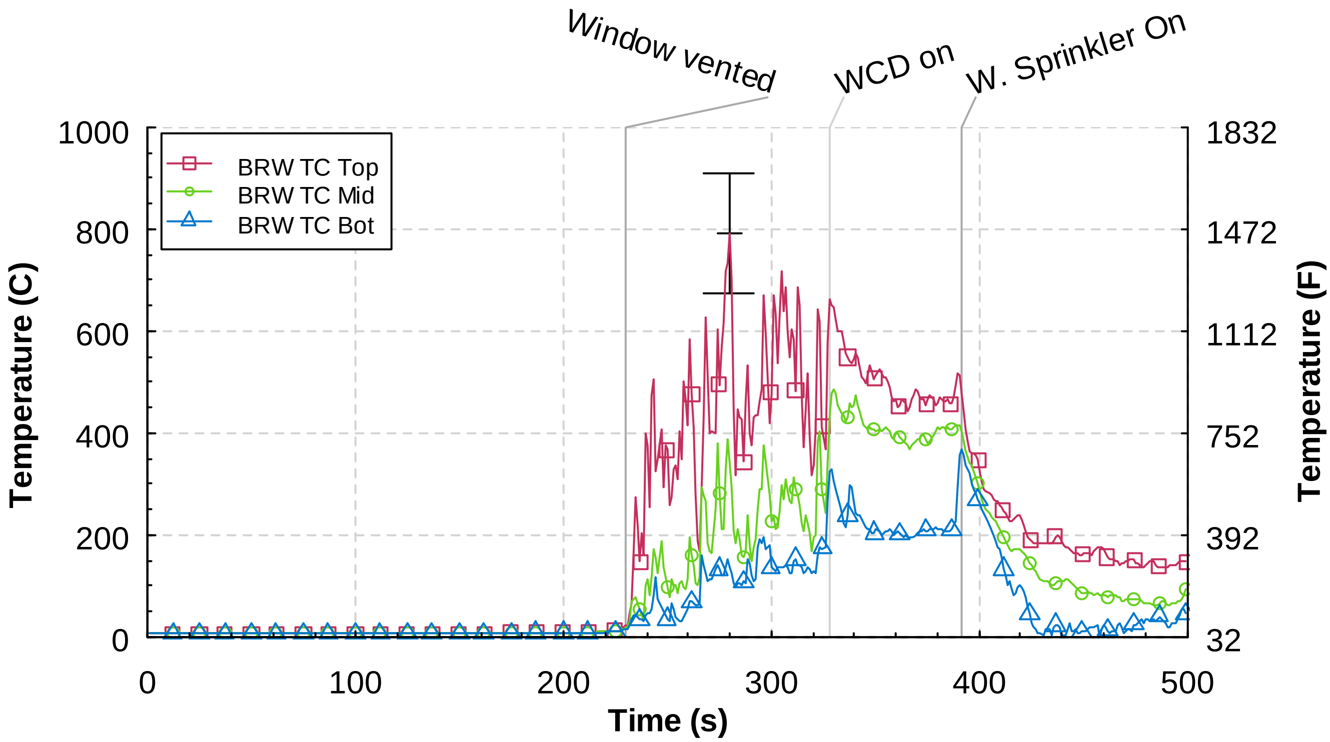

Figure 5.5.3-1. Temperature versus time from the bedroom window (BRW) thermocouple array, Experiment 5.

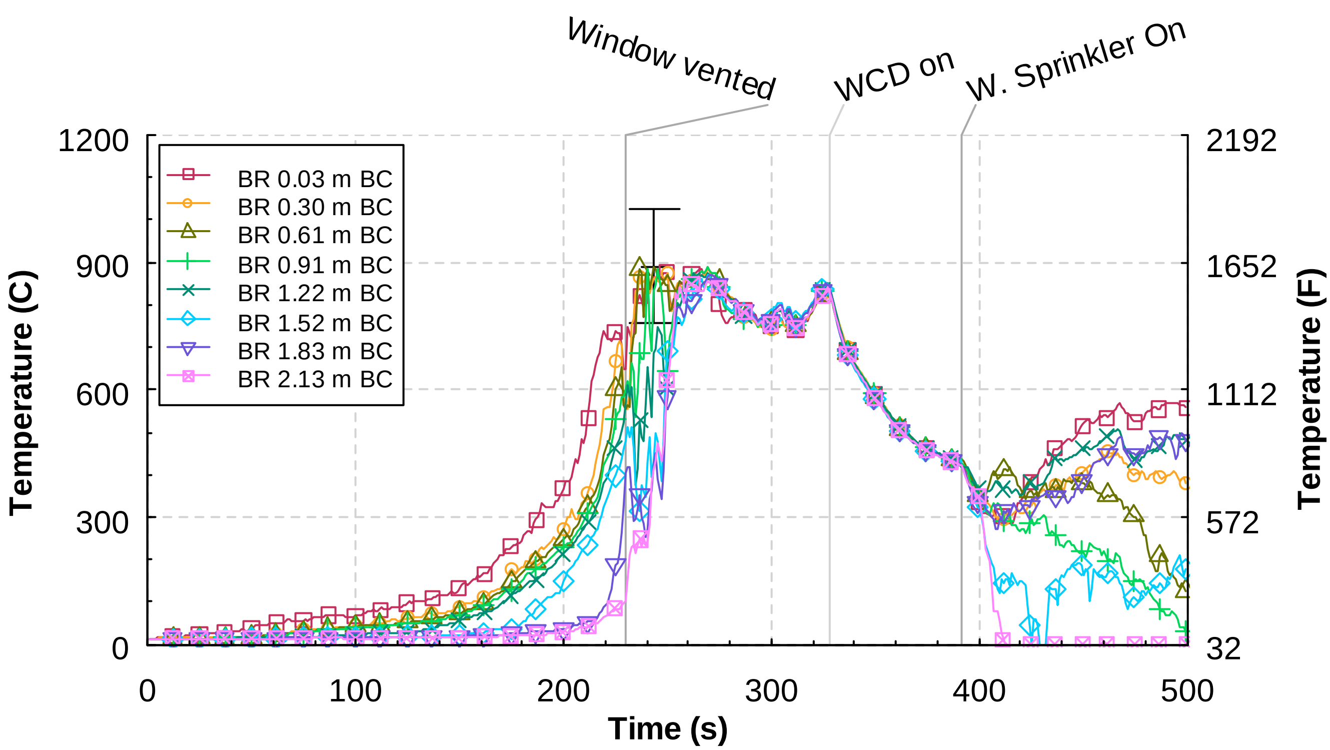

Figure 5.5.3-2. Temperature versus time from the bedroom (BR) thermocouple array, Experiment 5.

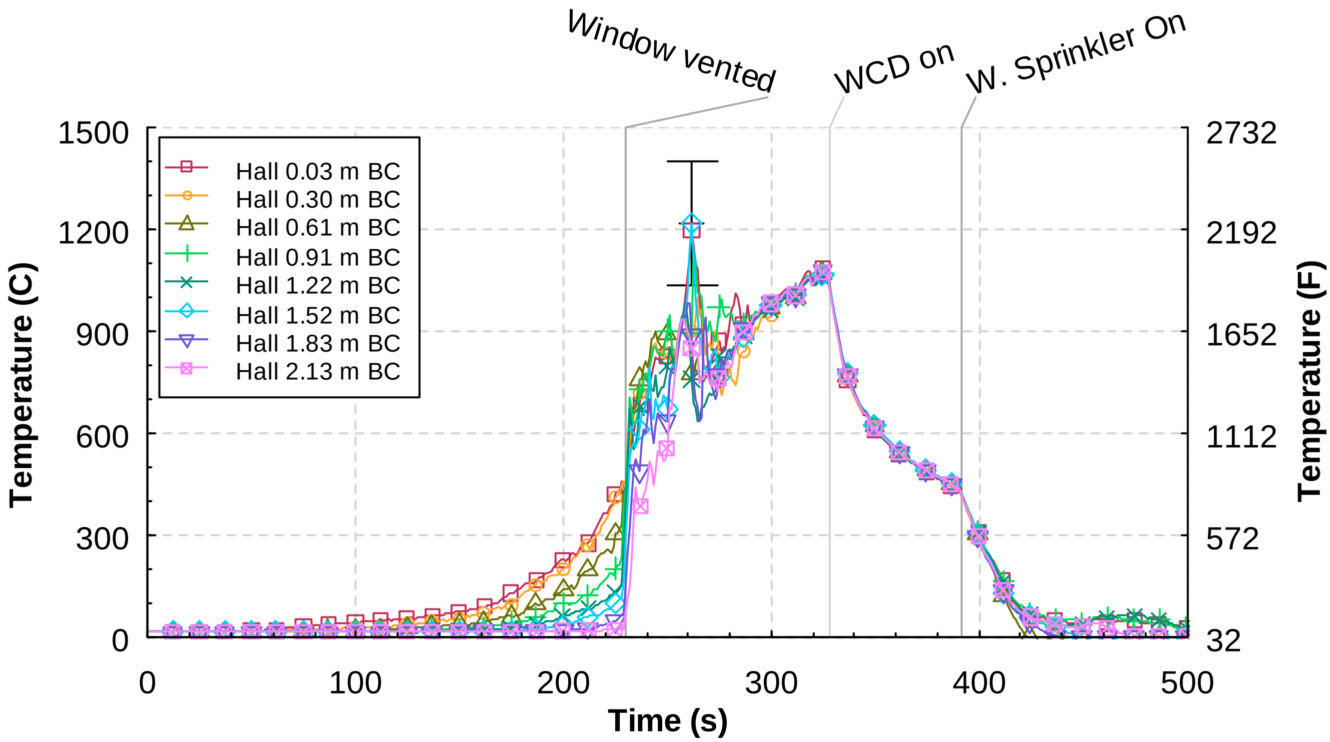

Figure 5.5.3-3. Temperature versus time from the hall thermocouple array, Experiment 5.

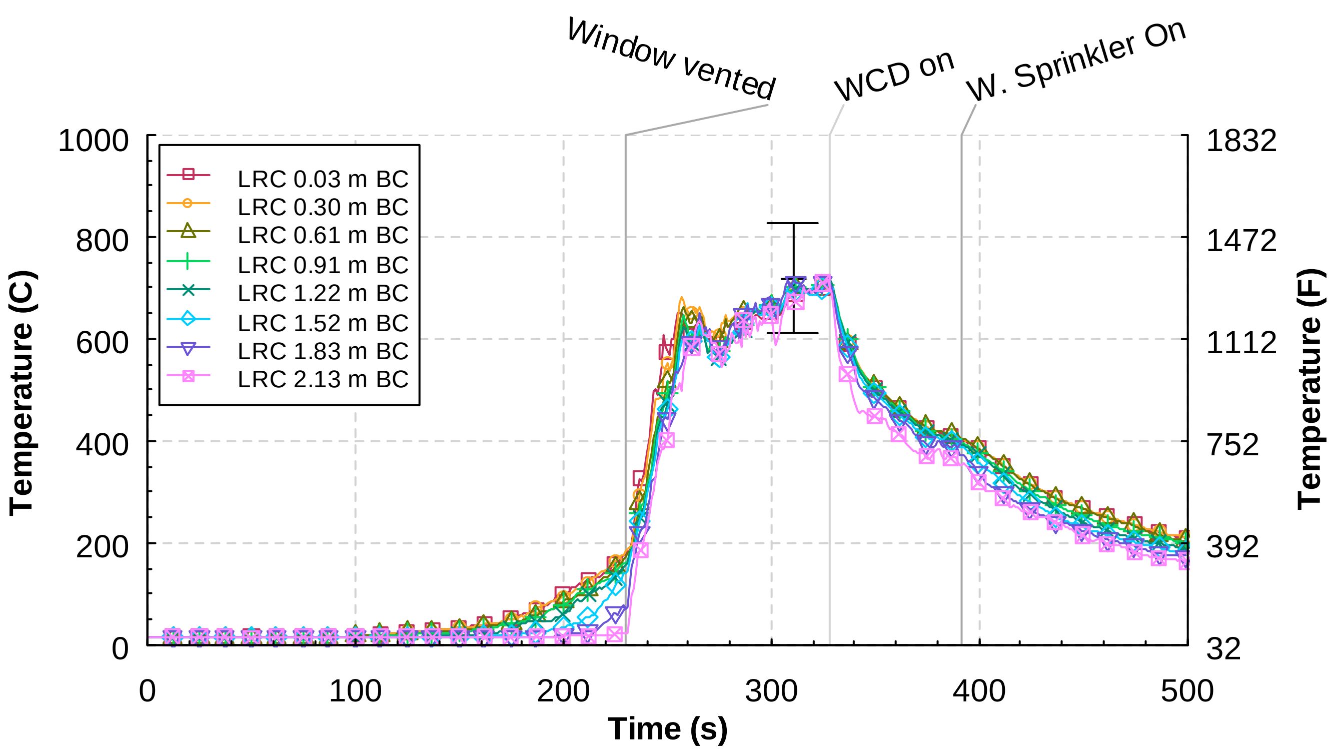

Figure 5.5.3-4. Temperature versus time from the living room corner (LRC) thermocouple array, Experiment 5.

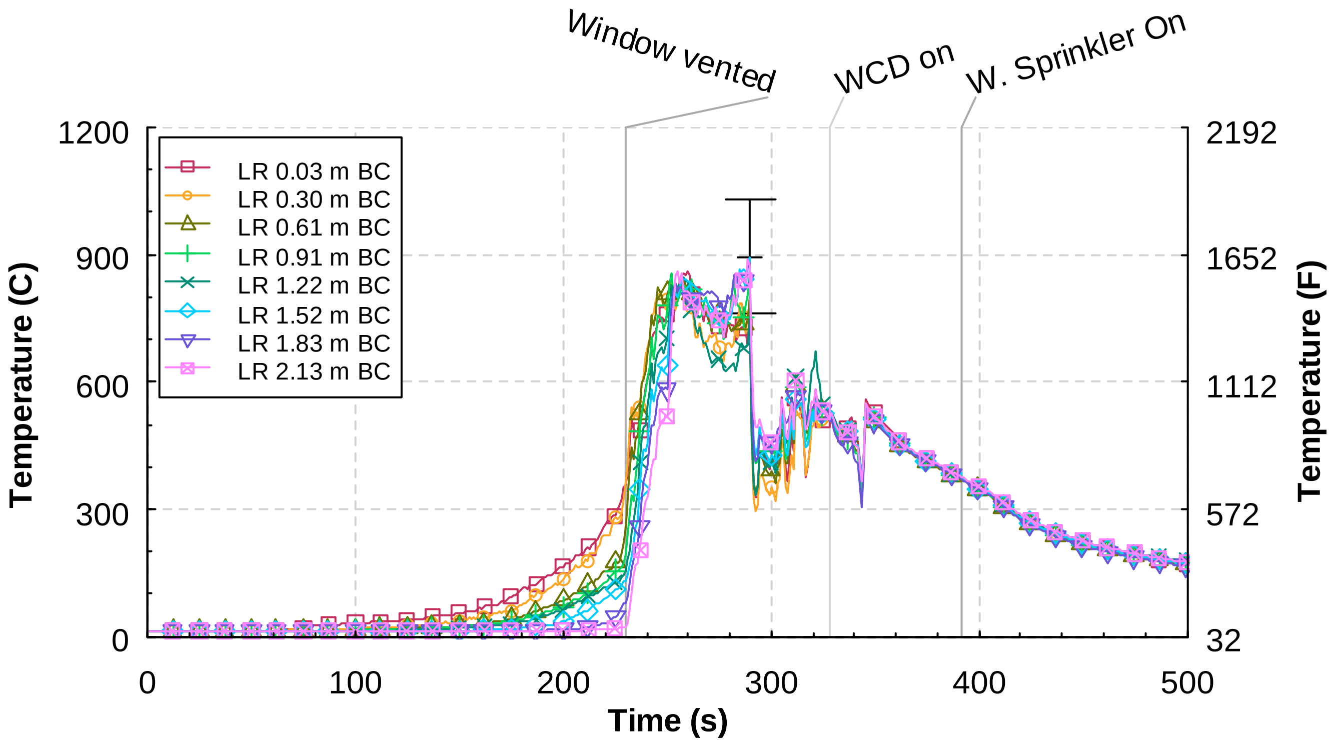

Figure 5.5.3-5. Temperature versus time from the living room (LR) thermocouple array, Experiment 5.

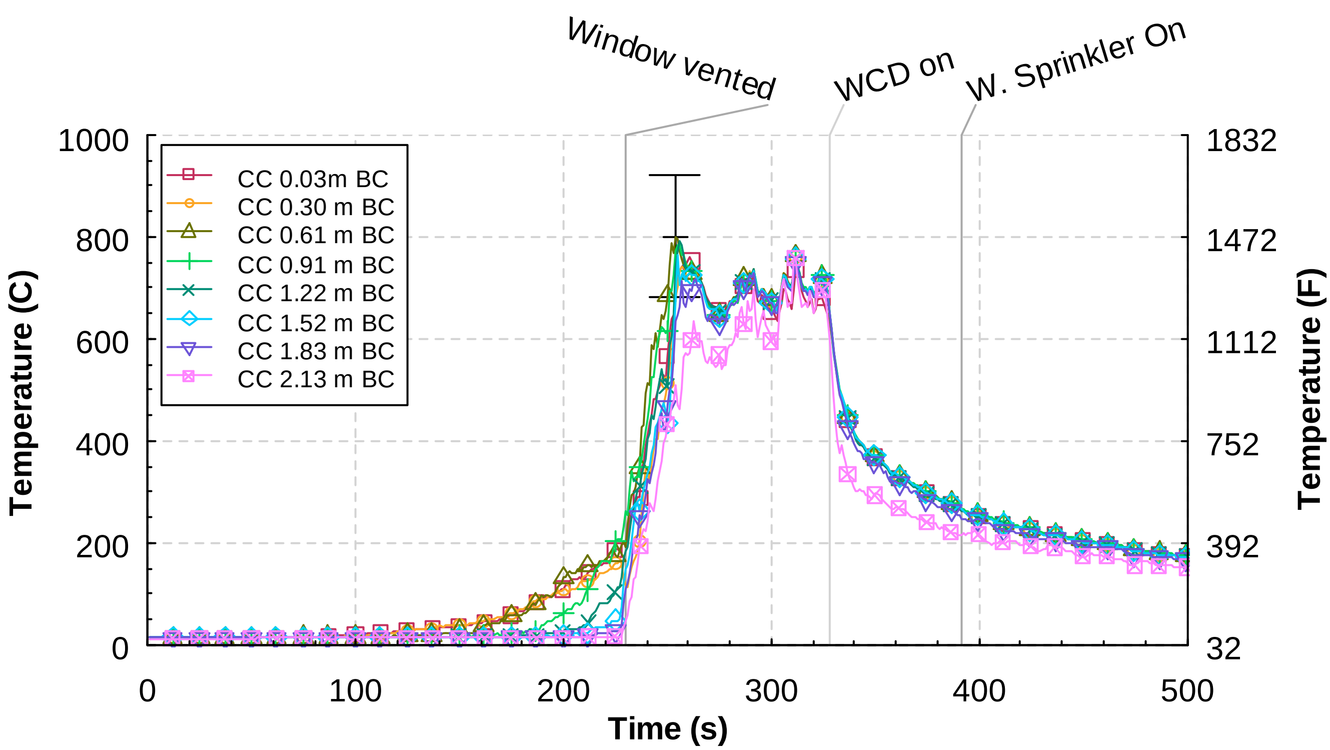

Figure 5.5.3-6. Temperature versus time from the corridor center (CC) thermocouple array, Experiment 5.

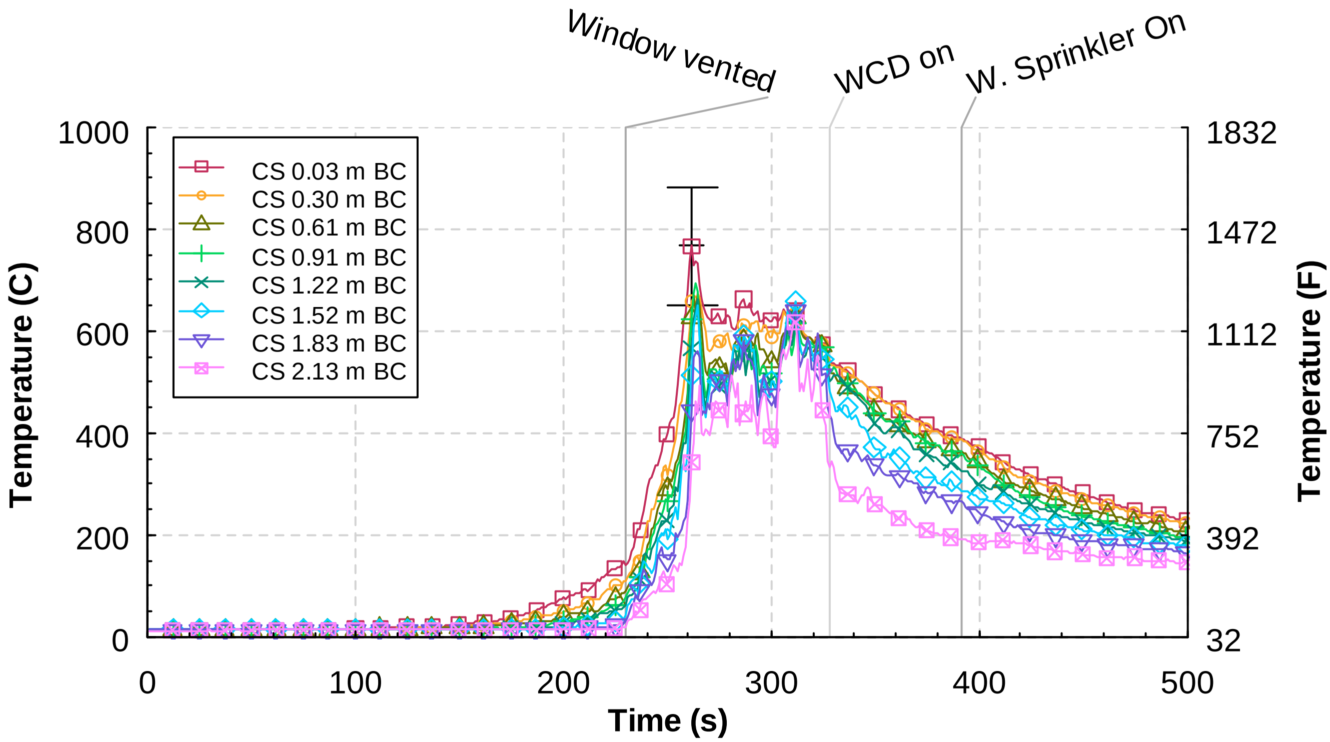

Figure 5.5.3-7. Temperature versus time from the corridor south (CS) thermocouple array, Experiment 5.

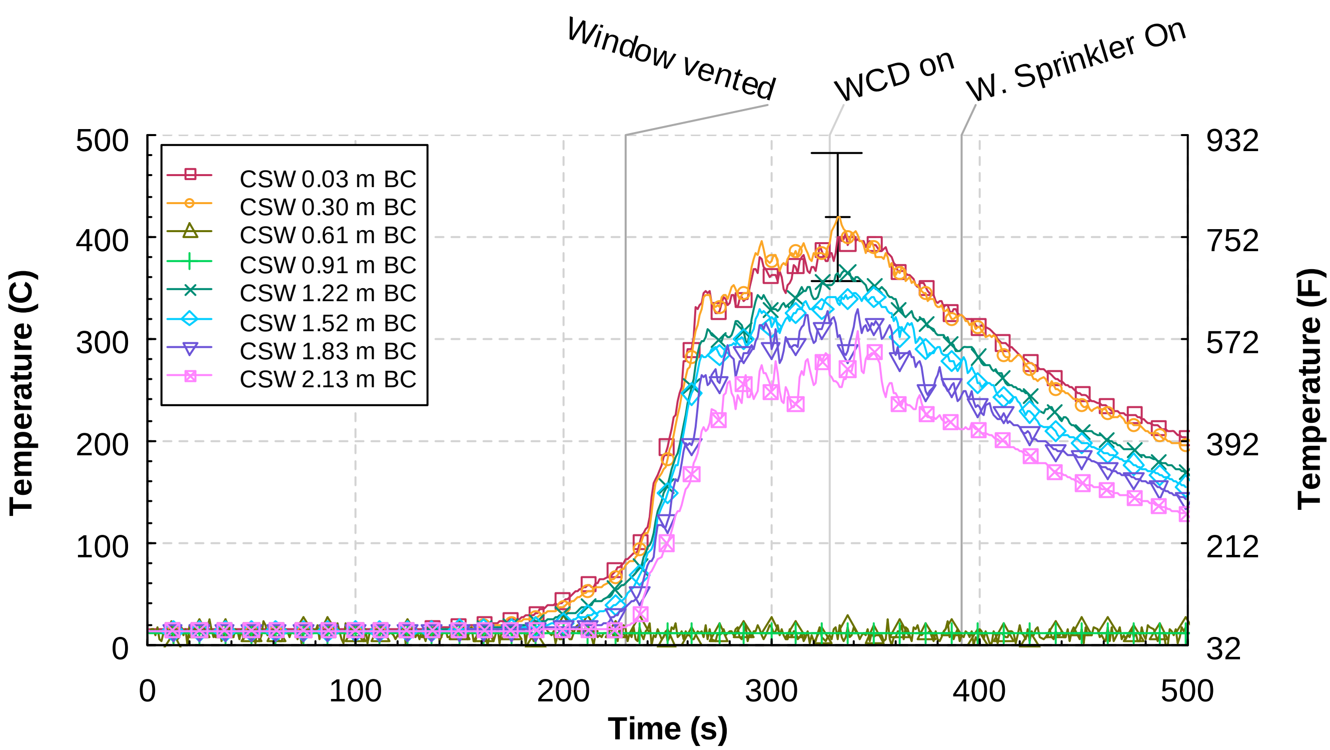

Figure 5.5.3-8. Temperature versus time from the corridor southwest (CSW) thermocouple array, Experiment 5.

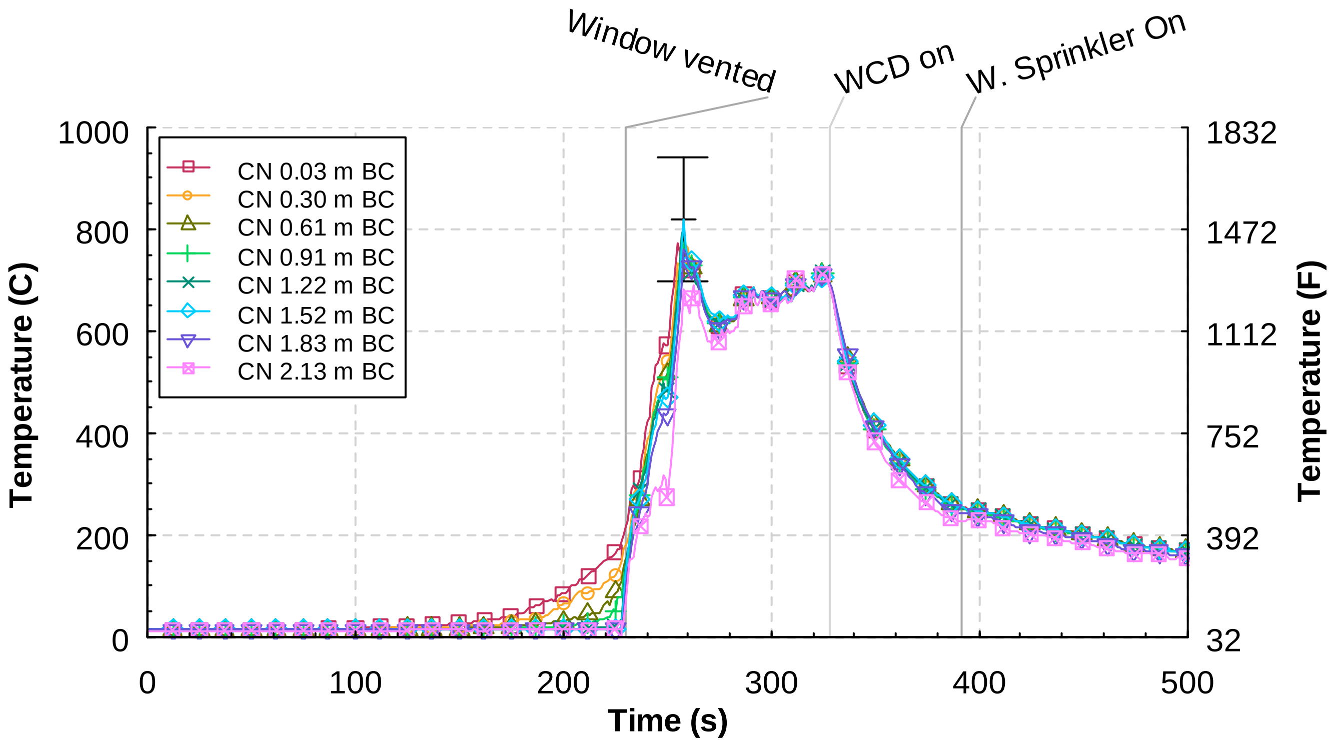

Figure 5.5.3-9. Temperature versus time from the corridor north (CN) thermocouple array, Experiment 5.

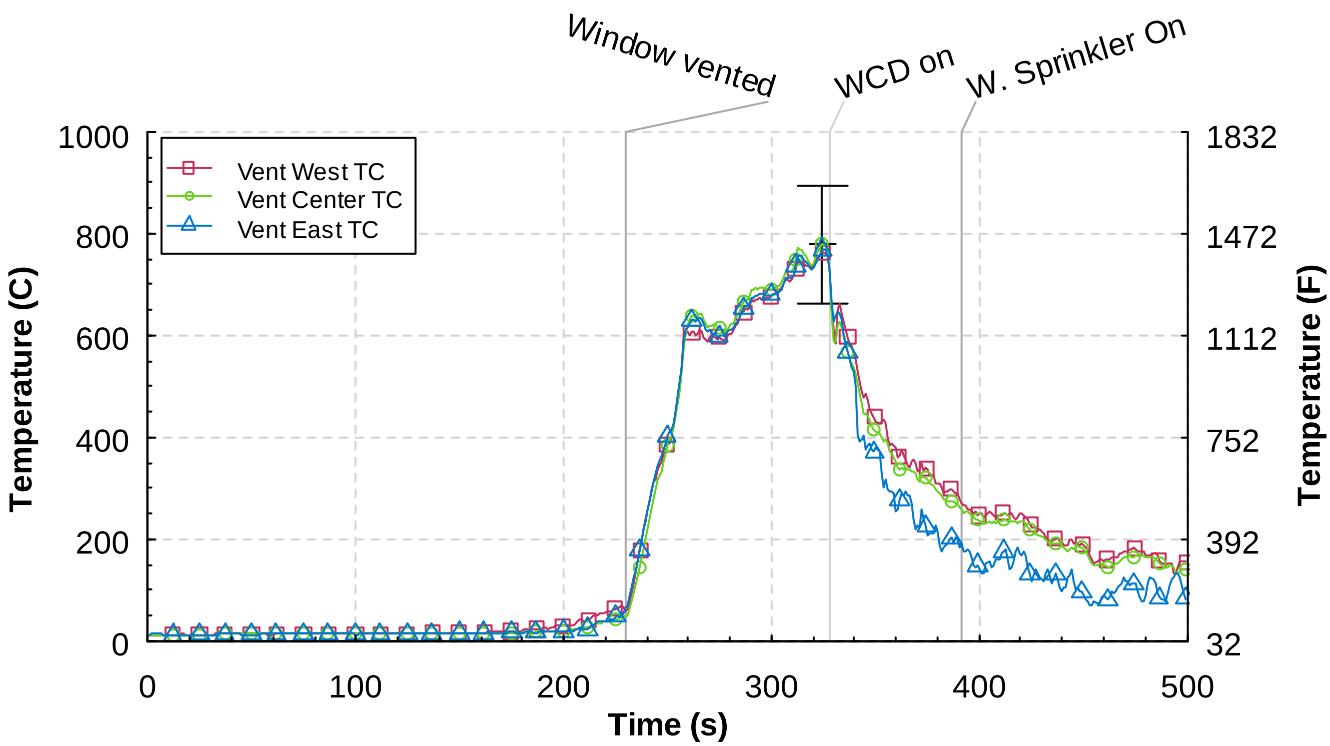

Figure 5.5.3-10. Temperature versus time from the ceiling vent thermocouple array, Experiment 5.

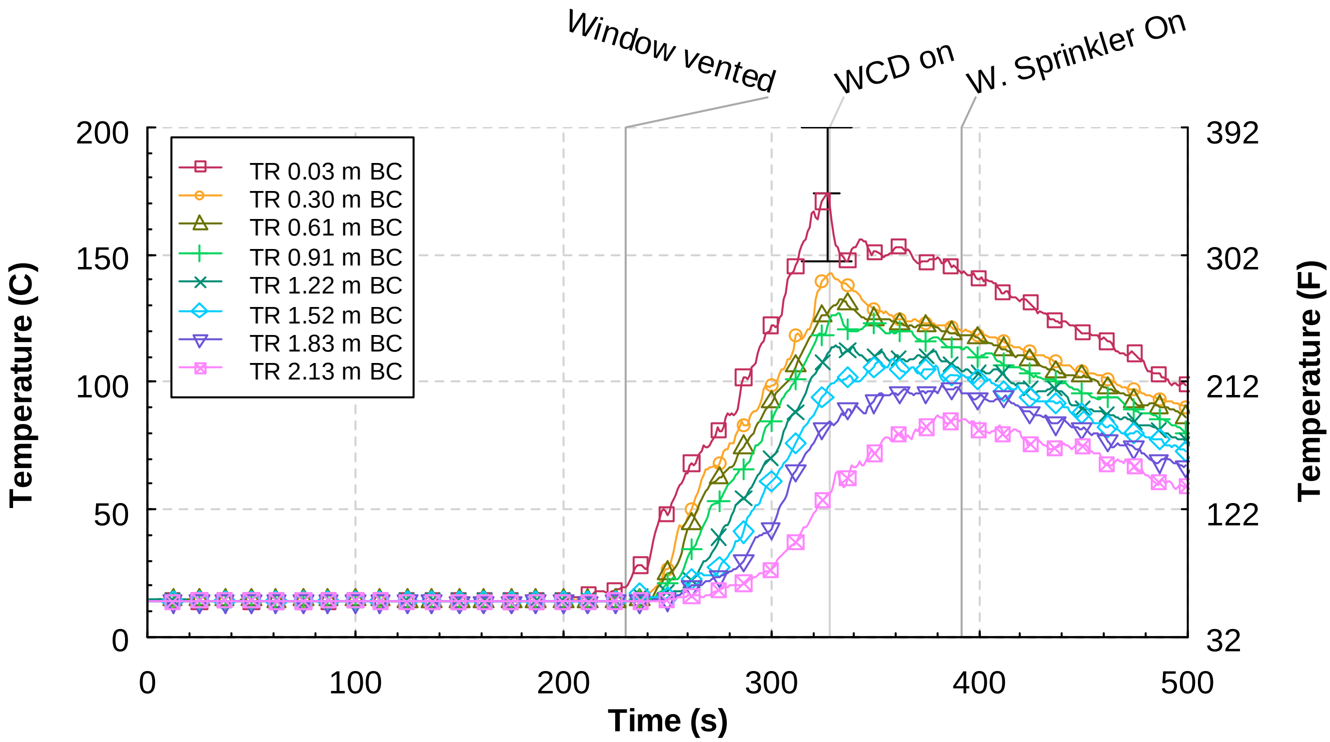

Figure 5.5.3-11. Temperature versus time from the target room (TR) thermocouple array, Experiment 5.

