NISTIR 7468

Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Fire Experiments

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Abstract

A series of six experiments was conducted in a high-rise apartment building in Chicago, Illinois during November 2006. Experiments on each of the fire floors utilized portable fans and another utilized a large truck or trailer mounted fan. Two experiments on the third floor examined the effects of wind driven fire conditions. All of the experiments created high temperatures and dense smoke conditions in the hallway. Numerous configurations were used during the experiments and the ability of the fans to keep smoke and heat out of the stairwell was analyzed. The minimum design pressures of NFPA 92A were used as baselines to compare to the actual pressures measured.

In this limited set of experiments, portable fans and mounted fans were able to quickly clear the stairwell of smoke and maintain a pressure high enough to prevent smoke infiltration into the stairwell.   Positive pressure ventilation (PPV) fans utilized correctly can increase the effectiveness and safety of fire fighters and survivability of occupants in high-rise buildings. When configured properly, PPV fans can meet or exceed previously established performance criteria for fixed smoke control systems.

The primary objective of this report is to present the reduced data generated by the experiments. More detailed analyses will be included in subsequent publications.

Disclaimer

Introduction

Between 1985 and 2002, there have been approximately 385 000 fires in high-rise buildings greater than seven stories. These fires resulted in 1600 civilian deaths and more than 20 000 civilian injuries [1]. Smoke movement in high-rise buildings poses serious challenges for the fire service. Attempting to control the smoke movement is difficult because fire fighting operations require opening potential smoke barriers between the source of water and the fire. Buoyancy of hot gases and stack effect[i] due to temperature differences between the inside and outside of the building cause smoke[ii] travel in high-rise buildings. This smoke enters vertical shafts in the building such as stairwells, and can block evacuation of occupants and can hinder fire fighting operations.

It is common for the fire service to encounter smoke filled stairwells upon their arrival at an apartment fire scene. If the stairwells are not smoke-filled, they soon become smoke filled once fire department operations begin. Dividing the stairwells in a high-rise building into attack and evacuation stairwells is a common tactic. This tactic entails the fire service utilizing one stairwell for fire attack and allowing smoke to flow into the stairwell as hose lines are stretched onto the fire floor and another stairwell for evacuation in which the stairwell is not opened onto the fire floor in an attempt to keep it as free of smoke as possible. However, the tactic may not keep the evacuation stairwell free of smoke. Stairwell door assemblies have been observed to leak and it is possible to have smoke enter the stairwells without ever opening a stairwell door.

Under normal fire fighting operating conditions, the attack stairwell door to the fire floor is opened and the stairwell becomes completely filled with smoke above the fire floor. Typically, the fire department will open the bulkhead door or vent at the top of the stairwell to remove the smoke on the fire floor. This does not always accomplish the desired effect. While it allows the smoke to exit the structure; the stairwell is now the flow path for the fire gases. The flow of hot gases through stairwell doorways can create extreme hazards for fire fighters. Safe operations above the fire floor in the attack stairwell are now limited because the stairwell is full of smoke and hot gases.

In order for the fire department to operate safely above the fire floor, the evacuation stairwell must be utilized. Unfortunately, the evacuation stair may be contaminated as well, due to smoke infiltration through the cracks of the doorway to the fire floor. The pressure created by the fire causes the hot gases and smoke to flow into the stairwell even with the door completely closed. This assumes that the evacuation stairwell door is never opened by occupants attempting to evacuate or a team of fire fighters attempting to enter the fire floor to perform search operations or stretch a back-up attack line from a different location.

During a fire on the third floor of a 16-story building, it is very possible that there will be 13-stories of stairwell that are contaminated with smoke. The fire department needs to search this area for occupants that may have attempted to escape, but were overcome by smoke on the way

[i] **Stack Effect –** The vertical airflow within buildings caused by the temperature-created density differences between the building interior and exterior or between two interior spaces.
[ii] **Smoke –** The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

out. A difficulty arises in that fire fighters may not have enough air in their Self Contained Breathing Apparatus (SCBA) to make it up to the top and back down, potentially leaving them trapped on an upper floor. The option exists to carry extra SCBA cylinders, but that adds more weight to an already heavily equipped fire fighter.

Another serious situation that can occur in high-rise buildings is a wind driven fire. The hazards of smoke and heat in the public halls and stairwells are similar, but the time frame in which it occurs can be catastrophic. Changes in building ventilation or presence of an external wind can increase the energy release of a fire. This can also increase the spread of fire gases through a building, placing building occupants and fire fighters in an environment that changes rapidly and may not be survivable. The trigger of this event could be as fast as a window failing or a door being opened. Several documented wind driven fires have resulted in fire fighter injuries and fatalities [2-4].

Different tactics need to be utilized to keep stairwells free of smoke, to increase the ability of occupants to egress and for fire fighters to operate. One possible solution is the proper use of positive pressure ventilation. National Fire Protection Agency (NFPA) 5000 requires that stairwells in current high-rise buildings be smoke proof [5]. NFPA allows three means to accomplish this, natural ventilation, mechanical ventilation incorporating a vestibule; and pressurizing the enclosure. This requirement, along with research and improved technology has led to an increase in the number of buildings that have stairwell pressurization systems. The research that has been done examining these systems suggests that if a pressure difference across the doorways is not less than 12.5 Pa (0.05 in. water column) in sprinklered buildings or 25 Pa (0.10 in. water column) in nonsprinklered buildings under likely conditions of stack effect or wind, then smoke will not infiltrate into the stairwells [6]. While these systems have proven to be effective and have been installed in many newer buildings, there are still a majority of high-rise buildings without these systems to protect stairwells.

The stairwell pressurization systems installed today are usually one of two types: single injection systems or multiple injection systems. The single injection systems have a blower installed in either the top or bottom of a stairwell to provide pressurization. The multiple injection systems have blowers that supply air at a number of floors over the height of the stairwell. The capacity of the blowers used and the number of blowers varies greatly dependent upon the height of the stairwell. Blower capacity can range from 850 m^3/h (500 ft^3/min) to as high as 170 000 m^3/h (100 000 ft^3/min) in some systems.

Technology in the fire service has increased greatly in the past 20 years, especially with regards to positive pressure ventilation (PPV) fans. Fans have been engineered and manufactured to provide flow capacities comparable to those specified for fixed or mounted stairwell pressurizations systems.

Typically, a PPV fan is placed about 1.2 m to 3.0 m (4 ft to 10 ft) outside the doorway of the structure [7]. It is positioned so that the “cone of air” produced by the fan extends beyond the boundaries of the opening. With the doorway within the cone of air, pressure inside the structure increases. An exhaust opening in the structure, such as an opening in the roof or an open window, allows the flow to escape due to the difference between the inside and outside air pressure. Smoke, heat and other combustion products are pushed out of the structure and replaced with ambient air.

In order for the fire service to provide the same level of protection that a fixed stairwell pressurizations system does, it requires thinking beyond the current PPV use in ventilation. Examination of the ability to pressurize is also needed. When a structure is pressurized and a vent is provided, the PPV fan creates a residual pressure inside the structure that is higher, forcing the flow to the lower pressure outside. The increased pressure provided by the fan works with the increased pressure created by the fire and combines the natural and mechanical ventilation forces to speed up the ventilation process.

This same principle can be used to ventilate a stairwell, but it leaves the section of the stairwell between the fire floor and the top of the stairwell full of smoke and hot gases until the fire has been extinguished. During the ventilation process, the residual pressure provided by the PPV fan slows the amount of smoke coming into the stairwell. Because there is less of a pressure gradient leading into the stairwell, it is possible that smoke and hot gases are still entering the stairwell. Fresh air forced in by the fan mixes with the smoke and hot gases as it travels past the fire floor and out of the vent at the top of the stairs. This reduces the concentration of the toxic smoke and cools the hot gases, but does not entirely eliminate the problem of a contaminated stairwell.

PPV fans that are utilized without a vent are able to create an elevated static pressure. The static pressure can be used to counter the increased pressure created by the fire. The fire naturally causes ventilation out of the fire floor and into the stairwell, which has a lower pressure. If the static pressure created by the fan is greater than the pressure created by the fire, then the smoke will be prevented from flowing into the stairwell.

The experiments that are summarized in this report examine the use of PPV fans to both ventilate and pressurize in coordination with door openings consistent with fire department high-rise operations during room fires in a residential apartment building. The fan size and placement was determined based on previous pressure experiments conducted in a 30-story high-rise in Toledo, Ohio [8].

Experimental Configuration

The experiments were conducted in a condemned 16-story high-rise apartment building. The building was constructed of poured concrete floors and ceiling deck with concrete block corridor walls and gypsum board interior walls. The overall building dimensions were 75.6 m wide by 20.8 m deep by 46.9 m tall. The left half of the building was utilized for the experiments. The door from the center stairwell to the right side of the building was sealed on every floor. The four sides of the building are depicted in Figures 1 through 4.

The corridors from the second to sixteenth floors were open air, only covered with an expanded metal screen on the front side. This is not representative of a typical high-rise structure, so the corridors on floors 3, 10 and 15 were enclosed with metal studs and two layers of gypsum board. This created four floors (1, 3, 10 and 15) and two stairwells (south and center) that were enclosed to create the experimental volume (Figure 5). There were no vents out of either of the stairwells, so the door to the 16th floor was used as the vent to the outside, similar to a bulkhead door, due to the lack of an enclosed corridor on the top floor.

The experimental series was comprised of 6 independent apartment fires with the apartment door to the corridor left open in order for smoke and heat to travel into the corridors and stairwells of the building. Floor 15 and floor 10 utilized a furnished living room in apartment 3 and apartment 5. Floor 3 included a furnished living room in apartment 3 and a furnished bedroom and living room in apartment 4 (Figure 6).

Figure 1. East or Front (Side A)

Figure 2. North or Left (Side B)

Figure 3. West or Rear (Side C)

Figure 4. South or Right (Side D)

Figure 5. Experimental site outlined in red

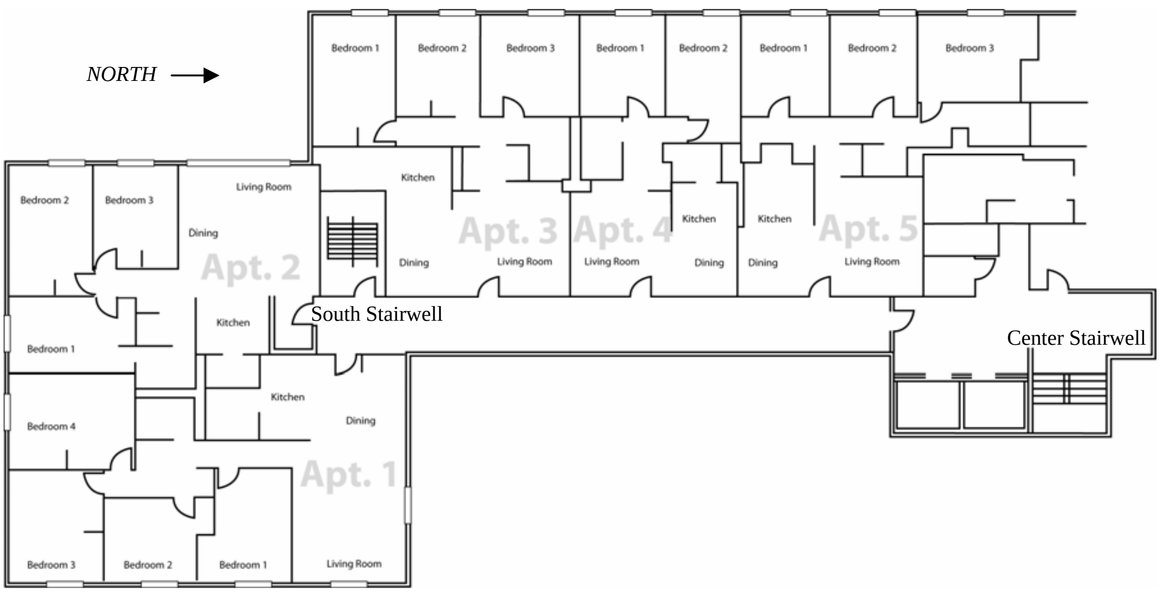

Figure 6. Floor Plan typical of floors 3, 10 and 15 (Left Half of Building)

Furnishings

The fuel load for the experiments was designed to simulate a common living room configuration. The purpose of the fuel load was to create high heat and dense smoke conditions in the apartment of origin and the common corridor. The overall dimensions and weights of the furnishings are listed in Table 1.

Table 1. Furnishings (Uncertainty ± 6%)

Item	Width (m)	Depth (m)	Height (m)	Weight (kg)
Chair	0.58	0.61	0.76	14.9
End Table	0.46	0.61	0.41	8.7
Twin Mattress	0.90	2.03	0.25	36.3
Dresser	1.37	0.51	0.61	56.7
Coffee Table	0.71	0.46	0.41	8.1
Sofa w/ Cushions	1.98	0.86	0.84	40.5
Sofa Mattress	1.83	1.35	0.11	17.0
Small Sofa w/ Cushions	1.24	0.64	0.84	26.7
Small Sofa Mattress	1.1	1.2	0.11	11.2
Stuffed Chair	0.64	0.91	0.84	20.3
Carpet (per m^2)	1.0	1.0	0.007	2.5
Padding (per m^2)	1.0	1.0	0.001	4.2

Each of the living rooms had the floor covered with high density cellular rubber carpet padding topped with a polypropylene backed nylon carpet. The living rooms on floors 10 and 15 were furnished similarly. Each contained a sleeper sofa, two chairs, two end tables, a coffee table and a lamp. The experiment in apartment 303 included the addition of a second sleeper sofa, a third chair and a stuffed chair. Apartment 304 had a furnished bedroom in addition to the living room. The bedroom furnishings included a twin bunk bed set, a chair, two dressers and a coffee table.

The sleeper sofa had a wood frame covered in upholstery (Figure 7). The metal sleeper frame was removed but the inner-spring mattress was folded and placed under the two polyurethane core seat cushions (Figure 8). The ignition point was located on the left side of the sofa in every experiment (Figure 9) with the exception of the experiment in apartment 304, where the ignition took place on the bunk bed.

The chairs included an upholstered wood frame and a 0.08 m (3.0 in) thick polyurethane core cushion (Figure 10). The stuffed chair and the small sofa were a narrower version of the sofa (Figures 11, 12). The small sofa had a mattress and the stuffed chair did not. The end tables, coffee tables and dressers were made of pressed wood board (Figures 13-15). The bunk beds were framed out with 0.038 m x 0.089 m (1.5 in x 3.5 in) pine boards (Figure 16). The twin mattresses were covered in cotton bedding consisting of flat sheets, pillows and pillow cases. The lamps were made of metal and had a small plastic shade and did not contribute significantly to the fire load.

Figure 7. 30 kg sleeper sofa in living room

Figure 8. 10 kg inner-spring mattress

Figure 9. 40 kg sofa with ignition point in rear left corner

Figure 10. 20 kg chair in living room

Figure 11. 20 kg stuffed chair in living room

Figure 12. 40 kg small sofa w/ mattress in living room

Figure 13. 3 kg wood end table in living room

Figure 14. 8 kg wood coffee table in living room

Figure 15. 60 kg wood dresser in bedroom

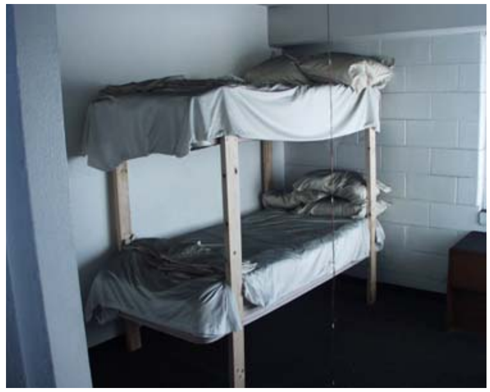

Figure 16. Bunk beds with 40 kg twin mattresses in bedroom

Fans

Four different fan types were used during this set of experiments (Table 2). Two different truck or trailer mounted fans and two different portable fans were used in various capacities (Figures 17-20). Each of the mounted fans was used to pressurize the stairwells as well as to create simulated wind conditions. The portable fans were placed inside the structure to pressurize both the south and center stairwells.

Table 2. Fan Details

Experiment (apartment)	Number of Fans	Identifier	Fan Shroud Size	Motor
1503	1	MVU	1.2 m (48 in)	Hydraulic (Truck Mounted)
1505	2	27	0.7 m (27 in)	Gasoline (9.0 hp)
1003	2	27	0.7 m (27 in)	Gasoline (9.0 hp)
	2	24	0.6 m (24 in)	Gasoline (9.0 hp)
1005	1	SVU	1.3 m (50 in)	Gasoline (Trailer Mounted)
303	2	27	0.7 m (27 in)	Gasoline (9.0 hp)
	2	24	0.6 m (24 in)	Gasoline (9.0 hp)
303 (Wind)	1	SVU	1.3 m (50 in)	Gasoline (Trailer Mounted)
304	1	SVU	1.3 m (50 in)	Gasoline (Trailer Mounted)
304 (Wind)	1	MVU	1.2 m (48 in)	Hydraulic (Truck Mounted)


Figure 17. SVU [9]

Figure 18. MVU [10]


Figure 19. 0.7 m (27 in) fan


Figure 20. 0.6 m (24 in) fan

Instrumentation

The data collected during the experiments included differential pressure, gas temperature, heat flux, carbon monoxide, meteorological data, video, thermal imaging and sound levels. The uncertainty associated with these measurements is located in Table 17. Unit conversions and reference values for this data is located in Appendix H. A differential pressure transducer and thermocouple were located on the door knob of every floor in the south stairwell (Figure 21). The door knobs were approximately 1.0 m (3.3 ft) above the floor. A small diameter tube was run through the door to the opposite door knob to reference the pressure readings to the floor side. The thermocouples were bare-bead, type K, with a 0.5 mm (0.02 in) nominal diameter.

Thermocouples were also located in the fire apartments and corridors to provide temperatures for the environment that building occupants and fire fighters may encounter and to measure the thermal effects of ventilation (Figure 22). Each living room had a vertical array of 8 thermocouples located near the center of the room with measurement locations of 0.025 m, 0.30 m, 0.61 m, 0.91 m, 1.22 m,1.52 m, 1.83 m and 2.13 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the ceiling. Thermocouple arrays were also placed in the corridor adjacent to the south stair, center stair and in the middle of the corridor. The experiment in apartment 304 had a similar thermocouple array in each of the two bedrooms.

Schmidt-Boelter heat flux gauges were placed on the fire floors in the potential paths of fire fighters advancing on the fire. All of the gauges were located 1.0 m (3.3 ft) above the floor. Each location had two gauges, one mounted horizontally facing the fire and one mounted vertically facing the ceiling (Figure 23). The heat flux gauges were co-located with the thermocouple arrays, in the fire apartment and in the corridor. The corridor had heat flux gauges located adjacent to the south stairwell, center stairwell and in the middle of the corridor.