5.5.4 Heat Flux

The time history from all five heat flux gauges is given in Figure 5.5.4-1. The heat flux in the bedroom increased to more than 40 kW/m^2 prior to the window failure. After the window vented, the heat flux measurement in the bedroom increased to 120 kW/m^2 in 40 s. Every other heat flux measurement exceeded 60 kW/m^2 in the same period of time after window failure.

After the WCD was deployed the heat fluxes throughout the structure decreased to below 50 kW/m^2 in less than 10 s. The heat fluxes steadily decreased to approximately 40 kW/m^2 in the bedroom and less than 15 kW/m^2 in the rest of the structure, just prior to water application.

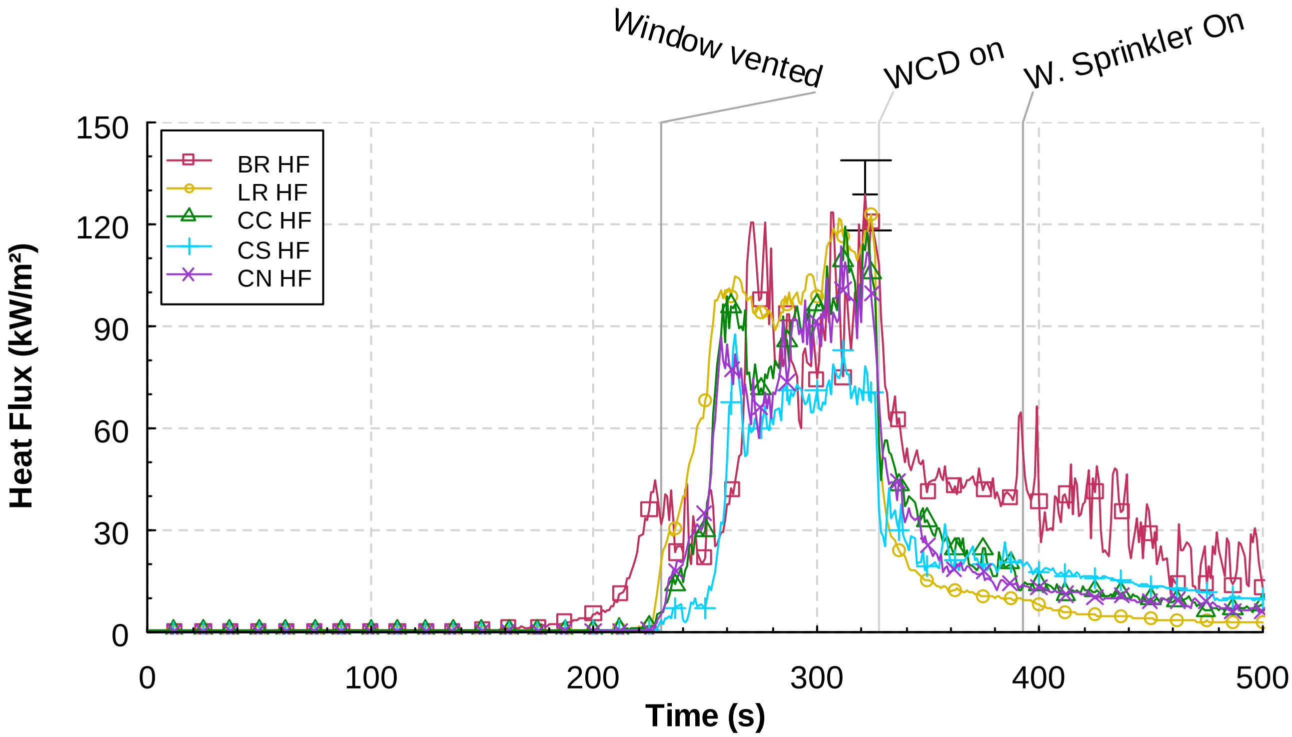

Figure 5.5.4-1. Heat flux versus time at five locations, Experiment 5.

5.5.5 Pressure

Figure 5.5.5-1 shows the pressures at the 5 measurement locations. There was little pressure change in the structure prior to window failure. After window failure the pressures in the structure increased and became fairly steady. The closer to the source of the simulated wind the higher the pressure was. The bedroom pressure increased to an average of 55 Pa, the hallway and living room pressure increased to approximately 35 Pa, the dead end side of the corridor increased to approximately 20 Pa and the vent side of the corridor increased to 10 Pa.

After the WCD was deployed all of the pressures in the structure transitioned to negative. As the pressure stabilized, the pressure in the bedroom decreased to approximately -25 Pa and the pressures decreased to -30 Pa at the vent end of the corridor. While all of the pressures were negative, the gases were still able to flow from a higher pressure (bedroom) to a lower pressure (corridor vent). The magnitude of the negative pressure was created by the flow of hot gases out of the structure and the lack of available make-up air, creating a partial vacuum. The application of water had little to no impact on the pressures, but as the structure cooled the pressures slowly increased.

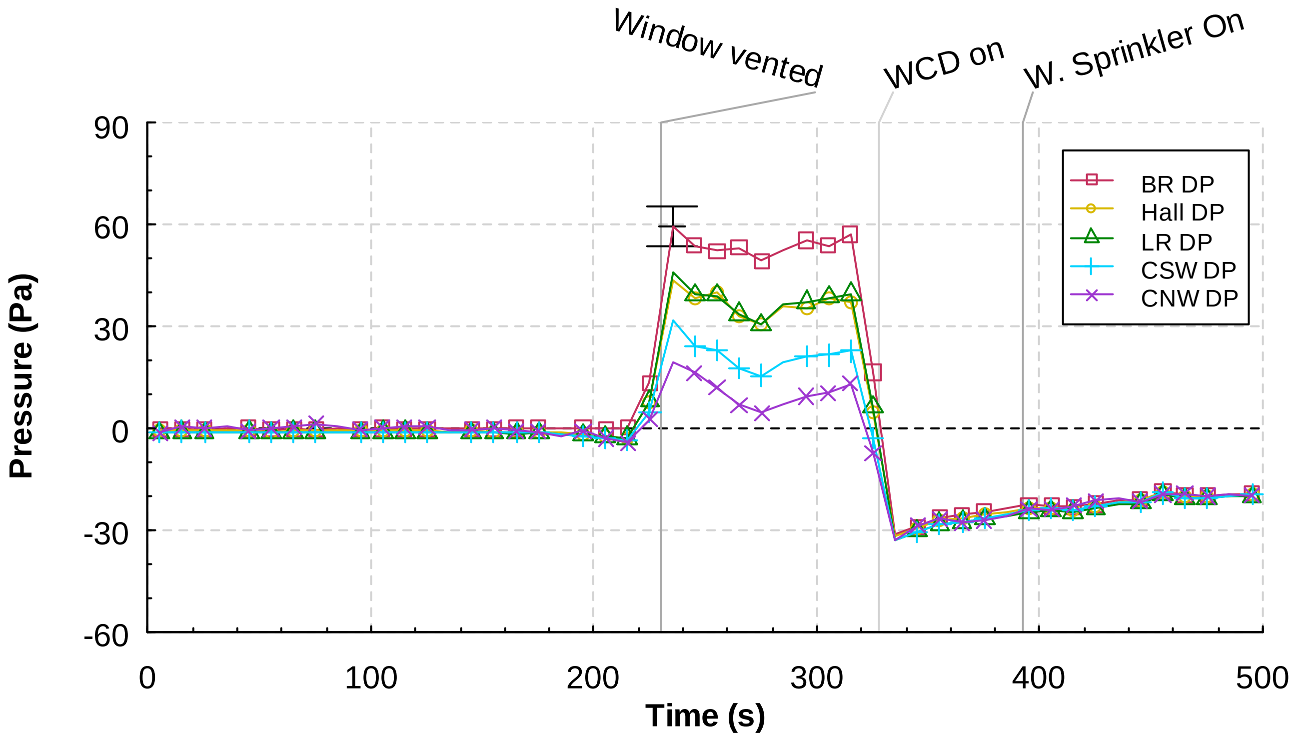

Figure 5.5.5-1. Pressure versus time at five locations, Experiment 5.

5.5.6 Velocities

Figure 5.5.6-1 provides the velocity measurements from the bi-directional probes that are located outside of the window. The positive velocities were flowing into the window. There was a fluctuation of velocities at the window as the hot gases were trying to exit the window opening while the simulated wind was forcing the gases back into the window. The average velocities shown in the graph indicate that the flow was mainly into the window at the middle and bottom probes and out of the window at the top probe once the room transitioned to flashover. Velocities ranged from 6 m/s (13.4 mph) into the window to 6 m/s (13.4 mph) out of the window. After the WCD was deployed the reading are not reliable as the WCD was pushed up against all of the probes.

Figure 5.5.6-2 shows the velocities at the hall array position. On this graph, the positive direction is from west to east. The probe located 0.3 m (1 ft) below the ceiling captures the velocity of the ceiling jet as it moved down the hall away from the bedroom and peaked at approximately 3.0 m/s (6.7 mph) prior to window failure. After window failure the velocity increases to above 5 m/s (11.2 mph) at the top probe and 7 m/s to 10 m/s at the middle and bottom measurement locations. The top probe read lower because of the impact of the size of the doorway. The lintel, which extended 0.4 m (1.3 ft) below the ceiling, slowed the flow or caused turbulence which slowed the flow.

Figure 5.5.6-3 displays the velocities from the south corridor position. The positive direction is from north to south. This was the dead end side of the corridor so there was no steady flow through this area. There was a lot of recirculation and changes in the magnitude of the velocity. Flows ranged from -1 m/s to 2 m/s while the wind was flowing through the structure. With the WCD in place the flow became steady between 0 m/s at the bottom probe and 2 m/s at the top probe, toward the vent.

The velocities from the north corridor position are shown in Figure 5.5.6-4. The positive flow direction for this location is from south to north. Prior to window failure, the ceiling jet/hot gas layer velocities reached a peak of approximately 0.6 m/s (1.4 mph) at 0.3 m (1 ft) below the ceiling. After the window vented the velocities increased to a peak of approximately 7 m/s (15.7 mph) and a range of 3.5 m/s to 7.5 m/s. The velocities decreased to a range of 1 m/s to 2 m/s after WCD deployment and nozzle activation.

The measurements from the bi-directional probes installed in the exhaust vent, 2.44 m (8.0 ft) above the ceiling are given in Figure 5.5.6-5. The flow direction up and out of the structure is positive in the figure. Prior to the window being vented the peak flow velocity is less than 2 m/s (4.5 mph). After the window was vented, the velocities at all three probes were similar and flowing out of the structure at a speed of approximately 7 m/s (15.7) to 9 m/s (20.1 mph). After WCD deployment, the velocities decreased to 1 m/s to 3 m/s but were still unidirectional out of the structure. The activation of the low flow nozzle had little impact on the vent flow velocity.

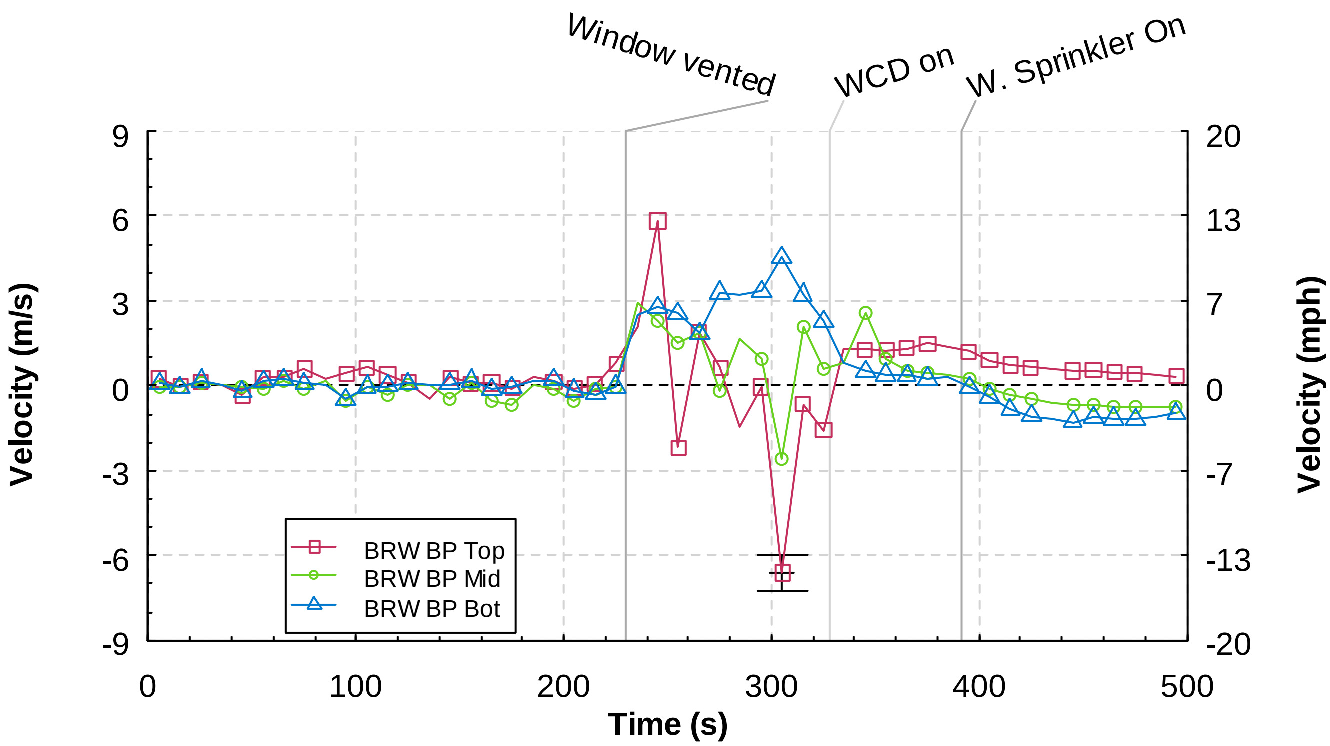

Figure 5.5.6-1. Velocity versus time from the bedroom window (BRW) bi-directional probe array, Experiment 5.

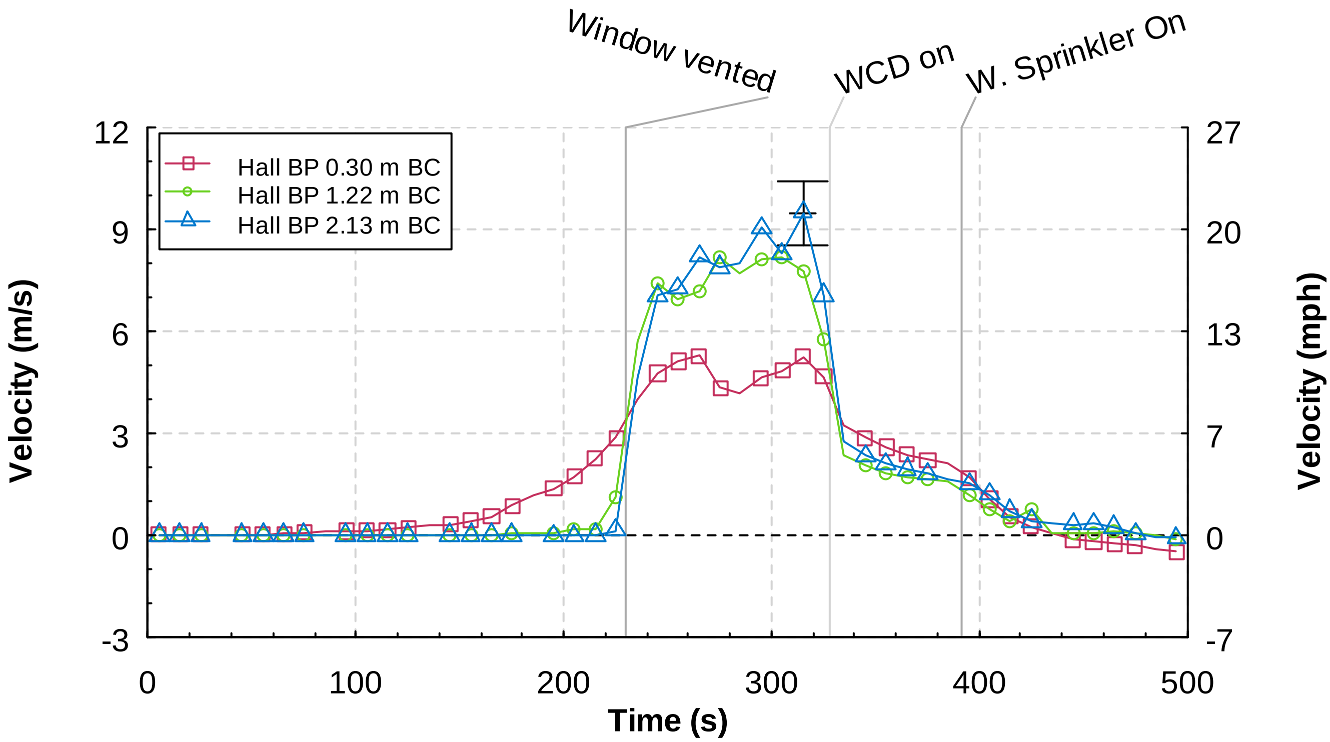

Figure 5.5.6-2. Velocity versus time from the hall bi-directional probe array, Experiment 5.

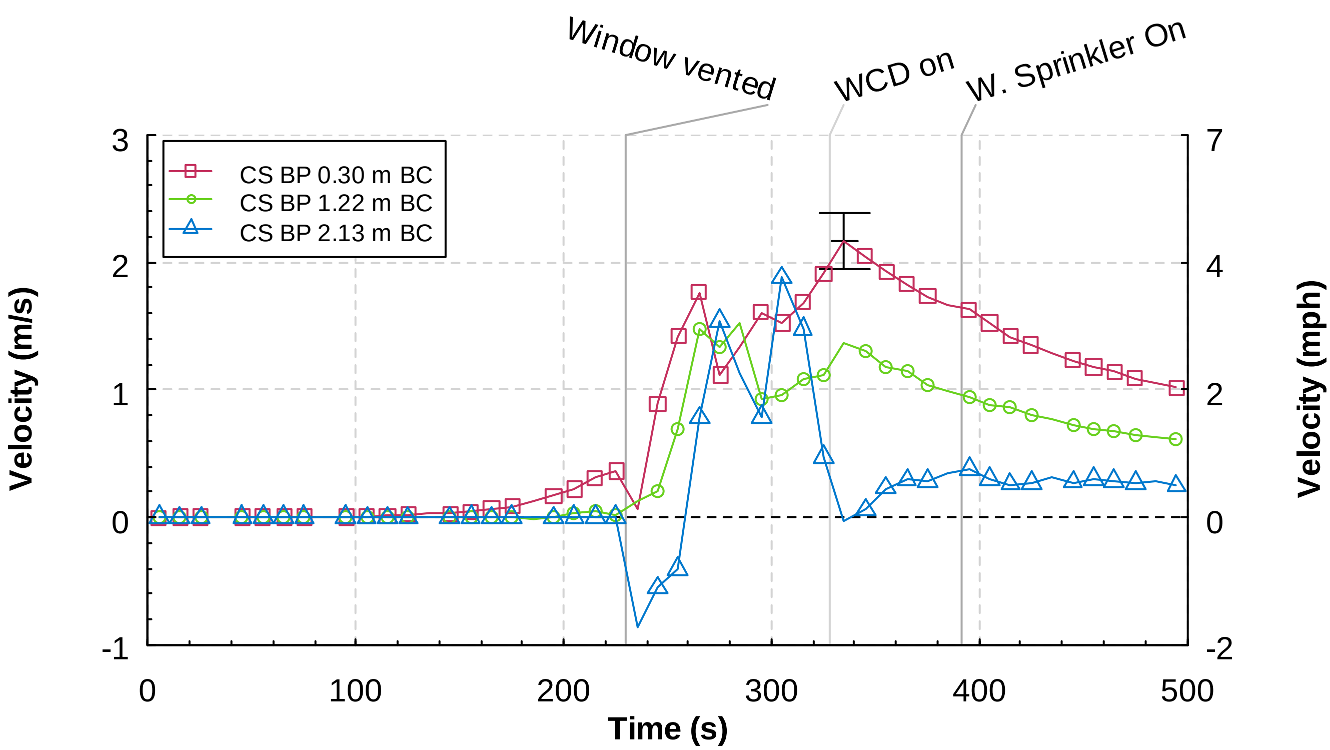

Figure 5.5.6-3. Velocity versus time from the corridor south (CS) bi-directional probe array, Experiment 5.

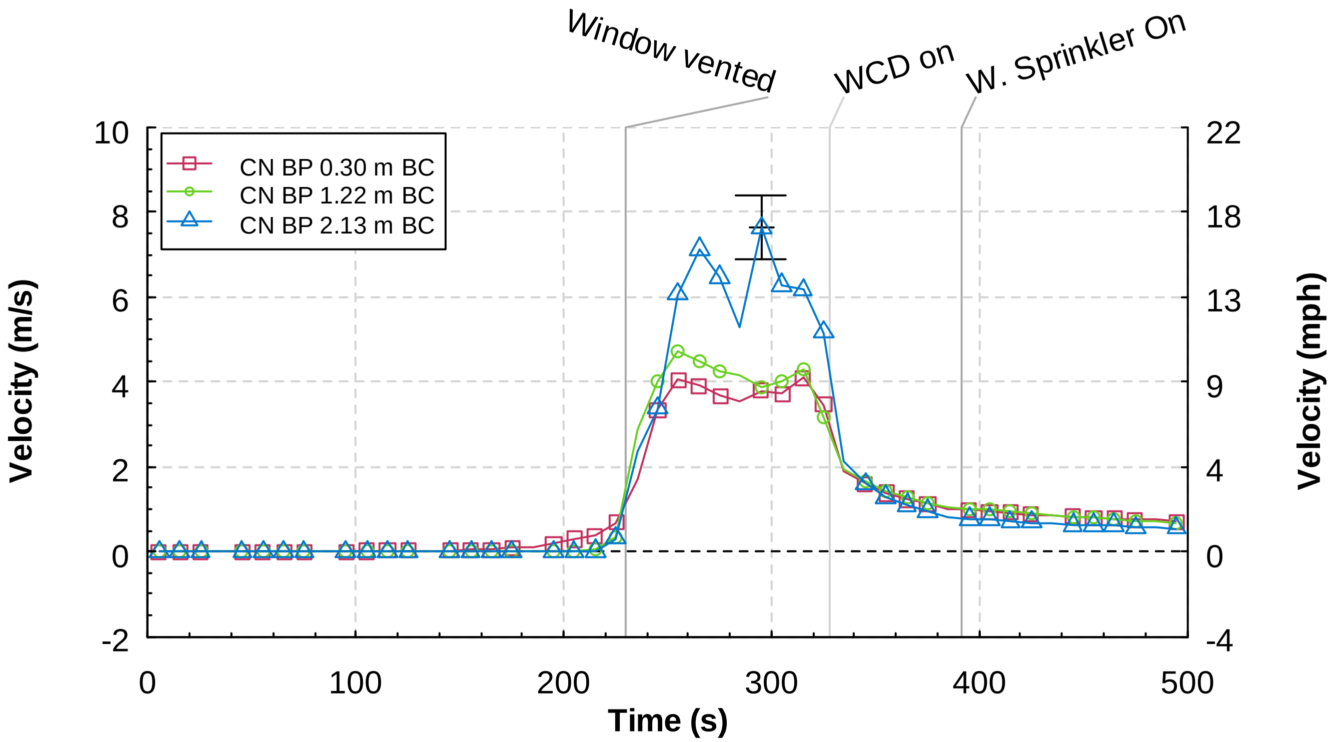

Figure 5.5.6-4. Velocity versus time from the corridor north (CN) bi-directional probe array, Experiment 5.

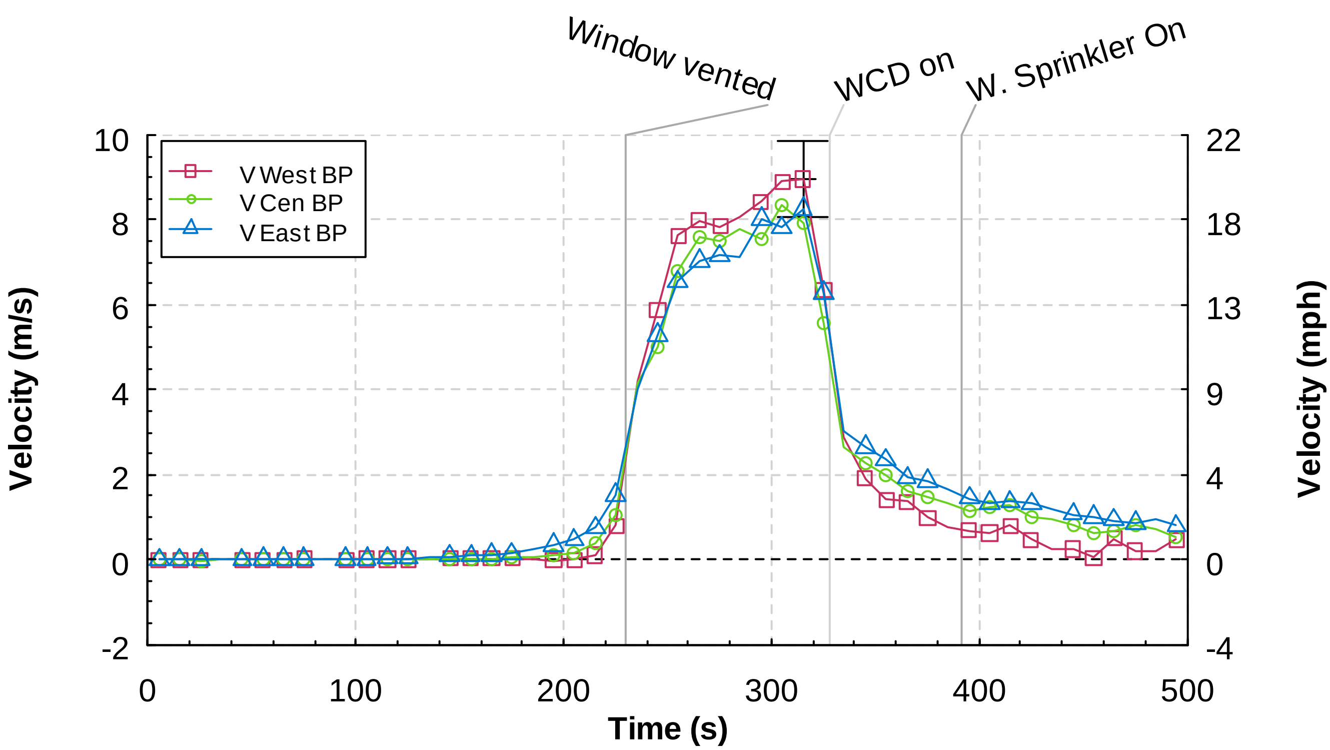

Figure 5.5.6-5. Velocity versus time from the ceiling vent (V) bi-directional probe array, Experiment 5.

5.5.7 Gas Concentrations

Figure 5.5.7-1 shows the gas concentration measurements made in the lower level of the bedroom. The upper gas sampling probe for the bedroom did not function correctly and was not included. The gas concentrations in the lower portion of the bedroom began to change at approximately 190 s, as the hot gas layer developed and extended down 1.83 m (6.0 ft) from the ceiling to interact with the sampling probe. Just prior to window failure the oxygen concentration decreased to 10 % and the CO_2 concentration increased to 10 %. After the window vented at 230 s, the fresh air came in through the window and mixed with the lower portion of the hot gas layer, which temporarily increased the oxygen and decreased the carbon dioxide and carbon monoxide for about 30 s. After this mixing, the oxygen quickly dropped to below 3 %, the CO_2 increased to 14 % and the CO increased to 6 %. After the WCD was deployed the oxygen decreased from 3 % to 1 %. Similar trends took place in the CO_2 and CO readings as they both increased approximately 3 %.

Figure 5.5.7-2 and Figure 5.5.7-3 provide the measurements from the upper and lower gas sampling probes, respectively, in the living room. The magnitudes and trends of the living room gas concentrations are very similar to those of the bedroom. One main difference is a smaller impact when air was introduced by the failing of the window. Much of the oxygen entering the window was consumed by the fire in the bedroom and it did not make it to the living room. The oxygen concentration in the living room at the top and bottom probed dropped to 1 % before deploying the WCD. The CO_2 reached as high as 19 % and the CO readings peaked at 4 % prior to WCD deployment and 7 % afterwards.

Figure 5.5.7-3 also includes the total hydrocarbon readings from the upper gas sampling probe in the living room. The total hydrocarbon readings begin to increase at about the same time as the CO readings but continue to increase to a peak of 13 % with the WCD in place and the oxygen concentration at a minimum. The concentration decreases after the activation of the low flow nozzle.

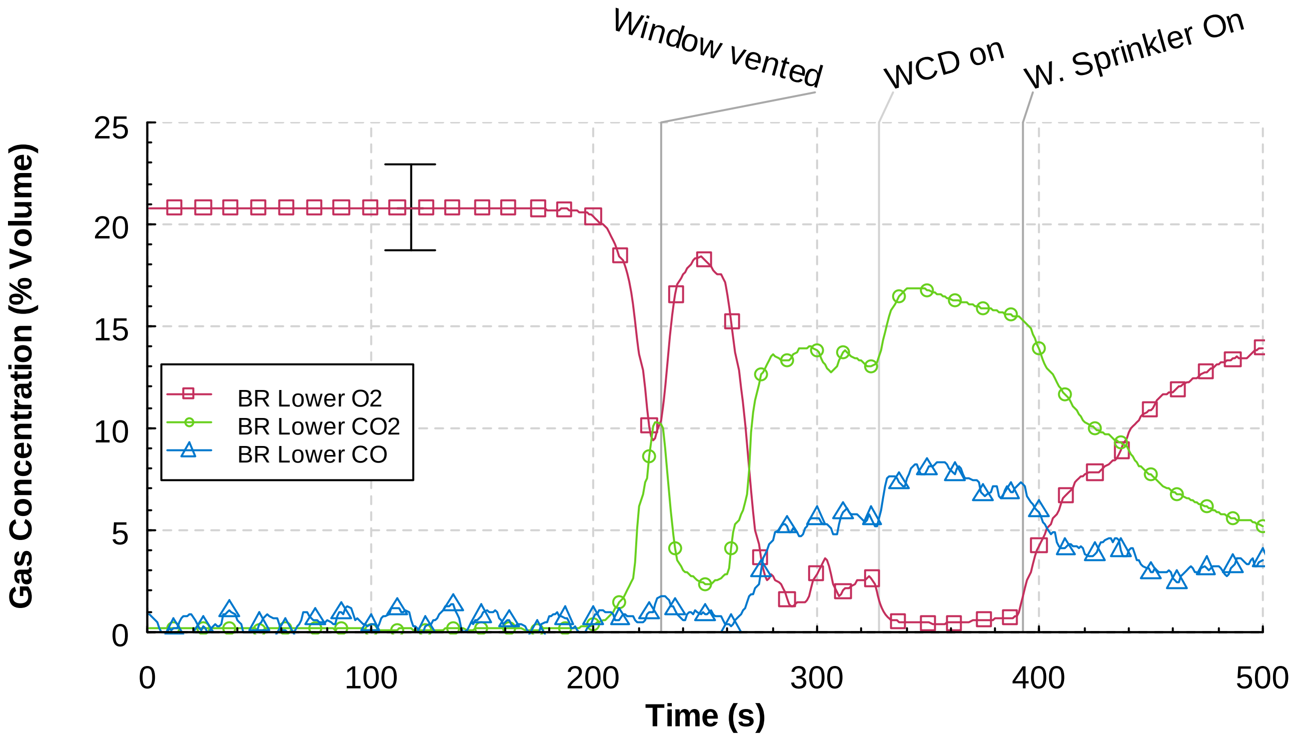

Figure 5.5.7-1. Oxygen, carbon dioxide, and carbon monoxide percent volume versus time from the lower bedroom (BR) sampling location, Experiment 5.

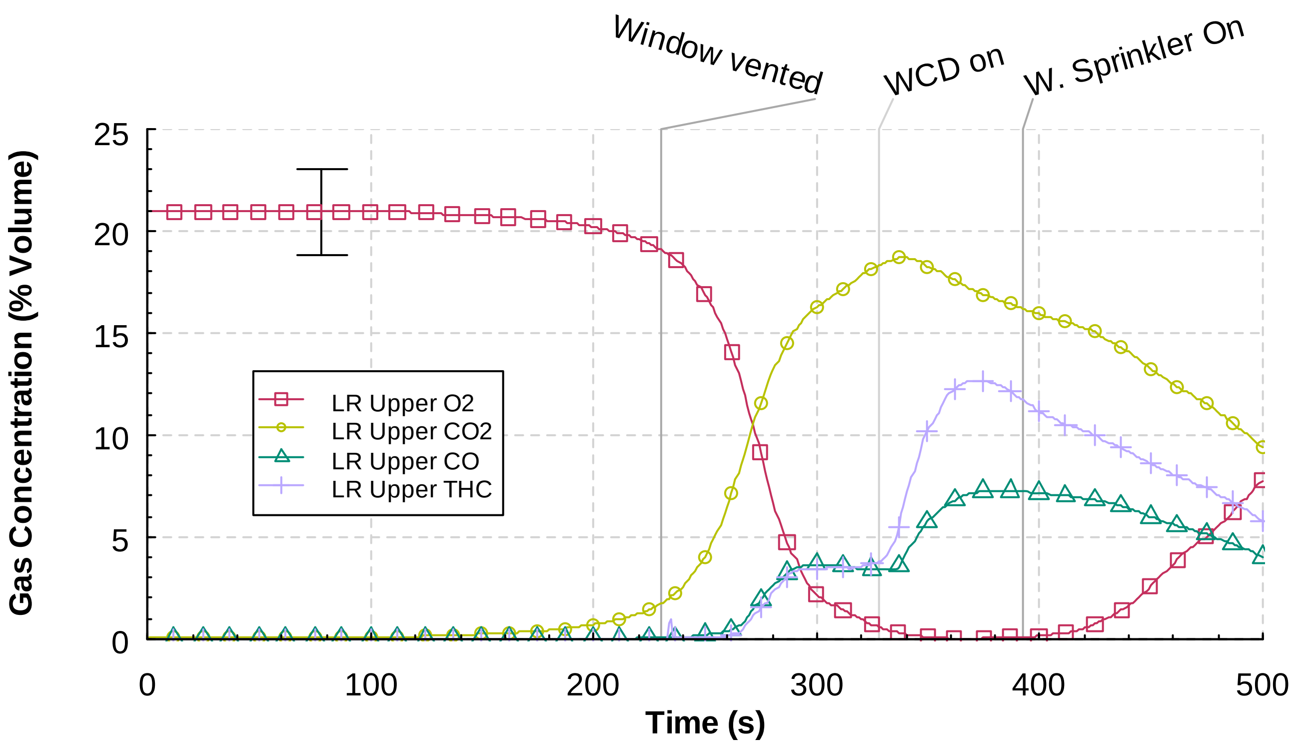

Figure 5.5.7-2. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper living (LR) room sampling location, Experiment 5.

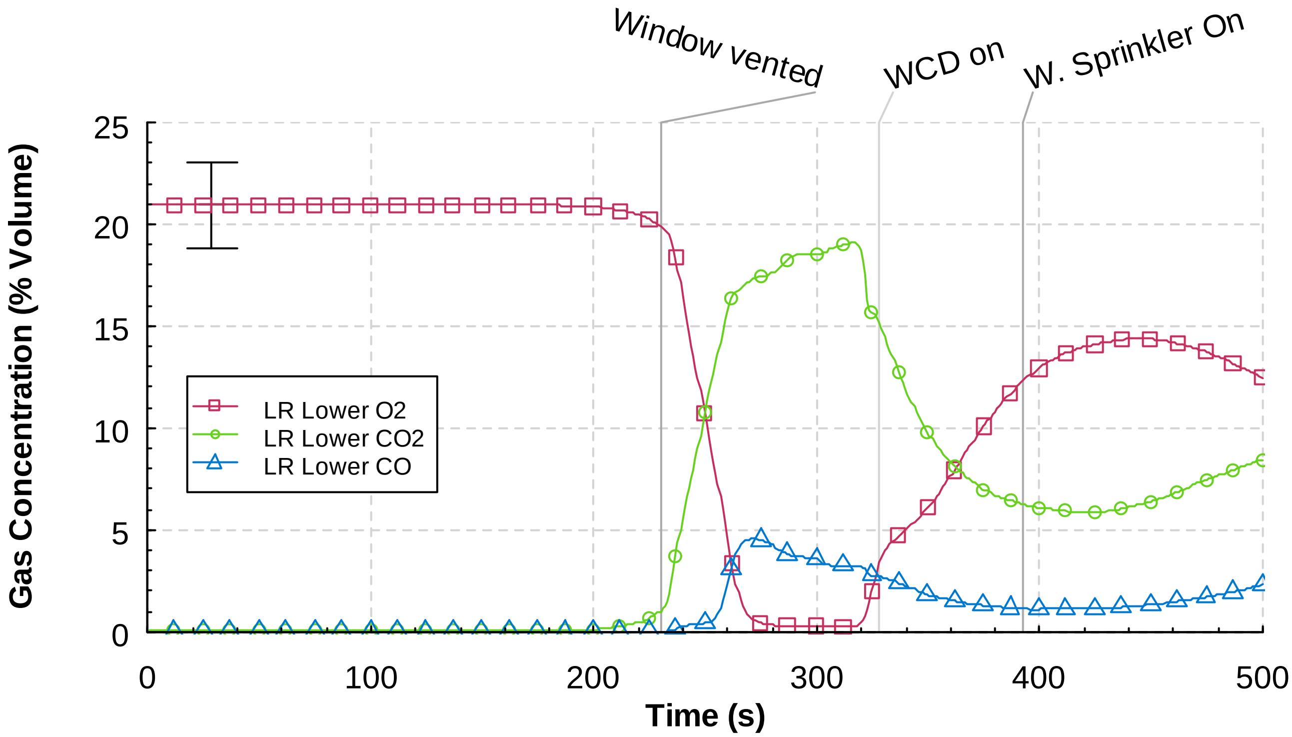

Figure 5.5.7-3. Oxygen, carbon dioxide, and carbon monoxide percent volume versus time from the lower living room (LR) sampling location, Experiment 5.

5.6 External Water Application (indirect attack) WDF 6 (fog)

The sixth experiment in the series was conducted to examine the impact of wind on the structure fire and quantify the impact of externally applied water sprays. After the window vented and the fire was observed to be fully developed, the window sprinkler, flowing 1.9 l/s (30 gpm), was activated, followed by the addition of a fog spray on the fire environment in the structure. The fog spray originated from an adjustable fog nozzle at the narrow setting (approximately 30º), flowing approximately 5.0 l/s (80 gpm). Initially the fog spray was discharged parallel to the west wall of the structure in front of the window opening. The spray was stopped and the nozzle, with the same settings, was repositioned to discharged directly into the window opening, such that the spray pattern nearly filled the window opening. The experimental preparations were made as described in Section 4. The fan speed used in this experiment was 1500 RPM, which provided a 3.0 m/s to 4.0 m/s (7 mph to 9 mph) wind speed at the window opening. A trash container fuel package was ignited remotely with and electric match to start the experiment at Time = 0 s. A time line of the experiment is presented in Table 5.6-1. The results for the experiment are presented in the following sections: observations, heat release rate, temperature, heat flux, pressure, velocity, and gas concentrations. An uncertainty range marker is included in each graph.

Table 5.6-1. Experiment 6 Timeline

Time (s)	Event
0	Ignition
60	Visible smoke layer
165	Window vented
168	Hot gas flow to floor in corridor IR

171	Window cleared
267	Window sprinkler on
293	Stream across window
330	Hose off
347	Stream Into window
395	Fan off
403	Begin suppression
427	Fire out
432	Sprinkler off
457	Fan on
537	Test complete

5.6.1 Observations

The observations are presented as a series of images captured from eight camera locations, six were video cameras and two were thermal imaging cameras. The camera positions are shown in Figure 4.1.3-1.

Figure 5.6.1-1 through Figure 5.6.1-15, present sets of eight images one from each camera position, at a given time, from the time of ignition to 420 s after ignition. Each image view is labeled. The first four views at the top of each figure show the west wall and window of the structure and then follow a path through the interior of the structure with a view of the bed room, the living room and a view (looking west) through the open door to the corridor. The second set of four views, at the bottom of each figure provide a video view of the north east portion of the corridor and a view of the inside of the target room door. The thermal imaging cameras provide a view of the east corridor, looking north, and a view of the inside of the target room.

Figure 5.6.1-1 shows the conditions at the time of ignition. At this point, the six video views are clear and unobstructed. However, the thermal images provide limited thermal contrast, because the surfaces in the view were at nearly equal temperature.

The images in Figure 5.6.1-2 were captured 60 s after ignition. The fire from the trash container began to spread to the bed. Light colored smoke was produced and a thin smoke layer had developed across the ceiling of the bedroom. There was no smoke or change in thermal condition, in the living room, target room or corridor at this time.

The images in Figure 5.6.1-3 were recorded at 120 s after ignition. The fire had spread to the area between the bed and the upholstered chair with a flame height of approximately 1.2 m (4.0 ft) above the floor. The smoke layer was approximately 1.2 m (4.0 ft) thick throughout the bedroom. Smoke was beginning to spread through the hallway and into the living room. Small amounts of smoke and heat had reached the corridor at 120 s. The target room appeared clear of smoke.

The window vented due to the heat transferred from flame impingement at 165 s after ignition. Figure 5.6.1-4 shows the images recorded at 174 s after ignition, just after the window opening had been completely cleared. The flames can be seen flowing out of the window and across the end of the bed. The living room, doorway and corridor views have been obscured. The thermal image from the corridor shows that heat has filled the living room doorway from top to bottom and that the flow had extended across the corridor and impinged on the east wall. A thin layer of smoke has flowed into the target room. The thermal image from the target room shows the heat flowing in around the upper perimeter of the door.

Figure 5.6.1-5 shows the conditions at 180 s after ignition. Flames are seen filing the bedroom and moving across the floor level. The camera views in the living room, hallway and corridor are still obscured by smoke. Conditions in the image from the corridor IR camera and the target room views have not changed much since the previous figure.

Figure 5.6.1-6 was captured at 192 s after ignition. Flames were pulsing out of the top of the window opening. Flames can be seen in the bedroom at the floor level, coming through the hallway and into the living room. Flames are also shown extending out through the doorway into the corridor. The metal door to the target room had flames coming from the top right corner and from under the door. The smoke layer in the target room had increased in thickness. The thermal image from the target room exhibits heat moving into the target room from the entire perimeter of the steel door.

Figure 5.6.1-7 shows the conditions at 240 s after ignition. Flames were pulsing out of the window opening. Smoke was obscuring the views in the bedroom, living room and corridor. The amount of heat entering the hallway has caused the image from the corridor IR camera to deteriorate substantially. The visual image in the target room showed flames continuing to burn under the door. The visibility at the lower layer in the target room remained good.

The images in Figure 5.6.1-8 were recorded at 265 s after ignition, a few second before the window sprinkler was activated. Flames appeared to fill the entire bedroom. The views from the inside the bedroom, living room, and corridor were completely obscured by smoke. The thermal view of the corridor continued to show large quantities of heat but the ability to view any of the structure was lost. The target room video view continued to show flames around the bottom of the target room door. The thermal view shows the outlines of the metal door detail, as the door had increased in temperature.

At 287 s after ignition, the images in Figure 5.6.1-9 were recorded. The window sprinkler had been activated for 20 s. Flames stilled pulsed from the window opening. The flames near the window appeared to partially blocked by soot. The interior video views were still obscured, only a glow was visible in the bedroom view. The thermal view of the corridor was obscured due to high thermal conditions. Conditions in the target room had decayed as the hot gas layer dropped within 0.30 m (1 .0 ft) of the floor. Flames were still visible under the door to the hallway. In the thermal image of the target room door, the door had become whiter in color, indicating that had become hotter.

Figure 5.6.1-10 shows the conditions at 300 s after ignition, or approximately 8 s after the water fog was started across the window opening. The interior video views were still obscured by smoke. The thermal image from the corridor was still saturated due to high heat conditions. In the target room, the smoke layer was near the floor, flames were no longer visible coming under the door. The door continued to to heat up, as shown in the target room thermal view.

Figure 5.6.1-11 shows the conditions at 330 s after ignition, just as the fog water was shut off. The window sprinkler was still activated. The area in the center of the window opening was free from fire.

All of the interior video views were still obscured by soot. The corridor thermal image shows more contrast indicating that the thermal conditions in that location had cooled. The target room thermal image shows that the door remained hot.

The images in Figure 5.6.1-12 were recorded at 345 s after ignition, just prior to the activation of the fog stream into the window opening. The volume of flame visible through the window opening had decreased. All of the interior video views were obscured by smoke. The thermal images showed cooler conditions in the corridor and a hotter target room door when compared with the previous figure.

Figure 5.6.1-13 shows the conditions 13 s after the fog spray directly into the window was started. The images seem similar to the images in Figure 5.6.1-12.

The images in Figure 5.6.1-14 were recorded after 50 s of direct, fog stream application. The flames in the bedroom had decreased. The interior video views were still obscured. The corridor thermal view shows continued cooling. The black area on the east wall across from the door is indicative of the wall cooling due to the water. Portions of the target room door appear to have been impacted by the water in the areas that appear dark.

The post-test images are shown in Figure 5.6.1-15. The fire in the bedroom had been suppressed. The conditions in the corridor continued to cool. All other views had not changed. Post test inspection indicated that the protective covers for the interior video cameras were coated with soot.

Figure 5.6.1-1. Experiment 6, ignition.

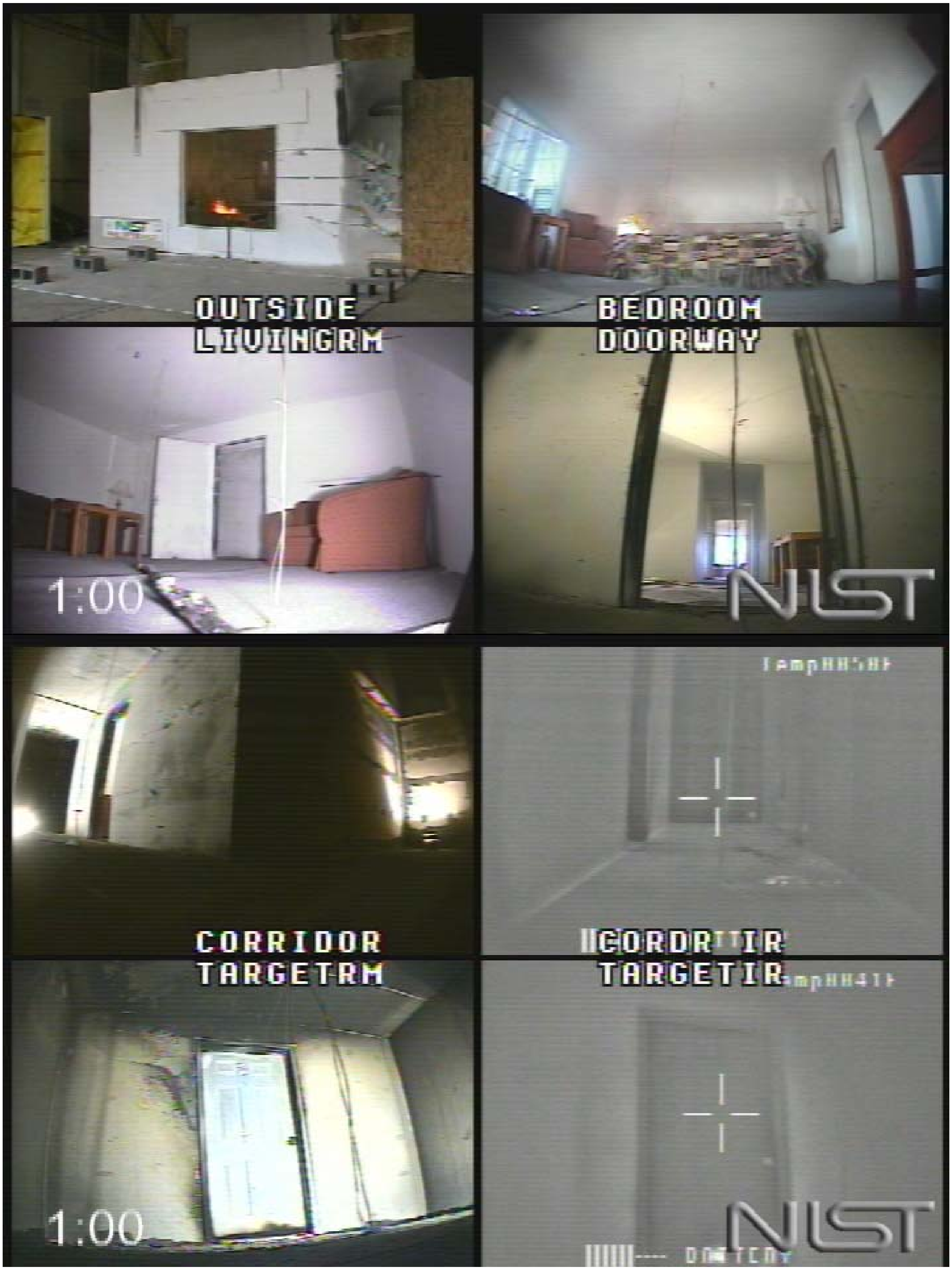

Figure 5.6.1-2. Experiment 6, 60 s after ignition.

Figure 5.6.1-3. Experiment 6, 120 s after ignition.

Figure 5.6.1-4. Experiment 6, window fully vented, 174 s after ignition.

Figure 5.6.1-5. Experiment 6, 180 s after ignition.

Figure 5.6.1-6. Experiment 6, corridor flames, 192 s after ignition.

Figure 5.6.1-7. Experiment 6, 240 s after ignition.

Figure 5.6.1-8. Experiment 6, 265 s after ignition.

Figure 5.6.1-9. Experiment 6, 287 s after ignition, 20 s after window sprinkler activation.

Figure 5.6.1-10. Experiment 6, 300 s after ignition.

Figure 5.6.1-11. Experiment 6, fog stream across window off, 330 s after ignition.

Figure 5.6.1-12. Experiment 6, direct fog stream on, 345 s after ignition.

Figure 5.6.1-13. Experiment 6, 360 s after ignition.

Figure 5.6.1-14. Experiment 6, 400 s after ignition.

Figure 5.6.1-15. Experiment 6, 420 s after ignition.

5.6.2 Heat Release Rate

Figure 5.6.2-1 shows the heat release rate time history for Experiment 6. The increase in measured heat release rate is delayed because for the first 160 s after ignition because no heat or combustion products generated by the fire flowed out of the structure. After the window failed, at 165 s after ignition, the increase in heat release rate was clear. The heat release rate reached a peak of approximately 17 MW, 45 s after window failure, followed by a quick drop to 8 MW and return to 15 MW over the next 30 s. The window sprinkler was activated at 267 s and hose was sprayed across the window at 293 s which caused the heat release rate to drop to just above 10 MW. At 347 s, the hose stream was shut off, repositioned in front of the window and reactivated. This action actually increased the heat release rate to a peak of approximately 16 MW for about 30 s but ultimately caused a drastic heat release rate reduction. At 395 s, the fan was shut off and manual suppression ended the test shortly thereafter.

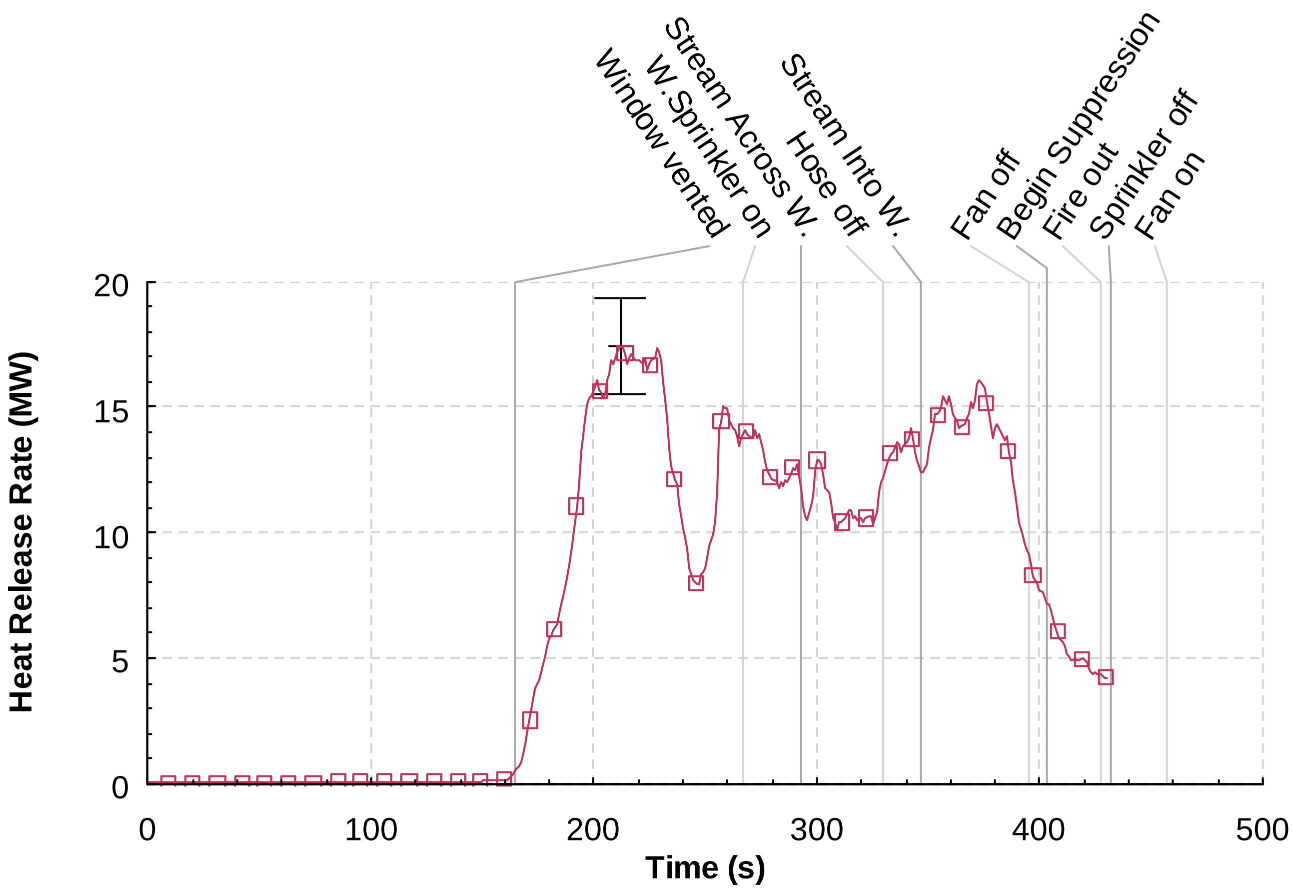

Figure 5.6.2-1. Heat release rate versus time, Experiment 6.

5.6.3 Temperatures

Figure 5.6.3-1 through Figure 5.6.3-11 provides the temperature measurements from the thermocouple arrays shown in Figure 4.1.3-1. The figures are given in order from the western most measurement point, the bed room window opening, and moving through the structure toward the east; bedroom, hall, living room, corridor, south and southwest portions of the corridor (closed end) and then to the north section of the corridor and ending with the exhaust vent. The last temperature graph has temperatures associated with the target room.

The three thermocouples located in the window opening, shown in Figure 5.6.3-1, provide insight into the ventilation conditions at the window. After window failure at 165 s temperatures fluctuate as the flames are pulsing out of the window and wind is blowing into the window. The highest temperatures are located in the top of the window opening. Activation of the window sprinkler at 267 s as well as use of the fog hose stream across and into the window reduced the temperatures at the window from a peak of 550 ºC (1022 ºF) to less than 50 ºC (122 ºF) in the span of 100 s.

The measurements from the thermocouple array located in the center of the bedroom are given in Figure 5.6.3-2. Prior to the window failure, the temperatures in the bedroom increased from ambient conditions to a peak of approximately 650 ºC (1202 ºF) near the ceiling. At the same time, the temperatures, 2.13 m (7.00 ft) below the ceiling, were almost 50 ºC (122 ºF). Flashover conditions were reached, based on temperatures from ceiling to floor being in excess of 900 ºC (1652 ºF), at approximately 200 s after ignition and 40 s after window failure. Activation of the window sprinkler at 267 s reduced all temperatures in the room and use of the fog stream across the window further decreased all levels to less than 300 ºC (572 ºF). As the hose stream was shut off, repositioned in directly into the window and turned back on again, the temperatures in the room stratified and the upper half of the room began to increase. Temperatures near the ceiling topped 600 ºC (1112 ºF) while the floor remained at ambient conditions.

The data from the hall thermocouple array is presented in Figure 5.6.3-3. The temperatures slowly increased and stratified as the fire in the bedroom developed. The ceiling temperature in the hallway reached approximately 350 ºC (662 ºF), while the temperature 2.13 m (7.00 ft) below the ceiling was still ambient just prior to window failure. 30 s after window failure the temperatures peaked to 950 ºC (1742 ºF) at the ceiling, but then decreased for 50 s. At 250 s, all temperatures returned to the peak level until the window sprinkler was activated. The window sprinkler, combined with the fog stream across the window cut all temperatures down to 50 ºC (122 ºF). When the hose stream was redirected into the window, temperatures restratified and began to increase up to 300 ºC (572 ºF) in the upper layers of the hallway.

The data from the living room corner thermocouple array is shown in Figure 5.6.3-4. 20 s after window failure, the temperatures from floor to ceiling were in excess of 600 ºC (1112 ºF). No significant change in temperature conditions were noted with the use of the window sprinkler or the fog stream across the window. When the hose stream was directed into the window, temperatures in the hallway increased to just below 800 ºC (1472 ºF) for 20 s but then fell below 400 ºC (752 ºF) prior to the end of the test.

The temperatures from the center of the living room are shown in Figure 5.6.3-5 for the time history of the experiment. Again, there was a dramatic temperature increase seconds after the window failure. As the hot gases were forced through the living room the temperatures elevated from 300 ºC (572 ºF) at the ceiling and ambient at the floor to 800 ºC (1472 ºF) from floor to ceiling. Temperatures decreased for the next 50 s but then began to increase even with the window sprinkler activation. The use of the fog stream across the window at 293 s, however, caused temperatures to drop to 550 ºC (1022 ºF) and stabilize for a short time period. When the stream was redirected into the window, temperatures began to increase once again for approximately 20 s but then declined significantly to levels below 300 ºC (572 ºF).

Temperature conditions in the corridor are given in Figure 5.6.3-6 through Figure 5.6.3-9. Temperture records for the center and north corridor regions were similar in nature but were slightly different in scale. The center and north regions peaked at 800 ºC (1472 ºF) 30 s after window failure then reduced in temperature 600 ºC (1112 ºF) . Window sprinkler activation and the fog stream application across the window steadily increased temperatures up until the fog stream was redirected into the window but the center region topped out at 800 ºC (1472 ºF) while the north region hit 950 ºC (1742 ºF). Fog stream application into the window significantly decreased temperatures in both regions throughout the remainder of the test. The south and southwest regions of the corridor both rapidly increased in temperature 30 s after window failure with the south reaching 600 and southwest reaching 350 at the ceiling. Both regions were more stratified in nature and declined slightly or remained relatively constant until the fog stream was directed into the window. The window sprinkler and fog application across the window did not have a significant effect on temperature differences. Directing the fog stream into the window increased both the south and southwest corridor regions for approximately 10 s before all temperatures declined to the end of the test.

The temperatures at the exhaust vent are given in Figure 5.5.3-10. These thermocouples were at the same elevation located 2.44 m (8 ft) above the ceiling of the corridor. The three thermocouples were spaced 0.51 m (1.67 ft) apart along the east-west centerline of the vent. These temperatures increased from less than 100 ºC (212 ºF) to greater than 600 ºC (1112 ºF) in about 30 s following window failure. Temperatures increased with the use of the window sprinkler and fog stream application both across and into the window to a peak of 1000 ºC (1832 ºF). 10 s prior to shutting the fan off, temperatures drastically reduced for the rest of the test period.

The final temperature graph displays the temperature time history for the target room (Figure 5.5.3-11). All of the temperatures remained near ambient until the window failed. After window failure, temperatures stratified and continually increased until the hose stream was applied across the window. The temperatures leveled off at this point, with ceiling and floor temperatures measuring 140 ºC (284 ºF) and 80 ºC (176 ºF) respectively, but remained stratified until 10 s prior to shutting the fan off. After the fan was shut off, temperatures suddenly collectively to 60 ºC (140 ºF) but then began to increase at a steady state once again.

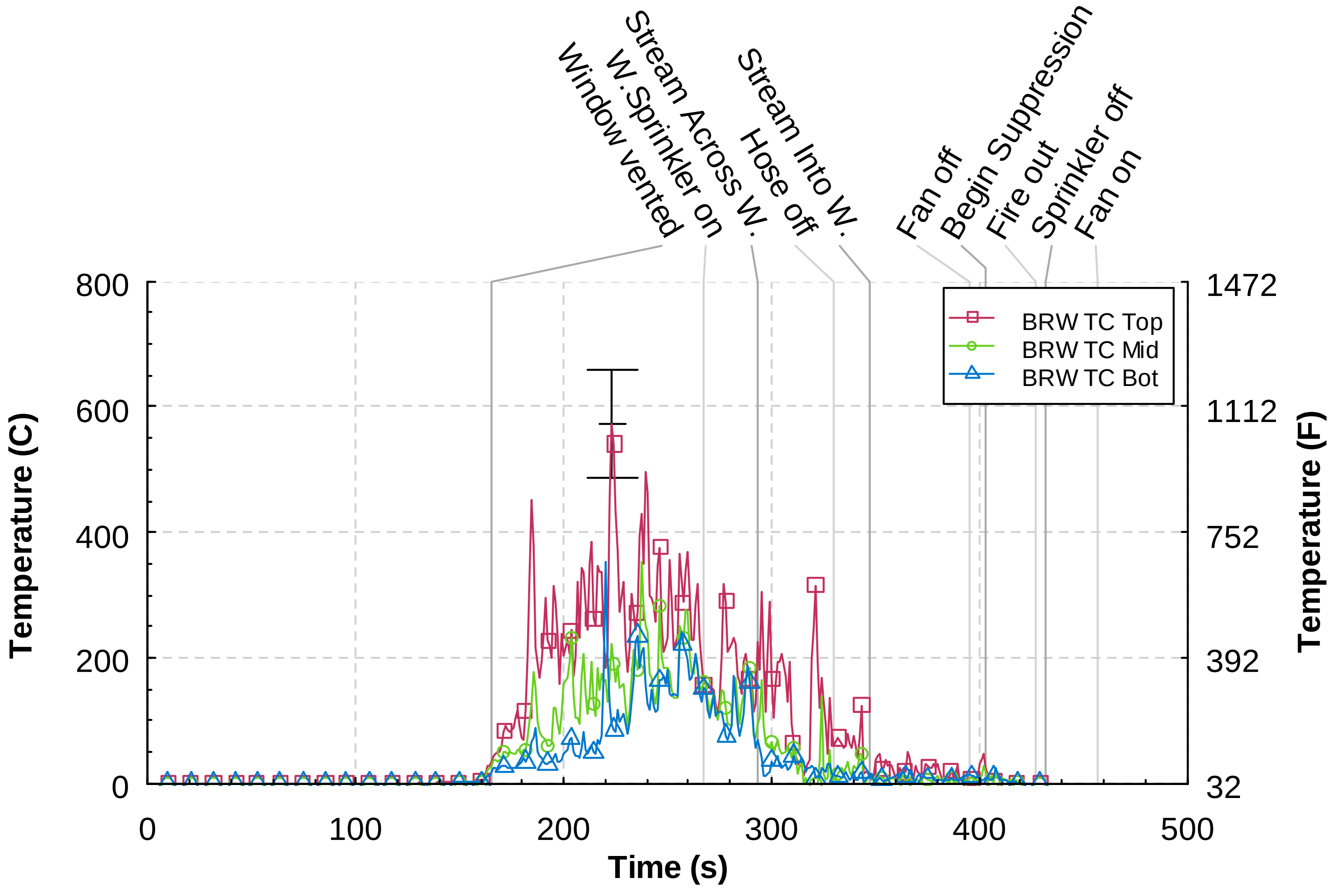

Figure 5.6.3-1. Temperature versus time from the bedroom window (BRW) thermocouple array, Experiment 6.

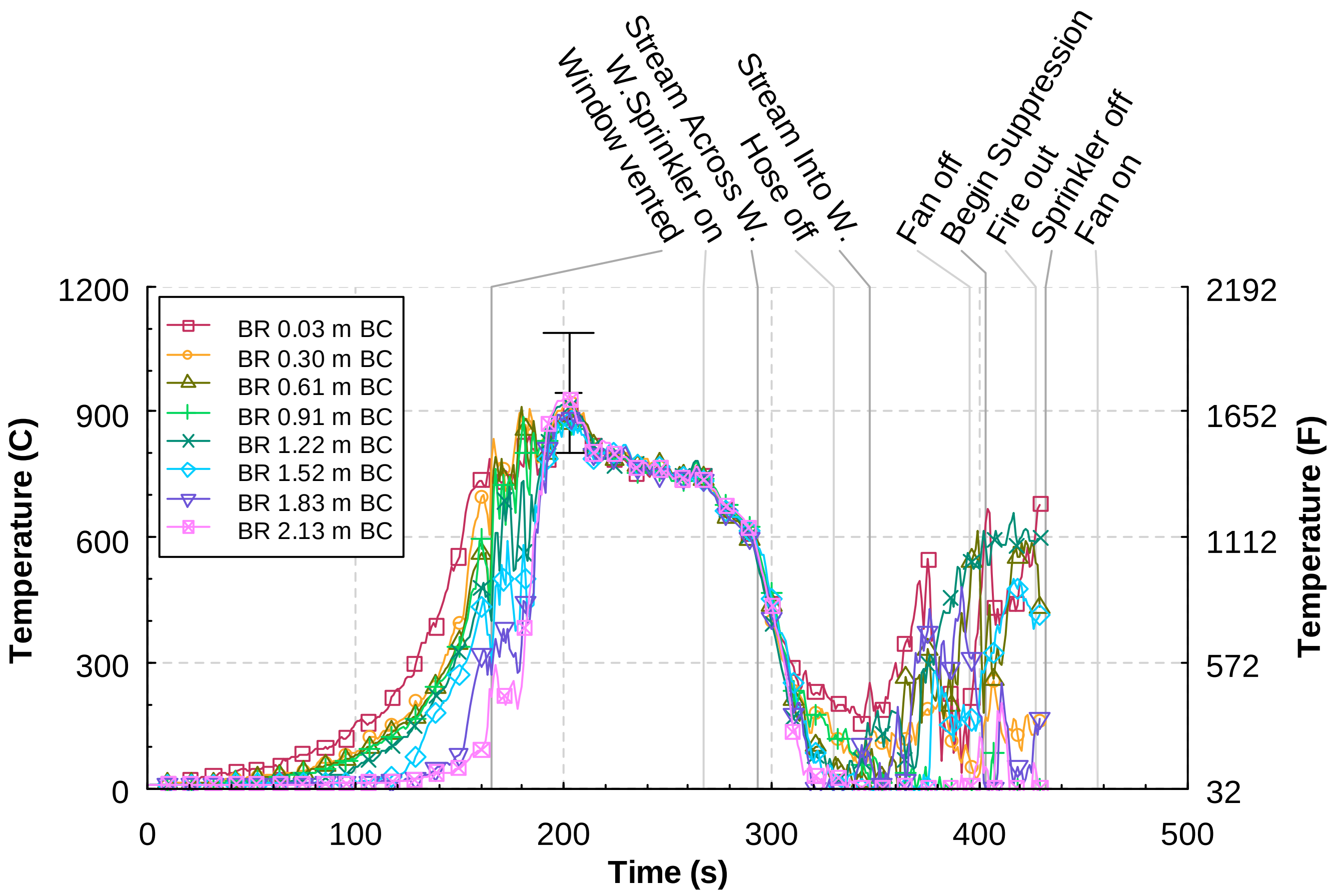

Figure 5.6.3-2. Temperature versus time from the bedroom (BR) thermocouple array, Experiment 6.