Carbon monoxide was measured in both stairwells as well as in the corridor. The carbon monoxide meters were co-located with the heat flux gauges. Measurements were made using a portable chemical cell monitor with built-in sample pump (Figure 24). The monitors were also located on the stairwell side of the door handle on their respective floors. The CO meters were the same models as those typically available for fire department use. The sensors had a maximum upper limit that was less than the range of CO created during the experiments. The calibrated range of the CO meters was 0 ppm (0 %) to 750 ppm (0.0075 %). At values above 750 ppm (0.0075 %), the chemical sensors were saturated and the reported values probably under-report actual gas concentrations.

Weather was monitored and recorded during each of the experiments using two portable weather stations. Average temperature, average wind speed and average wind direction were recorded continuously. One weather station was located 15.2 m (50 ft) from the centerline of the main entrance, 2.5 m (8 ft) above the ground (Figure 25). The second weather station was located on the roof between the south and center stairwells, 2.5 m (8 ft) above the ground (Figure 26).

Video cameras and thermal imaging cameras were placed inside and outside the building to monitor both smoke and heat conditions throughout each test. As many as six video camera views and two thermal imaging views were recorded during each test (Figures 27, 28). Internal camera locations included the fire apartment, south stairwell, center stairwell, and the middle and ends of the corridor.

Sound measurements were taken with an analog sound meter at various locations including next to the fan and inside the structure to analyze any potential impact on fire ground communications. The meter had an operating range of 40 dBA to 120 dBA (Figure 29).

Figure 21. Pressure transducer

Figure 22. Thermocouple tree in hallway

Figure 23. Heat flux gauge

Figure 24. CO meter

Figure 25. Ground weather station


Figure 26. Roof weather station


Figure 27. Video camera in stairwell

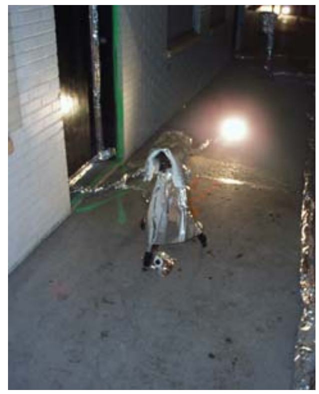
Figure 28. Protected IR camera on tripod in the hallway

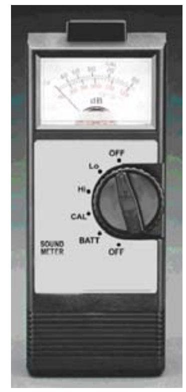

Figure 29. Sound Meter

Experimental Procedure

Prior to ignition in each experiment, a computerized data acquisition system was started. Data were collected from each instrument every 6 s. Video cameras recording the experiment were also started at this time. After at least 180 s of background data were collected, a remote matchbook ignition was used to ignite the left, rear corner of the sofa cushion in each experiment with the exception of the experiment in apartment 304. This experiment was ignited on the pillow of the lower bunk of the bunk beds.

After ignition, the fire was allowed to grow until the living room reached flashover conditions and visibility from the video camera output became limited in both the apartment and corridor. As smoke began to leak into the stairwell, the effect of different ventilation tactics were tested. Ventilation tactics included the use of compartment sized fans and larger mounted fans. The compartment size fans were positioned inside the structure both at the base of the stairwell and two floors below the fire floor. The larger mounted fans were placed at the front entrance (East side) to the building.

Additional doors and ventilation points were utilized to simulate conditions such as fire fighters operating and occupants leaving the building. The 16th floor doorway was used for vertical ventilation and the fire floor door was opened to simulate fire fighters entering the floor.

During the experiments on the third floor, apartment 303 and apartment 304, the larger mounted fans were used to simulate a wind condition by blowing in through an apartment window (Figure 30). Air velocity measurements were made with a hand-held anemometer from inside the window prior to each experiment. Both fans were throttled up to the engine speed that created an average velocity of approximately 11 m/s (25 mi/h). The same engine speed was utilized during each of the experiments. A fire blanket was also deployed during the experiment in apartment 303 to determine its effect on the wind and fire conditions.

A fire blanket is a tool that is available to the fire department that is made of fire resistive materials and can be deployed from the floor above the fire. The blanket is deployed from the windows above and adjacent to the window that the wind is entering the fire apartment (figure 30). The blanket is dropped over the window and secured on the floor below the fire floor, covering the window and greatly reducing the wind flow into the fire apartment. Hand-held anemometer measurements inside the apartment prior to the experiments yielded wind velocities of less than 0.4 m/s (1 mi/h) through the fire blanket.

Experiments were run until the fire burned down and smoke production was minimal. The experimental duration varied between 10 min and 50 min depending on the ventilation and fuel available during each experiment. Detailed tables of the experimental event changes are included in the results section.

Figure 30. Trailer and truck mounted fans in position to create simulated wind

Results

The results of the experiments include experiment timelines, photographs, videos, and pressure, temperature, heat flux, carbon monoxide, and weather measurements.

Experiment Timelines

The timelines were developed from observations made during the experiment, review of the video, and the data. The timelines for the six experiments are given in Tables 3 through 8. Photographs before, during and after each experiment are presented in Figures 31 through 51.

Table 3. Timeline for experiment in apartment 1503

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed
0	Ignition
465	Stair door on floor 15 open
582	Stair door on floor 16 open (exterior vent)
845	Stair door on floor 16 closed
870	Stair door on floor 15 closed
875	Stair door on floor 16 open
895	MVU started
938	MVU up to speed (1800 rpm)
960	Stair door on floor 16 closed
1025	Stair door on floor 15 opened 0.08 m (3 in)
1068	Stair door on floor 15 open
1475	FF crew moves down hallway
1485	FF crew removes gypsum board blocking rear of apartment
1580	Two chairs placed on sofa
1640	MVU turned off
1788	MVU turned on (1800 rpm)
3184	Experiment Terminated


Figure 31. 1503 - Prior to ignition


Figure 32. 1503 – Smoke from hallway leaks


Figure 33. 1503 – Post test (Same view as figure 31)

Table 4. Timeline for experiment in apartment 1505

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed
0	Ignition
340	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
392	Stair door on floor 16 open
411	Stair door on floor 13 opened
416	0.7 m (27 in.) fan turned on at floor 13 [1.2 m (4 ft.) 80 degrees]
442	Stair door on floor 16 closed
469	Stair door on floor 15 opened 0.08 m (3 in)
489	Stair door on floor 15 opened
808	Stair door on floor 14 open
838	Stair door on floor 14 closed
1074	Both fans turned off
1148	Stair door on floor 1 closed
1162	Stair door on floor 13 opened
1167	0.7 m (27 in.) fan turned on at floor 13 [1.2 m (4 ft.) 80 degrees]
1241	0.7 m (27 in.) fan turned off at floor 13
1250	Stair door on floor 13 closed
1329	Stair door on floor 1 open
1545	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
1717	Stair door on floor 13 opened
1722	0.7 m (27 in.) fan turned on at floor 13 [1.2 m (4 ft.) 80 degrees]
2172	Experiment Terminated

Figure 34. 1505 - Prior to ignition

Figure 35. 1505 – Smoke from bedroom


Figure 36. 1505 – Post test (Same view as figure 34)

Table 5. Timeline for experiment in apartment 1003

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed
0	Ignition
223	Stair door on floor 10 open
248	Stair door on floor 16 open
297	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
317	Stair door on floor 8 open
322	0.7 m (27 in.) fan turned on at floor 8 [1.2 m (4 ft.) 80 degrees]
346	Stair door on floor 16 closed
480	Stair door on floor 1 open (center stairwell)
491	0.6 m (24 in.) fan turned on at floor 1 center stairwell [1.2 m (4 ft.) 80 deg]
528	Stair door on floor 9 open (center stairwell)
533	0.6 m (24 in.) fan turned on at floor 9 center stairwell [1.2 m (4 ft.) 80 deg]
593	Stair door on floor 16 open (center stairwell)
803	0.7 m (27 in.) fan turned off at floor 1
803	0.6 m (24 in.) fan turned off at floor 1 (center stairwell)
803	0.6 m (24 in.) fan turned off at floor 9 (center stairwell)
810	Stair door on floor 9 closed (center stairwell)
891	0.7 m (27 in.) fan turned off at floor 8
896	Stair door on floor 8 closed
1093	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
1235	Stair door on floor 16 open
1300	Overhaul initiated
1480	Experiment Terminated

Figure 37. 1003 - Prior to ignition

Figure 38. 1003 – Smoke from bedroom

Figure 39. 1003 – Post test (same view as figure 37)

Table 6. Timeline for experiment in apartment 1005

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed
0	Ignition
221	Stair door on floor 10 open
276	Stair door on floor 16 open
336	SVU turned on (3600 rpm)
351	Stair door on floor 16 closed
626	Stair door on floor 1 open (center stairwell)
661	Stair door on floor 16 open (center stairwell)
896	Stair door on floor 16 closed (center stairwell)
973	SVU turned down to idle
1328	SVU turned up (3600 rpm)
1396	Stair door on floor 1 closed (center stairwell)
1506	Overhaul begins
1626	Experiment Terminated


Figure 40. 1005 - Prior to ignition


Figure 41. 1005 – Smoke from bedroom


Figure 42. 1005 – Post test (same view as figure 40)

Table 7. Timeline for experiment in apartment 303

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed
0	Ignition
264	SVU turned on (Simulated wind)
278	SVU at full throttle (4300 rpm)
339	Stair door on floor 3 open
349	Stair door on floor 16 open
444	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
444	0.7 m (27 in.) fan turned on at floor 1 (Center Stairwell) [1.2 m (4 ft.) 80 deg]
584	0.6 m (24 in.) fan turned on at floor 5 [1.2 m (4 ft.) 80 degrees]
589	Stair door on floor 5 open
668	0.6 m (24 in.) fan turned off at floor 5
687	0.7 m (27 in.) fan turned off at floor 1
687	0.7 m (27 in.) fan turned off at floor 1 (Center Stairwell)
719	0.7 m (27 in.) fan turned on at floor 1 (Center Stairwell) [1.2 m (4 ft.) 80 deg]
747	Fire Blanket Deployed on Bedroom Window
789	Stair door on floor 3 open (1/2)
806	Stair door on floor 3 closed
844	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
873	Stair door on floor 16 open
1016	Stair door on floor 3 opened 0.08 m (3 in)
1027	Stair door on floor 3 closed
1061	Stair door on floor 16 closed
1066	Stair door on floor 3 opened 0.08 m (3 in)
1071	Stair door on floor 3 closed
1092	Stair door on floor 16 open
1130	Stair door on 16 closed
1146	Stair door on floor 5 open
1151	0.6 m (24 in.) fan turned on at floor 5 [1.2 m (4 ft.) 80 degrees]
1158	Stair door on floor 3 opened 0.08 m (3 in)
1207	0.6 m (24 in.) fan turned off at floor 5
1212	Stair door on floor 5 closed
1218	Stair door on floor 3 open
1278	0.7 m (27 in.) fan turned off at floor 1
1379	SVU turned off
1461	Fire Blanket Removed From Window
1520	0.7 m (27 in.) fan turned on at floor 1 [1.2 m (4 ft.) 80 degrees]
1994	Stair door on floor 5 open
1999	0.6 m (24 in.) fan turned on at floor 5 [1.2 m (4 ft.) 80 degrees]
2279	Experiment Terminated


Figure 43. 303 - Prior to ignition


Figure 44. 303 – Smoke prior to wind


Figure 45. 303 – Smoke during wind


Figure 46. 303 – Fire blanket deployed

Table 8. Timeline for experiment in apartment 304

Time (s)	Event
	Background
	Base of south stair and front door open, Center stair closed, 304 Bedroom Window Open
0	Ignition
138	MVU turned on
151	MVU (1200 rpm) Simulated 20-25 mph wind
160	Stair door on floor 3 open 1/2 (Center Stairwell)
189	Stair door on floor 3 open 0.08 m (3 in) to 0.2 m (8 in)
214	Stair door on floor 16 open
279	Stair door on floor 3 closed
304	SVU turned on (3800 rpm)
430	Stair door on floor 16 closed
513	MVU turned off
513	SVU turned off
629	Experiment Terminated


Figure 47. 304 – Living room prior to ignition


Figure 48. 304 – Bedroom prior to ignition


Figure 49. 304 – Smoke prior to wind


Figure 50. 304 – Fire during wind


Figure 51. 304 – Post test looking back to the bedroom

Pressure Data

The pressure measurements versus time graphs are located in the appendices B through G. The experiment time lines are integrated into the graphs to display the pressure changes after the configuration changes. The pressures were quasi-steady for the different configurations. These pressures are graphed versus the floor number for the different configurations in Figures 52 through 57 for the six experiments. Detailed lines are located at the NFPA minimum design pressures. Floors that are missing a data point had a malfunctioning pressure transducer or the door was open providing no differential pressure.

Average pressures during the different configurations during the experiment in apartment 1503 are in Figure 52 and Table 9. Ambient differential pressures were below 5 Pa before the experiment began and late in the experiment when the MVU was turned off. Pressures were mostly above 80 Pa in the stairwell with all of the doors closed and the MVU pressurizing 7.6 m (25 ft) from the front door. When the door on floor 15 was opened 0.08 m (3 in), the pressures dropped throughout the stairwell but remained above 50 Pa. Pressures with one door open, either on the 16th floor or on the 15th floor, dropped significantly, but remained above 25 Pa below the 11th floor. The upper floors remained above 12.5 Pa with the exception of the 15th floor, while the 16th floor was open.

The experiment in apartment 1505 utilized portable fans to pressurize the south stairwell. Average pressures during the experiment are in Figure 53 and Table 10. Ambient pressures during this experiment also remained below 5 Pa. Placing a 0.7 m (27 in) fan at the base of the south stairwell, setback 1.2 m (4 ft) and angled up to 80 degrees (i.e. 10 degrees back from vertical), increased the stairwell pressures by 9 Pa to 14 Pa. Opening a single door on the 15th floor or the 16th floor decreased the stairwell pressures to 9 Pa to 11 Pa at the bottom of the stairwell to approximately ambient towards the top of the stairwell. A single 0.7 m (27 in) fan at the 13th floor with all other doors closed created increased pressures in the entire stairwell with the exception of the 2nd floor as compared to the single fan at the base of the stairwell. Pressurizing the stairwell with two 0.7 m (27 in) fans, one at the 1st floor and one at the 13th floor, resulted in pressures ranging from 16 Pa to 21 Pa independent of the doors opened on the upper floors. With no doors opened the pressures reached as high as 26 Pa, while opening two doors on the 14th and 15th floors decreased the pressures as low as 7 Pa.

Average pressures for the experiment in apartment 1003 created by portable fans are in Figure 54 and Table 11. The ambient pressures prior to the experiment were at or below 5 Pa with a transient increase to 9 Pa on floor 13. The single 0.7 m (27 in) fan on the 1st floor and with the fire floor door open and the 16th floor door open, raised pressures lower in the building as high as 17 Pa, but pressures above the 8th floor fell below ambient. A single 0.7 m (27 in) fan on floor 8 with the 10th floor open, kept pressures in the entire stairwell above 12.5 Pa except for floor 2. Utilizing both fans was effective at keeping stairwell pressures up to the 7th floor above 25 Pa regardless of ventilation opening above the 9th floor. All pressures remained above 12.5 Pa except when the 10th and 16th floor doors were both open.

The average pressures for the configurations during the experiment in apartment 1005 are in Figure 55 and Table 12. Ambient pressures prior to the experiment ranged from 0 Pa to 11 Pa in the stairwell. Pressures up to 64 Pa were recorded with the SVU running and the fire floor door open on the 10th floor. The same configuration had pressures as low as 21 Pa above the fire floor. When the center stairwell was opened in addition to the south stairwell, the pressures declined to 13 Pa to 40 Pa below the fire floor and 10 Pa to 15 Pa above the fire floor.

The experiment in apartment 303 had pressures created by a simulated wind as well as by portable fans. The average pressures for this experiment are in Figure 56 and Table 13. The ambient stairwell pressures for this experiment were impacted by a natural wind. The fire floors (3, 10, 15) were enclosed, therefore creating an interior stairwell. The wind was able to reach the low side of the pressure transducers on the non-fire floors lowering the pressures, while the leakage into the stairwell caused a slight increase in pressure on the fire floors. This wind effect remained constant through the experiment so the impact of the fans can be determined by the change in differential pressure. The ambient pressure on the fire floors was approximately 11 Pa and the ambient pressure on all other floors was zero.

The simulated wind created by the SVU blowing into the third floor caused the pressure on floor 3 to drop to zero and caused an increase of approximately 1 Pa throughout the rest of the stairwell. The third floor pressure may have been negative, but the pressure transducer was unidirectional and did not have the range to measure negative pressures. When the third floor door was opened, the pressure on floors 5 through 10 increased to 10 Pa. Above floor 10, there was a minimal impact. With floor 3 and 16 open, the impact of the wind on the upper floor pressures was greater. A fire blanket was deployed over the fire apartment window that the simulated wind was being introduced. This fire blanket prevented any pressure impact created by the wind in the south stairwell. While the fire blanket was deployed, portable fans were used to pressurize the south stairwell. Single fans at the base of the stairwell increased the pressure above 14 Pa in most of the stairwell. Multiple fans, one at the base of the stair and one on the 5th floor, increased the pressure above 25 Pa and as high as 37 Pa in the stairwell.

Average pressures from the configurations during the experiment in apartment 304 are shown in Figure 57 and Table 14. This experiment also had a simulated wind, but it was created by the MVU instead of the SVU used for the experiment in apartment 303. The SVU was used at the front door to pressurize the stairwell against the effects of the simulated wind on the fire. Ambient differential pressures were approximately 10 Pa to 12 Pa on the enclosed floors and less than 5 Pa on the other floors before the experiment began. The addition of the wind through the fire apartment decreased the third floor pressure to zero and increased the rest of the stairwell by 3 Pa to 5 Pa. The third floor door was opened allowing the wind to flow into the stairwell and the pressures increased as much as 20 Pa on the fifth floor. With the simulated wind still impacting the fire apartment, the SVU was activated at the front door. With the SVU running and the 16th floor door open, pressures increased to above 10 Pa throughout the stairwell. After the 16th floor door was closed, the pressures increased to above 33 Pa.