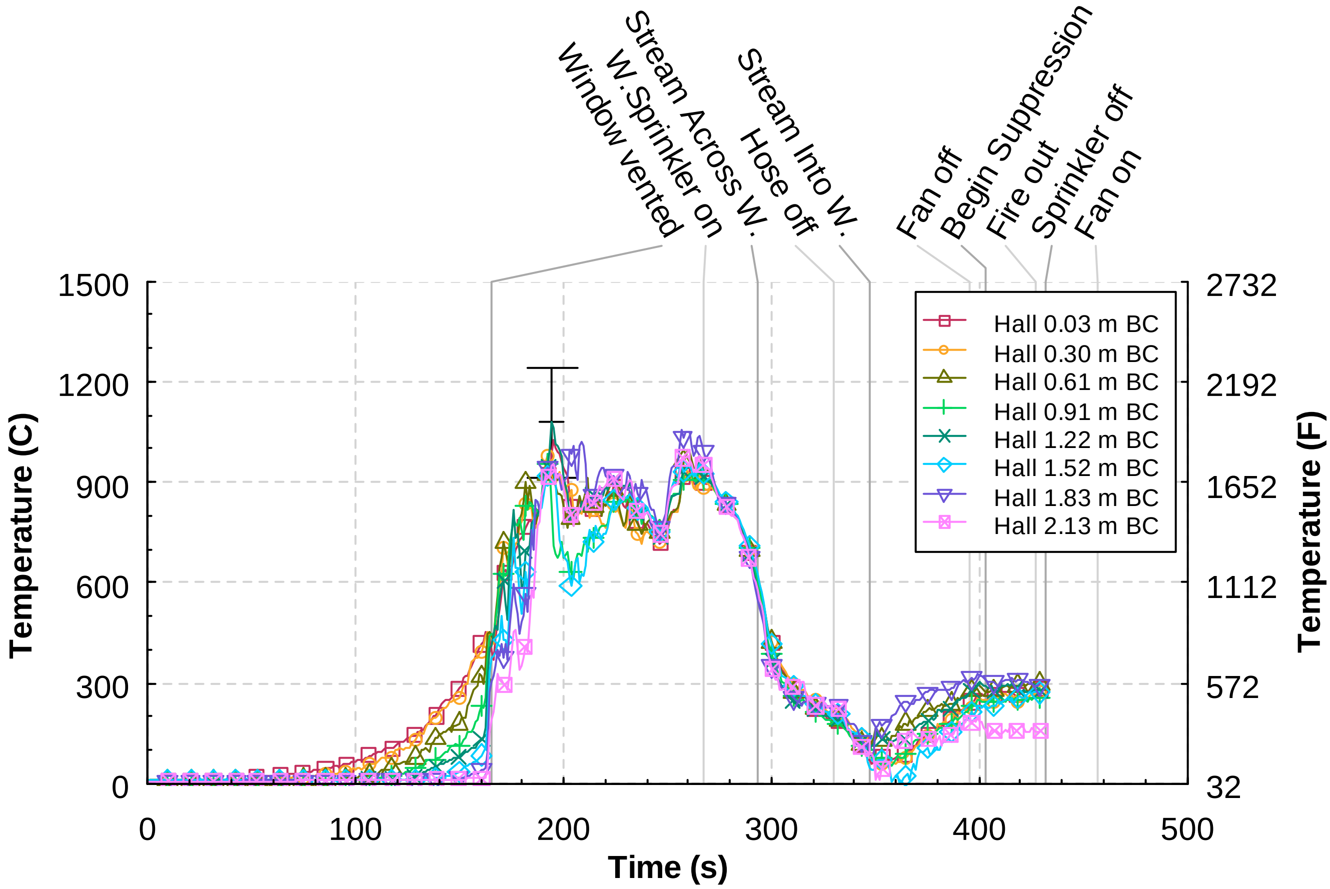

Figure 5.6.3-3. Temperature versus time from the hall thermocouple array, Experiment 6.

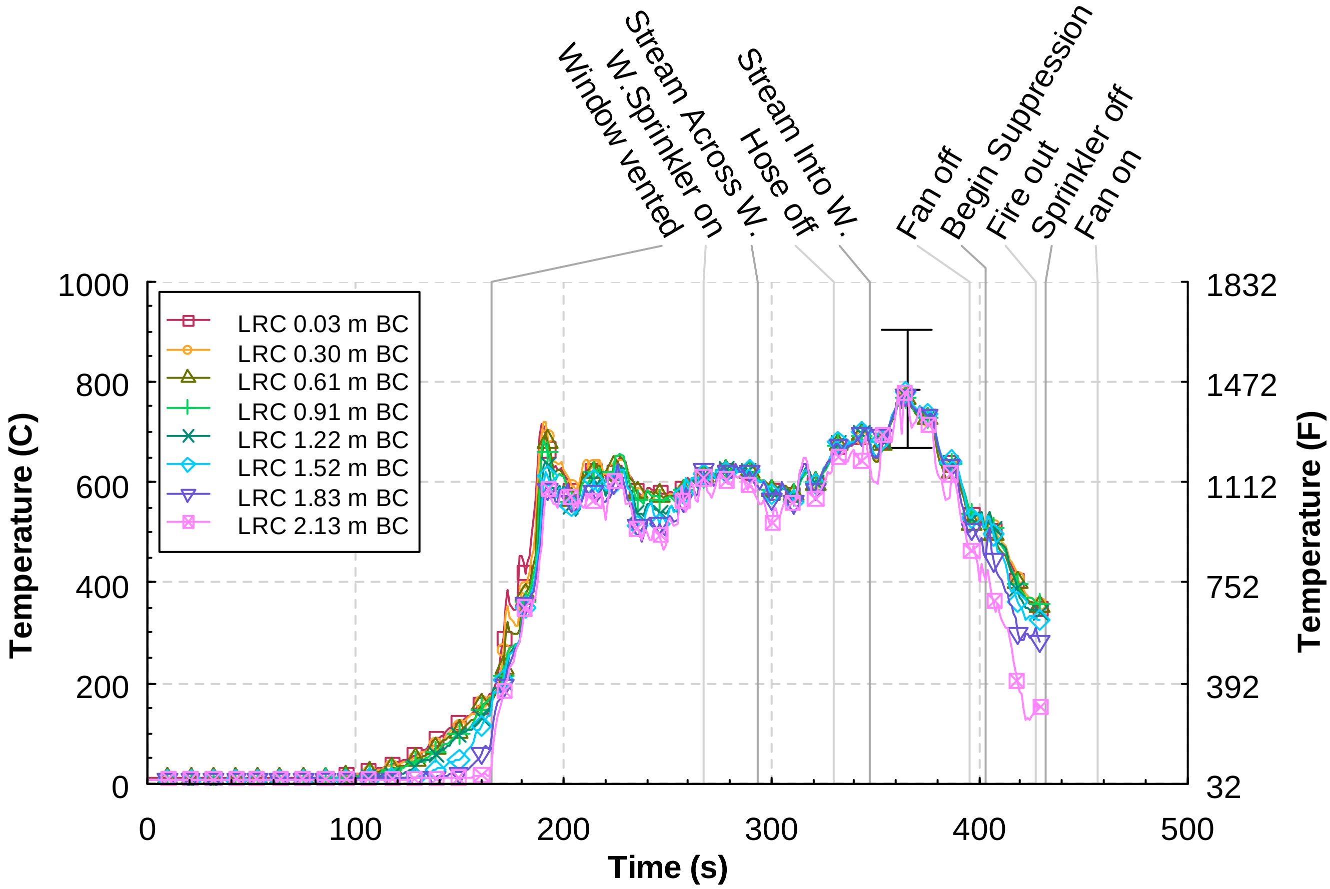

Figure 5.6.3-4. Temperature versus time from the living room corner (LRC) thermocouple array, Experiment 6.

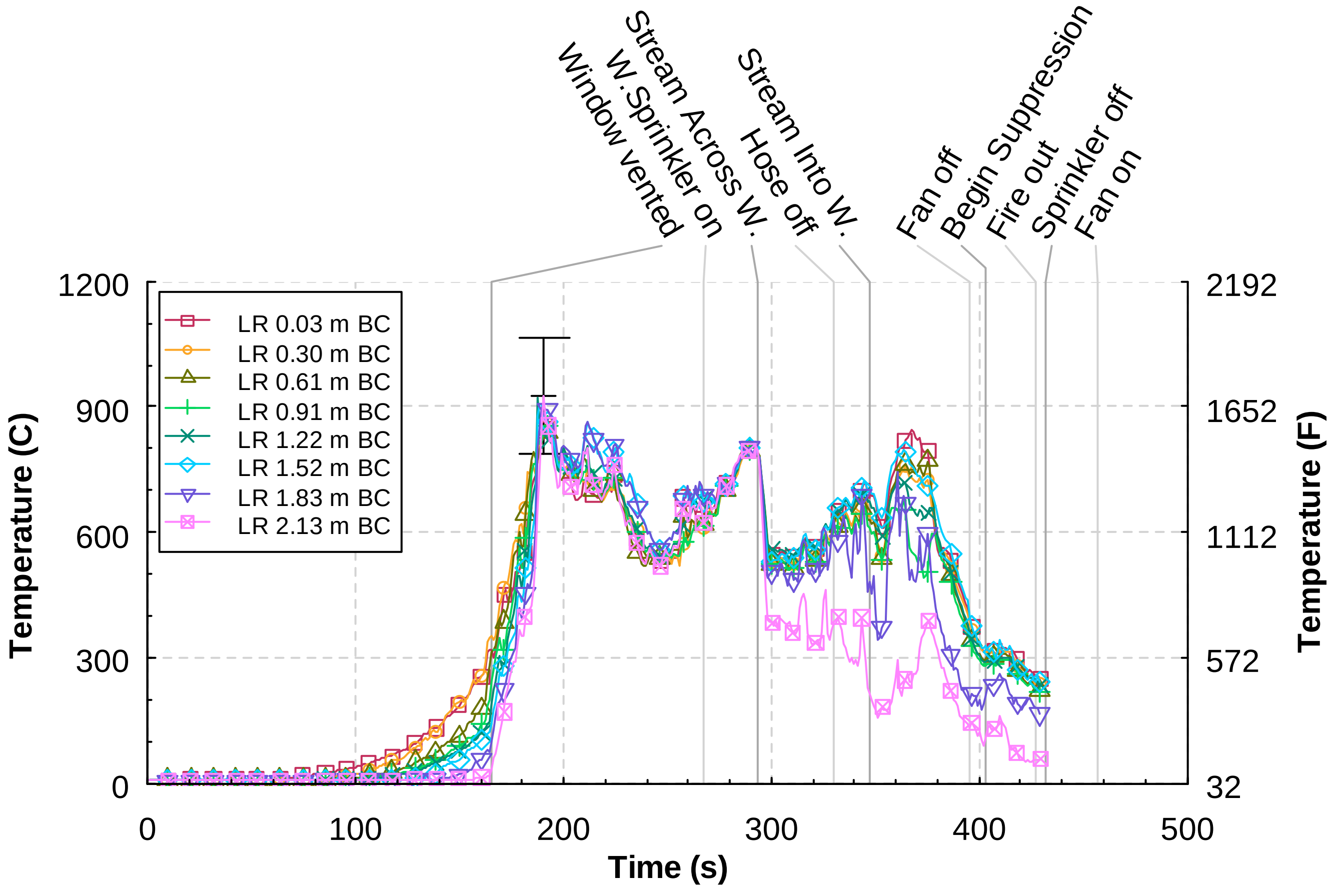

Figure 5.6.3-5. Temperature versus time from the living room (LR) thermocouple array, Experiment 6.

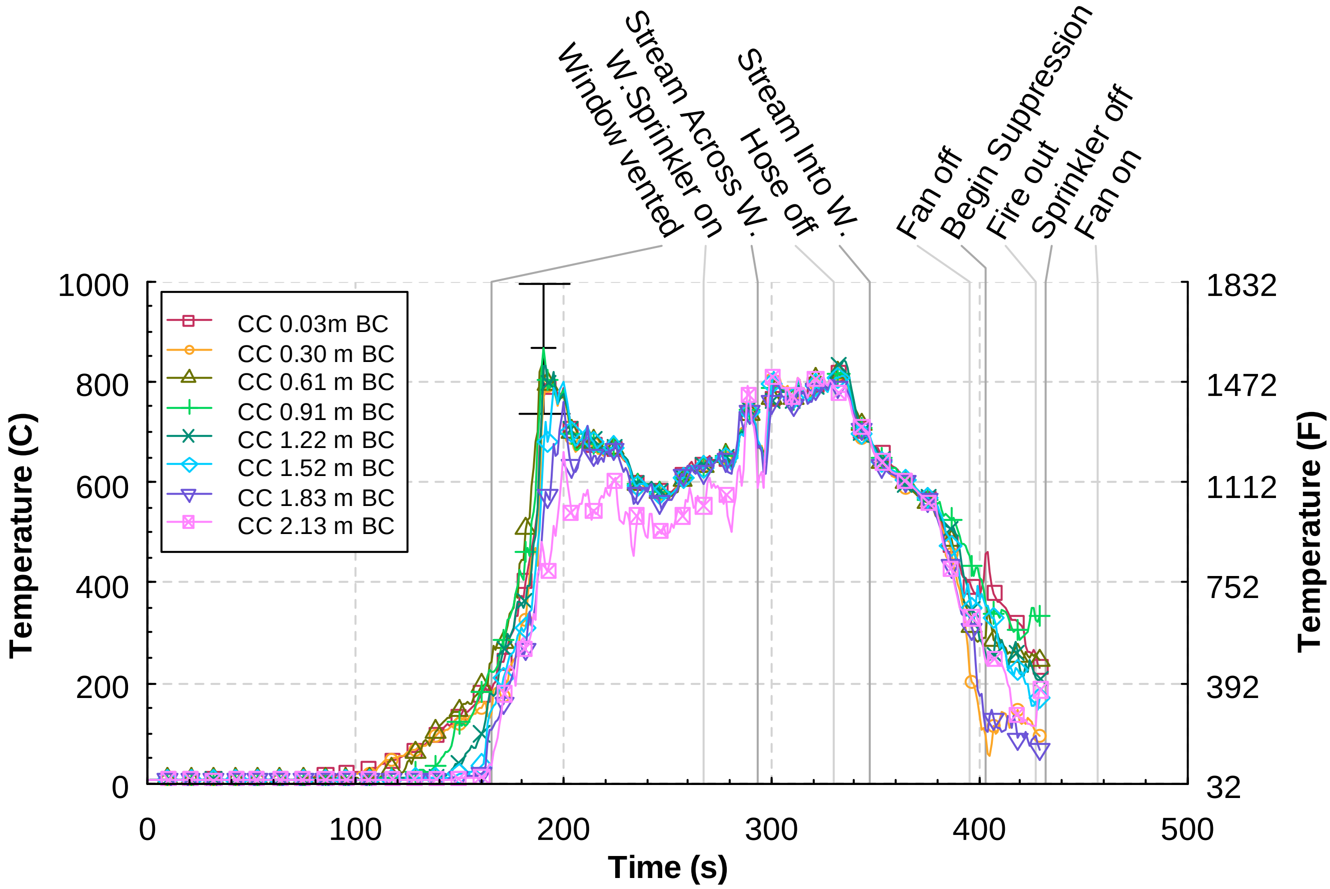

Figure 5.6.3-6. Temperature versus time from the corridor center (CC) thermocouple array, Experiment 6.

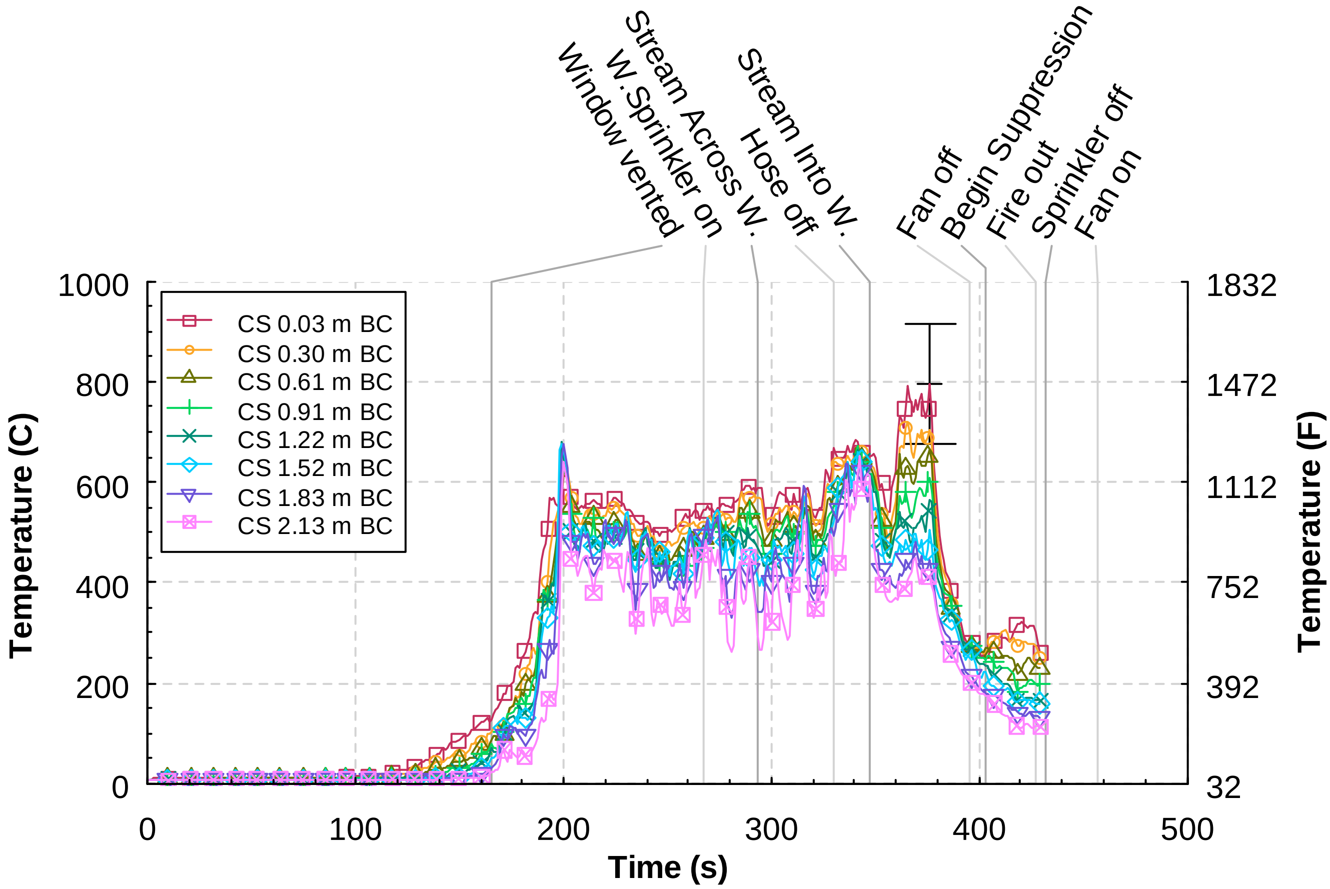

Figure 5.6.3-7. Temperature versus time from the corridor south (CS) thermocouple array, Experiment 6.

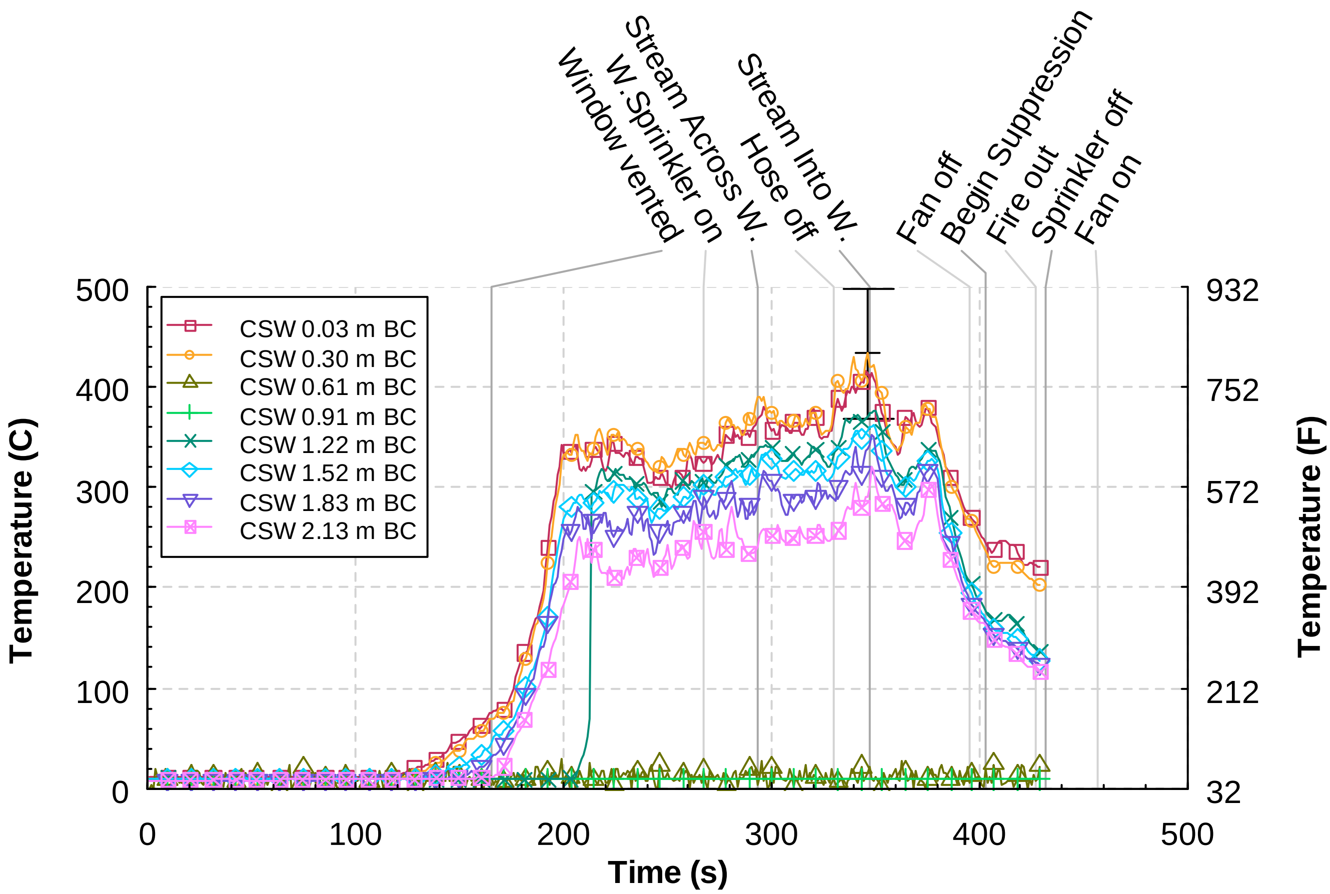

Figure 5.6.3-8. Temperature versus time from the corridor southwest (CSW) thermocouple array, Experiment 6.

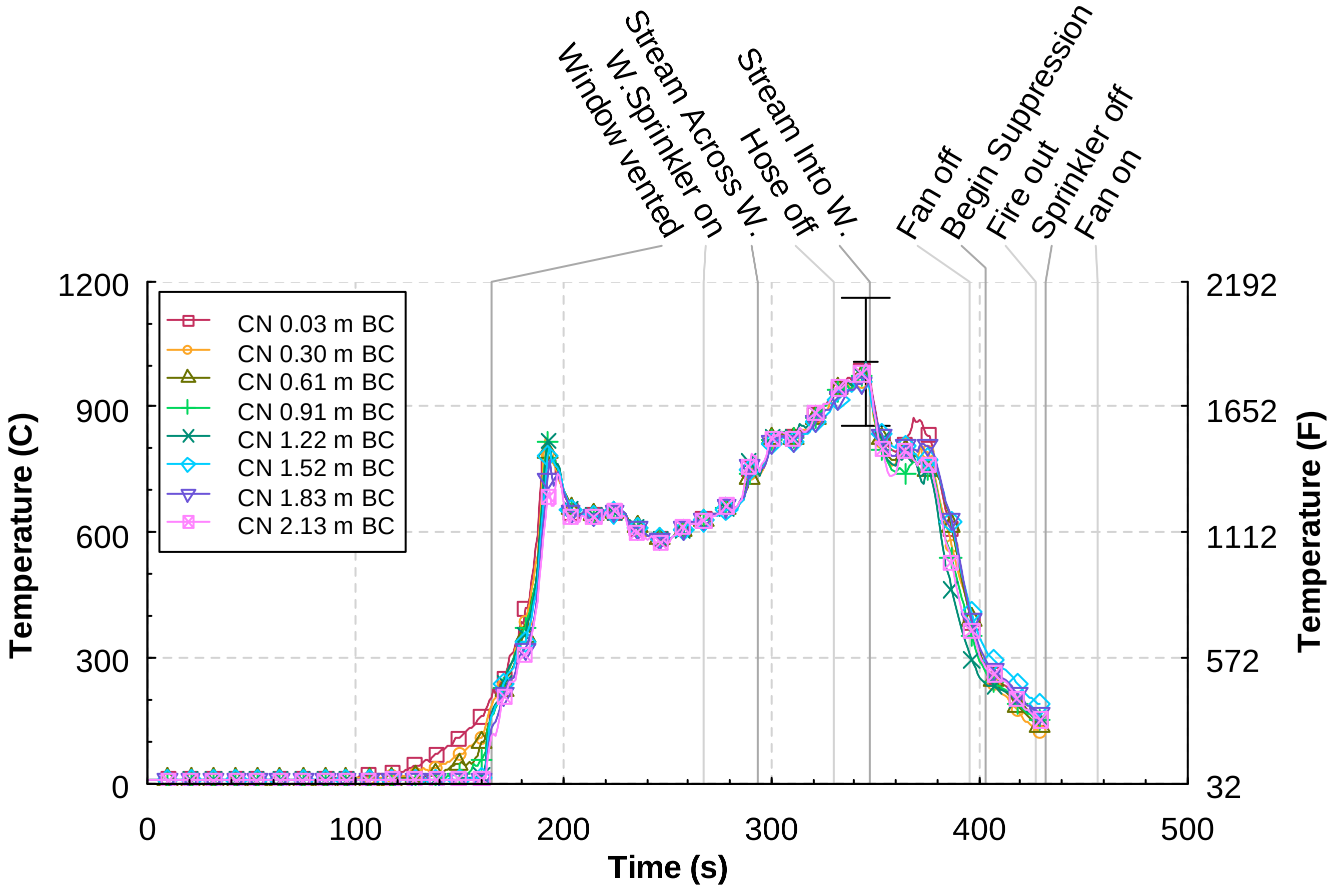

Figure 5.6.3-9. Temperature versus time from the corridor north (CN) thermocouple array, Experiment 6.

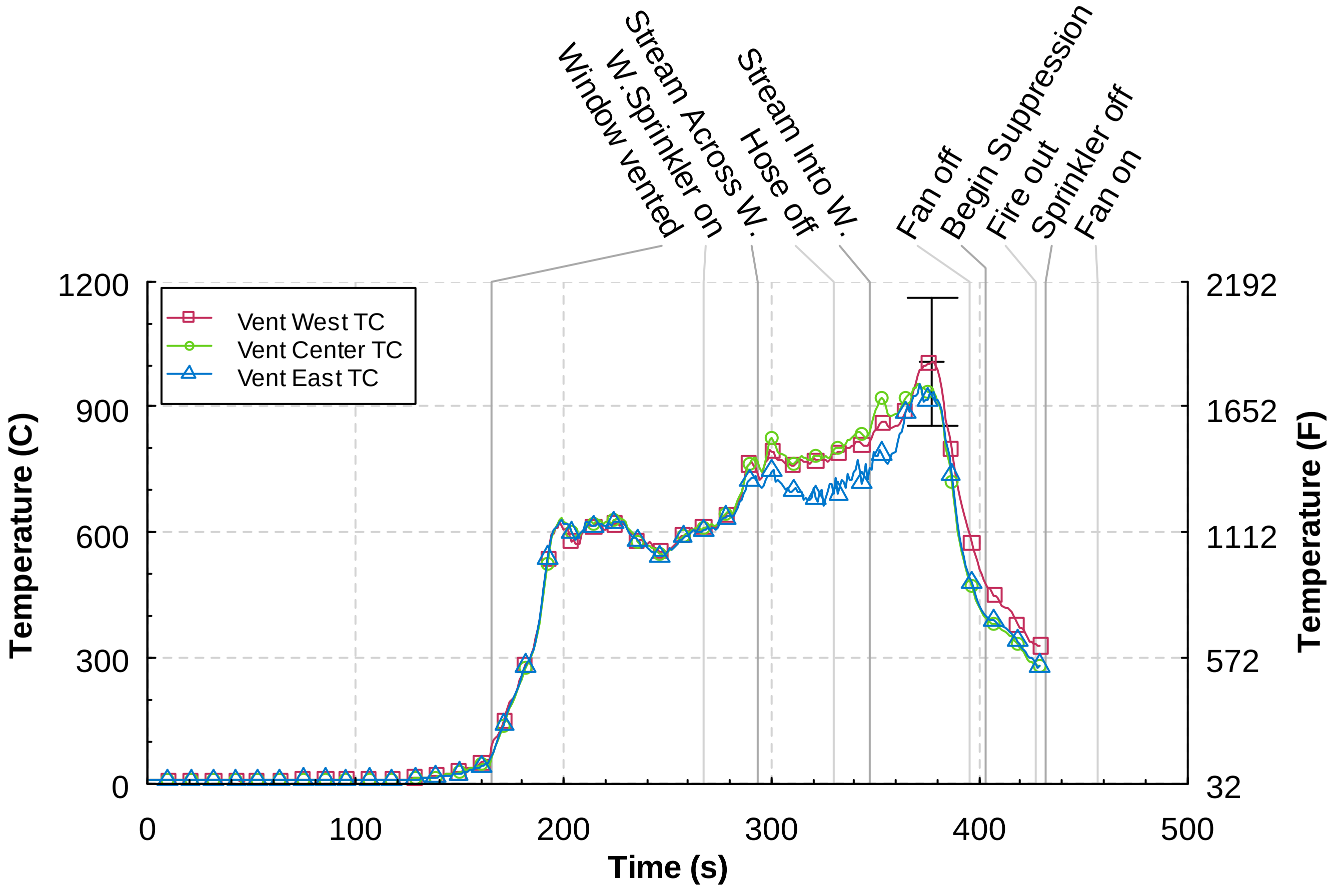

Figure 5.6.3-10. Temperature versus time from the ceiling vent thermocouple array, Experiment 6.

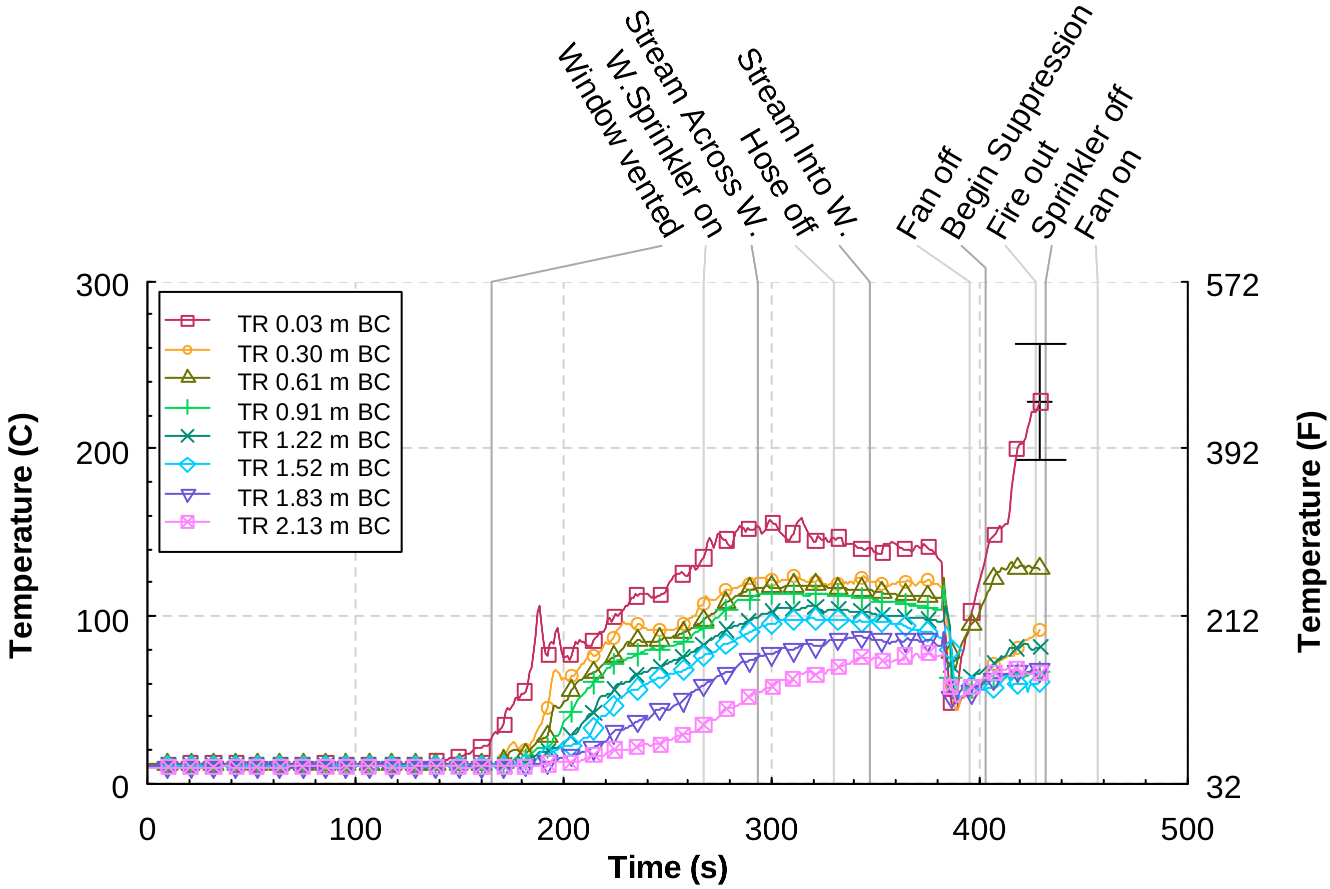

Figure 5.6.3-11. Temperature versus time from the target room (TR) thermocouple array, Experiment 6.

5.6.4 Heat Flux

The time history from all five heat flux gauges is given in Figure 5.6.4-1. The heat flux in the bedroom increased to 20 kW/m^2 prior to the window failure. After the window vented, the heat flux measurement in the bedroom increased to just under 200 kW/m^2 in 90 s but dropped very quickly once the sprinkler activated. The bedroom heat flux continued down to near ambient for the remainder of the test.

All other heat flux measurements also had a quick increase during the first 60 s of the test but reduced in value shortly after. The window sprinkler activation and associated hose stream applications increased the heat flux measurements but were sporadic in nature.