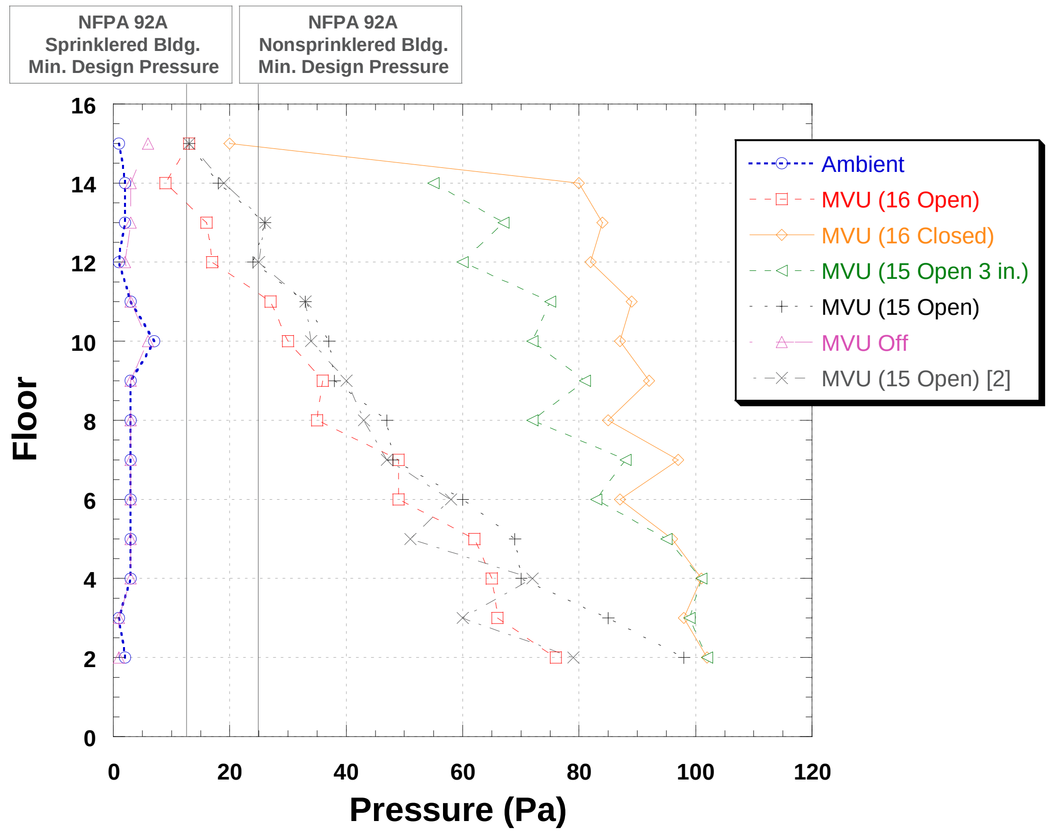

Figure 52. Pressure vs. Floor with MVU at front door for fire in apartment 1503 (Uncertainty ±10%)

Table 9. Average stairwell pressure during events for fire in apartment 1503 (Uncertainty ±10%)

Floor	Ambient	MVU (16 Open)	MVU (16 Closed)	MVU (15 Open 3 in.)	MVU (15 Open)	MVU Off	MVU (15 Open)
	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	No Data	Open	No Data	No Data	No Data	No Data	No Data
15	1	15	20	Open	13	6	13
14	2	52	80	55	18	3	19
13	2	53	84	67	26	3	26
12	1	53	82	60	24	2	25
11	3	53	89	75	33	3	33
10	7	60	87	72	37	6	34
9	3	61	92	81	38	3	40
8	3	60	85	72	47	3	43
7	3	68	97	88	48	3	47
6	3	67	87	83	60	3	58
5	3	70	96	95	69	3	51
4	3	71	101	101	70	3	72
3	1	64	98	99	85	1	60
2	2	69	102	102	98	1	79
1	Open	Open	Open	Open	Open	Open	Open

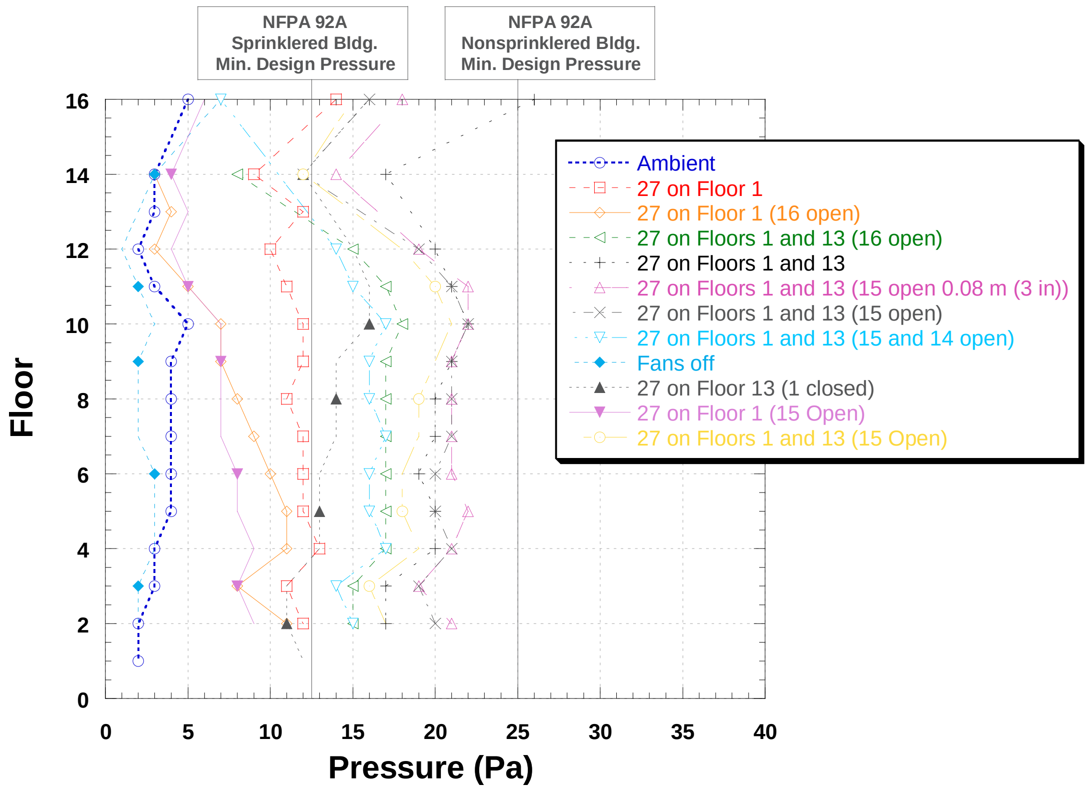

Figure 53. Pressure vs. Floor with 0.7 m (27 in.) fan for fire in apartment 1505 (Uncertainty ±10%)

Table 10. Average stairwell pressure during events for fire in apartment 1505 (Uncertainty ±10%)

	Ambient	27 on Floor 1	27 on Floor 1 (16 open)	27 on Floors 1 and 13 (16 open)	27 on Floors 1 and 13	27 on Floors 1 and 13 (15 open 0.08 m (3 in))
Floor	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	5	14	Open	Open	26	18
15	No Data	No Data	No Data	No Data	No Data	No Data
14	3	9	3	8	17	14
13	3	12	4	Fan (Open)	Fan (Open)	Fan (Open)
12	2	10	3	15	20	19
11	3	11	5	17	21	22
10	5	12	7	18	22	22
9	4	12	7	17	21	21
8	4	11	8	17	20	21
7	4	12	9	17	20	21
6	4	12	10	17	19	21
5	4	12	11	17	20	22
4	3	13	11	17	20	21
3	3	11	8	15	17	19
2	2	12	11	15	17	21
1	2	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)

Table 10 (cont.)

Floor	27 on Floors 1 and 13 (15 open)	27 on Floors 1 and 13 (15 and 14 open)	Fans off	27 on Floor 13 (1 closed)	27 on Floor 1 (15 Open)	27 on Floors 1 and 13 (15 Open)
	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	16	7	7	16	6	15
15	Open	Open	Open	Open	Open	Open
14	12	Open	3	12	4	12
13	Fan (Open)	Fan (Open)	2	Fan (Open)	5	Fan (Open)
12	19	14	1	15	4	18
11	21	15	2	16	5	20
10	22	17	3	16	7	21
9	21	16	2	14	7	20
8	21	16	2	14	7	19
7	21	17	2	14	7	19
6	20	16	3	13	8	18
5	20	16	3	13	8	18
4	21	17	3	13	9	19
3	19	14	2	11	8	16
2	20	15	2	11	9	17
1	Fan (Open)	Fan (Open)	Open	12	Fan (Open)	Fan (Open)

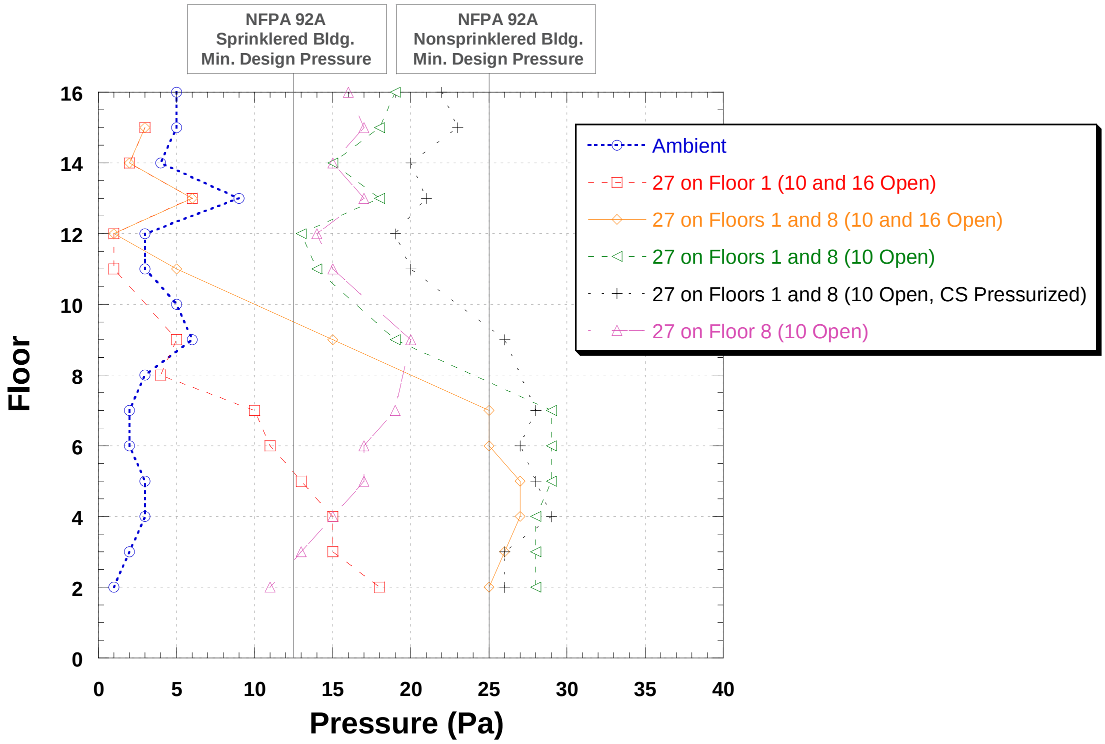

Figure 54. Pressure vs. Floor with 0.7 m (27 in.) fan for fire in apartment 1003 (Uncertainty ±10%)

Table 11. Average stairwell pressure during events for fire in apartment 1003 (Uncertainty ±10%)

Floor	Ambient	27 on Floor 1 (10 and 16 Open)	27 on Floors 1 and 8 (10 and 16 Open)	27 on Floors 1 and 8 (10 Open)	27 on Floors 1 and 8 (10 Open, CS Pressurized)	27 on Floor 8 (10 Open)
	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	5	Open	Open	19	22	16
15	5	3	3	18	23	17
14	4	2	2	15	20	15
13	9	6	6	18	21	17
12	3	1	1	13	19	14
11	3	1	5	14	20	15
10	5	Open	Open	Open	Open	Open
9	6	5	15	19	26	20
8	3	4	Fan (Open)	Fan (Open)	Fan (Open)	10
7	2	10	25	29	28	19
6	2	11	25	29	27	17
5	3	13	27	29	28	17
4	3	15	27	28	29	15
3	2	15	26	28	26	13
2	1	18	25	28	26	11
1	Open	Fan (Open)	Fan (Open)	Fan (Open)	Open	Open

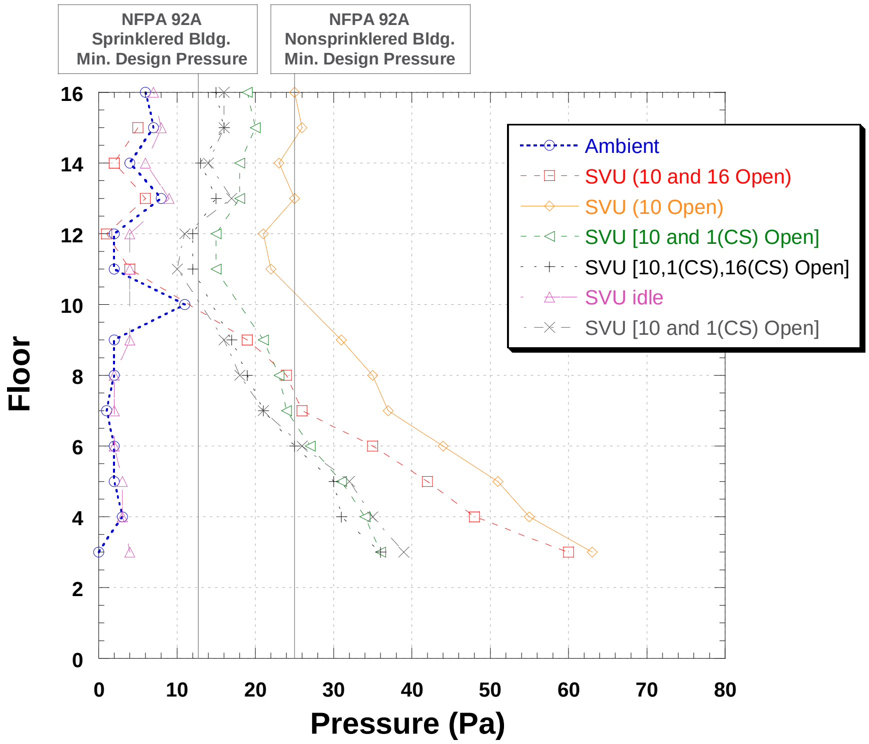

Figure 55. Pressure vs. Floor with SVU at front door for fire in apartment 1003 (Uncertainty ±10%)

Table 12. Average stairwell pressure during events for fire in apartment 1005 (Uncertainty ±10%)

Floor	Ambient	SVU (10 and 16 Open)	SVU (10 Open)	SVU [10 and 1(CS) Open]	SVU [10,1(CS),16 (CS) Open]	SVU idle	SVU [10 and 1(CS) Open]	SVU (10 Open)
	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	6	Open	25	19	15	7	16	18
15	7	5	26	20	16	8	16	19
14	4	2	23	18	13	6	14	17
13	8	6	25	18	15	9	17	19
12	2	1	21	15	12	4	11	14
11	2	4	22	15	12	4	10	15
10	11	Open	Open	Open	Open	Open	Open	Open
9	2	19	31	21	17	4	16	24
8	2	24	35	23	19	2	18	28
7	1	26	37	24	21	2	21	31
6	2	35	44	27	25	2	26	38
5	2	42	51	31	30	3	32	47
4	3	48	55	34	31	3	35	51
3	0	60	63	36	36	4	39	58
2	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
1	Open	Open	Open	Open	Open	Open	Open	Open

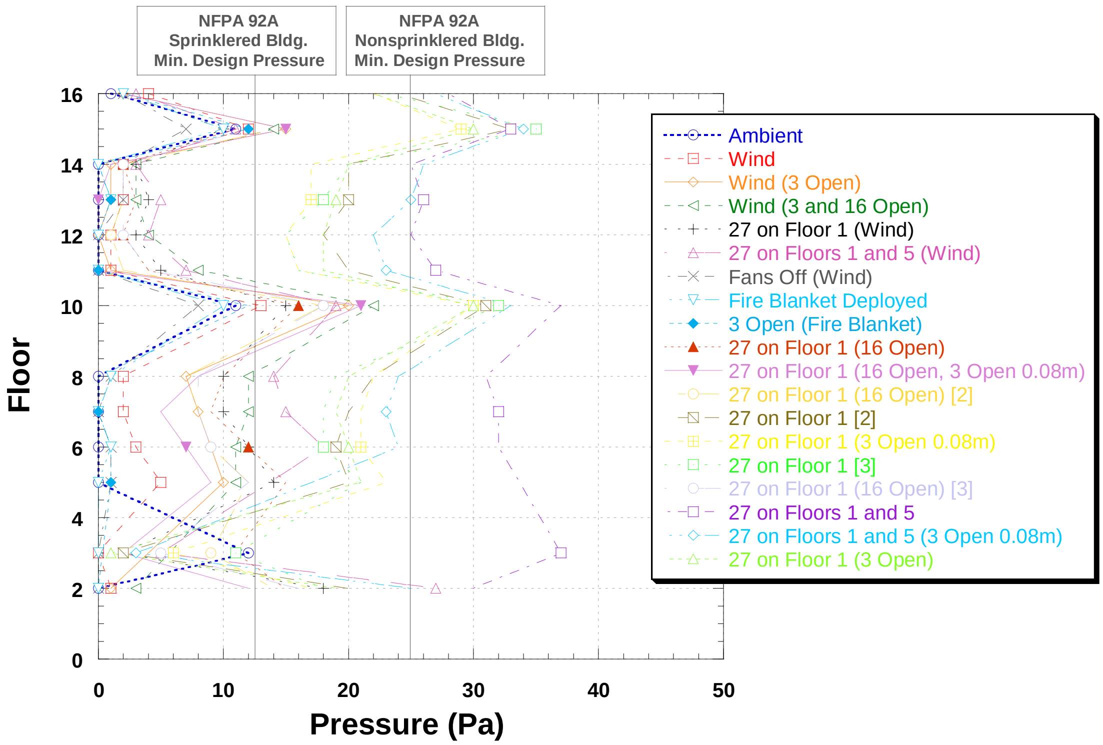

Figure 56. Pressure vs. Floor with 0.7 m (27 in.) fan and SVU simulated wind for fire in apt. 303 (Uncertainty ±10%)

Table 13. Average stairwell pressure during events for fire in apartment 303 (Uncertainty ±10%)

	Ambient	Wind	Wind (3 Open)	Wind (3 and 16 Open)	27 on Floor 1 (Wind)	27 on Floors 1 and 5 (Wind)	Fans Off (Wind)
Floor	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)	Pressure (Pa)
16	1	4	2	Open	2	3	2
15	11	12	15	14	10	11	7
14	0	2	1	3	3	3	2
13	0	2	1	3	4	5	2
12	0	1	0	4	3	4	0
11	0	1	1	8	5	7	0
10	11	13	20	22	15	19	8
9	No Data	No Data	No Data	No Data	No Data	No Data	No Data
8	0	2	7	12	10	14	1
7	0	2	8	12	10	15	0
6	0	3	9	11	12	18	1
5	0	5	10	11	14	Fan (Open)	1
4	No Data	No Data	No Data	No Data	No Data	No Data	No Data
3	12	0	Open	Open	2	5	0
2	0	1	1	3	18	27	0
1	Open	Open	Open	Open	Fan (Open)	Fan (Open)	Open

Table 13 (cont.)

Floor	Fire Blanket Deployed Pressure (Pa)	3 Open (Fire Blanket) Pressure (Pa)	27 on Floor 1 (16 Open) Pressure (Pa)	27 on Floor 1 (16 Open, 3 Open 0.08m) Pressure (Pa)	27 on Floor 1 (16 Open) [2] Pressure (Pa)	27 on Floor 1 [2] Pressure (Pa)
16	2	2	Open	2	Open	24
15	10	12	11	15	14	33
14	0	0	2	1	2	20
13	1	1	3	0	2	20
12	0	0	2	0	1	18
11	0	0	4	0	2	20
10	10	12	16	21	18	31
9	No Data	No Data	No Data	No Data	No Data	No Data
8	1	0	10	8	7	22
7	0	0	9	5	8	20
6	1	1	12	7	9	19
5	0	1	15	9	12	20
4	No Data	No Data	No Data	No Data	No Data	No Data
3	0	Open	11	2	9	2
2	0	0	15	12	14	20
1	Open	Open	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)

Table 13 (cont.)

Floor	27 on Floor 1 (3 Open 0.08m) Pressure (Pa)	27 on Floor 1 [3] Pressure (Pa)	27 on Floor 1 (16 Open) [3] Pressure (Pa)	27 on Floors 1 and 5 (Wind) Pressure (Pa)	27 on Floors 1 and 5 (3 Open 0.08m) Pressure (Pa)	27 on Floor 1 (3 Open) Pressure (Pa)
16	22	23	Open	28	27	22
15	29	35	12	33	34	30
14	17	20	2	25	26	20
13	17	18	2	26	25	19
12	15	15	2	25	22	18
11	16	16	4	27	23	18
10	30	32	18	37	33	30
9	No Data	No Data	No Data	No Data	No Data	No Data
8	22	19	8	31	24	20
7	21	18	8	32	23	19
6	21	18	9	32	24	20
5	23	21	12	Fan (Open)	Fan (Open)	21
4	No Data	No Data	No Data	No Data	No Data	No Data
3	6	11	5	37	3	1
2	17	18	16	30	25	19
1	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)	Fan (Open)

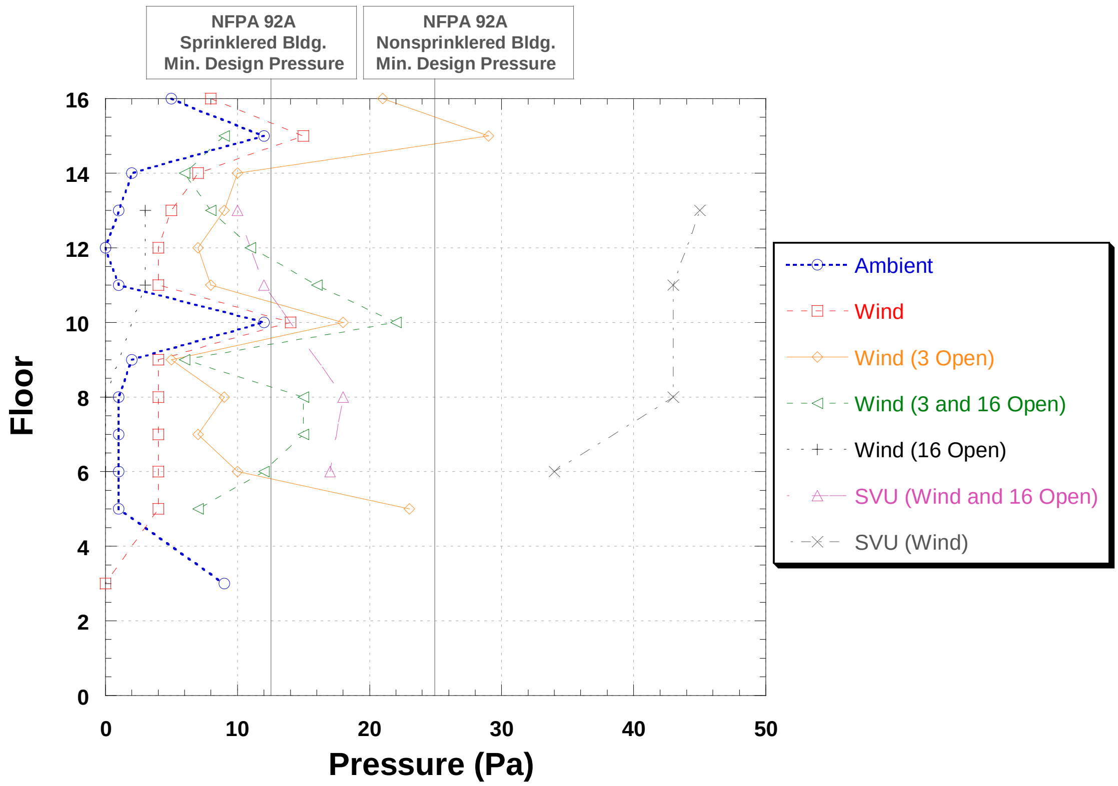

Figure 57. Pressure vs. Floor with SVU at front door and MVU simulated wind fore fire in apt. 304 (Uncertainty ±10%)

Table 14. Average stairwell pressure during events for fire in apartment 304 (Uncertainty ±10%)

Floor	Ambient Pressure (Pa)	Wind Pressure (Pa)	Wind (3 Open) Pressure (Pa)	Wind (3 and 16 Open) Pressure (Pa)	Wind (16 Open) Pressure (Pa)	SVU (Wind and 16 Open) Pressure (Pa)	SVU (Wind) Pressure (Pa)
16	5	8	21	Open	Open	Open	No Data
15	12	15	29	9	No Data	No Data	No Data
14	2	7	10	6	No Data	No Data	No Data
13	1	5	9	8	3	10	45
12	0	4	7	11	No Data	No Data	No Data
11	1	4	8	16	3	12	43
10	12	14	18	22	No Data	No Data	No Data
9	2	4	5	6	No Data	No Data	No Data
8	1	4	9	15	0	18	43
7	1	4	7	15	No Data	No Data	No Data
6	1	4	10	12	0	17	34
5	1	4	23	7	No Data	No Data	No Data
4	No Data	No Data	No Data	No Data	No Data	No Data	No Data
3	9	0	Open	Open	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data	No Data	No Data	No Data
1	Open	Open	Open	Open	Open	Open	Open

Temperature Data

Temperature measurements at each of the instrument locations are graphed versus time in the appendix. These graphs include lines to detail the events and configuration changes that occurred during the experiments. The thermocouple locations that correspond to those in the graphs are shown in Figure 58. The temperatures for each of the thermocouple locations at the ceiling and at 0.9 m (3 ft) from the floor are shown for each of the six experiments in Figures 59 through 70. The largest observed temperatures were typically located at the ceiling, while temperatures at 0.9 m (3 ft) would be more representative of what a fire fighter experiences. Table 15 shows the maximum temperatures at the ceiling and at 0.9 m (3 ft) for each experiment.

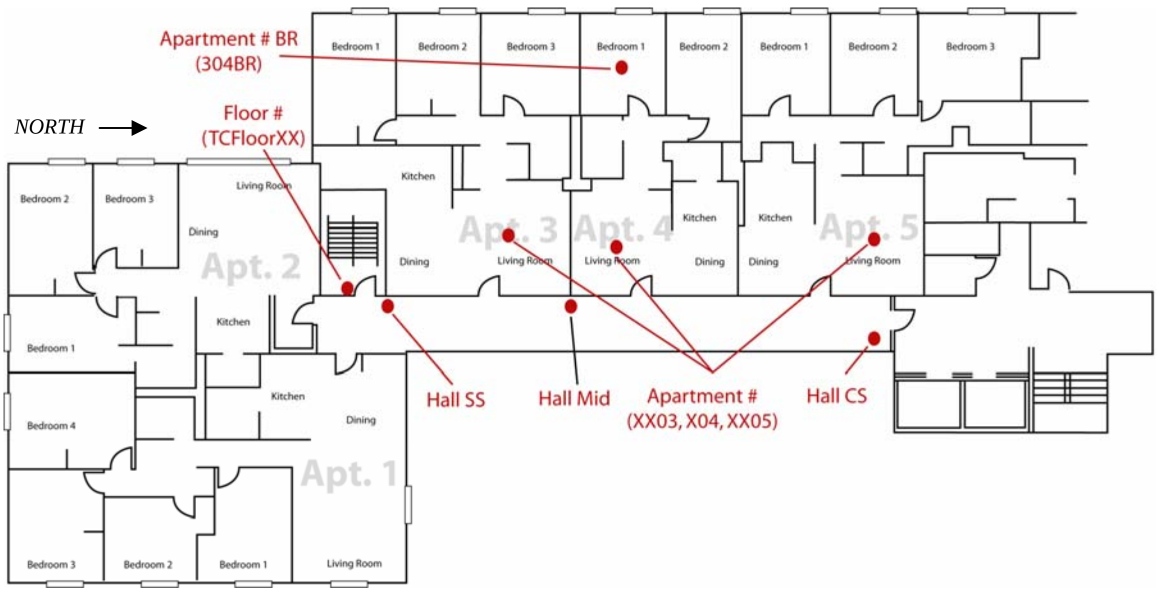

Figure 58. Thermocouple tree locations

Experimental temperatures in apartment 1503's living room reached 800 °C (1470 °F) at the ceiling and 500 °C (930 °F) at 0.9 m (3 ft) from the floor. The fire became ventilation limited at approximately 850 s based on the video and infrared views and the temperature fell to between 150 °C (300 °F) and 250 °C (480 °F). The MVU was turned on and the 16th floor was opened to vent the stairwell. The temperatures in the stairwell of up to 100 °C (210 °F) decreased down to near ambient. Later in the experiment, the rear of the apartment was ventilated and two chairs were added to the burning sofa. The MVU was turned off and the temperatures in the hallway and stairwell climbed back up to near 200 °C (390 °F). The MVU was turned on again with the fire floor door open and the temperatures declined rapidly.

The living room ceiling temperatures during the experiment in apartment 1505 reached 800 °C (1470 °F), then the room became ventilation limited and the temperature decreased to 200 °C (390 °F). The stairwell door was opened and the temperatures recovered to 850 °C (1560 °F). Hallway temperatures reached a maximum of 250 °C (480 °F) and stairwell temperatures remained below 100 °C (210 °F). The use of the fans lowered the stairwell temperatures by as much as 50 °C (120 °F) and it recovered by the same amount when the fans were turned off.

Experimental temperatures in apartment 1003's living room reached 800 °C (1470 °F) at the ceiling and 600 °C (1110 °F) at 0.9 m (3 ft) from the floor. More oxygen was available from a window on the rear of the apartment, so this experiment was likely less ventilation limited as compared to the prior experiments. Hallway ceiling temperatures reached 250 °C (480 °F) near the south stairwell and declined with the use of portable fans. The stairwell temperatures remained near ambient and were cooled by the fan air flow when they increased.

The living room ceiling temperatures during the experiment in apartment 1005 reached 800 °C (1470 °F). Temperatures 0.9 m (3 ft) from the floor peaked at 850 °C (1560 °F). This experiment also did not see large temperature drops due to limited oxygen. Hallway ceiling temperatures reached 225 °C (440 °F) throughout the hallway and declined with the use of the SVU. The stairwell temperatures remained near ambient and were cooled by the fan air flow when the fan was turned on at 340 s and 1330 s.

Temperatures during the experiment in Apartment 303 were greatly influenced by ventilation. A simulated wind was introduced through a bedroom window which caused temperatures to reach as high as 900 °C (1650 °F) in the living room. Temperatures as high as 600 °C (1110 °F) were reached in the hallway and the temperature in the stairwell peaked at 250 °C (480 °F) on the floor above the fire floor. A fire blanket was deployed to block the effects of the wind and the temperatures were held below 200 °C (390 °F) everywhere on the floor until the blanket was removed. The remaining fuel in the room began to burn causing temperatures to rise back up to 800 °C (1470 °F).

Temperatures during the experiment in apartment 304 were also greatly influenced by the simulated wind into the bedroom window. The bedroom and living room were furnished, which also played a role in the increased temperatures. Temperatures throughout the fire apartment and entire hallway reached 800 °C (1470 °F) to 900 °C (1650 °F). Some of the temperatures increased over 500 °C (930 °F) in less than 30 s. Temperatures in the stairwell on the floor above the fire increased from 35 °C (95 °F) to over 180 °C (360 °F) in less than 20 s. The reliability of temperatures after 400 s is not certain because the corridor lost integrity creating holes and thermocouple extension wires were damaged by thermal exposure.

Table 15. Maximum temperature readings (Uncertainty ± 15%)

Experiment	Living Room (°C)		Hall SS (°C)		Hall Mid (°C)		Hall CS (°C)	
	Ceiling	0.9 m (3 ft)	Ceiling	0.9 m (3 ft)	Ceiling	0.9 m (3 ft)	Ceiling	0.9 m (3 ft)
1503	800	500	250	150	225	125	150	150
1505	850	525	150	100	200	100	250	100
1003	800	600	250	100	175	75	125	100
1005	825	850	175	100	200	75	225	75
303	900	900	575	400	450	250	250	250
304	800	850	850	850	650	650	650	700

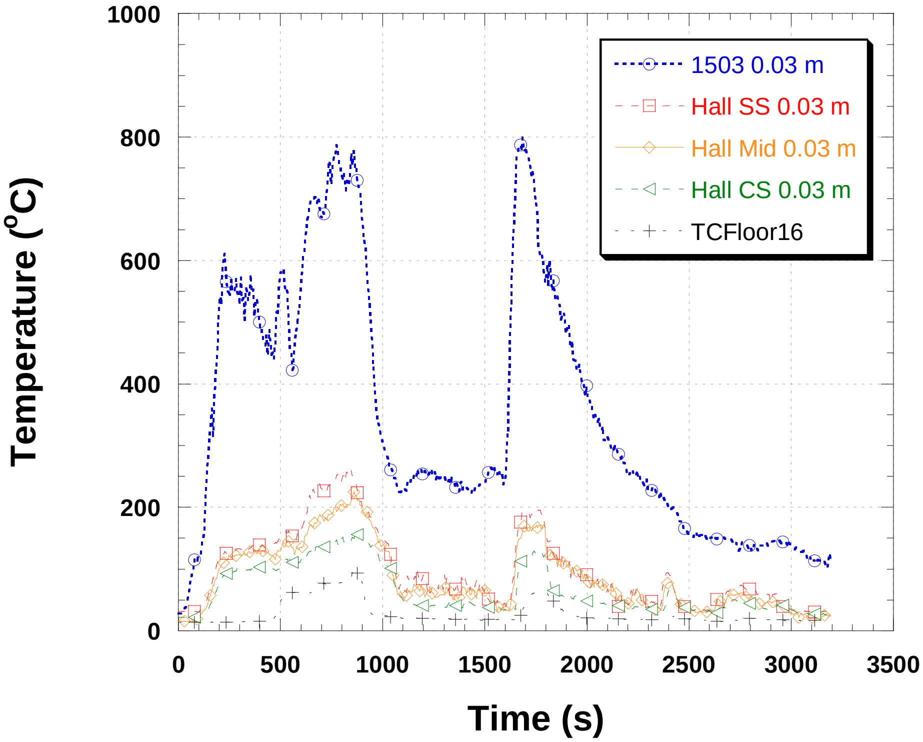

Figure 59. Gas temperatures at ceiling during apartment 1503 experiment (Uncertainty ± 15%)

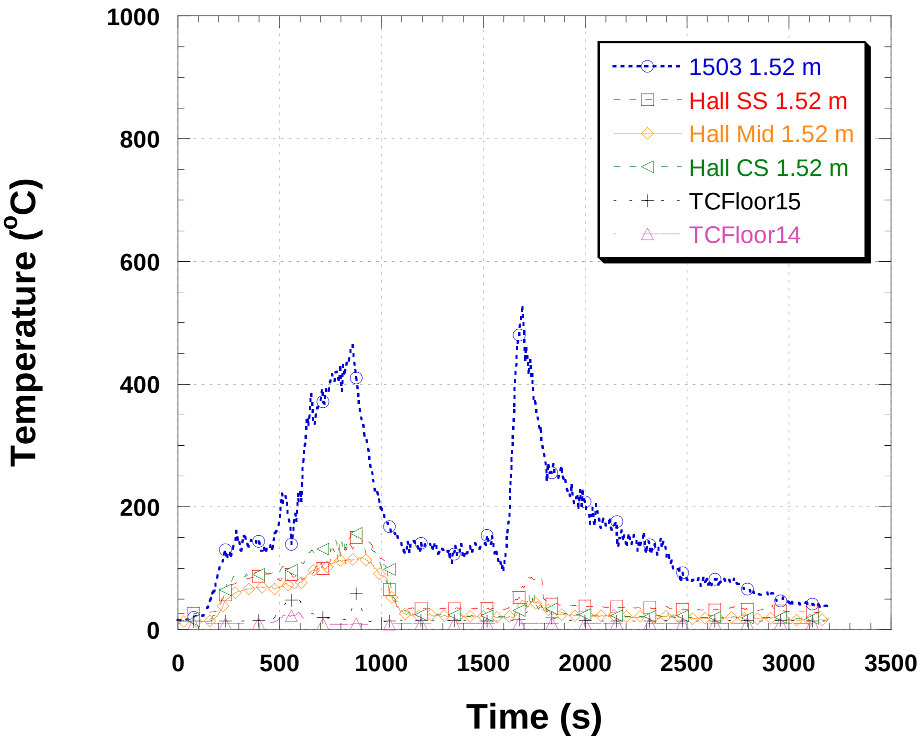

Figure 60. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 1503 experiment (Uncertainty ± 15%)

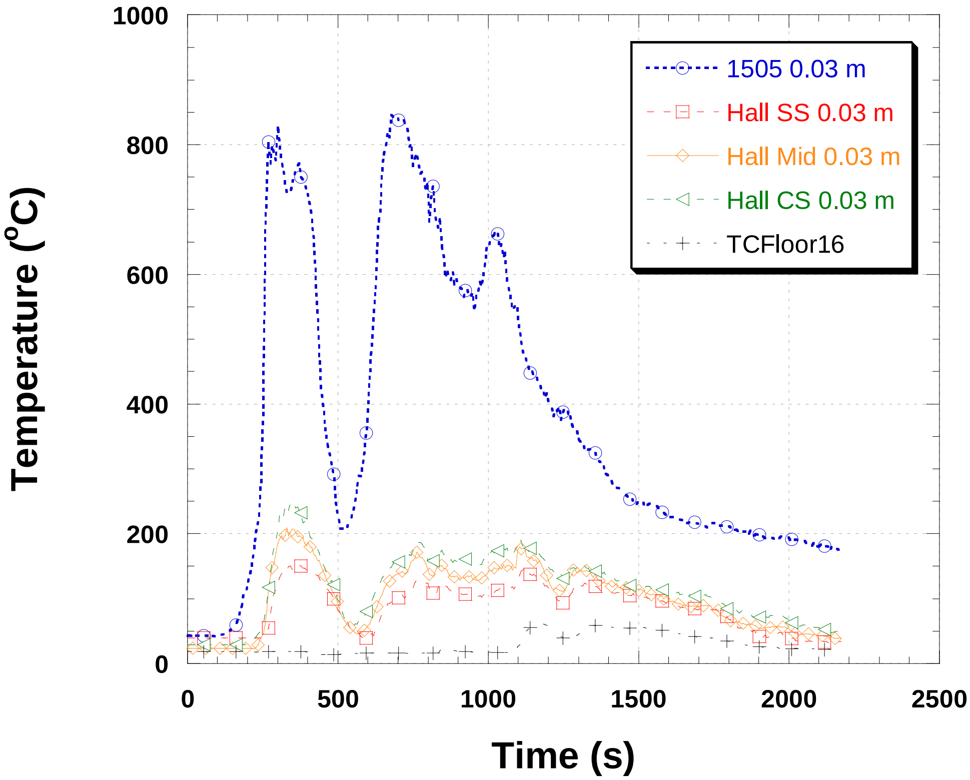

Figure 61. Gas temperatures at ceiling during apartment 1505 experiment (Uncertainty ± 15%)