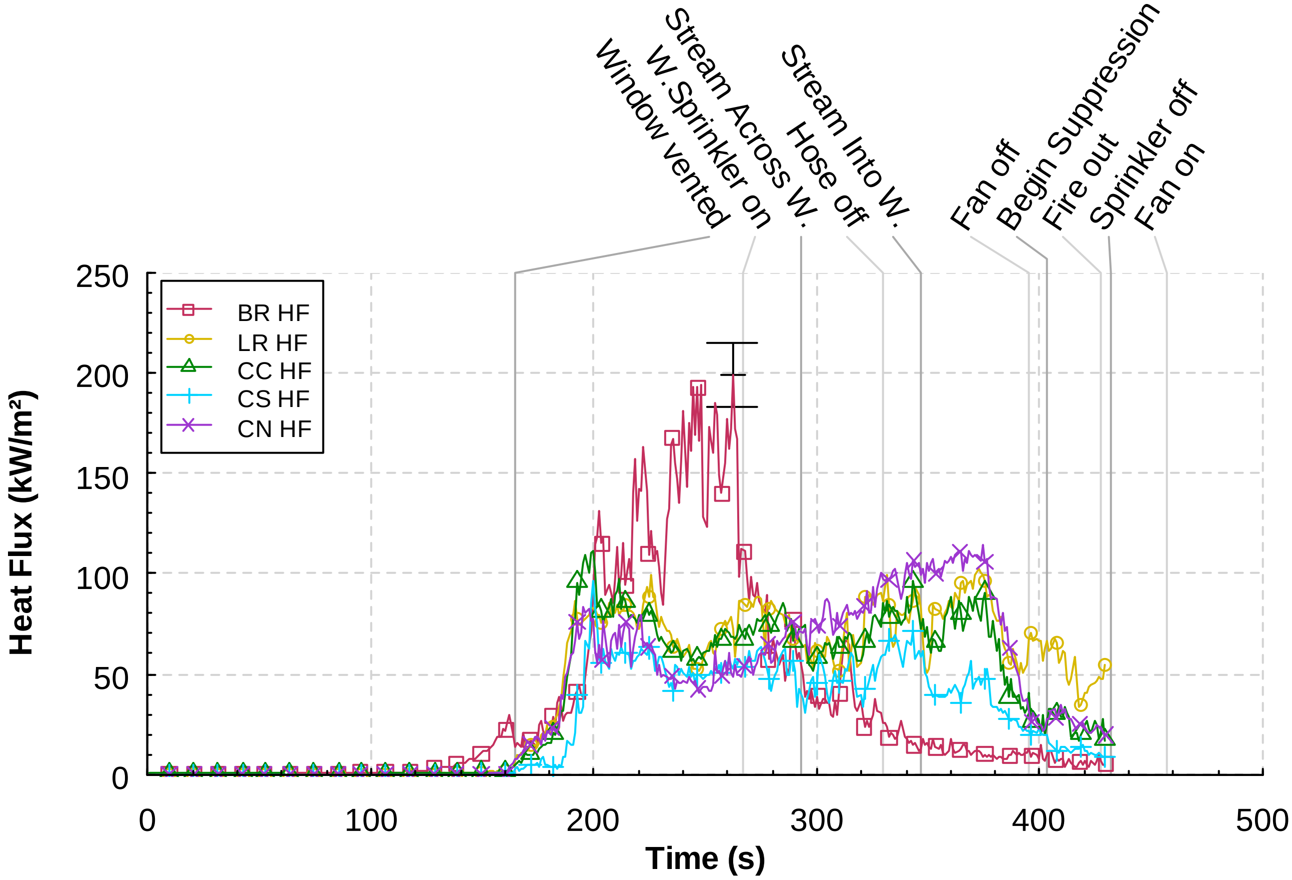

Figure 5.6.4-1. Heat flux versus time at five locations, Experiment 6.

5.6.5 Pressure

Figure 5.6.5-1 shows the pressures at the 5 measurement locations. There was little pressure change in the structure up to just prior to window failure. After window failure, the pressures in the structure increased at first, then declined but increased again over the span of 100 s. The closer to the source of the simulated wind the higher the pressure was. Pressures in the northwest and southwest corridors changed directions several times indicating a circulating air flow. The window sprinkler and fog stream across the window reduced all pressure values significantly but redirecting the stream into the window greatly increased the vaules once again. The bedroom, hallway and living room all peaked at 60 Pa while the southwest and northwest corridors hit 45 Pa and 30 Pa respectively. All pressures were reduced to 0 Pa once the fan was shut off.

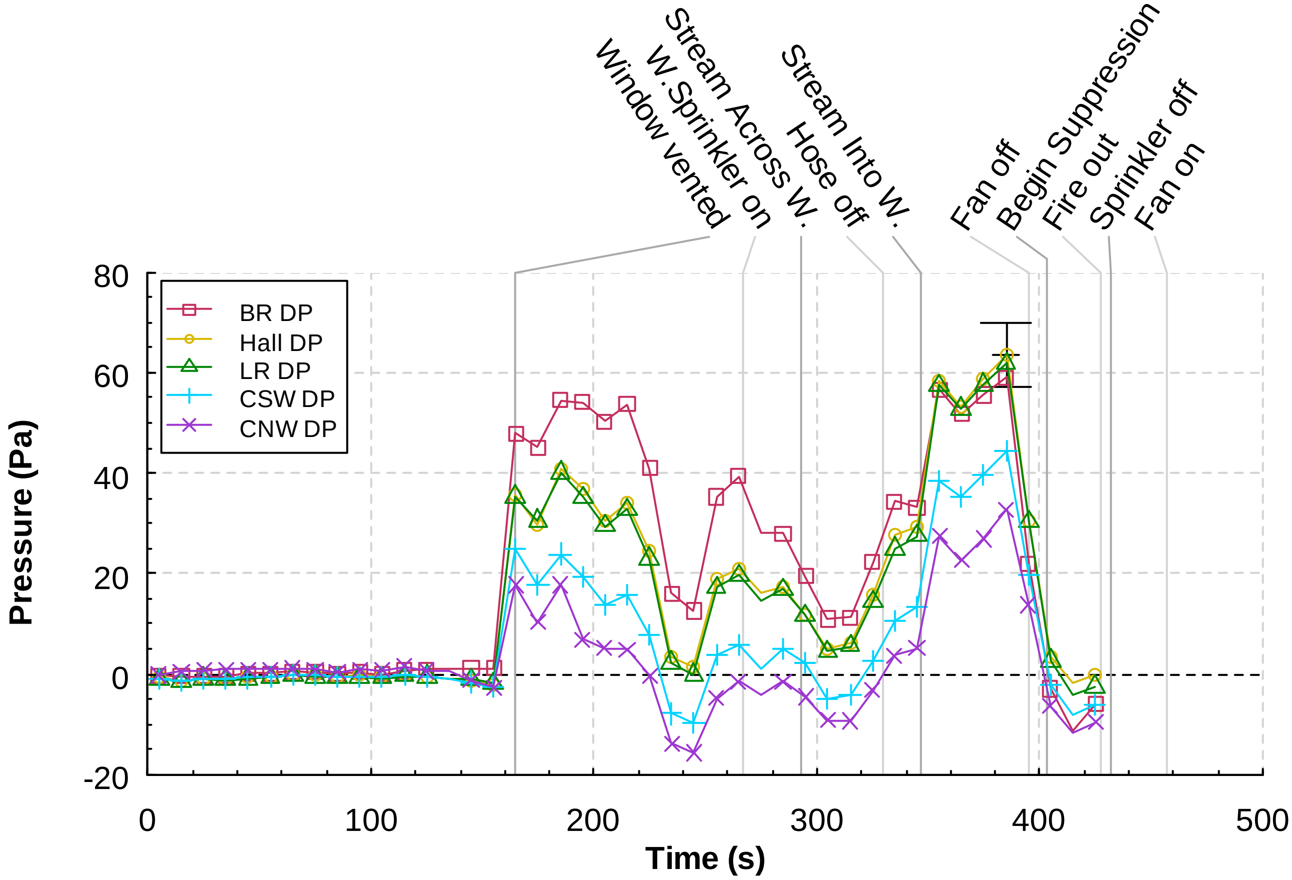

Figure 5.6.5-1. Pressure versus time at five locations, Experiment 6.

5.6.6 Velocities

Figure 5.6.6-1 provides the velocity measurements from the bi-directional probes that are located outside of the window. The positive velocities were flowing into the window. All bedroom window velocities increased to 1 m/s (2.2 mph) after the window failed and remained somewhat constant until the hose stream was directed across the window. Once the hose stream was redirected, the top pressure varied wildly from -18 m/s (40.2 mph) to +12 m/s (26.8 mph), the middle pressure spiked to 16 m/s (35.8 mph) and the bottom pressure jumped to 10 m/s (22.4 mph) but gradually reduced.

Figure 5.6.6-2 shows the velocities at the hall array position. On this graph, the positive direction is from west to east. All three probes recorded an increase in pressure just prior to and continued shortly after the window vented for approximately 40 s. The probes located at 1.22 m (4 ft) and 2.13 m (7 ft) each reached 8 m/s (17.9 mph) and remained relatively constant while the probe at 0.3 m (1 ft) reached 4 m/s (8.9 mph) and remined constant as well. When the sprinkler was activated and fog stream applied across the window, all three pressures reduced to 2 m/s (4.5 mph). However, when the hose stream was redirected into the window, the probes at 1.22 m (4 ft) and 2.13 (7 ft) began to oscillate while the probe at 0.3 m (1 ft) reduced to 0 m/s (0 mph).

Figure 5.6.6-3 displays the velocities from the south corridor position. The positive direction is from north to south. This was the dead end side of the corridor so there was no steady flow through this area.

There was significant recirculation and changes in the magnitude of the velocity. Flows ranged from -0.6 m/s to 2.2 m/s while the wind was flowing through the structure.

The velocities from the north corridor position are shown in Figure 5.6.6-4. The positive flow direction for this location is from south to north. Prior to window failure, the ceiling jet/hot gas layer velocities reached a peak of approximately 0.6 m/s (1.4 mph). After the window vented the velocities increased to a peak of approximately 6 m/s (13.4 mph) but then reduced. When the sprinkler was activated and the hose stream applied across the window, the velocities increased to a range of 5.8 m/s (13.0 mph) to 7.8 m/s (17.4 mph). When the hose stream was redirected through the window, the velocities decreased to a range of 2.0 m/s (4.5 mph) to 5.4 m/s (12.1 mph).

The measurements from the bi-directional probes installed in the exhaust vent, 2.44 m (8.0 ft) above the ceiling are given in Figure 5.6.6-5. The flow direction up and out of the structure is positive in the figure. Prior to the window being vented the peak flow velocity is less than 2 m/s (4.5 mph). After the window was vented, the velocities at all three probes were similar and flowing out of the structure at a speed of approximately 7 m/s (15.7 mph). Flowing the fog stream through the window increased the pressures to their peak range of 8 m/s (17.9 mph) to 12 m/s (26.8 mph).

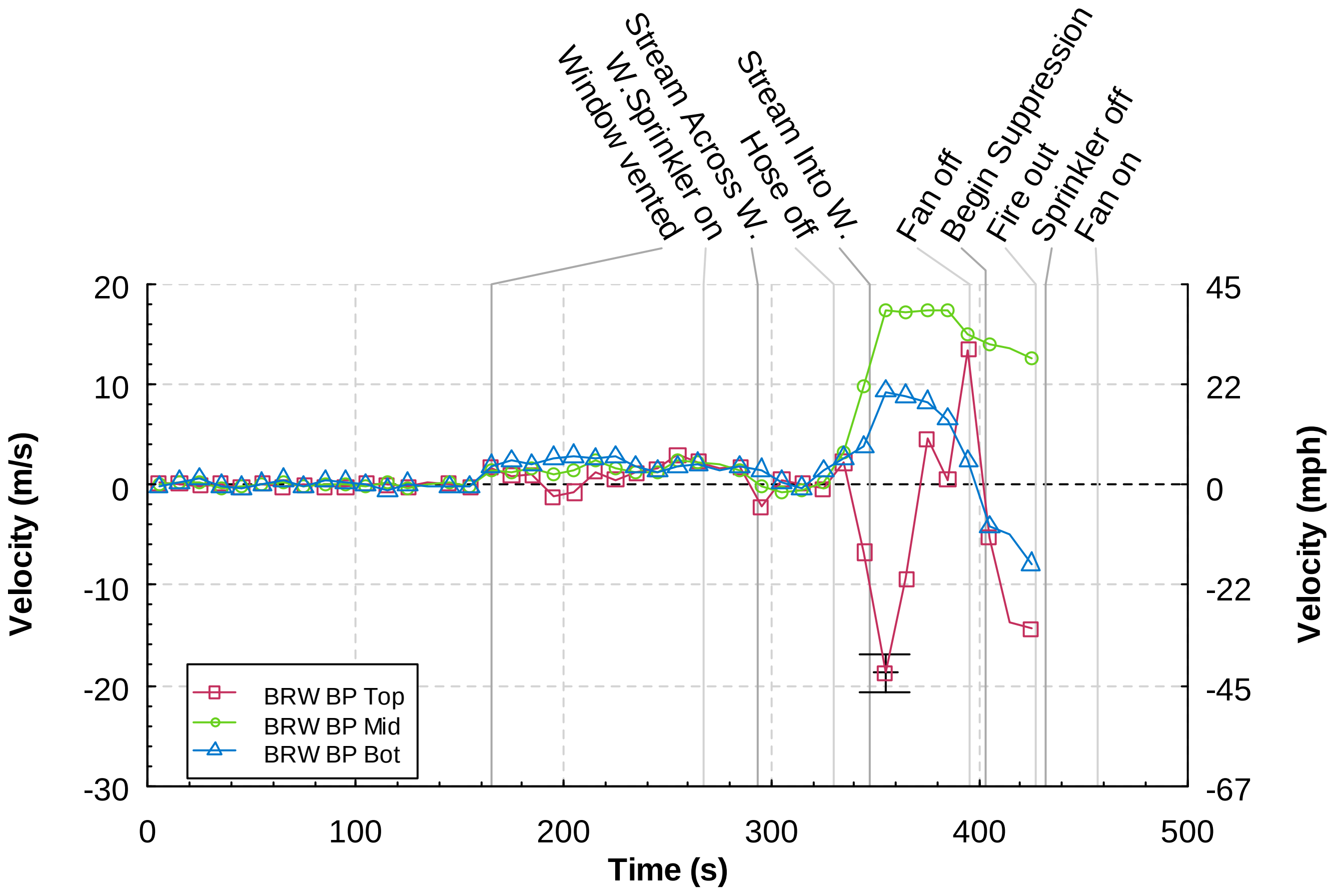

Figure 5.6.6-1. Velocity versus time from the bedroom window (BRW) bi-directional probe array, Experiment 6.

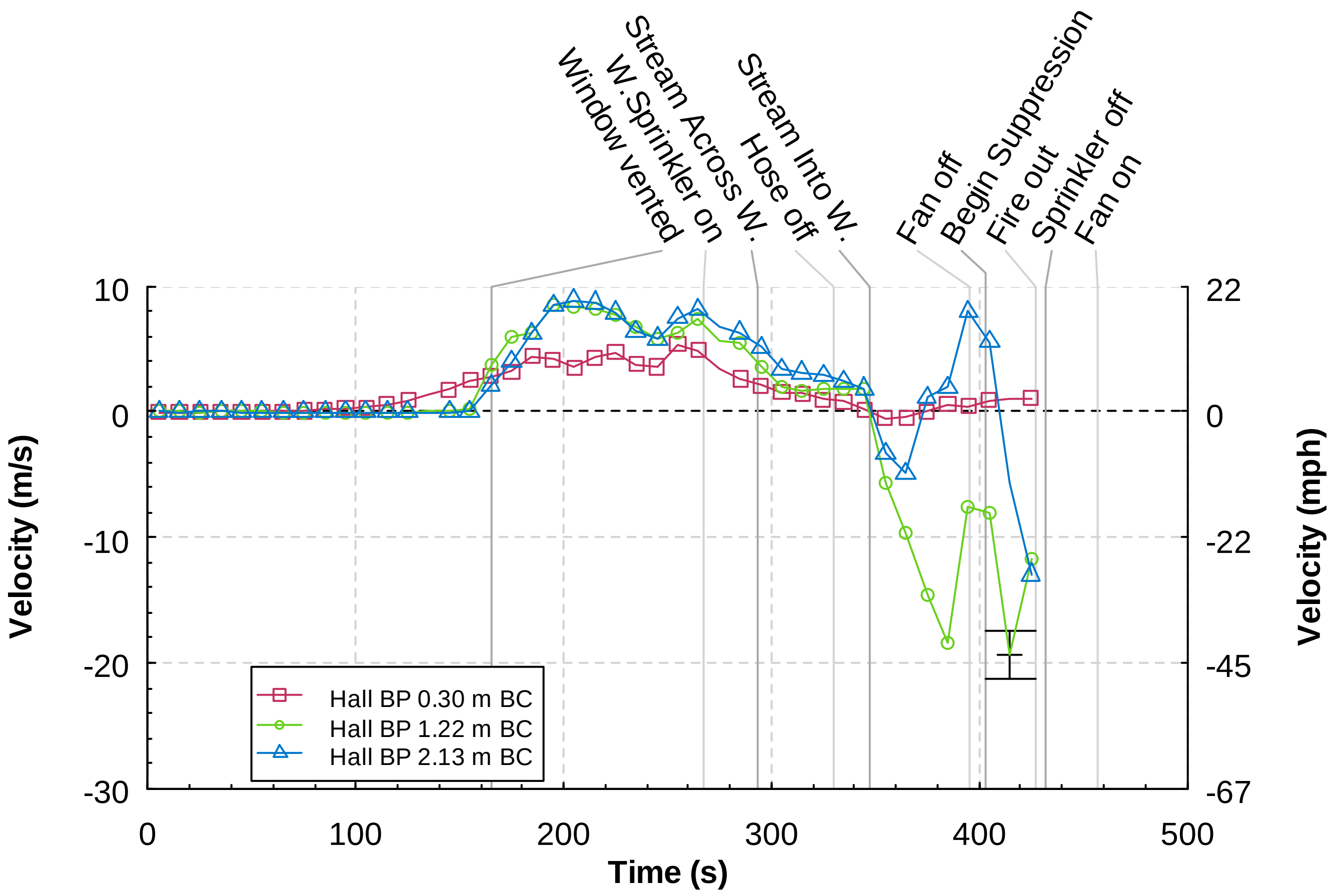

Figure 5.6.6-2. Velocity versus time from the hall bi-directional probe array, Experiment 6.

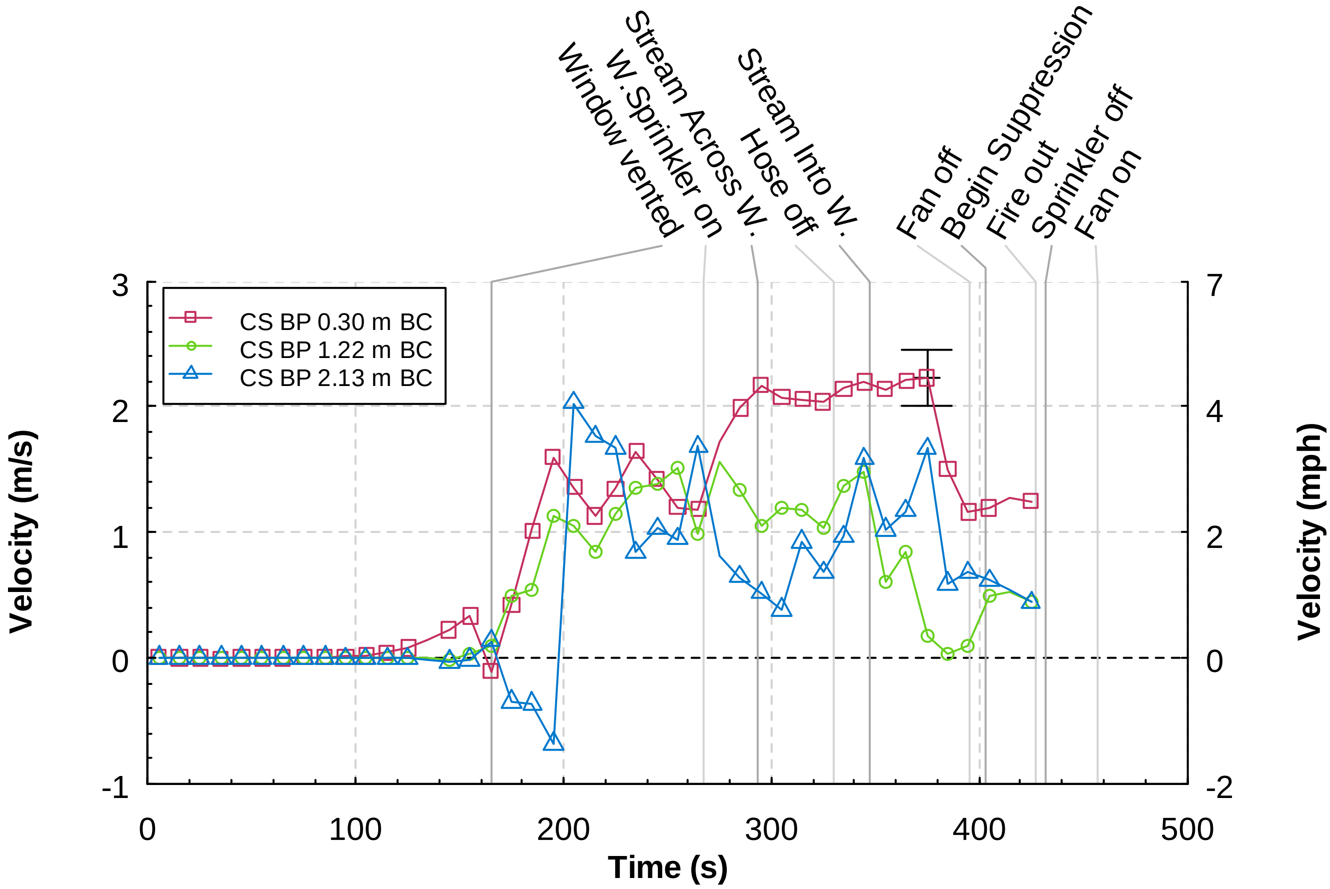

Figure 5.6.6-3. Velocity versus time from the corridor south (CS) bi-directional probe array, Experiment 6.

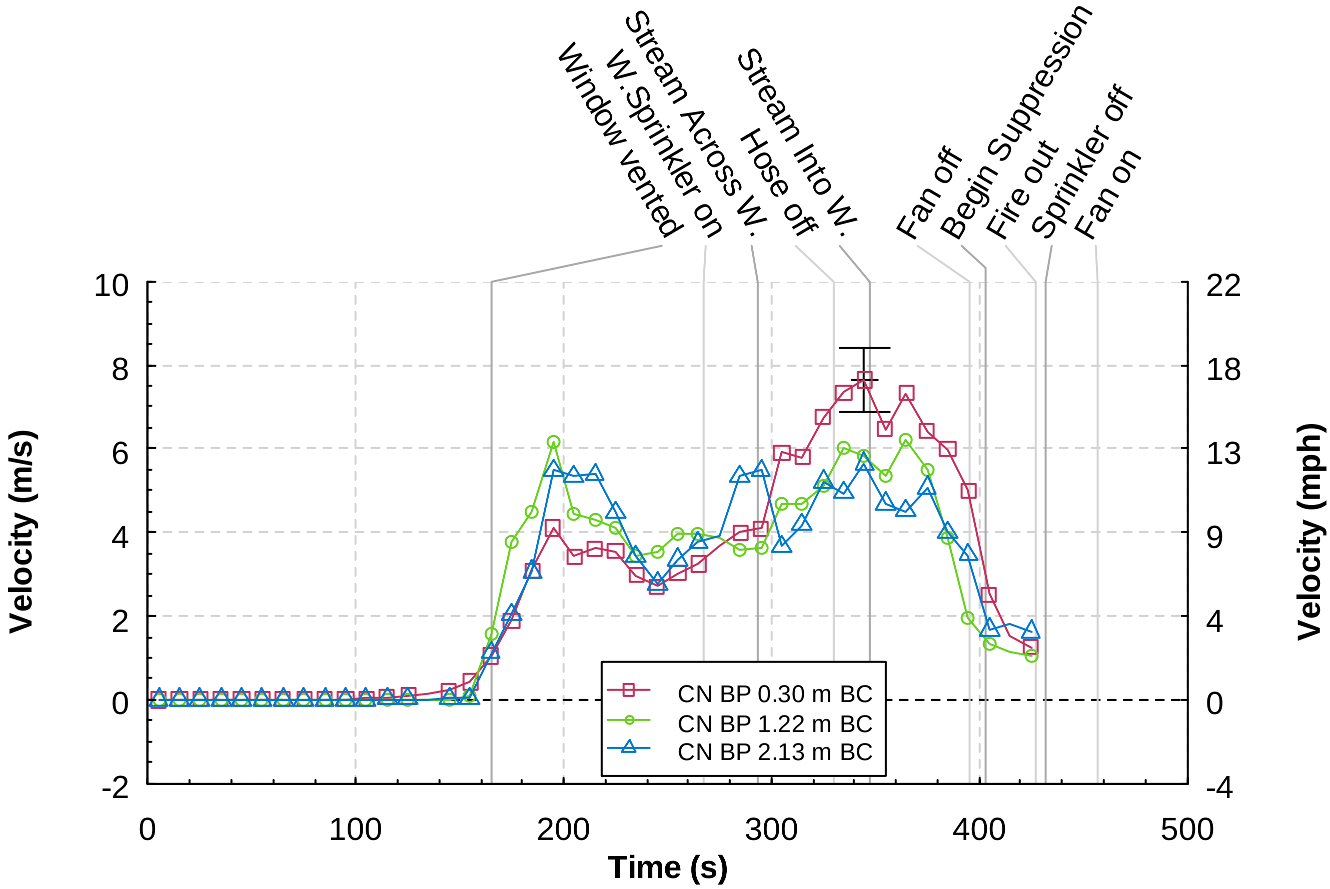

Figure 5.6.6-4. Velocity versus time from the corridor north (CN) bi-directional probe array, Experiment 6.

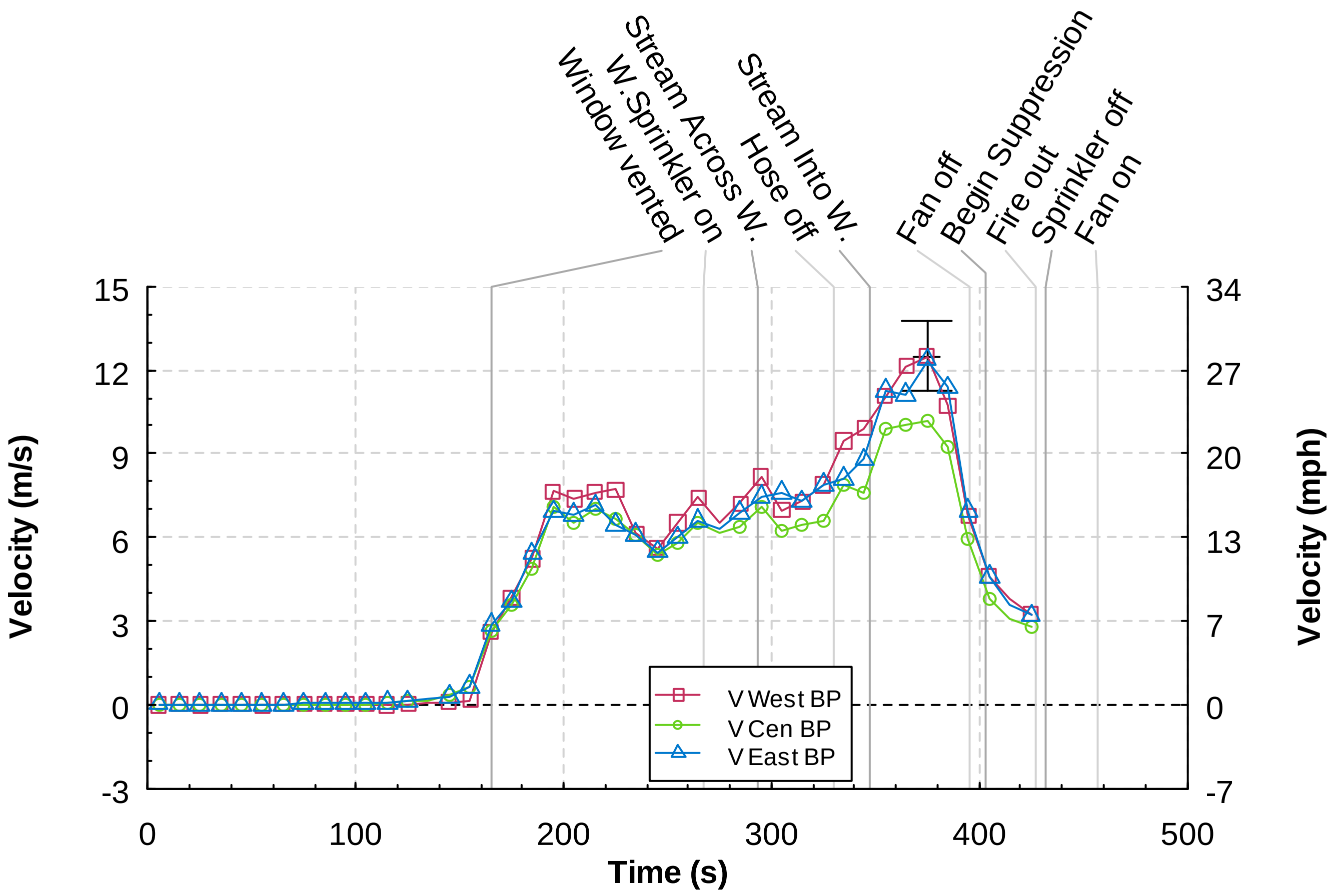

Figure 5.6.6-5. Velocity versus time from the ceiling vent (V) bi-directional probe array, Experiment 6.

5.6.7 Gas Concentrations

Figure 5.6.7-1 and Figure 5.6.7-2 show the gas concentration measurements made in the upper and lower levels of the bedroom. The gas concentrations in the upper portion of the bedroom began to change at approximately 100 s, as the hot gas layer developed and extended down 1.83 m (6.0 ft) from the ceiling to interact with the sampling probe. Just prior to window failure, the oxygen concentration decreased to 19 % and the CO_2 concentration increased to 2 %. After the window vented, the oxygen concentration dropped to near zero and the CO_2 concentration jumped to 10 % along with an increase to 5 % in CO concentration. When the sprinkler activated and the hose stream was applied across the window, the CO_2 wavered some, but the oxygen concentration increased and the CO concentration decreased. When the hose stream was redirected into the window, oxygen concentration increased to 16 %, CO_2 concentration dropped to 3 % and CO concentration fell to near zero once again. The only increase in total hydrocarbon concentration occurred 80 s after the window vented but a decline gradually occurred for the remainder of the test.

The gas concentrations in the lower portion of the bedroom began to change at approximately 150 s, as the hot gas layer developed and extended down 1.83 m (6.0 ft) from the ceiling to interact with the sampling probe. Just prior to window failure the oxygen concentration decreased to 9 % and the CO_2 concentration increased to 9 %. After the window vented at 165 s, the fresh air came in through the window and mixed with the lower portion of the hot gas layer, which temporarily increased the oxygen and decreased the carbon dioxide and carbon monoxide for about 30 s. After this mixing, the oxygen quickly dropped to below 5 %, the CO_2 increased to 12 % and the CO increased to 3 %. Wavering indicated a mixing of the air prior to sprinkler activation. Once the sprinkler activated and the hose stream applications were applied, an increase in oxygen concentration to 19 % and decreases in CO_2 and CO concentrations to 1 % and 0 % respectively occurred.

Figure 5.6.7-3 and Figure 5.6.7-4 provide the measurements from the upper and lower gas sampling probes, respectively, in the living room. Gas concentrations in the upper portion of the living room began to change at approximately 180 s. After the window vented, the oxygen concentration dropped from 20 % to near 0 % in the span of 100 s and remained there for the duration of the test. After the window vented, the CO_2 concentration jumped from 1 % to a peak of 17 % in the span of 100 s. The sprinkler activation did not have an effect but the fog stream across the window at 293 s caused the level to drop to 14 %. Placing the fog stream directly in the window at 347 s caused an increase to 16 % where is then leveled off. The CO and total hydrocarbon concentrations mirrored each other and initially rose to 5 % just prior to the sprinkler application. A small decrease occurred after sprinkler activation, but the fog stream across the window caused both values to increase once again. However, placing the hose stream into the window reduced both values to 3 %.

The gas concentrations in the lower portion of the living room began go change just prior to window ventilation. After the window vented, the oxygen concentration fell from 20 % to 1 % in 40 s and remained relatively constant. An increase to 4 % was noticied when the fog stream was placed into the window at 347 s. The CO_2 increased from 1 % to 16 % in 40 s but decreased with each successive application of water to 10 %. The CO concentration jumped from near 0 % to 4 % in 40 s but declined to 3 % with the sprinkler activation. The fog stream flowing across the window caused an increase to 6 % but as the stream was repositioned into the window, the concentration fell back to 4 %.

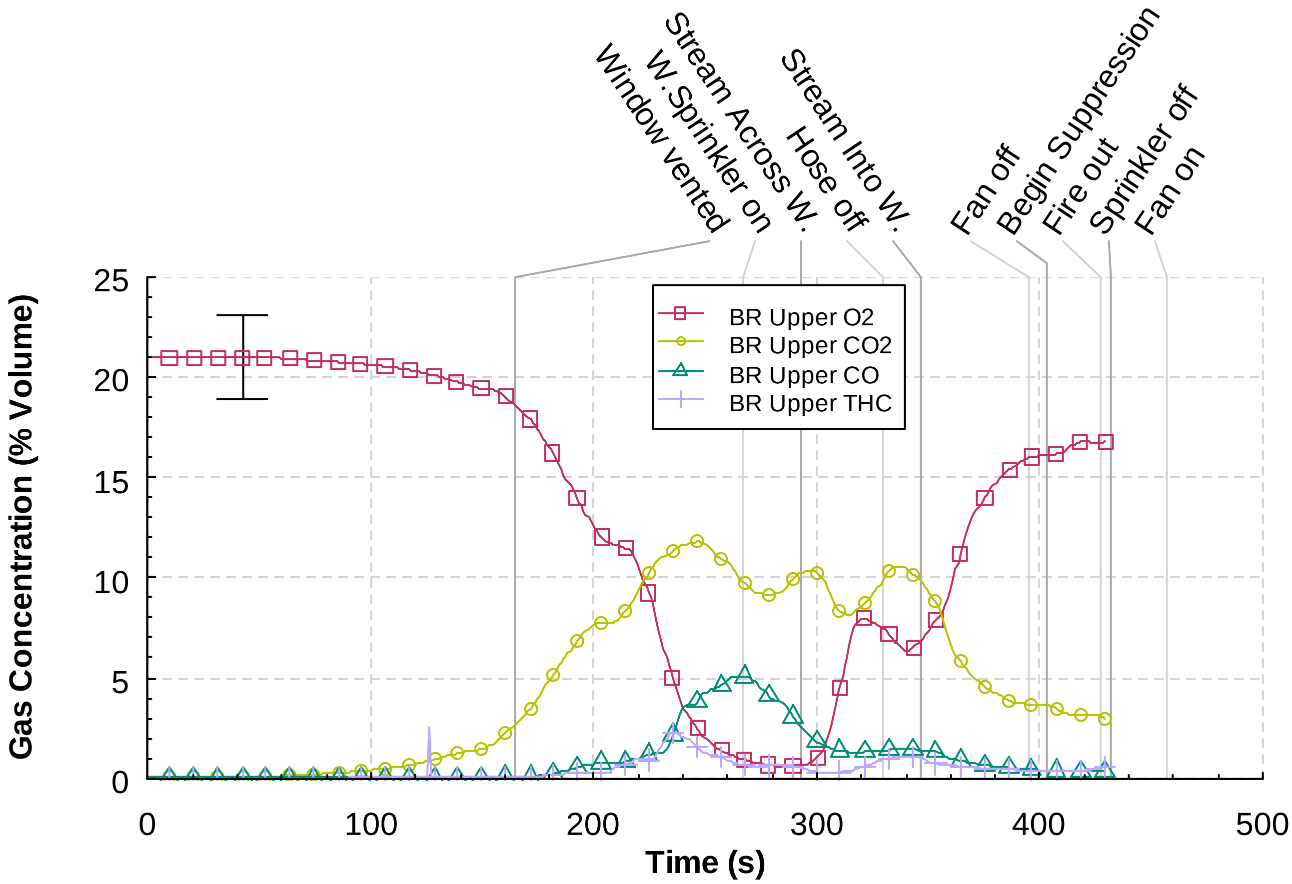

Figure 5.6.7-1. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper bedroom (BR) sampling location, Experiment 6.