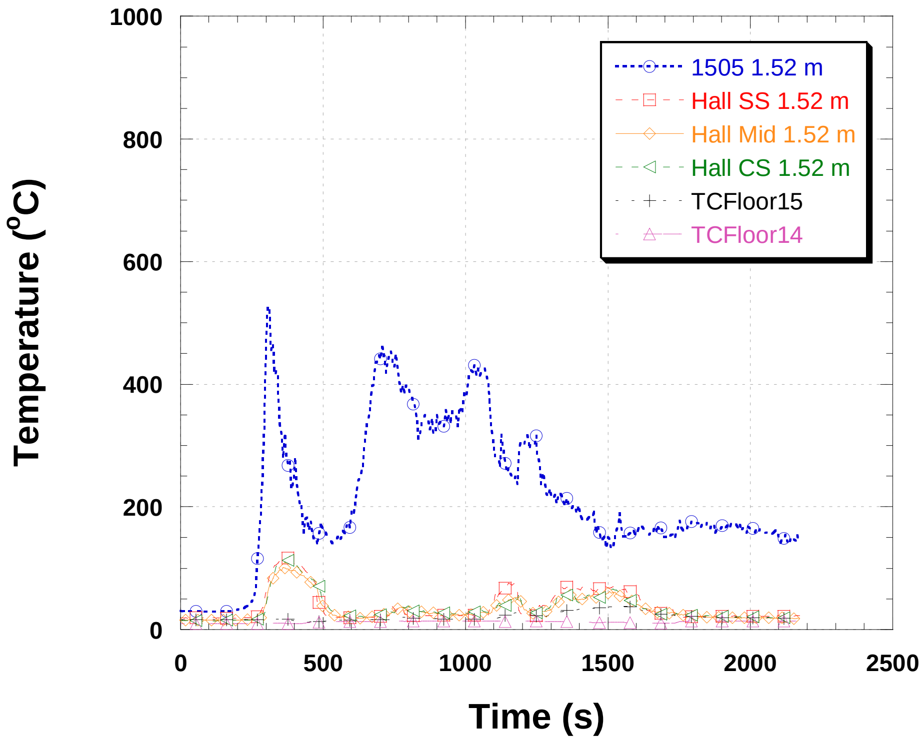

Figure 62. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 1505 experiment (Uncertainty ± 15%)

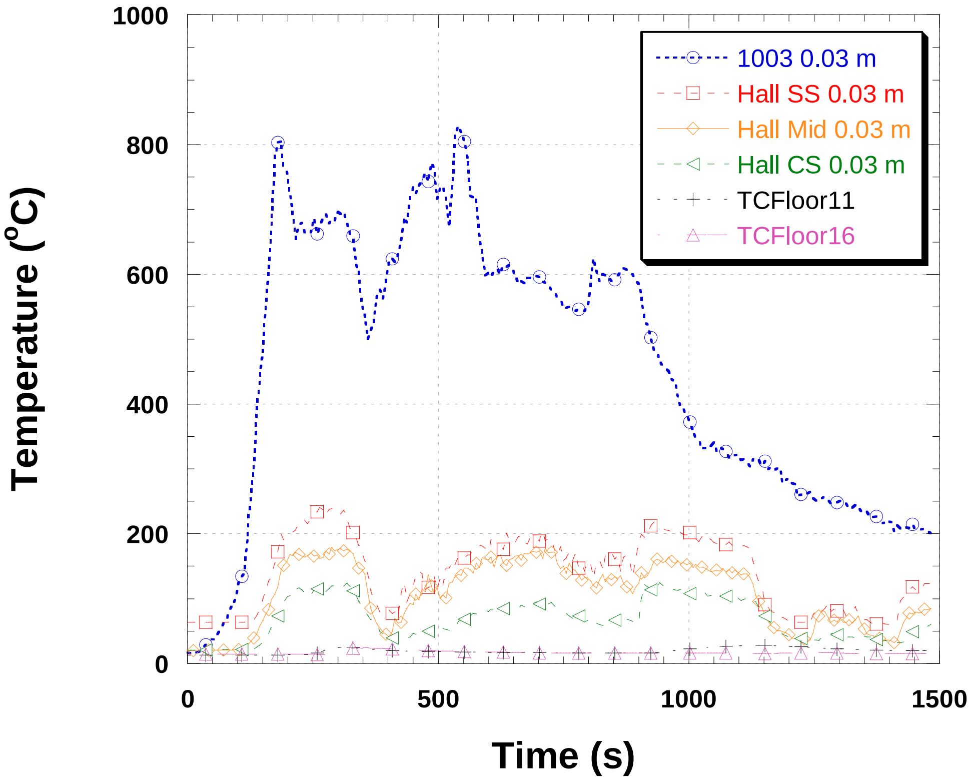

Figure 63. Gas temperatures at ceiling during apartment 1003 experiment (Uncertainty ± 15%)

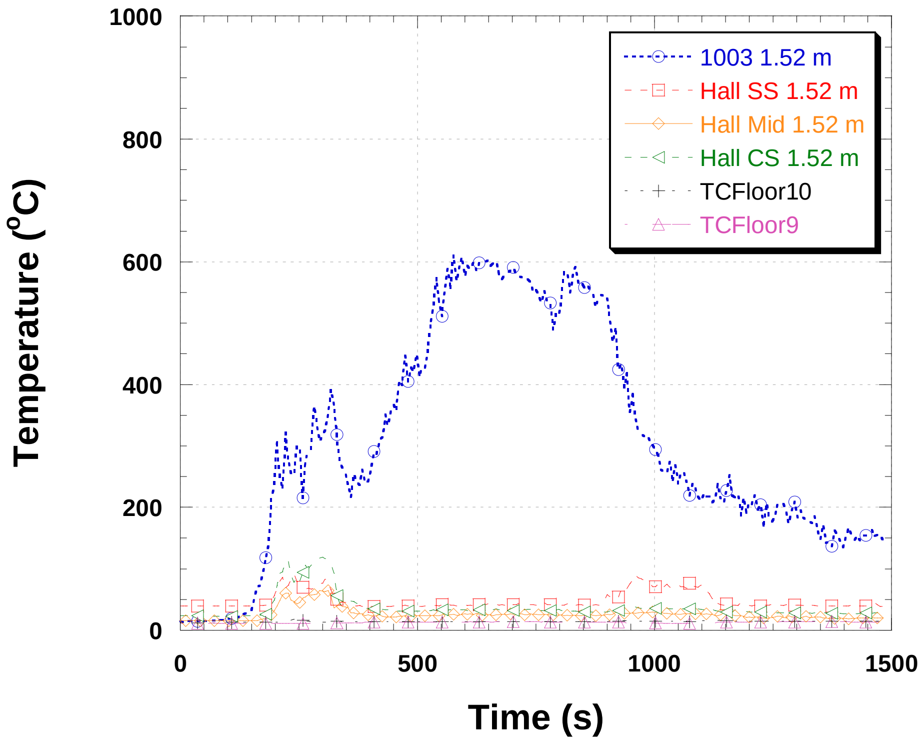

Figure 64. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 1003 experiment (Uncertainty ± 15%)

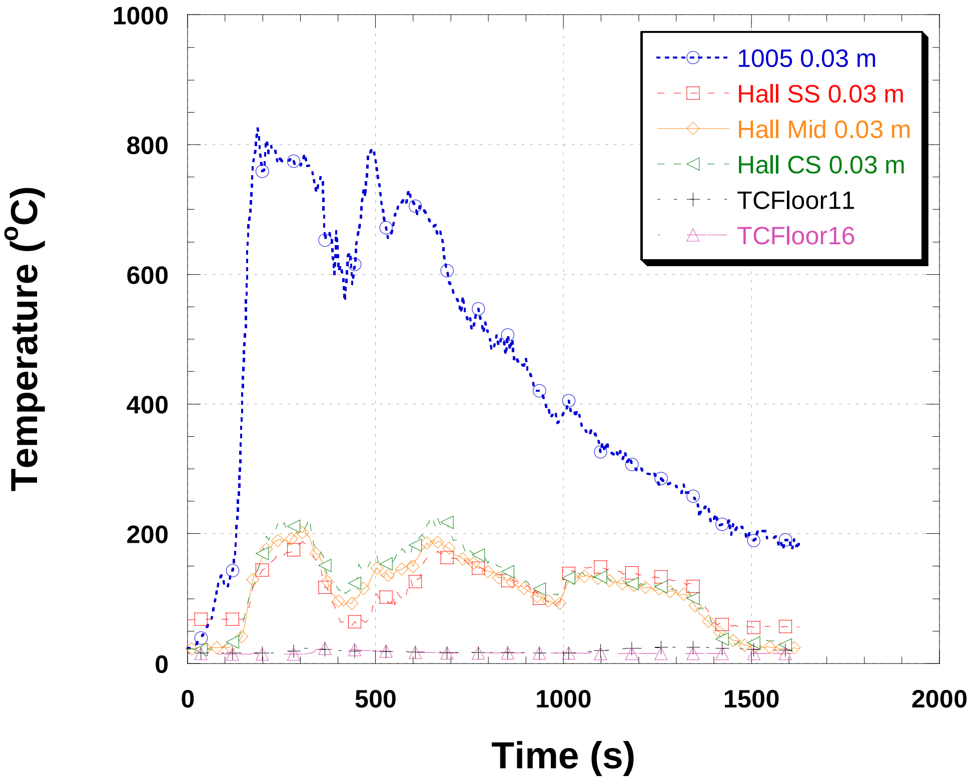

Figure 65. Gas temperatures at ceiling during apartment 1005 experiment (Uncertainty ± 15%)

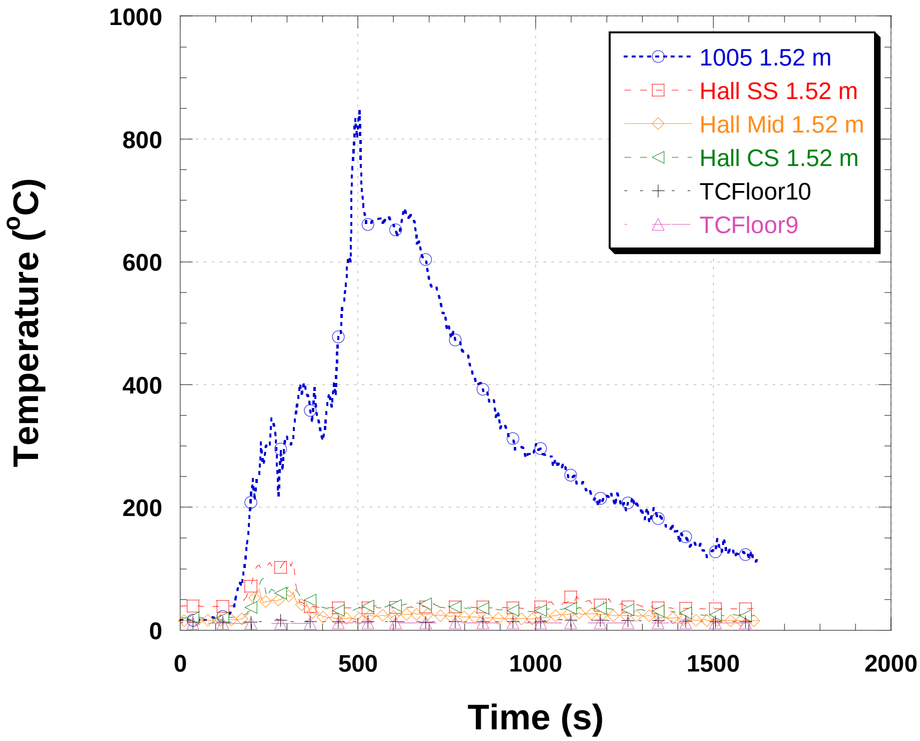

Figure 66. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 1005 experiment (Uncertainty ± 15%)

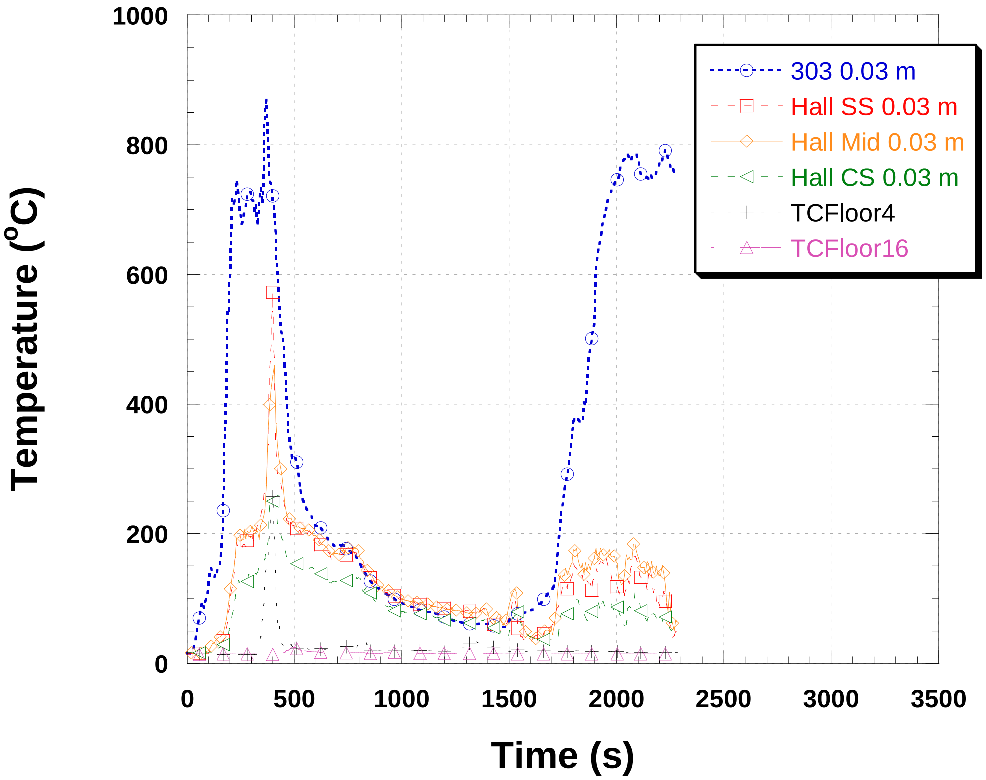

Figure 67. Gas temperatures at ceiling during apartment 303 experiment (Uncertainty ± 15%)

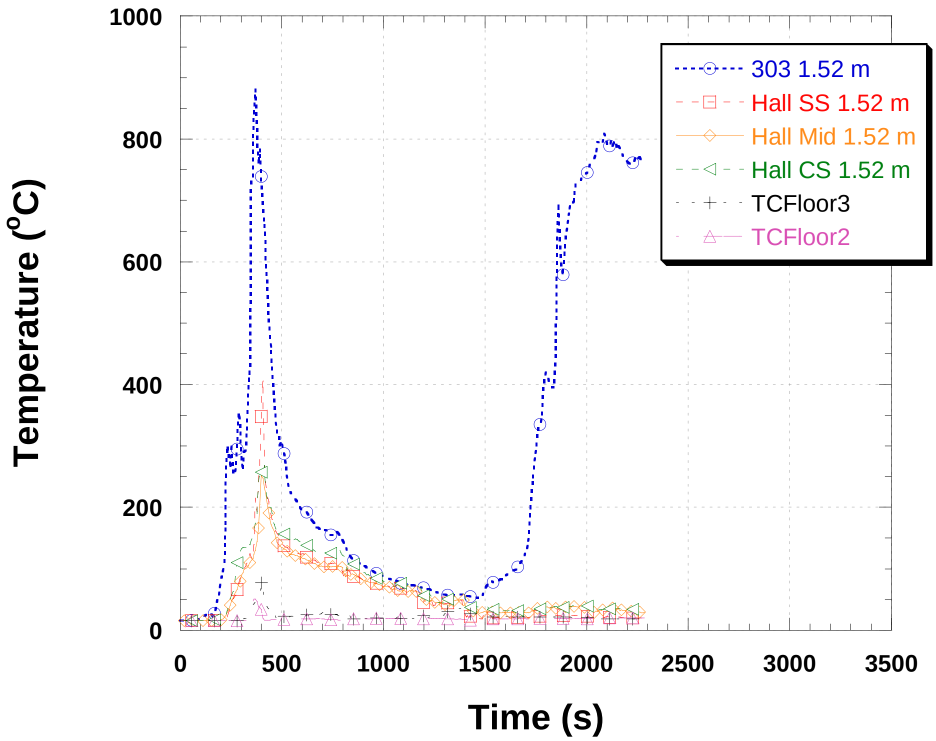

Figure 68. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 303 experiment (Uncertainty ± 15%)

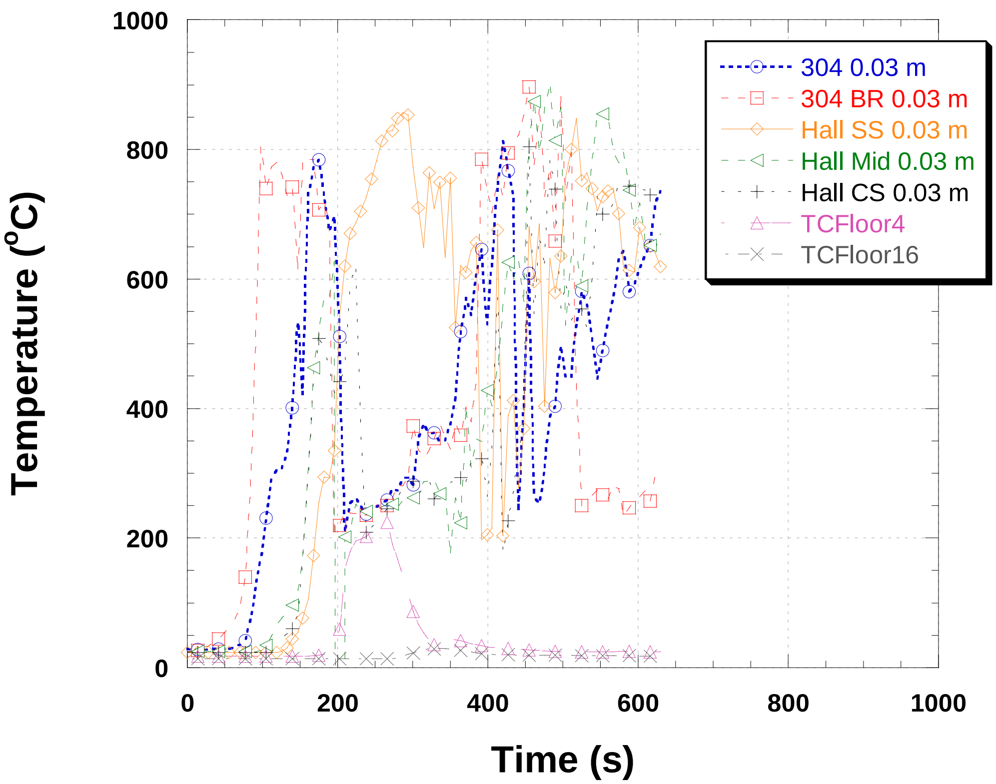

Figure 69. Gas temperatures at ceiling during apartment 304 experiment (Uncertainty ± 15%)