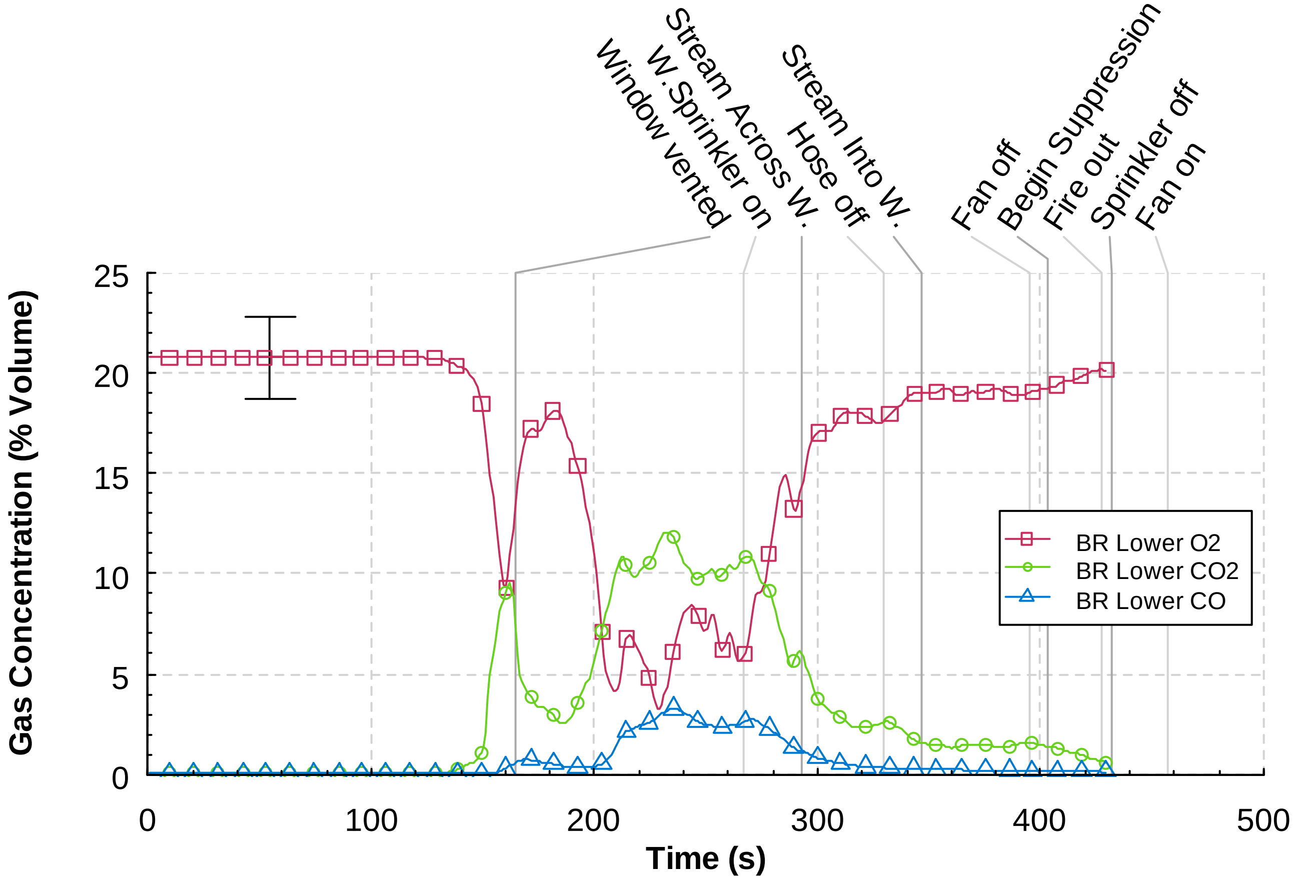

Figure 5.6.7-2. Oxygen, carbon dioxide, and carbon monoxide percent volume versus time from the lower bedroom (BR) sampling location, Experiment 6.

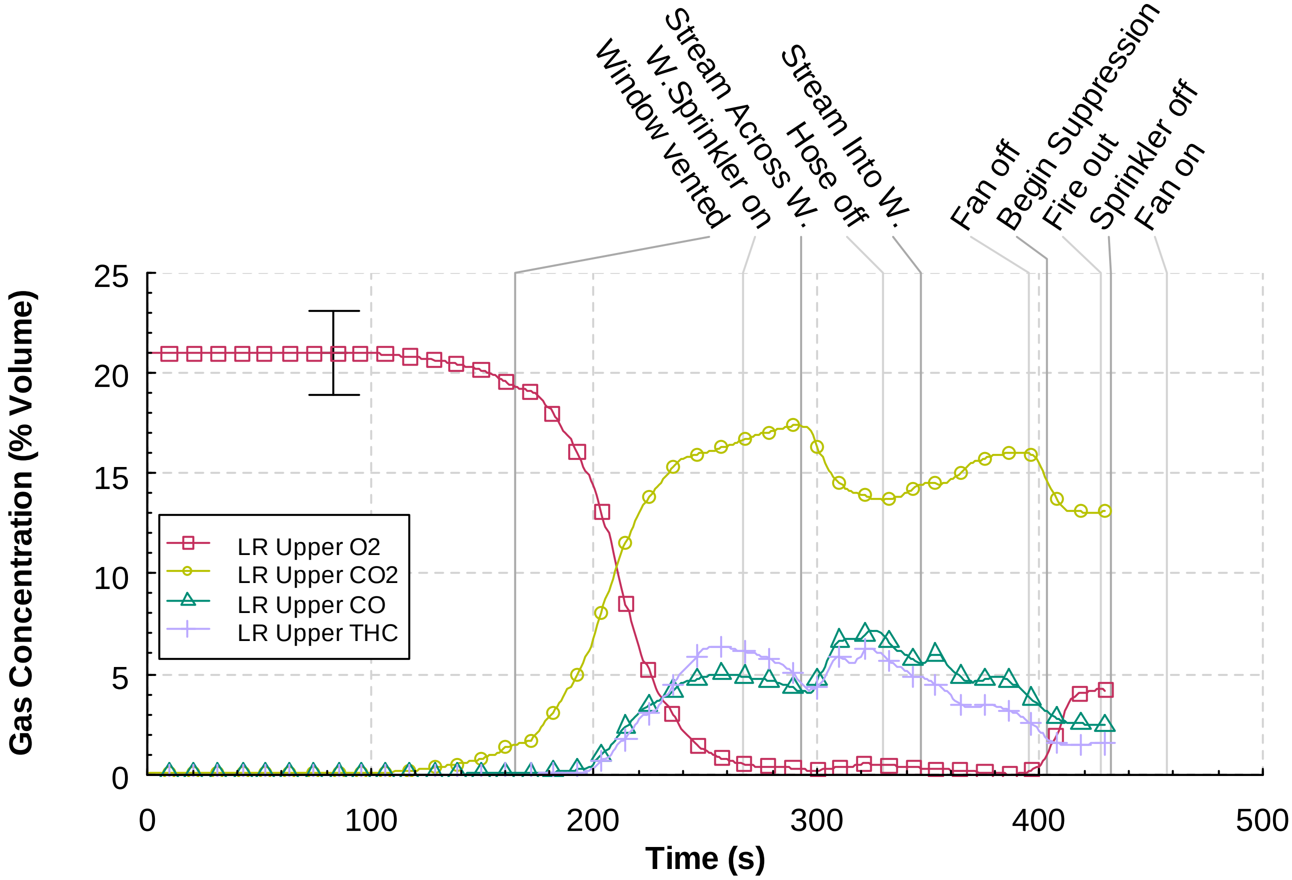

Figure 5.6.7-3. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper living (LR) room sampling location, Experiment 6.

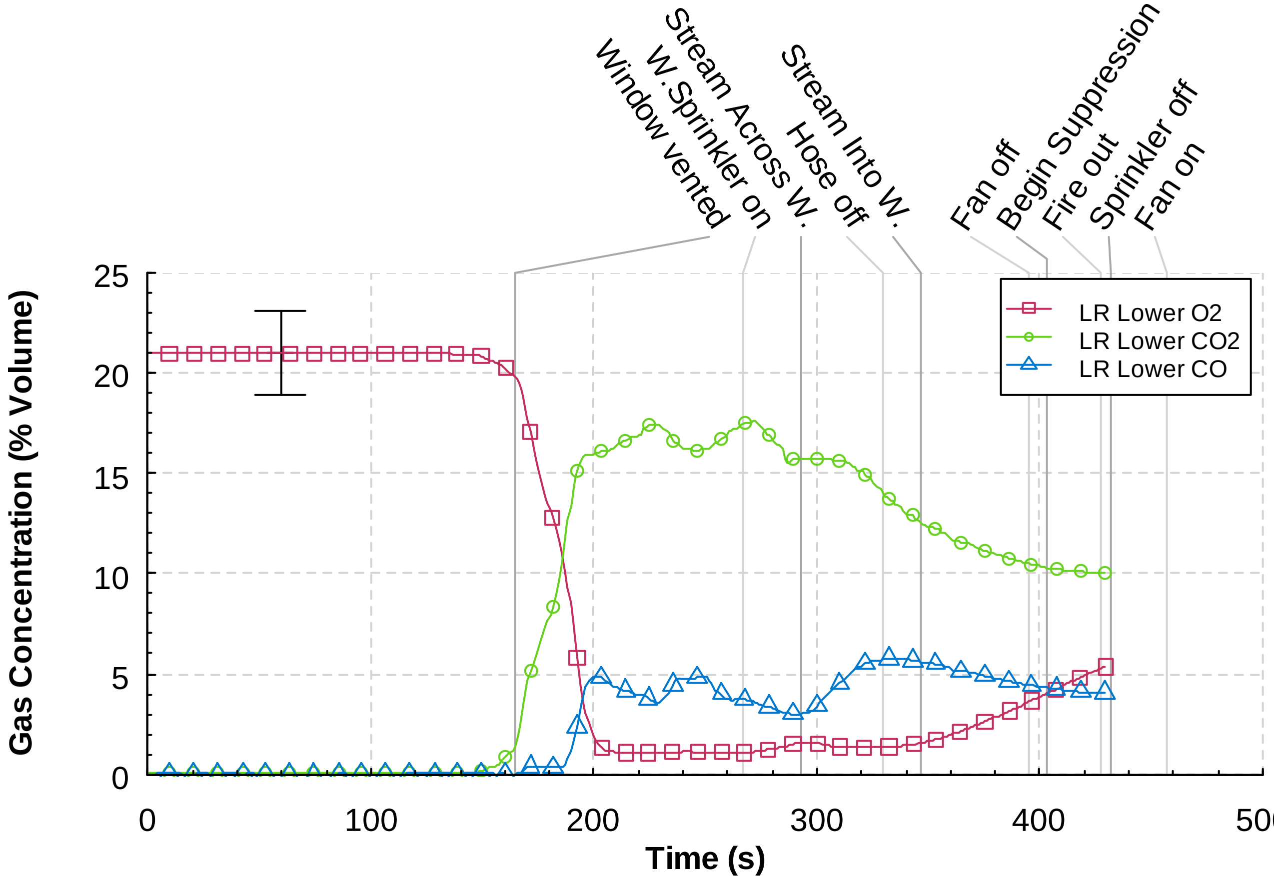

Figure 5.6.7-4. Oxygen, carbon dioxide, and carbon monoxide percent volume versus time from the lower living room (LR) sampling location, Experiment 6.

5.7 External Water Application (indirect attack) WDF 7 (smooth bore)

The seventh experiment in the series was conducted to examine the impact of wind on the structure fire, the impact of the doorway from the living room to the corridor closed and quantify the impact of a smooth bore water stream into the bedroom. The experimental preparations were made as described in Section 4. The fan speed used in this experiment was 1500 RPM, which provided a 3.0 m/s to 4.0 m/s (7 mph to 9 mph) wind speed at the window opening. A trash container fuel package was ignited remotely with and electric match to start the experiment at Time = 0 s. A time line of the experiment is presented in Table 5.7-1. The results for the experiment are presented in the following sections: observations, heat release rate, temperature, heat flux, pressure, velocity, and gas concentrations. An uncertainty range marker is included in each graph.

Table 5.7-1. Experiment 7 Timeline

Time (s)	Event
0	Ignition
200	Visible smoke layer
297	Window vented partially
310	Window cleared
377	Door open
435	Hose on, at ceiling
505	Sweeping ceiling
538	Hose off
545	Manual supression
550	Fire knocked down

5.7.1 Observations

The observations are presented as a series of images captured from eight camera locations, six were video cameras and two were thermal imaging cameras. The video camera and thermal imaging camera were removed from the target room and placed outside the structure. The video camera shows the "stack", which is the extension of the vent into the exhaust hood. The thermal imaging camera shows a similar view as the outside video camera.

Figure 5.7.1-1 through Figure 5.7.1-13 present sets of eight images, one from each camera position, at a given time, from the time of ignition to 550 s after ignition. Each image view is labeled. Figure 5.7.1-1 shows the conditions at the time of ignition. At this point, the six video views are clear and unobstructed. However, the thermal images provide limited thermal contrast, because the surfaces in the view were at nearly equal temperature.

The images in Figure 5.2.1-2 were captured 60 s after ignition. The fire has yet to extend out of the trash container. A smoke layer was beginning to form in the bedroom. There was no smoke or change in thermal condition in the living room or corridor at this time.

The images in Figure 5.2.1-3 were recorded at 120 s after ignition. The fire extended out of the trashcan and extended to the bed and the chair. The smoke layer was still forming in the bedroom. Smoke and heat had just started to flow into the living room. The outside thermal imaging view shows the fire visible through the glass window.

The images in Figure 5.7.1-4 were recorded at 180 s after ignition. The fire had spread to the area between the bed and the upholstered chair with a flame height of approximately 0.9 m (3 ft) above the floor. The smoke layer was approximately 0.9 m (3 ft) thick throughout the bedroom. Smoke was beginning to spread through the hallway and into the living room. No smoke and heat had made it into the corridor because the door to the corridor was closed.

Figure 5.7.1-5 shows the images recorded 60 s later at 240 s after ignition. The window was still fully intact. The flames were spreading across the side of the bed and onto the back of the chair. The smoke layer was lowering and darkening in the bedroom. A smoke layer was also developed in the living room. A slight haze of smoke was visible in the corridor and the thermal imaging view in the corridor shows some heat leaking around the metal door. No smoke was evident coming from the stack.

Figure 5.7.1-6 shows the images at 300 s after ignition. The smoke layer descended to the floor in most of the structure. The corner of the window had cracked and fell out. There was an increase in the amount of heat entering the corridor through cracks around the door and the visibility in the corridor was diminishing. Light smoke was visible from the stack.

The images in Figure 5.7.1-7 were recorded 312 s after ignition. The window opening had just been manually cleared. The flames could be seen flowing out of the window opening against the wind. Soot obscured the video views in the bedroom, living room and both of the cameras in the corridor. The image from the corridor IR camera shows hot gases being forced around the door at a higher velocity. Increased smoke was coming from the stack and filling the exhaust hood.

Figure 5.7.1-8 shows the conditions at 360 s after ignition. Flames are still flowing out of the top of the window opening. There was very little visibility in the rest of the structure. The door to the corridor was still closed so the heat was being forced around the door and through the hole for the door knob. The stack was being obstructed by smoke as well.

The images in Figure 5.7.1-9 were recorded at 420 s after ignition, 43 s after the door to the corridor was opened remotely. The bedroom was completely full of flames and flames were coming out of the window against the simulated wind. All of the internal video camera views were obscured by smoke. The corridor thermal imaging camera was completely saturated with hot gas flow and there is no usable image.

At 435 s after ignition, the hose stream was directed at the ceiling of the bedroom as shown in the outside view of Figure 5.7.1-10. The interior video views were still obscured by soot. The heat coming out of the bedroom window was diminished and the stack was still not visible.

Figure 5.7.1-11 shows the conditions at 480 s after ignition, or approximately 45 s since activation of the hose stream. The interior video views were still obscured by soot, but the bedroom view was returning to show flames. The thermal image from the corridor was still saturated with heat but started to improve in clarity. The outside thermal imaging view shows all of the heat going back into the structure.

Figure 5.7.1-12 shows the conditions at 540 s after ignition, which was about 2 s after the hose stream was turned off. Flames are still visible in the bedroom, but not coming out of the bedroom window. The internal views are still obscured but the thermal imaging view in the corridor has returned to a usable image showing little heat flow. The dark spots on the wall and floor also indicate that water made it to the corridor. The stack was once again visible showing a reduced smoke production rate.

The final images at 550 s after ignition show final suppression of the burning items remaining in the bedroom. The water did not reach the furnishings just inside the window so they needed to be extinguished from inside the window. All of the interior images were still obscured by soot deposition on the camera lenses.

Figure 5.7.1-1. Experiment 7, ignition.

Figure 5.7.1-2. Experiment 7, 60 s after ignition.

Figure 5.7.1-3. Experiment 7, 120 s after ignition.

Figure 5.7.1-4. Experiment 7, 180 s after ignition.

Figure 5.7.1-5. Experiment 7, 240 s after ignition.

Figure 5.7.1-6. Experiment 7, 300 s after ignition.

Figure 5.7.1-7. Experiment 7, window fully vented, 312 s after ignition.

Figure 5.7.1-8. Experiment 7, 360 s after ignition.

Figure 5.7.1-9. Experiment 7, 420 s after ignition.

Figure 5.7.1-10. Experiment 7, indirect suppression started, 438 s after ignition.

Figure 5.7.1-11. Experiment 7, 480 s after ignition.

Figure 5.7.1-12. Experiment 7, 540 s after ignition.

Figure 5.7.1-13. Experiment 7, direct suppression, 550 s after ignition.

5.7.2 Heat Release Rate

Figure 5.7.2-1 shows the heat release rate time history for Experiment 7. The increase in measured heat release rate is delayed because for the first 297 s after ignition no heat or combustion products generated by the fire flowed out of the structure. After the window failed, at 297 s after ignition, the increase in heat release rate was clear, however a more significant increase occurred after the door was opened at 377 s. The heat release rate reached a peak of approximately 22 MW, 43 s after the door was opened. An exterior hose stream equipped with a smooth bore nozzled was applied through the window opening and directed at the ceiling at 435 s which significantly reduced the heat release rate from 16 MW to 6 MW. The hose stream continued to flow water in a sweeping pattern across the ceiling at 505 s which further reduced the heat release rate until it was manually suppressed at 545 s.

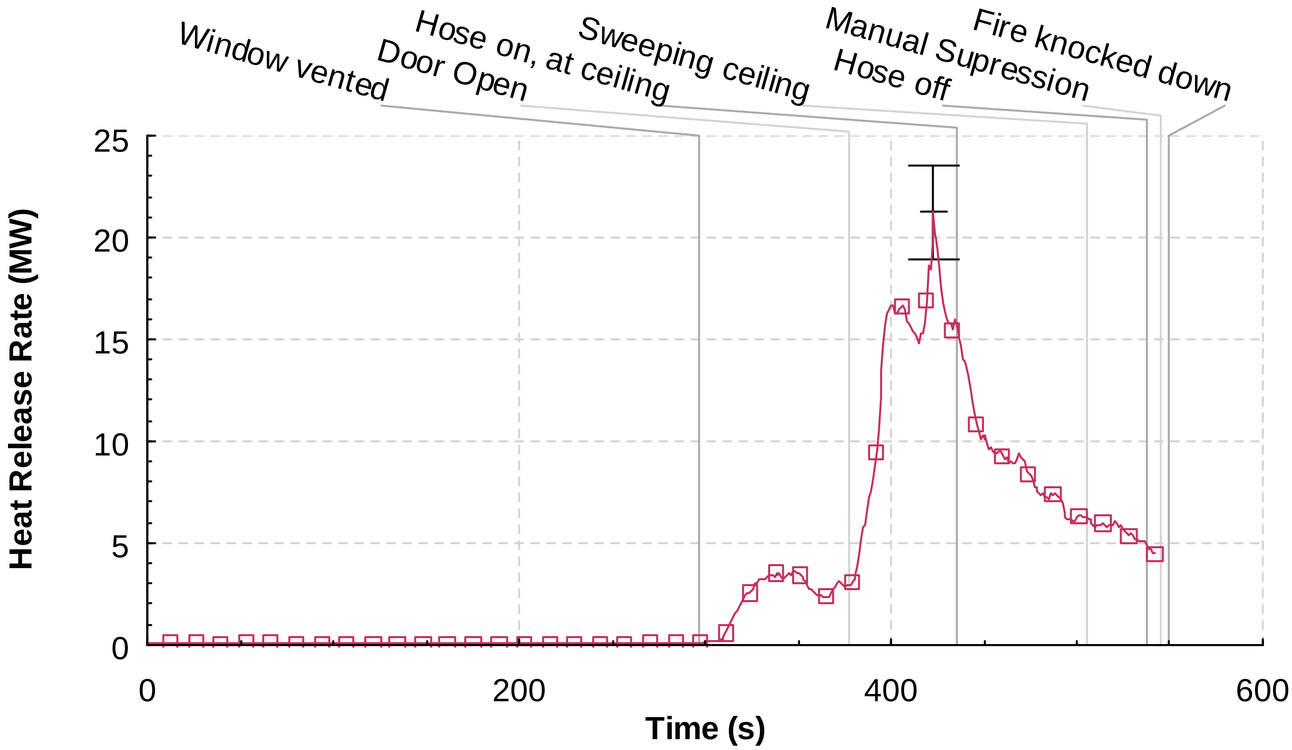

Figure 5.7.2-1. Heat release rate versus time, Experiment 7.

5.7.3 Temperatures

Figure 5.5.3-1 through Figure 5.7.3-11 provides the temperature measurements from the thermocouple arrays shown in Figure 4.1.3-1. The figures are given in order from the western most measurement point, the bed room window opening, and moving through the structure toward the east; bedroom, hall, living room, corridor, south and southwest portions of the corridor (closed end) and then to the north section of the corridor and ending with the exhaust vent. The last two temperature graphs have temperatures associated with the target room.

The two thermocouples located in the window opening, shown in Figure 5.7.3-1, provide insight into the ventilation conditions at the middle and bottom of the window. After window failure at 297 s temperatures fluctuate as the flames are pulsing out of the window and wind is blowing into the window.

The highest temperatures are located in the middle of the window opening and peaked just over 200 ºC (392 ºF). Temperatures continued to climbed eradically until the smooth bore nozzle applied water at the ceiling at 435 s. Temperatures steadily delined with reduced fluctuations until the fire was manually suppressed at 545 s.

The measurements from the thermocouple array located in the center of the bedroom are given in Figure 5.7.3-2. Temperatures stratified in the bedroom prior to the window failure to a peak just above 600 ºC (1112 ºF) near the ceiling. At the same time, the temperatures, 2.13 m (7.00 ft) below the ceiling, were almost 100 ºC (212 ºF). After the window vented, temperatures fluctuated greatly but remained relatively stratified. After the door was opened, however, all temperatures peaked at 900 ºC (1652 ºF) and immediately began to decline. The hose stream applied to the ceiling at 435 s caused a further temperature decline for all levels.

The data from the hall thermocouple array is presented in Figure 5.7.3-3. The temperatures slowly increased as the fire in the bedroom developed. The ceiling temperature in the hallway topped 400 ºC (752 ºF), while the temperature 2.13 m (7.00 ft) below the ceiling was slightly above ambient just prior to the window venting. At 330 s, 30 s after window failure the temperatures at the ceiling peaked close to 700 ºC (1292 ºF) while the temperature 2.13 m (7.00 ft) below the ceiling were just above 100 ºC (212 ºF). At this point, temperatures in the top half of the hallway began to decline while the lower half remained relatively constant. However, at 377 s, the door to the room was opened which immediately initiated a flashover. Temperatures floor to ceiling in the hallway spiked to 900 ºC (1652 ºF) and then began to decline. All temperatures remained above 700 ºC (1292 ºF) until the hose stream was deployed at the bedroom ceiling 60 s after flashover which caused a drastic reduction to nearly ambient conditions in the hallway. Following the initial temperature plummet, the bottom half of the room increased back up to 500 ºC (932 ºF) while the top half increase to approximately 600 ºC (1112 ºF). Sweeping the nozzle of the hose stream across the ceiling at 505 s caused all temperatures to generally equalize and slowly decline.

The data from the living room corner thermocouple array is shown in Figure 5.7.3-4. Temperatures increased and stratified up to the point of window failure. Following window failure at 297 s, temperatures leveled off for approximately 20 s but then continued to increase for another 10 s. A decrease in upper level temperatures occurred until the door was opened, which immediately caused all temperatures to spike. Temperatures remained somewhat stratified with the floor hitting 500 ºC (932 ºF) compared with almost 700 ºC (1292 ºF) at the ceiling level. All temperatures declined for approximately 10 s following the initial spike, but increased back to peak levels 20 s later. The hoseline directed at the bedroom ceiling immediately equalized and dropped all temperature levels below 400 ºC (752 ºF) and they continued to decline until the conclusion of the test.

The data from the living room thermocouple array is shown in Figure 5.7.3-5. Temperatures increased and stratified up to the point of window failure. Peak temperatures at the ceiling of nearly 300 ºC (572 ºF) began to decline for about 10 s following window failure but then again increased above 400 ºC (752 ºF). Another decrease in upper level temperatures occurred until the door was opened which immediately caused all temperatures to spike. Temperatures at the floor however, remained cooler than all others, 650 ºC (752 ºF) compared with 850 ºC (752 ºF). All temperatures declined for approximately 20 s following the initial spike, but increased back to peak levels shortly after. Activation of the hoseline at 377 s immediately dropped all temperature levels below 400 ºC (752 ºF) and they continued to decline to the conclusion of the test.

Temperature conditions in the corridor are given in Figure 5.7.3-6 through Figure 5.7.3-9. The four thermocouple arrays located just outside the doorway from the living room all elevated very quickly after the door was opened. The conditions for the center and north corridor reacted in very similar fashion following the initial temperature spike in that both ceiling levels peaked at 700 ºC (1472 ºF) and then decreased to approximately 700 ºC (1292 ºF) within 10 s. The lower levels of both regions continued to increase in temperature until meeting a close equilibrium with the respective ceiling temperatures. Further, both center and north corridor temperatures sharply decreased when the hoseline opened up and continued to do so through the remainder of the test. The south corridor recorded similar temperature conditions when compared with the center and north regions. However, instead of equalizing with the remainder of the room after the initial temperature spike, the ceiling temperatures reduced in value and then increase back up to a peak of 650 ºC (1202 ºF). The implementation of the hose stream equalized and sharply reduced all the values. The southwest corridor recorded significantly lower values because it was positioned out of the flow path of the products of combustion. Temperatures in that region increased quickly for the first 10 s after the door was opened, but slowed in progress and did not peak to 320 ºC (608 ºF) for 40 s following the door opening. The thermocouple positioned 0.61 m (2.00 ft) below the ceiling malfunctioned and remained at ambient temperature throughout the test.

The temperatures at the exhaust vent are given in Figure 5.7.3-10. These thermocouples are at the same elevation located 2.44 m (8 ft) above the ceiling of the corridor. The three thermocouples are spaced 0.51 m (1.67 ft) apart along the east-west centerline of the vent. These temperatures increased from less than 100 ºC (212 ºF) to just less than 600 ºC (1112 ºF) in about 30 s following the opening of the door. Once water was applied, the temperatures dropped to 200 ºC (392 ºF) in 80 s. All three temperatures remained within close proximity throughout the test.

The final temperature graph displays the temperature time history for the target room (Figure 5.7.3-11). All of the temperatures remained near ambient until the hoseline was opened up directly at the ceiling. At this point, the ceiling temperature increased from 16 ºC (61 ºF) to 25 ºC (77 ºF) in the span of 70 s and sporadically hovered around that point for the duration of the test. All other temperature values remined close to ambient.

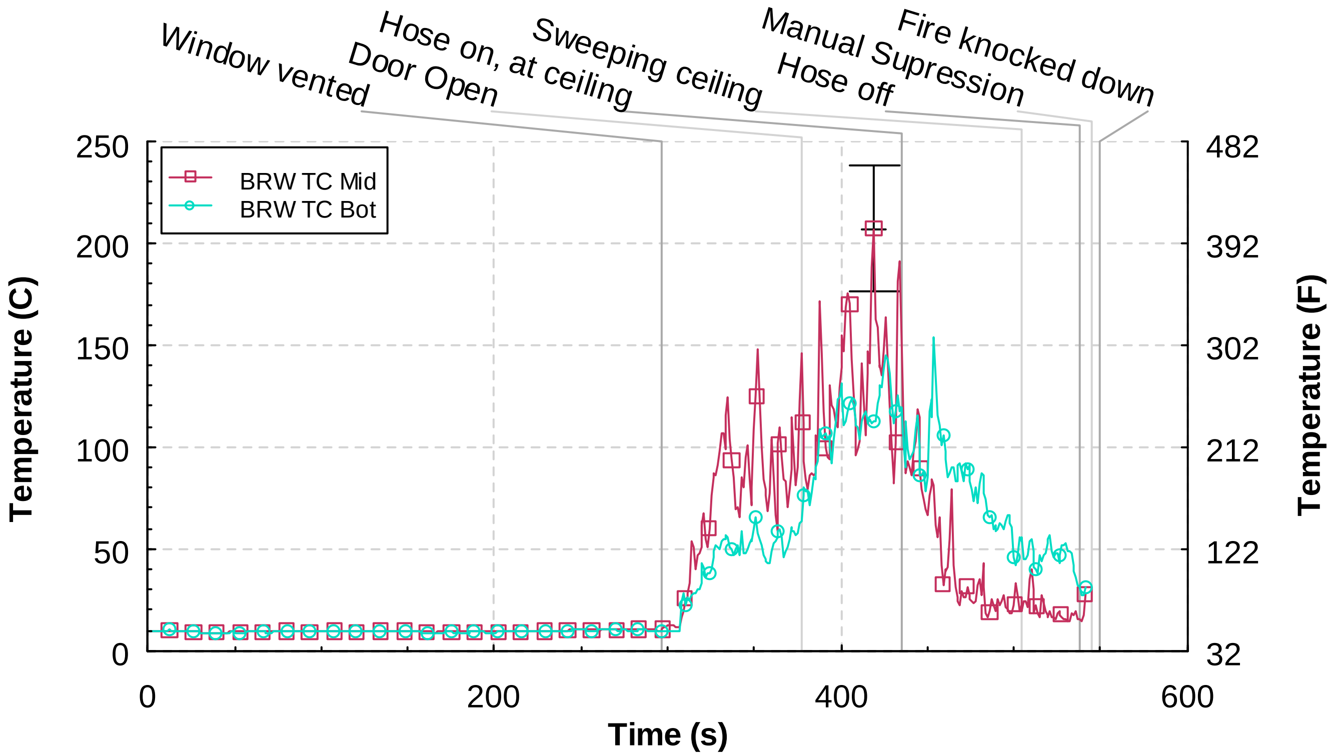

Figure 5.7.3-1. Temperature versus time from the bedroom window (BRW) thermocouple array, Experiment 7.

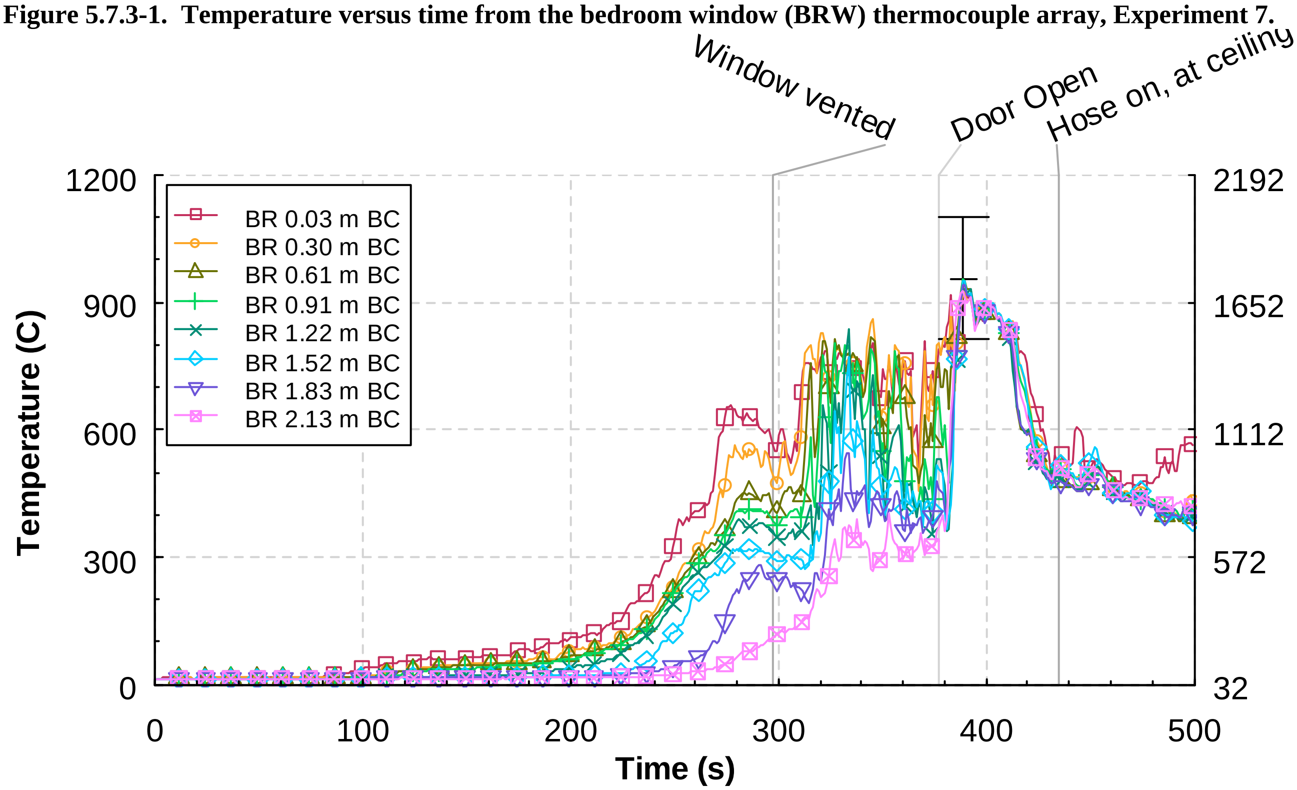

Figure 5.7.3-2. Temperature versus time from the bedroom (BR) thermocouple array, Experiment 7.