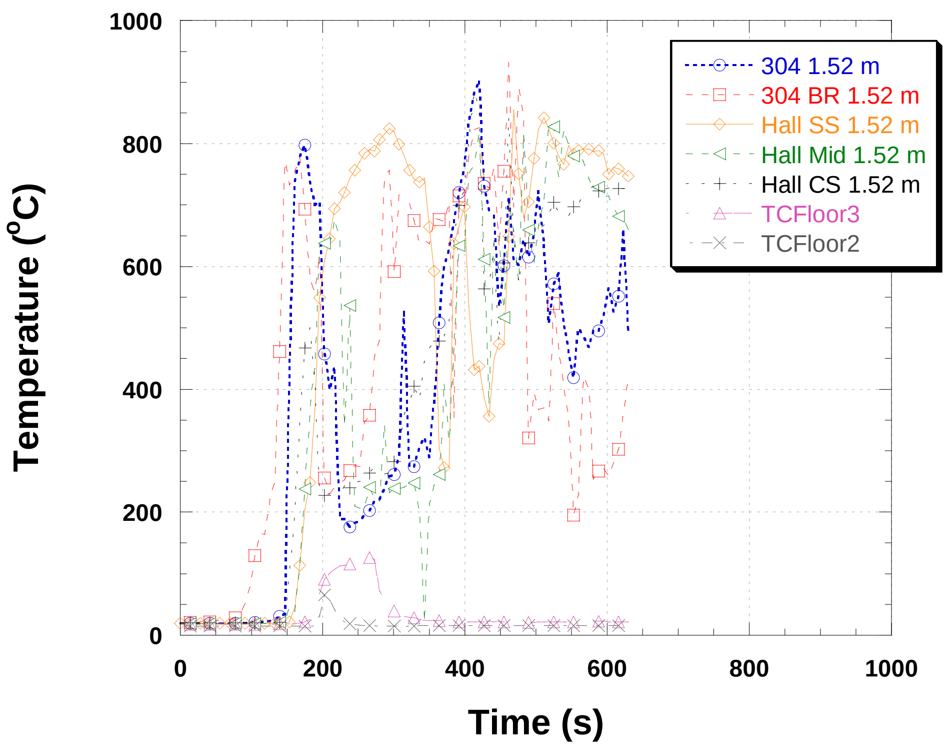

Figure 70. Gas temperatures at 1.2 m (3 ft.) above floor during apartment 304 experiment (Uncertainty ± 15%)

Heat Flux Data

The maximum heat fluxes observed during each experiment are in Table 15. Heat flux measurements at each of the instrument locations are graphed versus time in the appendix Figures. These graphs include lines to detail the events and configuration changes of the experiments. The heat flux gauge locations that correspond to those in the graphs are in Figure 71.

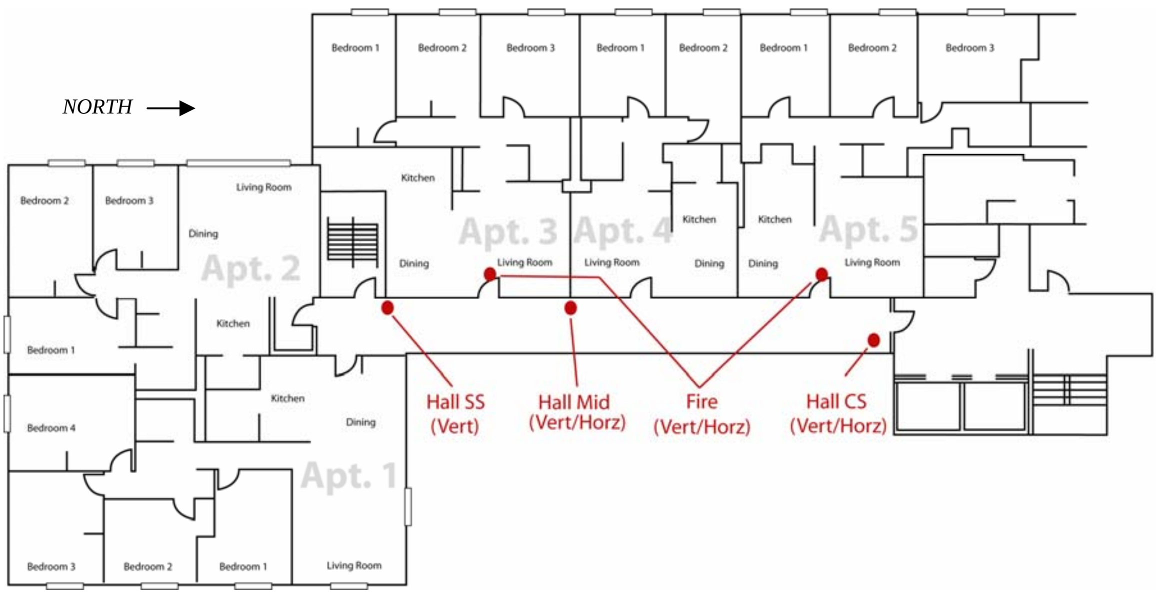

Figure 71. Heat flux gauge locations

The heat flux gauges placed in each of the fire rooms achieved heat fluxes that are consistent with flashover. The heat flux gauge located near the south stairwell in the horizontal orientation malfunctioned (Table 16). Heat flux gauges were not placed in the fire apartment for the experiment in apartment 304, due to the expected extreme heat flux conditions.

The experiment in Apartment 1503 exhibited a maximum fire room horizontal flux of 30.9 kW/m^2 and a vertical flux of 19.8 kW/m^2. These fluxes occurred after the fire was manually ventilated by removing the gypsum board blocking the rear of the apartment and additional fuel was added to the diminishing fire. The heat flux gauges in the hallway locations did not exceed 4.8 kW/m^2 at any of the locations.

The maximum heat fluxes in the experiment in Apartment 1505 were similar to those in the previous experiment on the 15th floor. The maximum heat flux in the living room of fire origin was 40.6 kW/m^2. The fluxes in the hallway locations did not exceed 6.3 kW/m^2.

The experiment in Apartment 1003 had a maximum fire room horizontal flux of 36.2 kW/m^2 and a vertical flux of 28.7 kW/m^2. The fire room maximum heat fluxes occurred after numerous ventilation actions had taken place. The heat flux gauges in the hallway locations did not exceed 4.2 kW/m^2 at any of the locations. The peaks for these heat flux gauges occurred during initial fire growth prior to complete smoke obscuration in the hallway.

Maximum heat fluxes in the living room of the experiment in apartment 1005 were approximately 80 kW/m^2 in both the horizontal and vertical orientations. These maximums occurred after forced ventilation from the SVU was allowed to flow through the fire apartment. The heat flux gauges in the hallway locations did not exceed 8.4 kW/m^2 at any of the locations. The peaks for the heat flux gauges located near the center stairwell occurred after ventilation and the other hallway heat flux gauges occurred during initial fire growth prior to complete smoke obscuration in the hallway.

The experiment in apartment 303 had a maximum fire room horizontal flux of 216.8 kW/m^2 and a vertical flux of 95.0 kW/m^2. These extreme heat fluxes occurred after the introduction of a simulated wind blowing through the bedroom in the rear of the fire apartment. Prior to the introduction of the wind the heat fluxes in the fire apartment exceeded 20 kW/m^2, consistent with flashover. The heat flux in the hallway near the south stair reached 23.2 kW/m^2 prior to stairwell pressurization. The heat flux in the middle of the hallway peaked at 13.3 kW/m^2 and the heat flux in the hallway near the center stairwell peaked at approximately 8.4 kW/m^2.

The experiment in apartment 304 had a higher magnitude simulated wind introduced through the rear bedroom by the MVU. In this experiment the fire began in the bedroom and was blown through the furnished living room. There was no heat flux gauge in the fire apartment. The heat flux in the hallway near the south stair reached 15.8 kW/m^2. The heat flux in the middle of the hallway near the fire apartment peaked at 45.4 kW/m^2 and the heat flux in the hallway near the center stairwell peaked at approximately 30.1 kW/m^2. The peak heat fluxes after 300 s were disregarded due to steam in the radiometer coolant lines.

Table 16. Maximum heat flux readings (Uncertainty -24% to +13%)

Experiment	FireVert (kW/m^2)	FireHorz (kW/m^2)	Hall SS Vert (kW/m^2)	Hall SS Horz (kW/m^2)	Hall Mid Vert (kW/m^2)	Hall Mid Horz (kW/m^2)	Hall CS Vert (kW/m^2)	Hall CS Horz (kW/m^2)
1503	19.8	30.9	4.4	NA	3.7	4.8	4.1	4.5
1505	40.6	32.9	6.3	NA	3.0	2.9	4.5	4.9
1003	28.7	36.2	4.2	NA	2.0	1.9	2.6	3.0
1005	81.0	76.2	5.5	NA	1.9	1.7	5.0	8.4
303	95.0	216.8	23.2	NA	10.1	13.3	7.5	8.3
304	NA	NA	15.8	NA	33.5	45.4	29.6	30.1

Carbon Monoxide Data

Carbon monoxide (CO) measurements at each of the instrument locations are graphed versus time in the appendix of each respective experiment. These graphs include lines to detail the events and configuration changes of the experiments. The CO meter locations that correspond to those in the graphs are in Figure 72. The CO meters were the same models as those typically available for fire department use. The sensors had a maximum upper limit that was less than the range of CO created during the experiments. The calibrated range of the CO meters was 0 ppm (0 %) to 750 ppm (0.075 %). At values above 750 ppm (0.075 %), the chemical sensors were saturated and the reported values probably under-report actual gas concentrations. All of the graphs have values above the maximum that the meters can read and are depicted as a flat line.

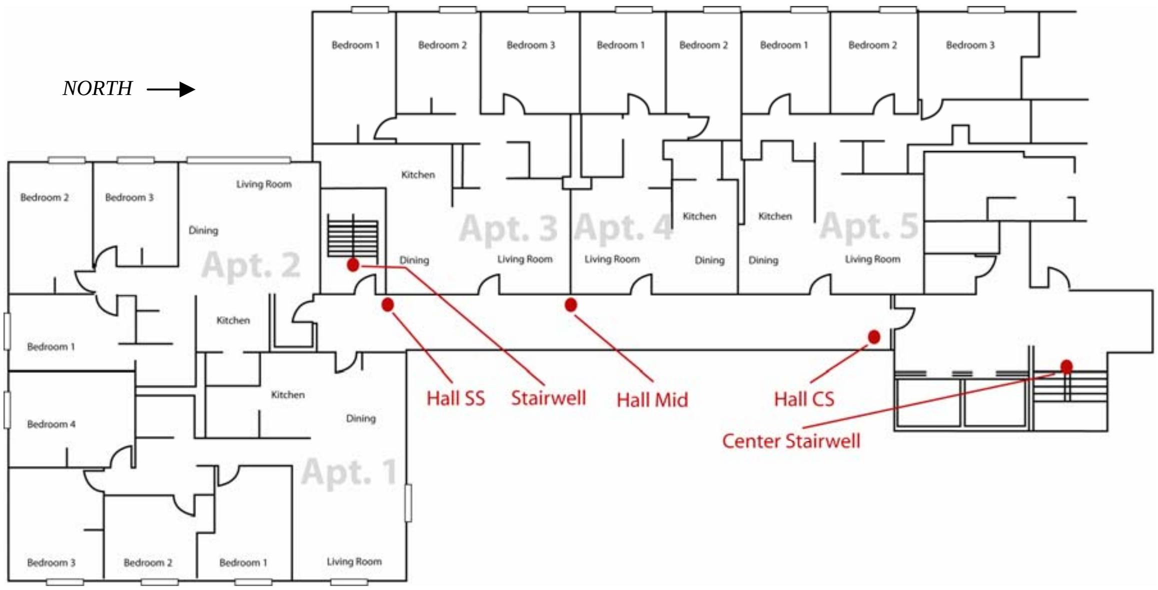

Figure 72. Carbon monoxide meter locations

CO readings in the hallway during the experiment in Apartment 1503 quickly reached a maximum value above 800 ppm (0.08 %) and remained there until the fire burned out and the fans ventilated the hallway. Prior to ventilation of the stairwell, the stairwell CO values exceeded 800 ppm (0.08 %), on both the 15th and 16th floors. During ventilation of the stairwell CO levels dropped below 200 ppm (0.02 %) and recovered to above 800 ppm (0.08 %) when the fan was turned off. Towards the end of the experiment, the levels dropped rapidly with ventilation by the MVU.

The experiment in Apartment 1505 also created CO levels in the hallway above the maximum range of the meters. The CO meter in the center stairwell peaked at 250 ppm (0.025 %) during the experiment. The center stairwell was not ventilated; the doors at the base of the stairwell, on the fire floor and bulkhead were closed. The CO concentration on the 16th floor in the south stairwell were decreased from 800 ppm (0.08 %) to 350 ppm (0.035 %) temporarily during ventilation. The CO concentration on the 15th floor in the south stairwell decreased from 800 ppm (0.08 %) to 100 ppm (0.01 %) temporarily during ventilation and returned to 800 ppm (0.08 %) when the fans were turned off.

The experiment in Apartment 1003 had a number of CO meters fail to operate properly early in the experiment. Two meters functioned as intended during the entire experiment. The CO level in the hallway reached the maximum of 750 ppm (0.075 %) early in the experiment and remained at the maximum during the entire experiment. The CO meter in the south stairwell on the 10^{th} floor reached as high as 200 ppm (0.02 %) when the fire floor door was opened, but declined to below 100 ppm (0.01 %) during ventilation.

The experiment in Apartment 1005 also had similar CO meter malfunctions. The CO level in the hallway reached the maximum of 750 ppm (0.075 %) early in the experiment and remained at the maximum for most of the experiment. The CO meter in the south stairwell on the 10^{th} floor reached as high as 180 ppm (0.018 %) when the fire floor door was opened, but declined to below 50 ppm (0.005 %) during ventilation until it also failed at 660 s.

The experiment in Apartment 303 created CO levels in the hallway above the maximum of the meters. The CO reading in the south stairwell was above the maximum readout of 850 ppm (0.085 %) within seconds after the simulated wind was started. The CO meter in the center stairwell peaked at 950 ppm (0.095 %) approximately 400 s into the experiment, but decreased as portable fans were used to ventilate the center stairwell. The CO readings decreased throughout the fire floor once the wind was stopped and the fire had consumed most of the fuel.

Weather Data

Average temperature, average wind speed and average wind direction for the weather stations on the ground and the roof were averaged over the duration of each of the experiments as shown in Table 17. The data from the roof weather station during the experiments in apartments 1003 and 1005 were missed due to issues with the power supply to the weather station. The weather conditions at the roof weather station were similar as compared to the ground data. Therefore the ground data can be used as an approximation to the overall weather conditions during those experiments.

The average temperatures remained fairly constant during all of the experiments. Temperatures ranged between 11 ^{o}C (52 ^{o}F) and 17 ^{o}C (63 ^{o}F). The outside temperatures remained constant during the experiments and were comparable to the interior stairwell temperatures, which minimized the stack effect.

Wind speed has the potential to greatly impact the effectiveness of PPV. The average wind speed for each experiment remained below 3.6 m/s (8.0 mph) and was typically below 2.0 m/s (4.5 mph) during the experiments. The wind had little impact on the experimental results. If there was wind, there were no gusts that would be expected to significantly impact any single experiment. The average wind direction was also examined to determine if the wind was into or out of one of the inlets or vents. The wind shifted over the course of the experimental series, but remained fairly constant during each of the individual experiments. The wind was mainly out of the south (180°) which had little impact of the flows into the ground floor or out of the vent which were both located on the east side of the building. The south stairwell was also interior to the building, which lessened the impact of any wind.

Table 17. Average Weather Conditions (Uncertainty ± 6 %)

Experiment (location)	Average Outside Temperature (°C)	Average Wind Speed (m/s)	Average Wind Direction (degrees from north)
1503 (Roof)	11.6	1.7	202.3
1503 (Ground)	12.2	0.7	146.2
1505 (Roof)	12.3	2.0	169.8
1505 (Ground)	12.7	1.1	156.1
1003 (Ground)	11.5	0.2	320.6
1005 (Ground)	11.0	0.7	307.3
303 (Roof)	17.1	3.6	236.8
303 (Ground)	17.2	0.5	115.5
304 (Roof)	13.3	2.1	83.7
304 (Ground)	13.3	1.3	309.0

Observations (Video and Thermal Imaging Recording Data)

A video camera and a thermal imaging camera were co-located in the south stairwell with views of the fire floor doorway. These cameras recorded during each of the experiments to determine when smoke and heat entered the stairwell. When the video camera was completely obscured by smoke, the thermal imaging camera was used to determine if heated gases and smoke were entering the stairwell.

The temperature displayed in the top right view of the Figures is the average surface temperature of the object or objects within the crosshairs in the center of the image. The camera has a fixed emissivity of 0.95 [11] which is representative of most surfaces found in the field of view of the thermal imaging camera. In the stairwell views, the crosshairs of the thermal imaging camera had the following objects: painted concrete block, painted steel door and door jam, and fire fighter turnout gear. All of these materials have emissivities in the range of 0.95 ± 0.05 [11].

The Figures captured from the video of the experiment in apartment 1503 show important times during the numerous events that took place. Figure 73-a shows the camera view of the south stairwell prior to ignition. Figure 73-b shows total smoke obscuration after the door to the fire floor is opened. After the door to the 16th floor was opened the smoke layer lifted and reached an equilibrium height as shown in Figure 73-c. Figure 73-d shows the smoke layer quickly dropped after the 16th floor door was closed. Less than 30 s later the fire floor door was closed, the 16th floor door was reopened and the MVU was started. The stairwell is quickly cleared of smoke (Figure 73-e). Once the smoke was cleared the 16th floor door was closed and the fire floor door was opened. No smoke was entering the stairwell with the MVU running (Figure 73-f). The smoke churned at the doorway, but did not enter the stairwell. Figure 73-g was taken 15 seconds after the MVU was turned off and the smoke quickly refilled the stairwell. The MVU was turned back on and the smoke was forced back onto the fire floor (Figure 73-h).

The thermal imaging Figures were captured during the same events as the video views at similar times. Figure 73-i shows the view prior to ignition with an ambient wall temperature of 16 ^{o}C (60 ^{o}F). As the heat filled the hallway, the door became heated around the edges and heat began to flow into the south stairwell (Figure 73-j). Figure 73-k was captured when the fire floor door was opened and the hot gases were able to flow up the stairwell. The fire fighter is blocking the crosshairs of the camera, so the estimated temperature in the field of view was that of his turnout gear. The MVU was started and the heat was forced out of the top of the stairwell and back onto the fire floor (Figure 73-l). The fan was turned off (Figure 73-m) and back on (Figure 73-n). The heat was held at the fire floor doorway and the stairwell wall was cooled from 31 ^{o}C (84 ^{o}F) to 23 ^{o}C (73 ^{o}F).

Figure 73-a

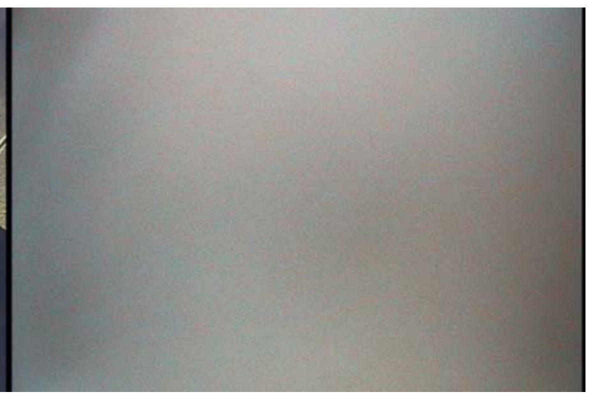

Figure 73-b

Figure 73-c

Figure 73-d


Figure 73-e


Figure 73-f


Figure 73-g


Figure 73-h

Figure 73-i

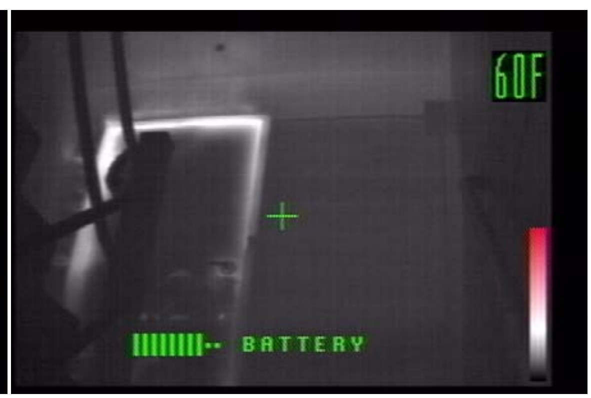

Figure 73-j

Figure 73-k **Figure 73-l**

Figure 73-m **Figure 73-n**

Figure 73. Visual and thermal imaging images captured during the experiment in apartment 1503.

The video frame captured in the south stairwell before ignition of the experiment in apartment 1505 is in Figure 74-a. Smoke leaked around the door with one 0.7 m (27 in) fan placed at the base of the stairwell (Figure 74-b). A second 0.7 m (27 in) fan was added at the 13th floor and the smoke was vented out of the 16th floor doorway (Figure 74-c). Figure 74-d shows that with two portable fans running the smoke was kept out of the stairwell with the fire floor door open 0.08 m (3 in). The door was then opened completely and the smoke was still kept out of the stairwell. The wall of smoke at the doorway is shown in fire 74-e. The door to floor 14 was opened and a little bit of smoke can be seen intermittently flowing into the stairwell (Figure 74-f). The smoke flow into the stairwell seen in Figure 74-g is a result of turning both fans off. Figure 74-h was captured 20 seconds after the fan on floor 13 was turned back on. The fan was turned off and the stairwell quickly filled with smoke again (Figure 74-i). Both fans were turned back on and the smoke was pushed back into the fire floor (Figure 74-j).

The thermal imaging frames in Figures 74-k through 74-p show similar trends as the visual views. When the fans were on, the heat was kept out of the stairwell. When they were turned off, the heat flowed into the stairwell. The temperature of the concrete block wall did not change significantly during the experiment.

Figure 74-a

Figure 74-b

Figure 74-c

Figure 74-d

Figure 74-e

Figure 74-f


Figure 74-g


Figure 74-h

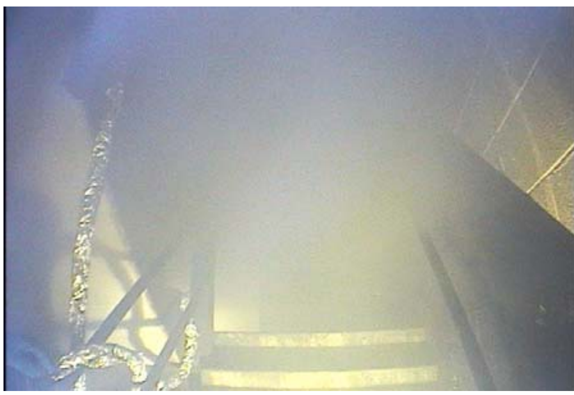
Figure 74-i


Figure 74-j

Figure 74-k

Figure 74-l

Figure 74-m

Figure 74-n

Figure 74-o

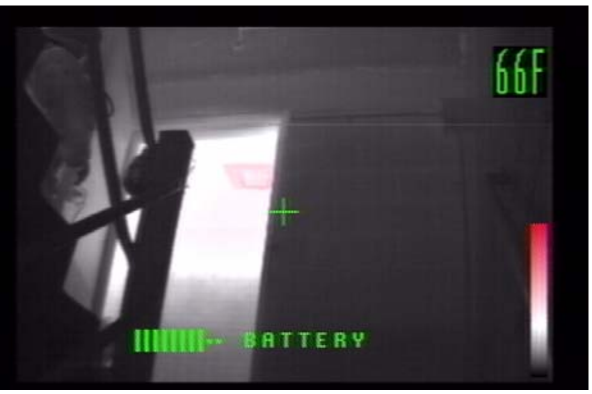

Figure 74-p

Figure 74. Visual and thermal imaging images captured during the experiment in apartment 1505.

Figure 75-a shows the doorway to the fire floor prior to ignition of the experiment in apartment 1003. After ignition but prior to the door being opened, the smoke enters the stairwell around the cracks of the door and a layer begins to form (Figure 75-b). The door on floor 10 was opened and the black smoke quickly began to fill the stairwell (Figure 75-c). The 16th floor door was opened and two 0.7 m (27 in) fans were turned on at floors 1 and 8. After less than 60 s, the stairwell was cleared of any smoke (Figure 75-d). The fans were turned off (Figure 75-e) and the smoke entered the stairwell. The fans were turned back on and the smoke was vented again. After ventilation the 16th floor door was closed, the fans were able to maintain a stairwell free of smoke (Figure 75-f).

Figure 75-g was captured from the thermal imaging camera prior to ignition. Figure 75-h shows the heat layer developed after the fire floor doorway was opened. After one fan was turned on, the heat layer lifted slightly (Figure 75-i), but the heat flow into the stairwell stopped with the use of two fans (Figure 75-j). The fans were turned off in Figure 75-k. Both fans were turned back on and Figure 75-l was captured 10 s after they were turned on. This demonstrated how quickly the addition of pressure can stop the flow of heated gases into the stairwell.

Figure 75-a

Figure 75-b

Figure 75-c

Figure 75-d

Figure 75-e

Figure 75-f

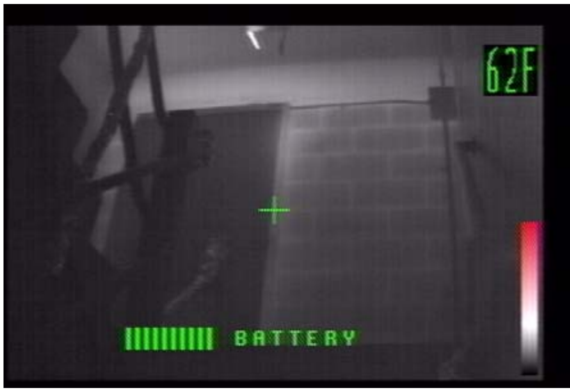

Figure 75-g

Figure 75-h

Figure 75-i

Figure 75-j

Figure 75-k

Figure 75-l

Figure 75. Visual and thermal imaging images captured during the experiment in apartment 1003.

The Figures captured below were from the experiment in apartment 1005. Figure 76-a was captured prior to ignition. Figure 76-b shows the dense smoke conditions created by opening the fire floor door. The following frame shows the effect that the SVU had on the smoke flow. The 16th floor door was opened; therefore the smoke in the stairwell was forced up and out of the stairwell while the smoke on the fire floor was kept from entering the stairwell (Figure 76-c). Figure 76-d shows that the smoke barrier maintained well and prevented smoke from entering the stairwell through the rest of the experiment. The SVU was turned off and the smoke flowed back into the stairwell (Figure 76-e).

Once the fire burned-down significantly, the SVU was turned back on and it was able to clear the hallway, all the way down to the fire apartment (Figure 76-f).

The thermal imaging camera images were captured during the same events as the video views at similar times. Figure 76-g shows the conditions prior to ignition with an ambient wall temperature of 18 °C (64 °F). Figure 76-h was captured when the fire floor door was opened and the hot gases were able to flow up the stairwell. The thermal imaging temperature of the wall increased to 25 °C (77 °F). The SVU was started and the heat was stopped from entering the stairwell (Figure 76-i). The fan was turned off (Figure 76-j) and back on (Figure 76-k). The heat was held at the fire floor doorway and the stairwell remained smoke-free and cool.

Figure 76-a

Figure 76-b

Figure 76-c

Figure 76-d

Figure 76-e

Figure 76-f

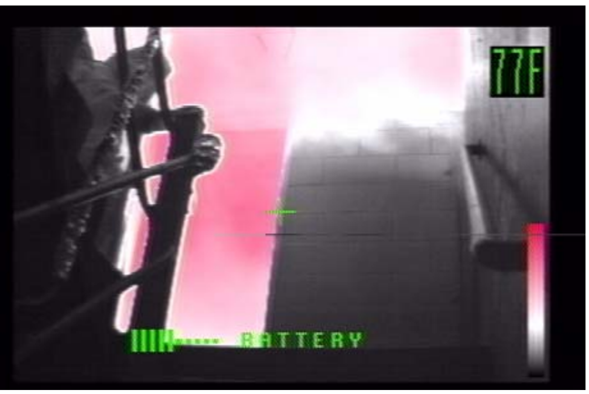

Figure 76-g

Figure 76-h

Figure 76-i

Figure 76-j

Figure 76-k

Figure 76. Visual and thermal imaging images captured during the experiment in apartment 1005.

Figure 77-a was captured prior to ignition of the experiment in apartment 303. Once the simulated wind was started utilizing the SVU smoke was forced into the stairwell through the cracks around and especially under the door (Figure 77-b). Even with the door closed visibility was greatly reduced in a matter of seconds (Figure 77-c). Figure 77-d was captured just after the door to the 3rd floor was opened. Figure 77-e shows the stairwell clearing of smoke with a fan on at floor 1 and at floor 5. The stairwell is actually cleared out but appears hazy due to the soot deposition on the camera lens. The camera lens was wiped off and then the fire floor doorway was opened 0.08 m (3 in) with one fan on at the base of the stairwell. This slowed the smoke flow into the stairwell down but did not completely stop it (Figure 77-f). A second fan was turned on at the 5th floor and the smoke was completely stopped (Figure 77-g). Figure 77-h shows the smoke flow into the stairwell with one fan on at the base of the south stairwell and the door to the fire floor completely open with a simulated wind condition through the fire apartment. Figure 77-i has the same setup but without the fan at the base of the stair turned on. Finally, Figure 77-j shows the stairwell clear of smoke again after turning both portable fans back on.

The thermal imaging Figures were captured during the same events as the video views at similar times. Figure 77-k shows the view prior to ignition with an ambient wall temperature of 17 ^{o}C (62 ^{o}F). The SVU was turned on to simulate the wind condition and heat was flowing into the stairwell around all for sides of the door (Figure 77-l). Figure 77-m was captured one second after the fire floor door was opened and the hot gases were able to flow into the stairwell. Figure 77-n was captured 5s after the door was opened and the heat quickly entered the stairwell, increasing temperatures. The door was opened halfway and the amount of heat entering the stairwell due to the wind forced flow caused the thermal image to become mostly white with little detail of the stairwell (Figure 77-o). The increase in temperature from 34 ^{o}C (93 ^{o}F) to 181 ^{o}C (357 ^{o}F) was mainly due to the thermal imaging camera crosshairs aimed on the brick wall in the hallway once the door was opened half way. Conditions quickly changed once the door to the hallway was closed (Figure 77-p). One portable fan was turned on and the heat flow into the stairwell around the cracks of the door was slowed down, but was not completely stopped due to the wind pressures being greater (Figure 77-q). However, when two fans were turned on the heat was held completely on the fire floor (Figure 77-

r). With the fans off and the fire blanket deployed over the window, the heat flow into the stairwell decreased greatly (Figure 77-s). Figure 77-t shows two fans running and the fire blanket deployed. The combination of these two tactics forced the heat down the hallway toward the fire room.

303

Figure 77-a

Figure 77-b

Figure 77-c

Figure 77-d

Figure 77-e

Figure 77-f

Figure 77-g

Figure 77-h

Figure 77-i

Figure 77-j

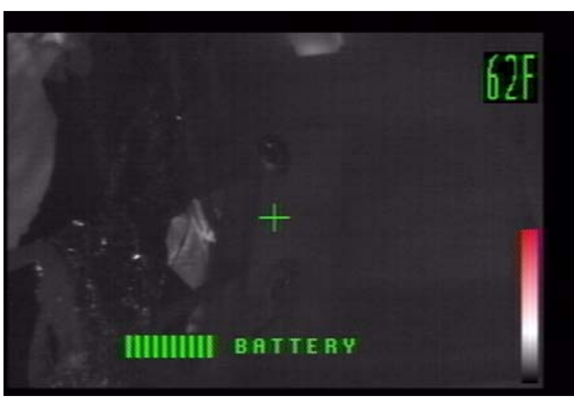

Figure 77-k

Figure 77-l

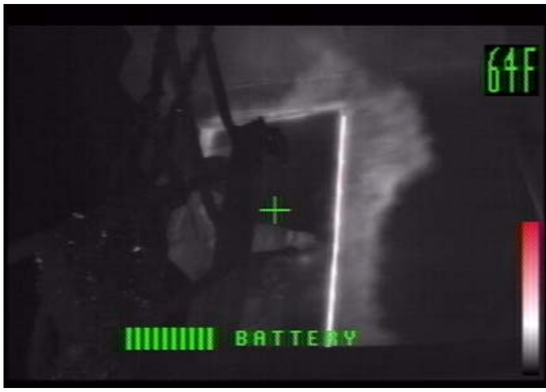

Figure 77-m

Figure 77-n

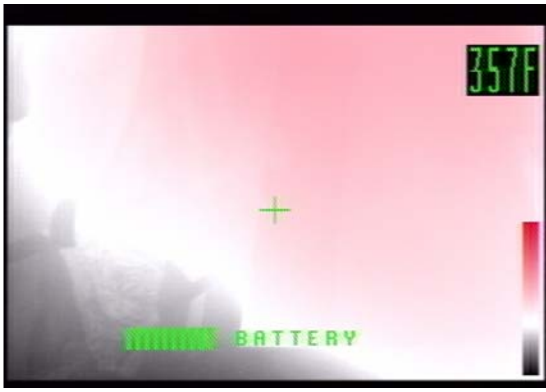

Figure 77-o

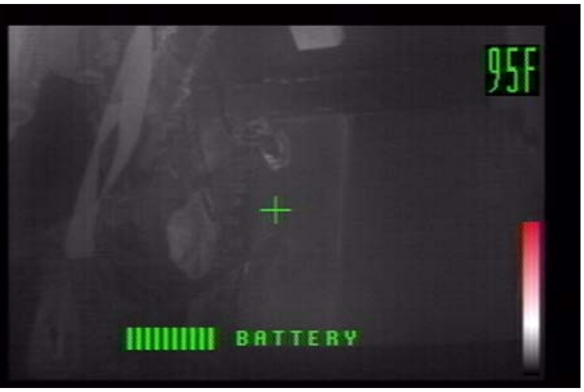

Figure 77-p

Figure 77-q

Figure 77-r

Figure 77-s

Figure 77-t

Figure 77. Visual and thermal imaging images captured during the experiment in apartment 303.

Figures 78-a through 78-d show the visual video view during the experiment in apartment 304. Figure 78-a shows the south stairwell fire floor doorway prior to ignition. After the simulated wind was started smoke was forced under the doorway (Figure 78-b). The fire floor door was opened 0.08 m (3 in) and seconds later the camera view was completely obscured (Figure 78-c). Once the door was closed, the SVU was started to ventilate and pressurize the south stairwell. The SVU was able to clear the stairwell and keep it clear, but this could not be visualized, because the video camera lens melted and left the view blurry (Figure 78-d).

Figure 78-e was captured from the thermal imaging camera prior to ignition. Figure 78-f shows the heat being forced around the cracks of the doorway once the simulated wind was started. The door was opened slightly for one second and the heat poured into the stairwell (Figure 78-g). Ten seconds later the heat is flowing into the stairwell and the door jamb temperature increased from 55 ^{o}C (131 ^{o}F) to 145 ^{o}C (293 ^{o}F) (Figure 78h). Figure 78-i was captured seconds before the door was closed and Figure 78-j was captured seconds after the door was closed. This showed the importance of controlling the stairwell door under wind driven conditions in order to keep smoke and heat from entering the stairwell. Once the stairwell door was closed, the SVU was turned on at the front of the building and was able to keep the heat from the wind driven fire out of the stairwell (Figure 78-k).

304

Figure 78-a

Figure 78-b

Figure 78-c

Figure 78-d

Figure 78-e

Figure 78-f

Figure 78-g

Figure 78-h

Figure 78-i

Figure 78-j

Figure 78-k

Figure 78. Visual and thermal imaging images captured during the experiment in apartment 304.

Uncertainty Analysis

There are different components of uncertainty in the length, differential pressure, gas temperature, heat flux, metrological, and carbon monoxide data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means [12]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 % confidence interval (2σ). Components of uncertainty are tabulated in Table 18. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as differential pressure, include past experience with the instruments.

Each length measurement was taken carefully. However due to some issues, such as obstructions and unleveled terrain there was a total expanded uncertainty of ± 6 % associated with the measurements.

Differential pressure reading uncertainty components are derived from pressure transducer instrument specifications. The transducers were factory calibrated and the zero and span of each was checked in the laboratory prior to the experiments.

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

The potential for soot deposition on the face of the water-cooled total heat flux gauges contributed significant uncertainty to the heat flux measurements. Calibration of heat flux gauges was completed at lower fluxes and then extrapolated to higher values and this resulted in a higher uncertainty in the flux measurement. Combining all of component uncertainties for total heat flux resulted in a total expanded uncertainty of – 24 % to + 13 % for the flux measurements.

Weather, carbon monoxide and sound measurement uncertainty was referenced to each of their published user's manuals. Weather and CO instruments have calibration certificates that are traceable to NIST standards. The carbon monoxide meters were factory calibrated prior to the experiments. The sound meter had a self-calibration setting.