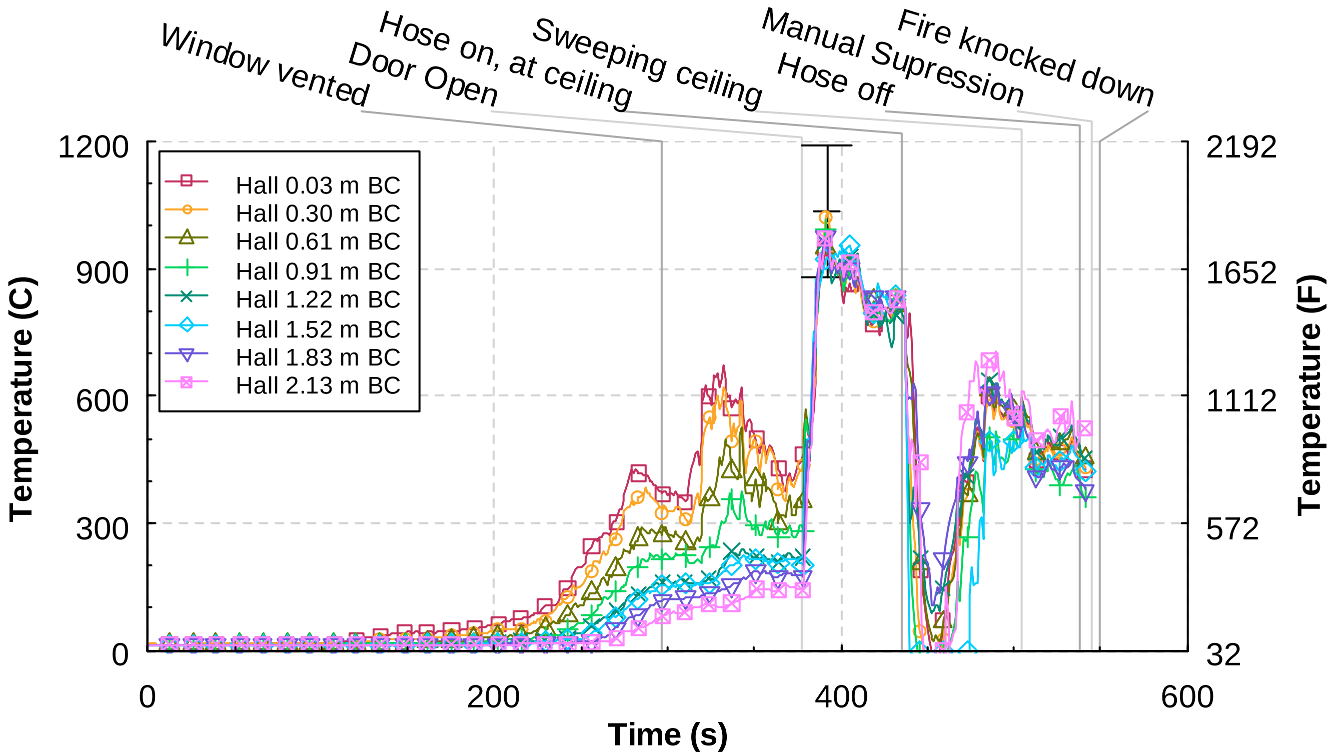

Figure 5.7.3-3. Temperature versus time from the hall thermocouple array, Experiment 7.

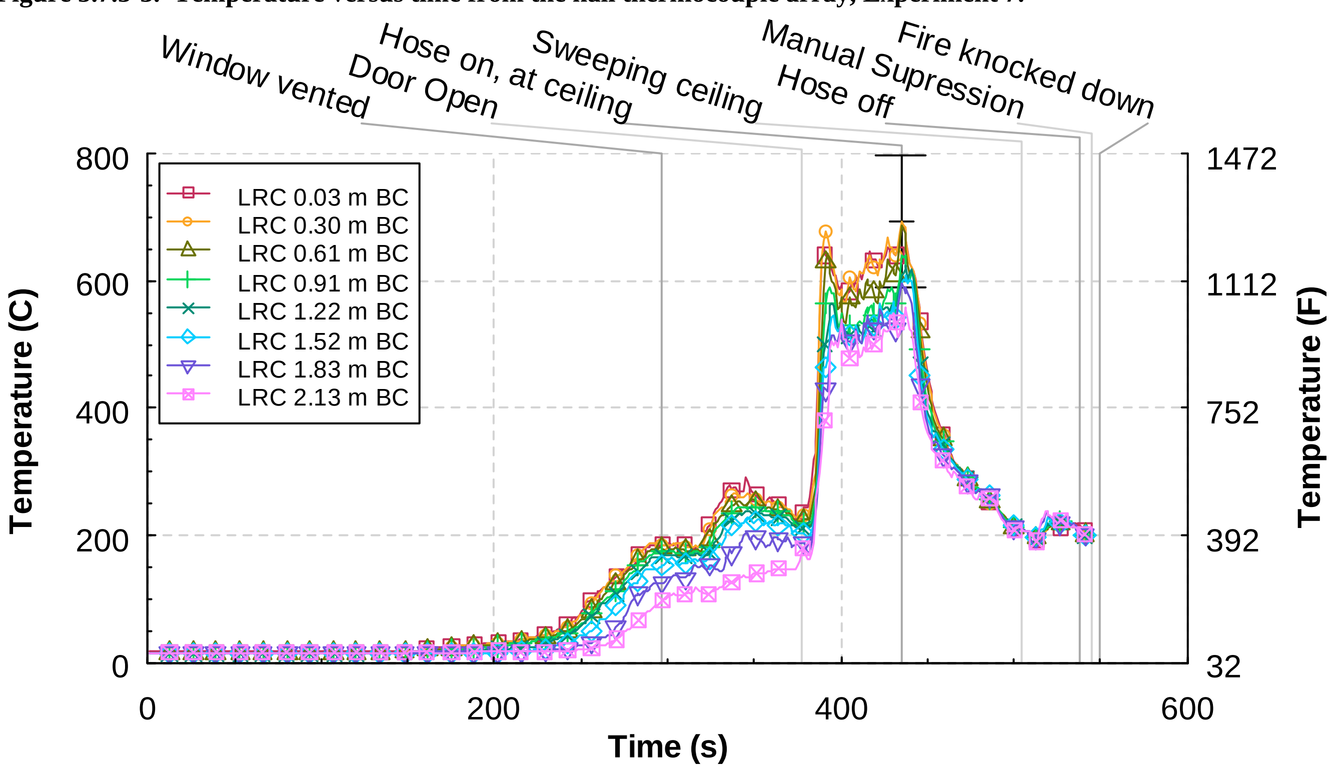

Figure 5.7.3-4. Temperature versus time from the living room corner (LRC) thermocouple array, Experiment 7.

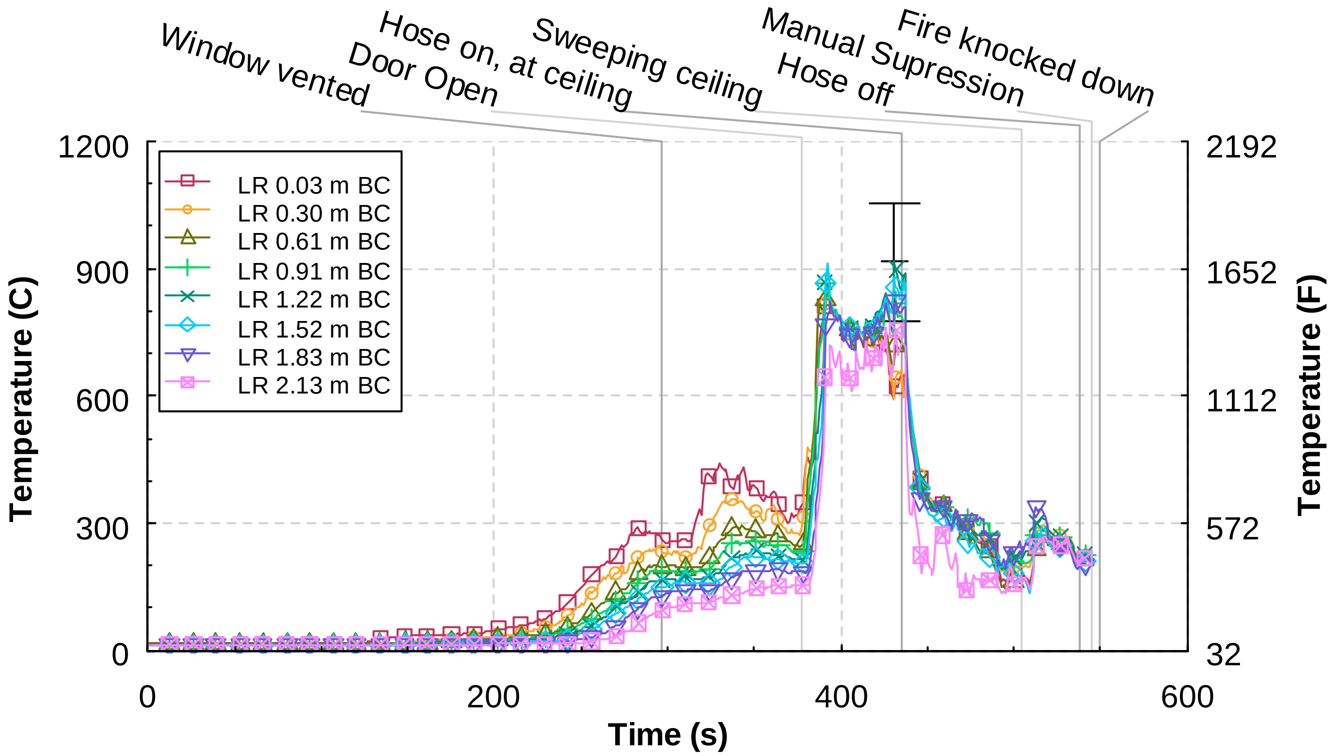

Figure 5.7.3-5. Temperature versus time from the living room (LR) thermocouple array, Experiment 7.

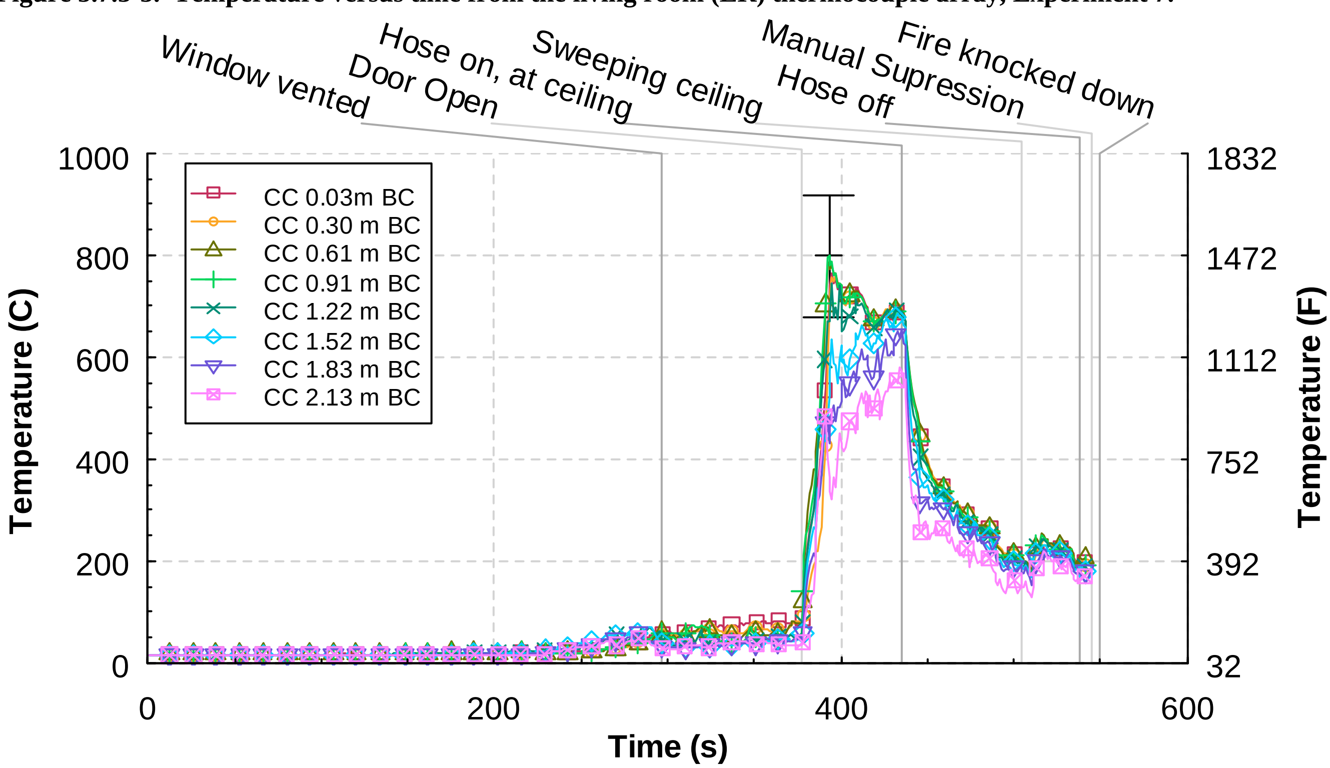

Figure 5.7.3-6. Temperature versus time from the corridor center (CC) thermocouple array, Experiment 7.

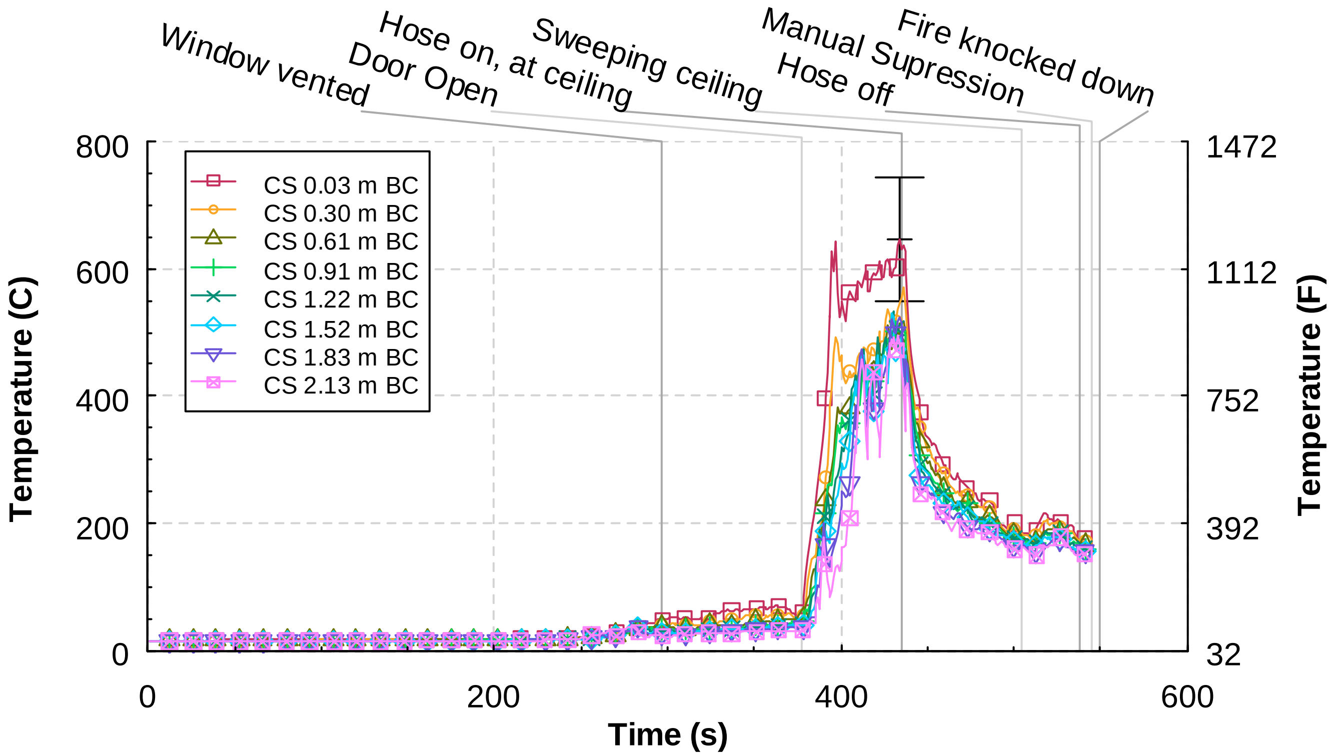

Figure 5.7.3-7. Temperature versus time from the corridor south (CS) thermocouple array, Experiment 7.

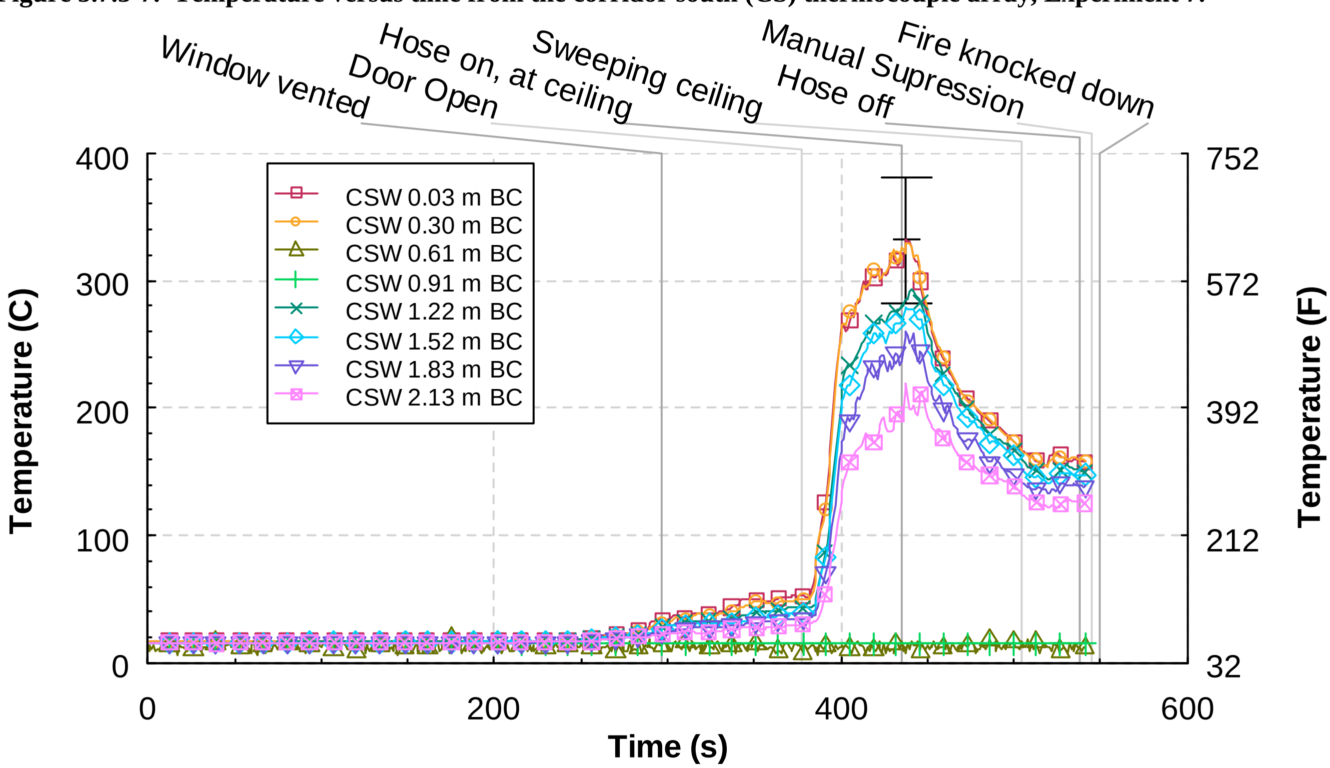

Figure 5.7.3-8. Temperature versus time from the corridor southwest (CSW) thermocouple array, Experiment 7.

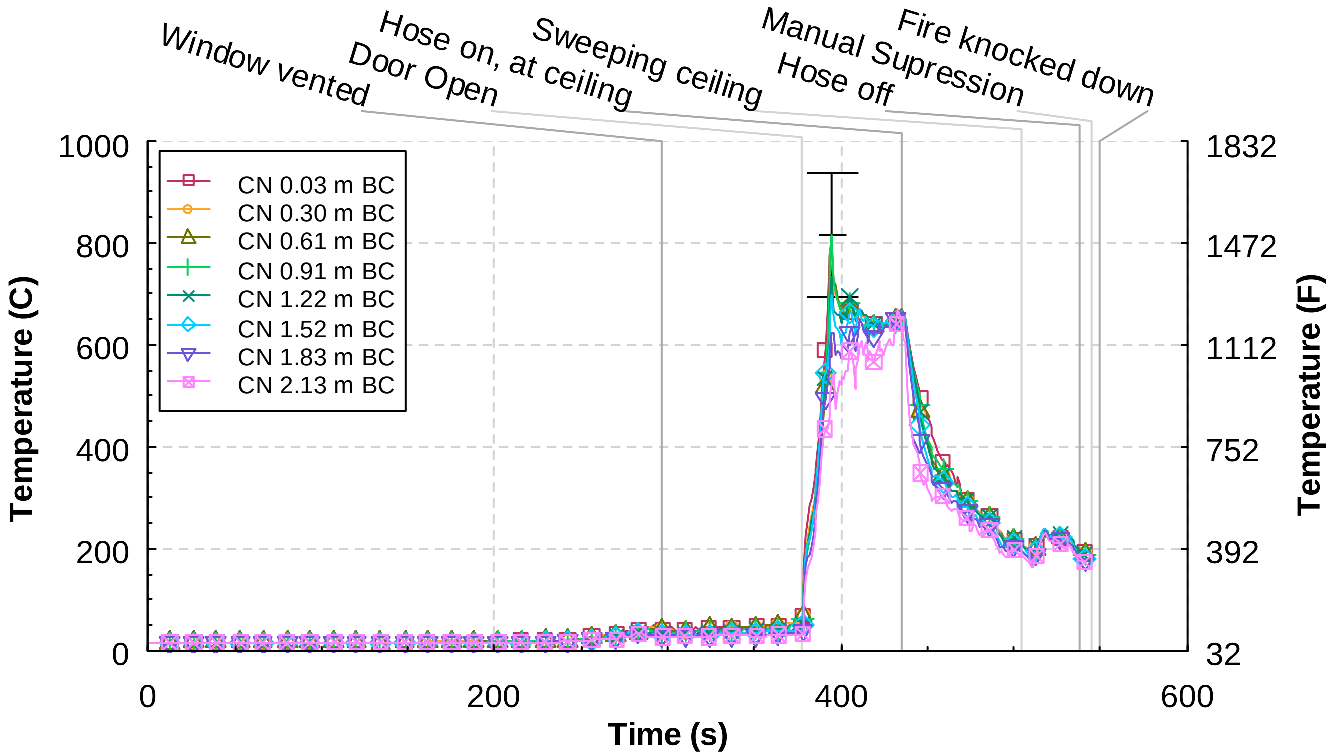

Figure 5.7.3-9. Temperature versus time from the corridor north (CN) thermocouple array, Experiment 7.

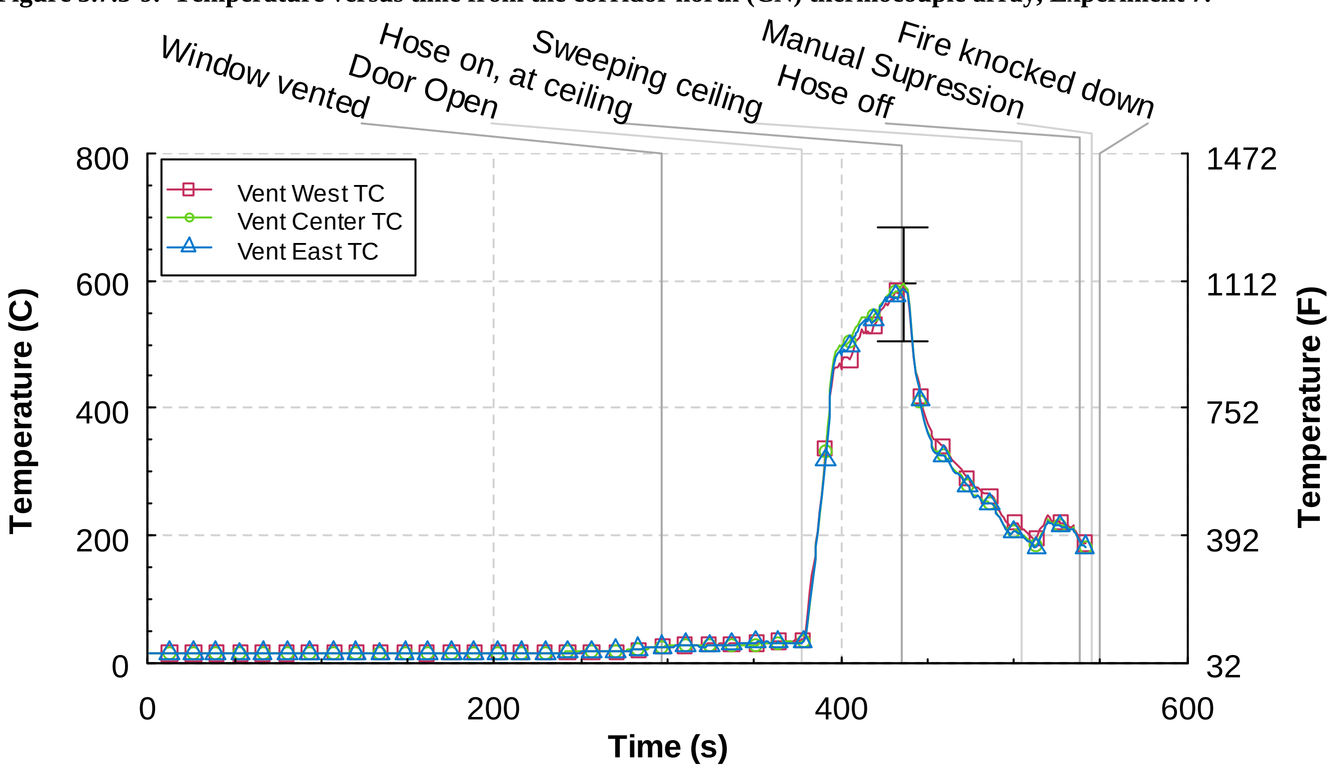

Figure 5.7.3-10. Temperature versus time from the ceiling vent thermocouple array, Experiment 7.

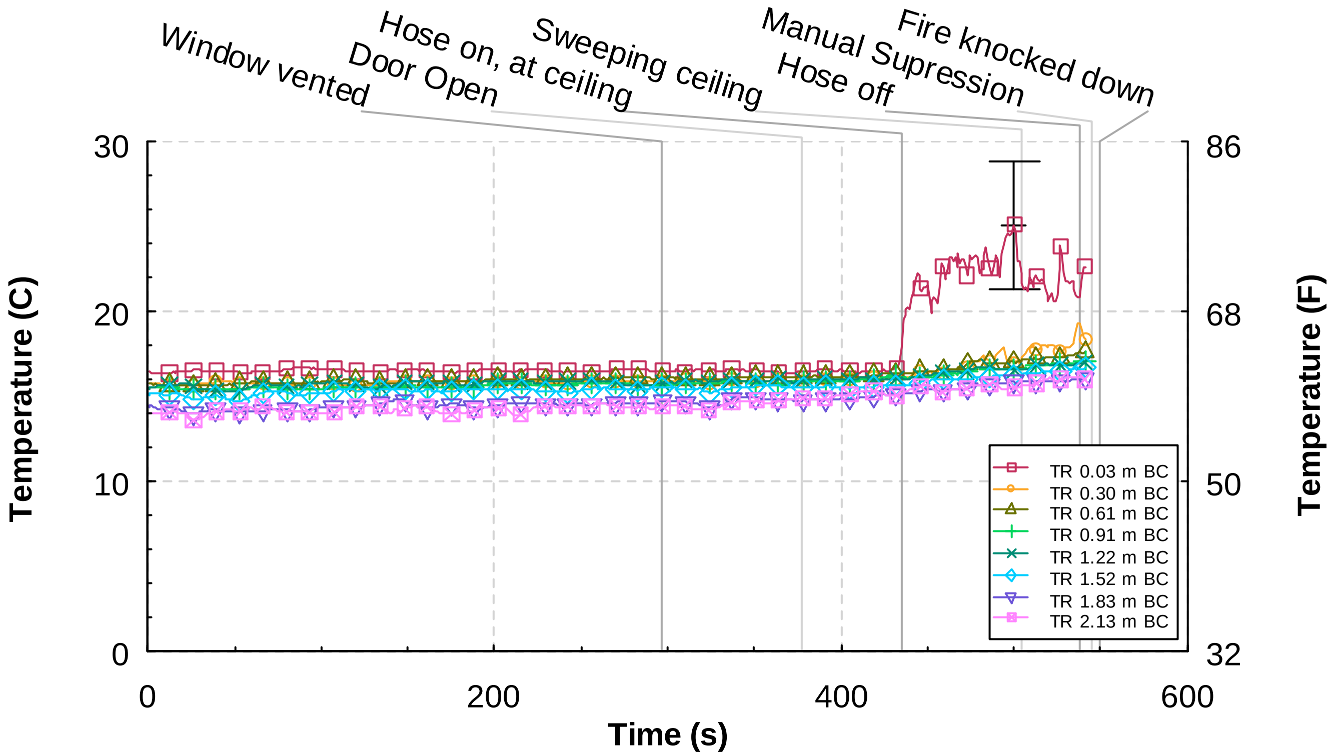

Figure 5.7.3-11. Temperature versus time from the target room (TR) thermocouple array, Experiment 7.

5.7.4 Heat Flux

The time history from all five heat flux gauges is given in Figure 5.7.4-1. The heat flux in the bedroom increased to approximately 25 kW/m^2 prior to the window failure. After the window vented, the bedroom heat flux increased to approximately 40 kW/m^2 but remained relatively constant and the living room heat flux increased to approximately 10 kW/m^2 until the door was opened. After the door was opened, the bedroom peaked to 110 kW/m^2 while all other levels topped 60 kW/m^2. When the hose stream was applied at 435 s, all heat flux values dropped at a constant rate to equilibrium at the conclusion of the test.

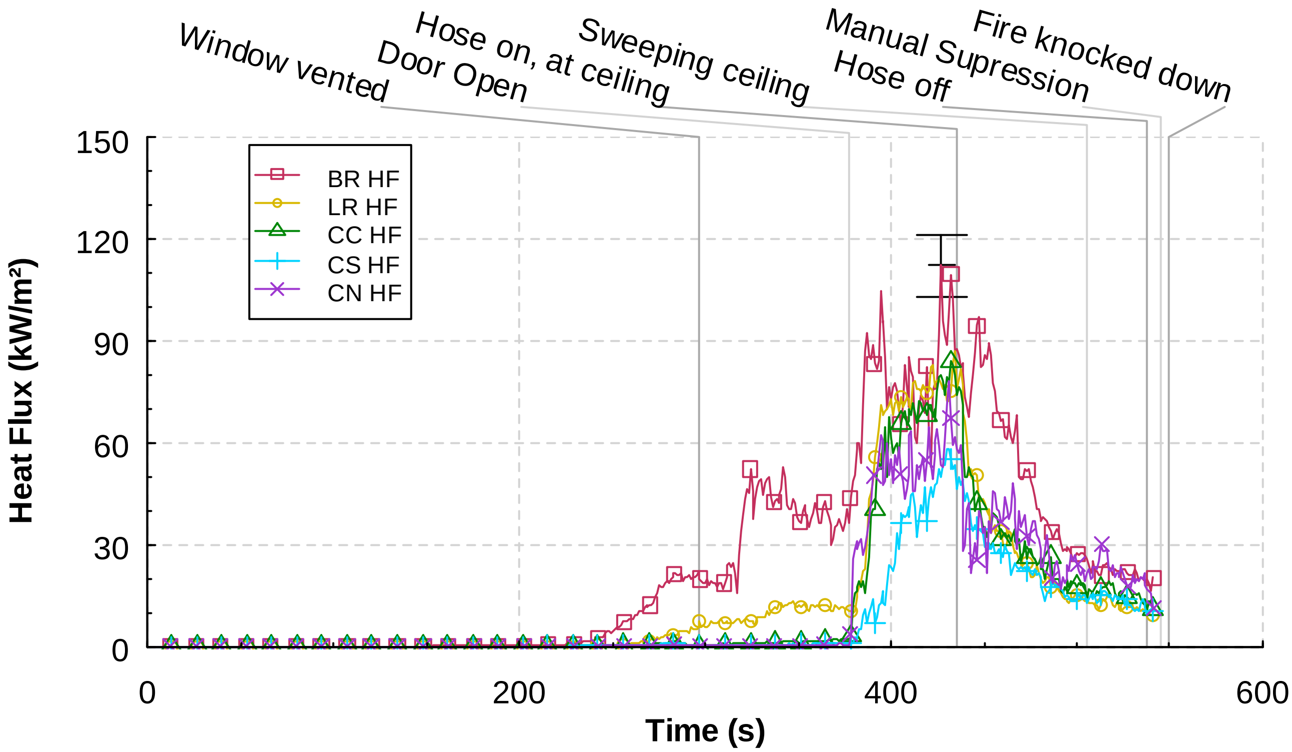

Figure 5.7.4-1. Heat flux versus time at five locations, Experiment 7.

5.7.5 Pressure

Figure 5.7.5-1 shows the pressures at the 5 measurement locations. The bedroom, hallway and living room all spiked just below 200 Pa approximately 10 s before the window vented. After the window vented at 297 s, the bedroom, hallway and living all dropped to 50 Pa but the northwest and southwest cooridors remained at 0 Pa. When the door was opened at 377 s, all of the pressures stratified according to distance away from the source. The bedroom reduced to 45 Pa, the hallway and living room reduced to 30 Pa while the northwest and southwest corridors increased to 20 Pa. The application of water had little impact on the pressures.

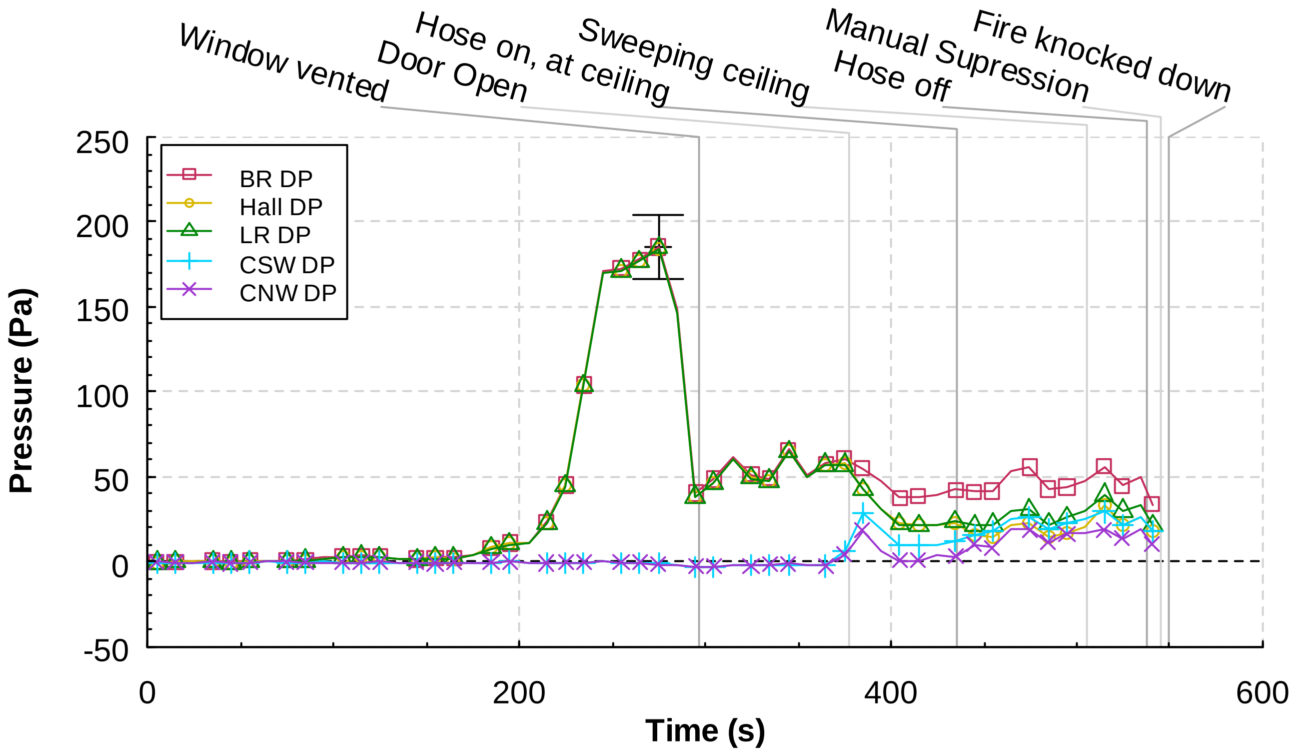

Figure 5.7.5-1. Pressure versus time at five locations, Experiment 7.

5.7.6 Velocities

Figure 5.7.6-1 provides the velocity measurements from the bi-directional probes that are located outside of the window. The positive velocities were flowing into the window. There was a fluctuation of velocities at the window as the hot gases were trying to exit the window opening while the simulated wind was forcing the gases back into the window. The average velocities shown in the graph indicate that the flow was mainly into the window at the middle and bottom probes and out of the window at the top probe once the room transitioned to flashover. Velocities ranged from 3 m/s (6.7 mph) into the window to 27 m/s (60.3 mph) out of the window with just the window vented. When the door was opened at 377 s, the middle and bottom velocities increased into the window only slightly but the top velocity decreased to 10 m/s (22.4 mph) out of the window. When the hose stream was applied at the ceiling, the middle and bottom velocities remained the same but the top velocity switched to an inward dirction at a peak of 25 m/s (55.9 mph) . However, the values of the top velocity fluctuated wildly, especially when the hoseline began the sweeping motion.

Figure 5.7.6-2 shows the velocities at the hall array position. On this graph, the positive direction is from west to east. Only a very small increase in inward velocity was noticed after the window vented. However, after the door was opened, the probe located 0.3 m (1 ft) below the ceiling, which captured the velocity of the ceiling jet as it moved down the hall away from the bedroom, peaked at approximately 3.0 m/s (6.7 mph). The other two probes increased to approximately 9 m/s (20.1 mph). When the hoseline was directed at the ceiling at 435 s, the bottom probe spiked to 50 inward but then reversed direction to 30 m/s (67.1 mph) in the span of 60 s. During the same time period, the middle probe reversed direction as well and peaked at 20 m/s (44.7 mph) while the top probe dropped to zero. When the hoseline was swept across the ceiling, the top probe stayed at zero, the middle probe fluctuated in both dirctions and the bottom probe remained at 30 m/s (67.1 mph) in an outwardly direction.

Figure 5.7.6-3 displays the velocities from the south corridor position. The positive direction is from north to south. This was the dead end side of the corridor so there was no steady flow through this area. There was a lot of recirculation and changes in the magnitude of the velocity however, this became most notable when the door was opened. Flows ranged from -1.2 m/s to 1.5 m/s while the wind was flowing through the structure.

The velocities from the north corridor position are shown in Figure 5.7.6-4. The positive flow direction for this location is from south to north. Prior to opening the door, there was no significant change in velocity. When the door was opened, the velocity at the top peaked at +1 m/s (2.2 mph) while the middle and bottom probes recorded peak velocities of -6.5 m/s (14.5 mph) and -7 m/s (15.7 mph) respectively. As the hoseline was directed at the ceiling, large fluctuations in all three probes was noticed in only the negative direction, indicating that the hoseline was facilitating a north to south flow for the entire corridor. Sweeping the nozzle across the ceiling further agitated the velocities, but all three remained in the same direction.

The measurements from the bi-directional probes installed in the exhaust vent, 2.44 m (8.0 ft) above the ceiling are given in Figure 5.5.6-5. The flow direction up and out of the structure is positive in the figure. No noticeable velocity change takes place prior to opening the door. After the door opened, all three velocities were similar and flowing out of the structure at a rate of approximately 6 m/s (13.4 mph to 7 m/s (16.7 mph). When the hose is directed at the ceiling, all three velocities reduce down to 3 over the span of 100 s.

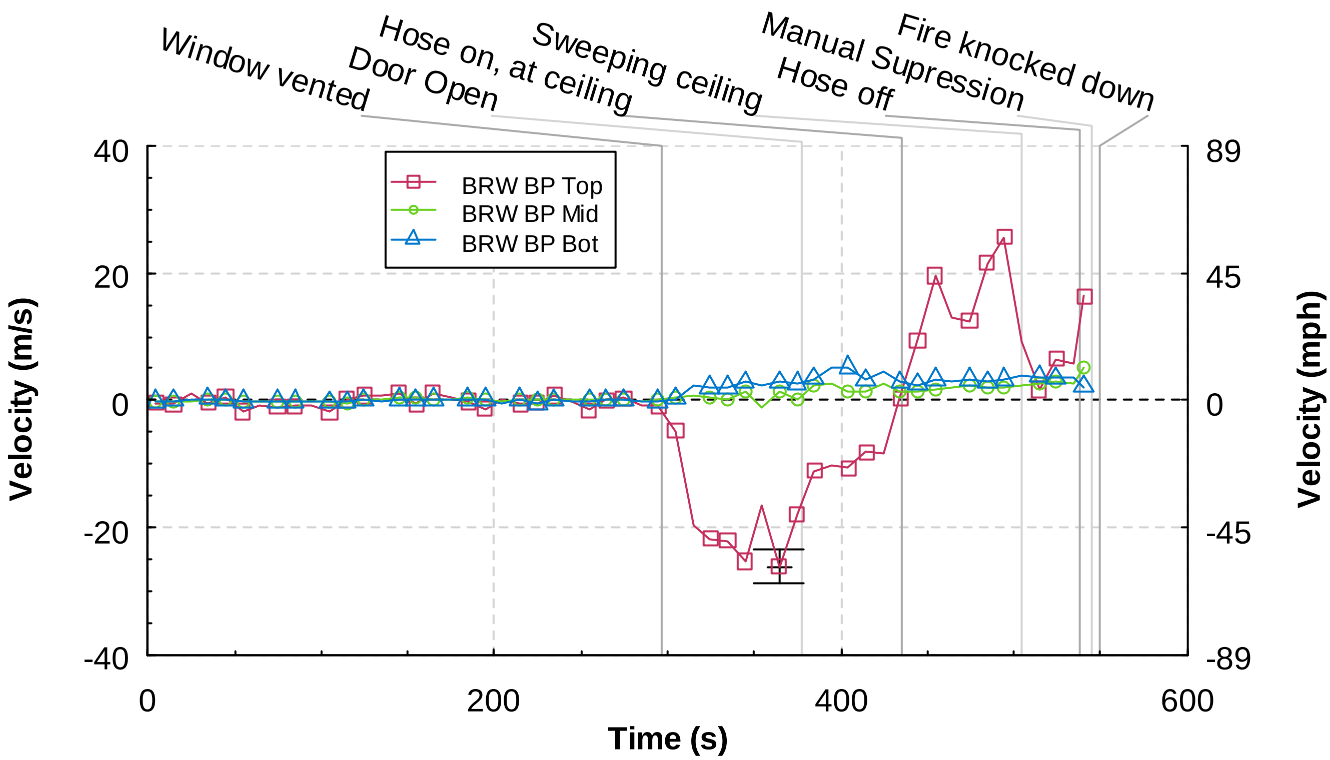

Figure 5.7.6-1. Velocity versus time from the bedroom window (BRW) bi-directional probe array, Experiment 7.

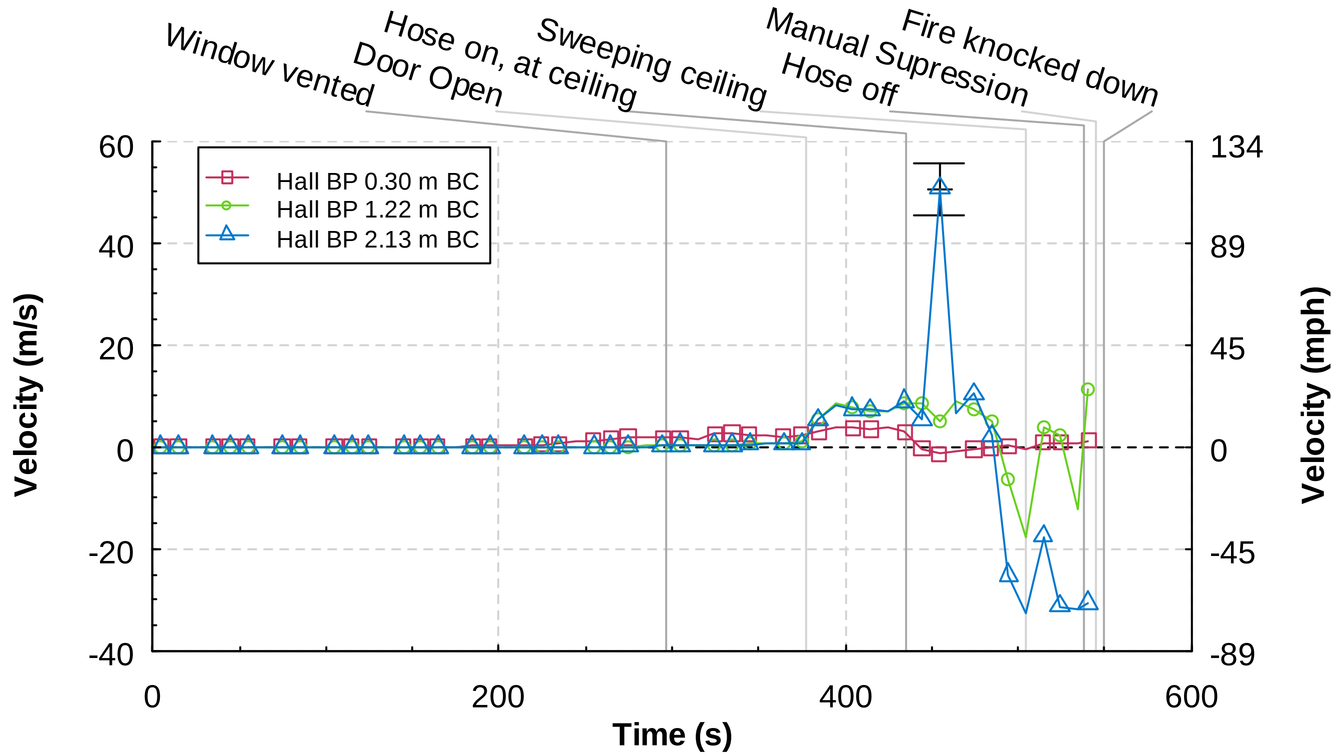

Figure 5.7.6-2. Velocity versus time from the hall bi-directional probe array, Experiment 7.

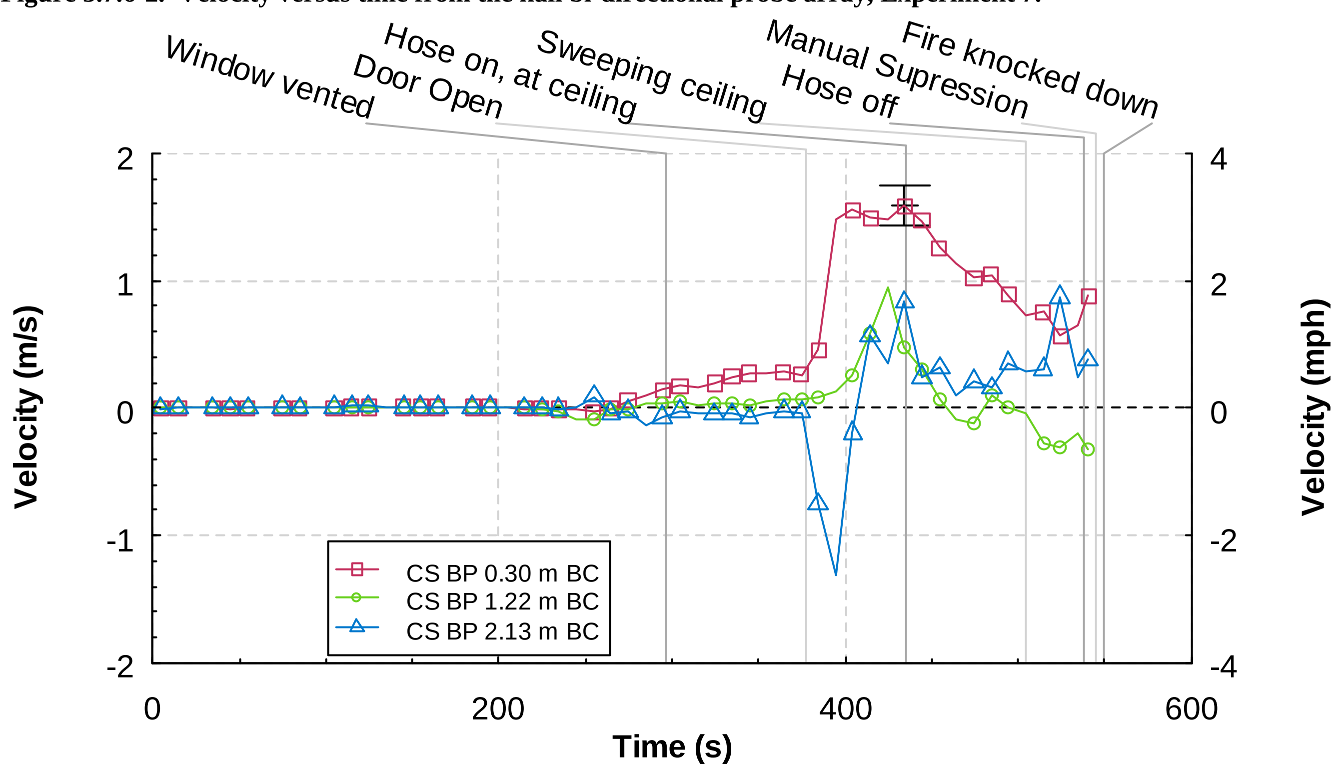

Figure 5.7.6-3. Velocity versus time from the corridor south (CS) bi-directional probe array, Experiment 7.

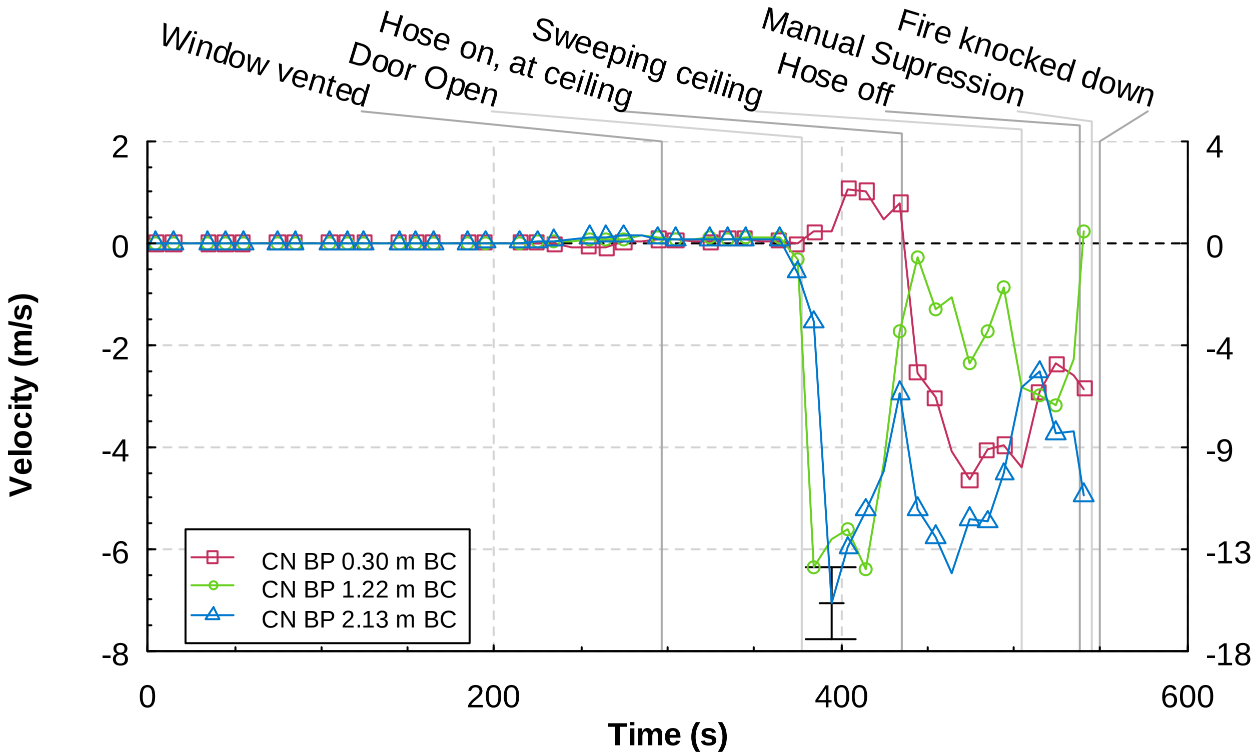

Figure 5.7.6-4. Velocity versus time from the corridor north (CN) bi-directional probe array, Experiment 7.

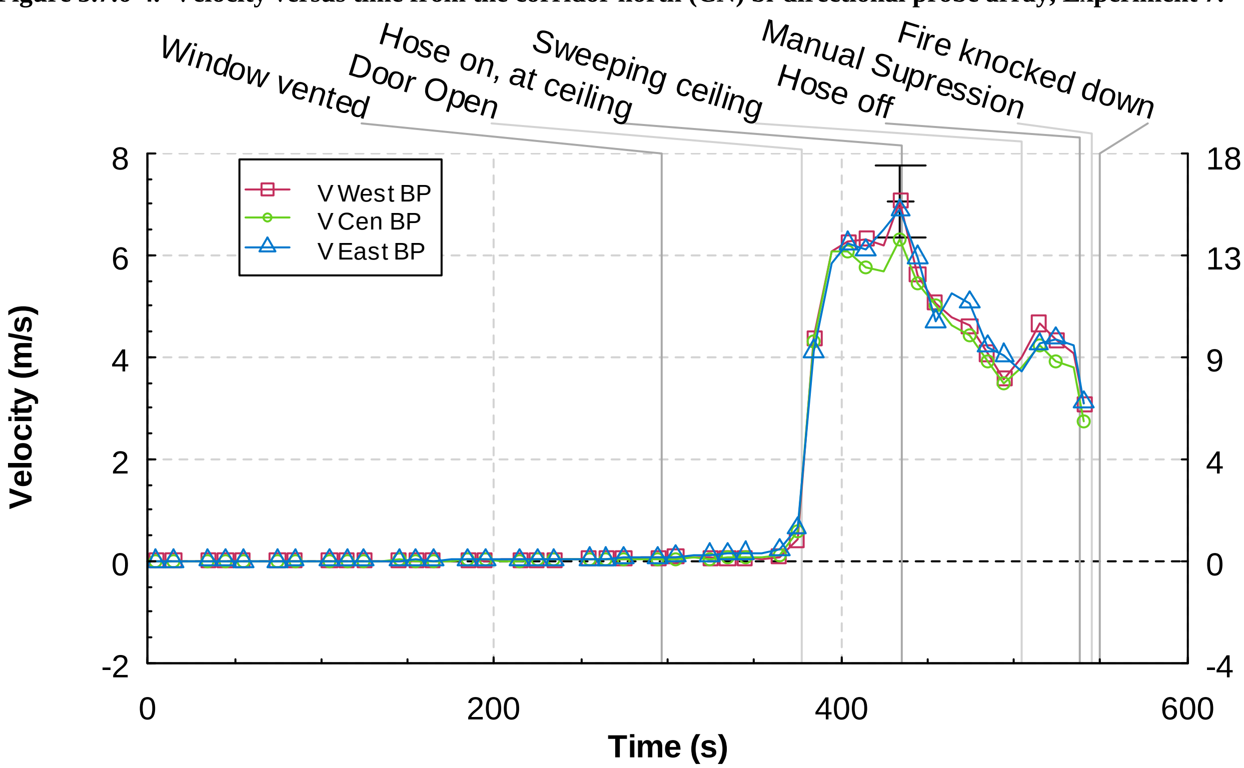

Figure 5.7.6-5. Velocity versus time from the ceiling vent (V) bi-directional probe array, Experiment 7.

5.7.7 Gas Concentrations

Figure 5.7.7-1 and Figure 5.7.7-2 show the gas concentration measurements made in the upper and lower level of the bedroom. The gas concentrations in the upper portion of the bedroom began to change at approximately 120 s, as the hot gas layer developed and extended down 1.83 m (6.0 ft) from the ceiling to interact with the sampling probe. Just prior to window failure the oxygen concentration decreased to 15 % and the CO_2 concentration increased to 5 %. Both factors continued to decrease until after the door was opened. After the door was opened at 377 s, the fresh air came in through the window and mixed with the lower portion of the hot gas layer, which temporarily increased the oxygen and decreased the carbon dioxide, carbon monoxide and total hydrocarbons for about 30 s. After this mixing, the oxygen quickly dropped to below 3 %, the CO_2 increased to 16 %, the CO increased to 3 % and the total hydrocarbons increased to 5 %. When the hose stream was applied to the ceiling at 435 s, a reversal of all components occurred. Oxygen concentration began to increase, while CO, CO_2 and total hydrocarbon readings began to decrease for the remainder of the test. Very similar results occurred in the lower bedroom readings with one notable difference. After the window vented at 297 s, fresh air mixed with the lower gas layer causing turbulent readings in the oxygen and carbon dioxide. After the door was opened at 377 s, carbon dioxide readings increased from 8 % to 16 % while oxygen concentrations decreased from 10 % to 1 %.

Figure 5.5.7-3 and Figure 5.7.7-4 provide the measurements from the upper and lower gas sampling probes, respectively, in the living room. The magnitudes and trends of the living room gas concentrations are very similar to those of the bedroom. However, the effects from the vented window appear more gradually in the living room than they do in the bedroom and the turbulent mixture of fresh air with the hot gas layer is not as readily apparent.

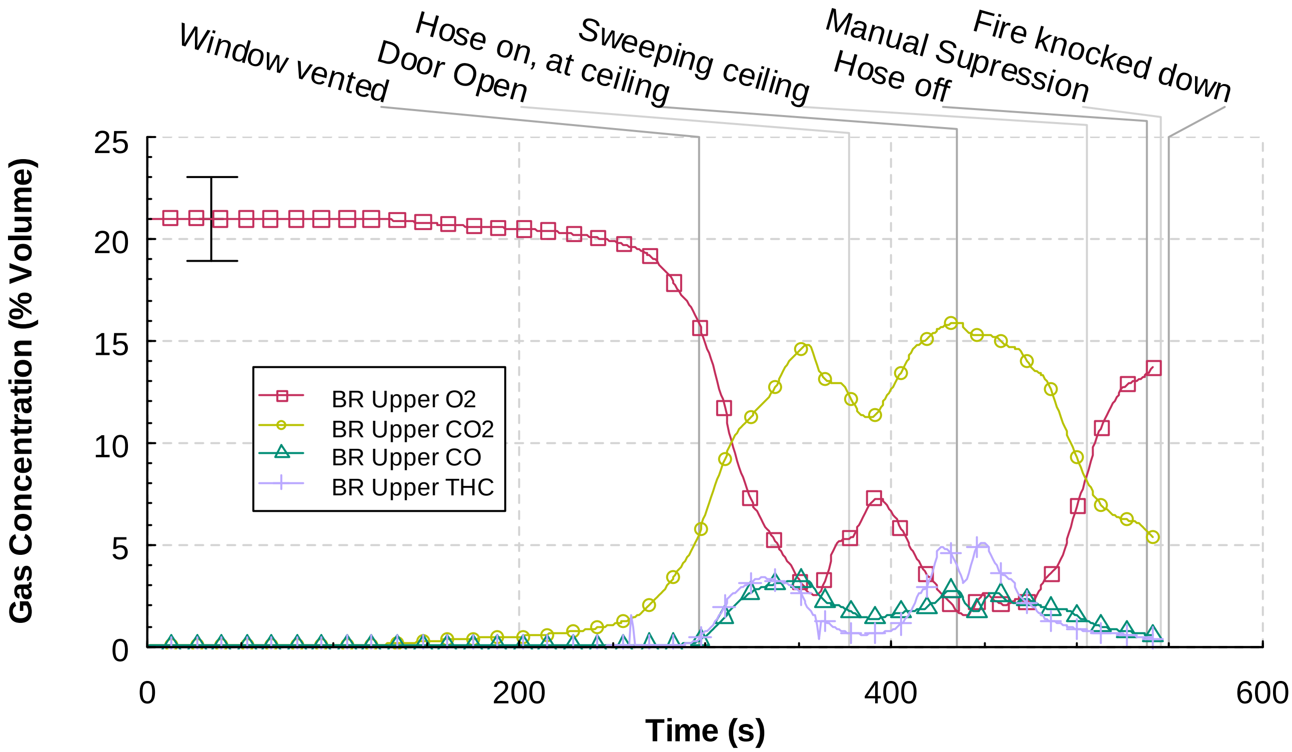

Figure 5.7.7-1. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper bedroom (BR) sampling location, Experiment 7.

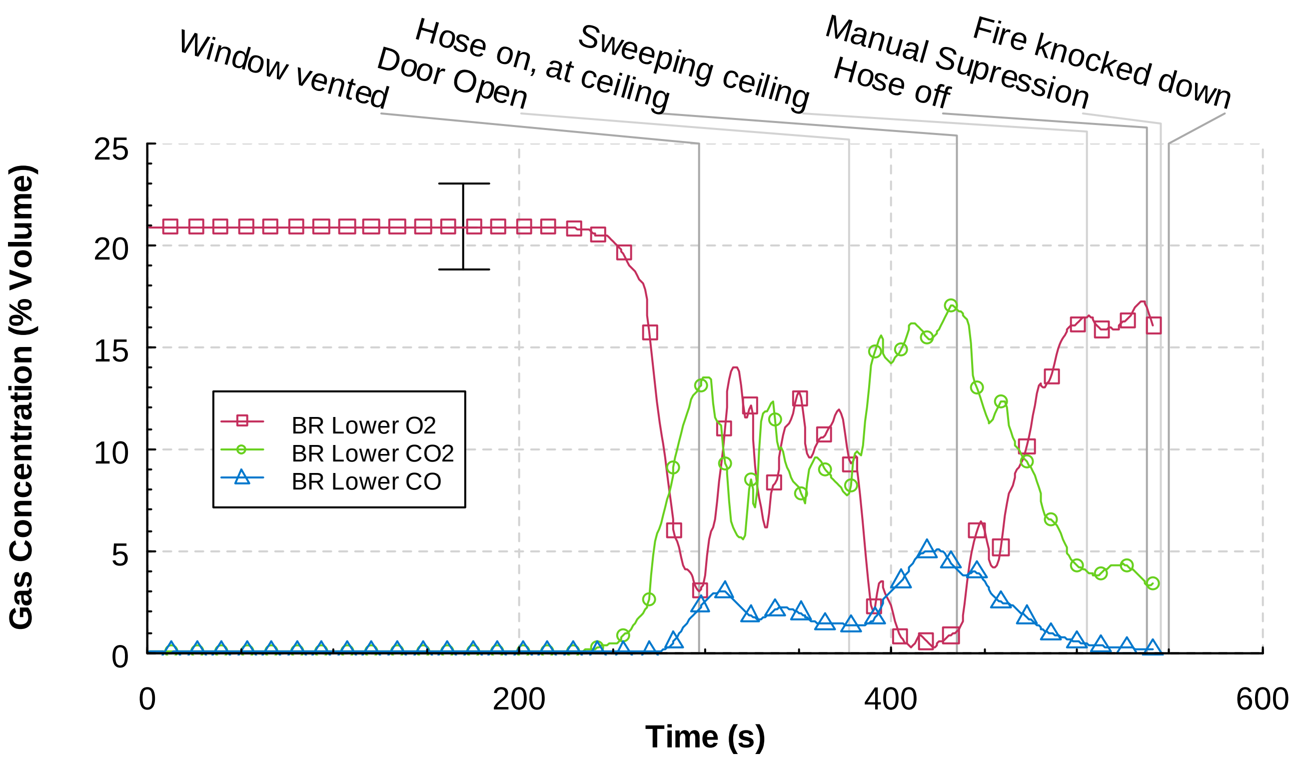

Figure 5.7.7-2. Oxygen, carbon dioxide, and carbon monoxide percent volume versus time from the lower bedroom (BR) sampling location, Experiment 7.

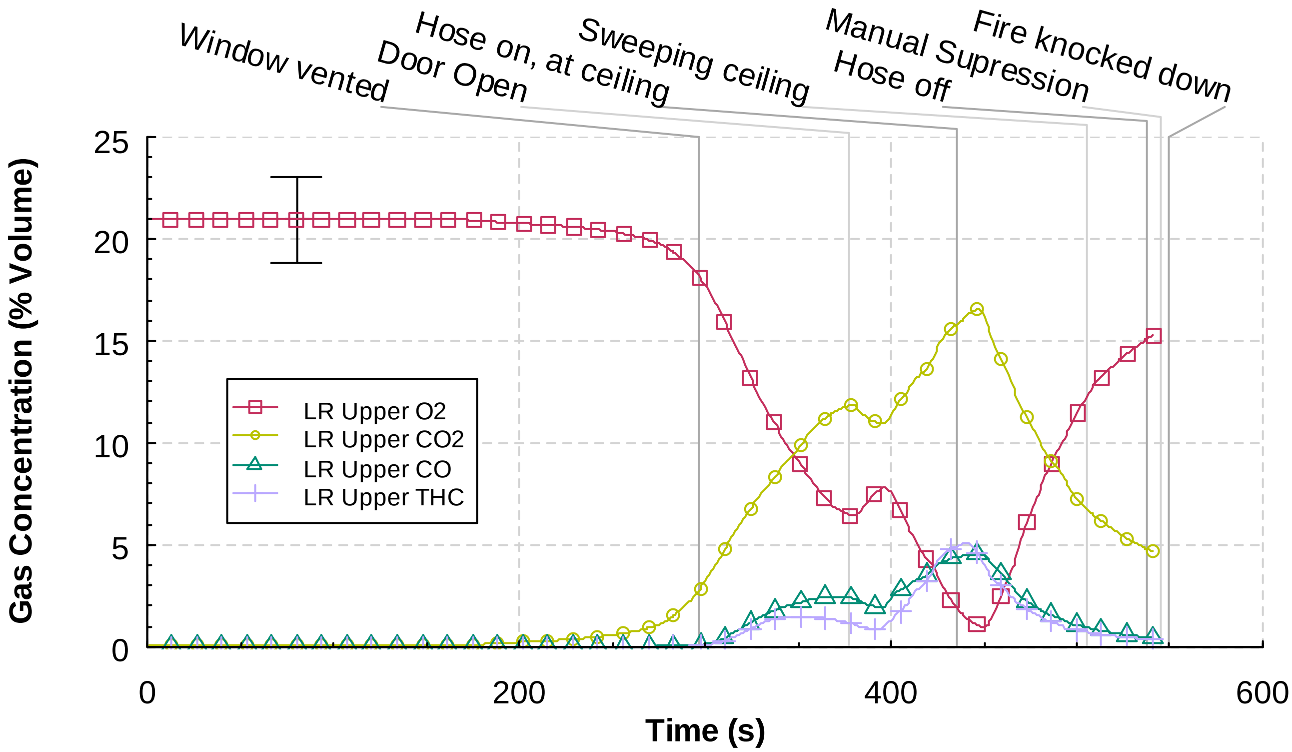

Figure 5.7.7-3. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper living (LR) room sampling location, Experiment 7.

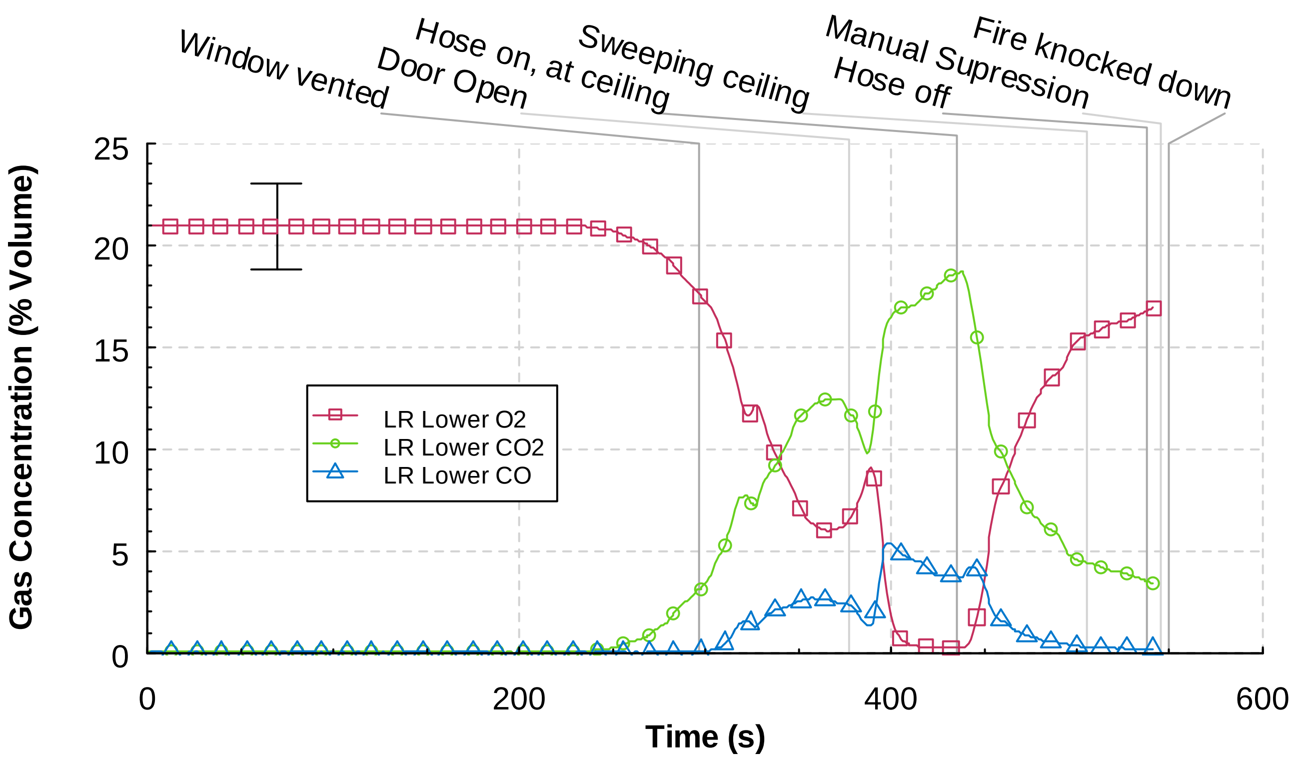

Figure 5.7.7-4. Oxygen, carbon dioxide, carbon monoxide, and total hydrocarbon percent volume versus time from the upper living (LR) room sampling location, Experiment 7.