Table 18. Uncertainty Analysis

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Length Measurements Instrumentation Locations Fan Location Building Dimensions Repeatability[1] Random[1]	± 1 % ± 1 % ± 1 % ± 2 % ± 2 %	± 3 %	± 6 %
Differential Pressure Calibration [13] Accuracy [13] Repeatability [1] Random [1]	± 2 % ± 1 % ± 3 % ± 3 %	± 5 %	± 10 %
Gas Temperature – Lower Layer Calibration[14] Radiative Cooling Radiative Heating Repeatability [1] Random [1]	± 1 % - 5 % to + 0 % - 0 % to + 5 % ± 5 % ± 3 %	± 8 %	± 15 %
Total Heat Flux Calibration Zero Soot Deposition Repeatability [1] Random [1]	± 3 % ± 2 % - 10% to + 0 % ± 5 % ± 3 %	- 12 % to + 7 %	- 24 % to + 13 %
Weather Measurements Temperature[15] Relative Humidity Average Wind Speed Wind Direction Barometric Pressure Repeatability[1] Random[1]	± 2 % ± 2 % ± 1 % ± 1 % ± 0.003 % ± 1 % ± 1 %	± 3 %	± 6 %
Carbon Monoxide Measurements Calibration[16] Accuracy[16] Repeatability[1] Random[1]	± 1 % ± 0.002 % ± 2 % ± 2 %	± 2 %	± 4 %

Sound Measurements Calibration[17] Accuracy[17] Repeatability[1] Random[1]	 ± 1 % ± 3 % ± 2 % ± 2 %	± 4 %	± 8 %
Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.			

Discussion

For this limited series of experiments, the fans and their locations were determined by the previous series of pressure experiments [8]. One experiment on each of the fire floors utilized portable fans and the other utilized a large truck (MVU) or trailer mounted (SVU) fan. All of the experiments created high temperatures and dense smoke conditions in the hallway. Numerous configurations were used during the experiments and the ability of the fans to keep smoke out of the stairwell was analyzed. The minimum design pressures of NFPA 92A were used as baselines to compare to the actual pressures measured.

This building was unsprinklered, therefore an attempt was made to obtain a minimum pressure of 25 Pa in the stairwell, in the area of the fire floor for all the experiments. Numerous scenarios were examined by changing fan placement and the location and number of open doors (Table 19). The scenarios in gray in Table 2 indicate that smoke was visualized entering the stairwell. The other events had no smoke entering the stairwell. Fire floor pressures are in brackets and shown in bold. Many configurations had the door to the fire floor partially or fully open. In these events, there was no differential pressure, so the fire floor pressure was estimated by examining the pressures at the floors above and below the fire floor. Many of the configurations that were successful in prohibiting smoke infiltration into the stairwell had pressures significantly below 25 Pa. The lowest pressure on a fire floor that was able to keep smoke out of the stairwell was 9 Pa. The maximum temperatures recorded in the south end of the hallway adjacent to the stairwell door ranged between 100 ^{o}C and 300 ^{o}C. Utilizing the 100 ^{o}C and 300 ^{o}C gas temperature in the equation provided in NFPA 92A to determine the pressure difference due to buoyancy of hot gases yields pressures of 4.1 Pa and 9.3 Pa respectively. This limited data from this practical set of configurations suggests that this correlation is consistent for estimating the pressure required to stop smoke spread.

This analysis only focused on the events that had no smoke entering the stairwell. Many of the configurations had very little smoke entering the stairwell due to the pressure increase. Pressurizing the stairwell always had a positive effect on the conditions in the stairwell. If the stairwell was not vented and only pressurized the heat and smoke flow into the stairwell was either stopped or at least slowed down improving the conditions in the stairwell. The fans never increased the amount of smoke able to flow into the stairwell.

Table 19. Experimental Events Indicating when Smoke was in the Stairwell

Experiment	Events				
1503	MVU (16 Open) **[>25 Pa]**	MVU (16 Closed) **[>25 Pa]**	MVU (15 Open 0.08 m) **[>25 Pa]**	MVU (15 Open) **[13 Pa]**	MVU Off **[4 Pa]**
1503 (Cont.)	MVU (15 Open) [2] **[13 Pa]**				
1505	27 on Floor 1 **[8 Pa]**	27 on Floor 1 (16 open) **[3 Pa]**	27 on Floors 1 and 13 (16 open) **[10 Pa]**	27 on Floors 1 and 13 **[21 Pa]**	27 on Floors 1 and 13 (15 open 0.08 m) **[16 Pa]**
1505 (Cont.)	27 on Floors 1 and 13 (15 open) **[14 Pa]**	27 on Floors 1 and 13 (15 and 14 open) **[7 Pa]**	Fans off **[3 Pa]**	27 on Floor 13 (1 closed) **[12 Pa]**	27 on Floor 1 (15 Open) **[4 Pa]**
1505 (Cont.)	27 on Floors 1 and 13 (15 Open) **[13 Pa]**				
1003	27 on Floor 1 (10 and 16 Open) **[3 Pa]**	27 on Floors 1 and 8 (10 / 16 Open) **[10 Pa]**	27 on Floors 1 and 8 (10 Open, CS Press.) **[16 Pa]**	27 on Floor 8 (10 Open) **[22 Pa]**	Fans Off **[2 Pa]**
1005	SVU (10 and 16 Open) **[11 Pa]**	SVU (10 Open) **[>25 Pa]**	SVU (10 and 1(CS) Open) **[19 Pa]**	SVU (10, 1(CS),16 (CS) Open) **[13 Pa]**	SVU idle **[4 Pa]**
1005 (Cont.)	SVU (10 and 1(CS) Open) **[12 Pa]**	SVU (10 Open) **[20 Pa]**			
303	Wind **[0 Pa]**	Wind (3 Open) **[0 Pa]**	Wind (3 and 16 Open) **[0 Pa]**	27 on Floor 1 (Wind) **[2 Pa]**	27 on Floors 1 and 5 (Wind) **[5 Pa]**
303 (Cont.)	Fans Off (Wind) **[0 Pa]**	Fire Blanket Deployed **[0 Pa]**	3 Open (Fire Blanket) **[0 Pa]**	27 on Floor 1 (16 Open) **[11 Pa]**	27 on Floor 1 (16 Open, 3 Open 0.08m) **[2 Pa]**
303 (Cont.)	27 on Floor 1 (16 Open) [2] **[9 Pa]**	27 on Floor 1 [2] **[10 Pa]**	27 on Floor 1 (3 Open 0.08m) **[15 Pa]**	27 on Floor 1 [3] **[15 Pa]**	27 on Floor 1 (16 Open) [3] **[10 Pa]**
303 (Cont.)	27 on Floors 1 and 5 **[>25 Pa]**	27 on Floors 1 and 5 (3 Open 0.08m) **[20 Pa]**	27 on Floor 1 (3 Open) **[18 Pa]**		
304	Wind **[0 Pa]**	Wind (3 Open) **[0 Pa]**	Wind (3 and 16 Open) **[0 Pa]**	Wind (16 Open) **[0 Pa]**	SVU (Wind and 16 Open) **[8 Pa]**
304 (Cont.)	SVU (Wind) **[>25 Pa]**				

MVU – 1.2 m hydraulic powered Truck mounted fan, SVU – 1.3 m gasoline powered Trailer mounted fan, 27 – 0.7m portable fan, ( ) – indicates door position, **[ ]** – Fire floor stairwell pressure

Typically a fixed stairwell pressurization system will only be installed in a building with a sprinkler system so that the fire is contained and the introduction of more oxygen will have minimal effects. A concern with the use of PPV fans is the ability of the fans to provide oxygen to the fire. This is possible but it is also controllable. Initially the stairwell can be cleared of smoke by having all of the stairwell doors closed and the roof vent or bulkhead door opened (Figure 79a). This tactic provides no fresh air to an apartment fire off of the hallway. Once the vent is closed and the stairwell is adequately pressurized, no smoke is able to enter the stairwell and the flow from the fan is able to go through the cracks around the fire floor doorway but none of the air has enough pressure behind it to readily make it all the way to the fire apartment (Figure 79b). Once the door to the fire floor is opened by advancing fire fighters a pressure balance or critical air velocity to prevent smoke backflow must occur to keep smoke out of the stairwell (Figure 79c). Ideally this critical air velocity would keep smoke out of the stairwell but not supply oxygen to the fire (Figure 79d). The results from these experiments indicate that this was achieved by the barriers of smoke that were visualized at the fire floor stairwell door and the lack of increase in fire intensity or smoke spread out of the vent window of the fire apartment. However more research needs to be conducted to determine the impact of diluted smoke being pushed back towards the source of the fire by the fan on the fire size (Figure 79e). The effect of fresh air being provided to a fire by PPV fans has been studied [18] but the introduction of diluted smoke to the fire for a period of time prior to the introduction of fresh air needs to be further researched.

The portable fans were able to vent through the fire apartment but only after the fire had burned down significantly allowing the flow to over-pressurize what was created by the fire. The mounted fans were able to create a flow through the fire apartment even when the fire was at its peak output. This was able to be limited by at least two ways, turn down the speed of the fan or allow the fan to pressurize a larger volume. An example of the larger volume is opening an additional stairwell or opening a floor below the fire floor. An advantage of the larger mounted fan is that it can pressurize multiple stairwells from the front of the building whereas two portable fans were required for each stairwell that needed to be pressurized. If limiting the air to the fire is not the priority and the priority is creating visibility in the hallway to the fire apartment then the larger fans were effective at clearing fire gases to the fire apartment door if the fire apartment was vented to the outside of the structure.

Temperatures in the fire apartments peaked at approximately 800 ^{o}C. The temperature in the entire hallway peaked between 100 ^{o}C and 300 ^{o}C at the ceiling level and 100 ^{o}C and 150 ^{o}C at 0.91 m above the floor. Heat fluxes in the fire apartment peaked at 81.0 kW/m^2. The peak heat fluxes in the hallway ranged between 1.9 kW/m^2 and 6.3 kW/m^2 depending on the location of the gauges in relation to the fire apartment. The CO levels on the fire floors for all of the experiments quickly exceeded the 800 ppm (0.008 %) maximum on the gas monitors. Stairwell CO levels dropped below 200 ppm (0.002 %) during ventilation. The average temperatures remained fairly constant during all of the experiments. Temperatures ranged between 11 ^{o}C (52 ^{o}F) and 17 ^{o}C (63 ^{o}F). The outside temperatures remained constant during the experiments and were comparable to the interior stairwell temperatures which minimized the stack effect.

Wind speed has the potential to greatly impact the effectiveness of PPV. The average wind speed remained below 3.6 m/s (8.0 mph) and was mostly below 2.0 m/s (4.5 mph) during the experiments. The wind appeared to have little impact on the experimental results. When there was wind there were no gusts that would impact one experiment over another experiment. The wind was mainly out of the south which had little impact of the flows into the ground floor or out of the vents which were both located on the east side of the building. The south stairwell was also interior to the building which lessened the impact of any wind.

One of the main toxic gases in combustion is carbon monoxide (CO). When examining PPV and preventing smoke infiltration there are two types of combustion that are important, the fire creating the smoke and the internal combustion of the fan motor. Both sources of CO must be monitored to maintain a safe environment for occupants as well as fire fighters.

A fire has the potential to produce a very large amount of CO. This amount could be on the order of 50,000 ppm (5 %) in an under-ventilated fire [19]. Tenability limits for incapacitation and death for a 5 minute exposure are 6000 ppm (0.6 %) to 8000 ppm (0.8 %) and 12,000 (1.2 %) to 16,000 ppm (1.6 %) respectively. CO is the ultimate major cause of death in fires. Using PPV fans to keep the CO produced by the fire along with the other harmful combustion products out of the stairwells greatly increases the chances of safe evacuation.

The internal combustion of a gasoline fan engine also produces CO. While the levels are much lower than the fire they have to be analyzed. CO meters were placed in both stairwells to monitor the fans impact on CO levels. The National Institute of Occupational Safety and Health (NIOSH) has established a recommended exposure limit for CO of 35 ppm (0.0035 %) as an 8-hour time weighted average (TWA) and 200 ppm (0.02 %) as a ceiling exposure [20]. A reading of 1200 ppm (0.12 %) is considered immediately dangerous to life and health (IDLH). The National Research Council (NRC) also defines emergency exposure guidance levels of, 1500 ppm (0.15 %) for 10 minutes, 800 ppm (0.08 %) for 30 minutes, 400 ppm (0.04 %) for 60 minutes and 50 ppm (0.005 %) for 24 hours [21].

Without the use of the fans the CO levels in the hallway and in the south stairwell during the fire almost always reached above the range of the meters. While this peak was around 800 ppm (0.08 %) it is conservative to say that many of the meter locations exceeded the IDLH threshold. In most cases, the use of the fans to vent the stairwell and to pressurize the stairwell to reduce smoke and CO levels allowed the CO levels to decrease from IDLH conditions to less than 200 ppm (0.02 %). Ultimately the CO produced by the PPV fans was at least one order of magnitude less than that created by the fire.

Both experiments on the third floor included a wind driven fire. It was quickly observed and supported by the data that a wind directed into the window of a fire apartment can have a significant impact on the speed and severity of fire growth. Conditions in the hallway changed from tenable to untenable so rapidly that a person in the hallway would have had trouble escaping the flow path, even in full personal protective equipment. The following tactical considerations were identified.

1) Controlling the door to either the fire apartment or stairwell can provide a safer area of refuge out of the direct flow path of fire gases.

2) A warning sign that a wind driven fire condition exists is the continuous forceful push of hot smoke from under the stairwell door at the fire floor.

3) If visibility is lost and a thermal imaging camera is available and the entire door appears hot, then proceed with caution.

4) If attempting to open the door, fire fighters should make sure that they have the ability to close the door quickly if, in fact, there is a wind driven condition.

5) The use of PPV fans to improve tenability in the stairwell during a wind driven fire was also effective but more research is needed to understand the benefits and limitations of this approach.

A fire blanket was used to minimize the impact of the wind on an apartment fire. Prior to the use of the blanket during the fire, the simulated wind speed was approximately 11 m/s (25 mph). The blanket was deployed over the window and the measurable wind speed inside the structure decreased to less than 0.4 m/s (1 mph). When used during the fire experiment, the fire blanket eliminated the wind driven effects on the fire. While the blanket proved to be a viable alternative tactic, more research needs to be conducted on its full capabilities. The blankets should be deployed on larger fuel loads, different wind speeds and various wind angles to further determine the blanket’s abilities and limitations.

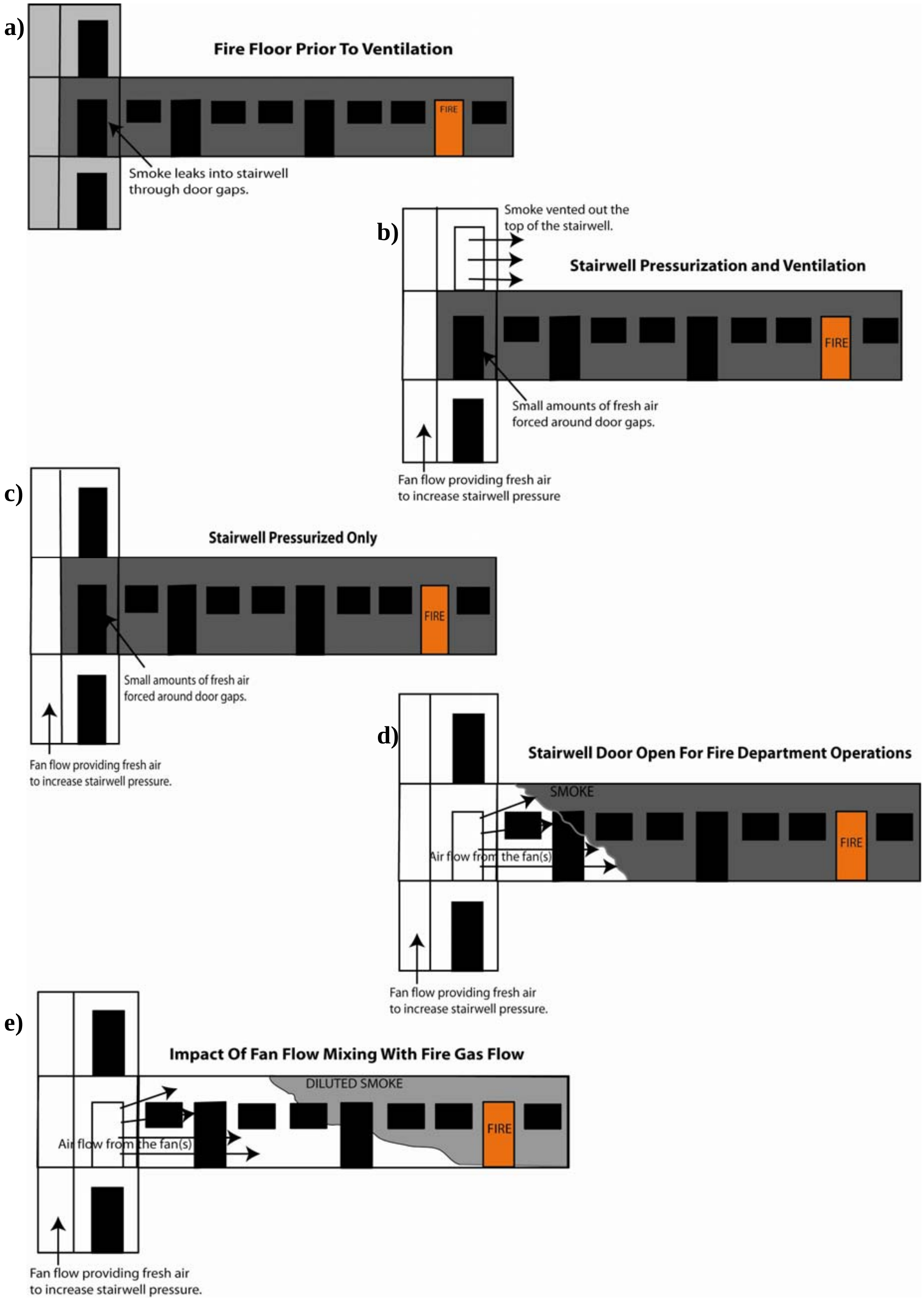

Figure 79. Diagrams for process of providing oxygen to the fire

Conclusions

This set of experiments examined the impact of positive pressure ventilation on smoke and heat spread from a post flashover fire in an apartment with a furnished living room. Both the portable fans and the mounted fans were able to create pressures to remove the smoke from and keep the target stairwell free of smoke under numerous conditions. The pressures measured during these experiments agreed with the correlation provided in NFPA 92A for using pressure difference as a smoke barrier.

The mounted fans positioned at the front of the structure were able to clear the stairwell quickly when vented and were able to keep smoke out of the entire stairwell with the fire floor door open. The mounted fans were also able to clear the smoke all the way back out of the fire apartment past the fire and through an open rear window. This was not the intent of the experiments so no measurements were taken on the effect of oxygen supplied to the fire or spread to target rooms. In order to keep from over pressurizing and flowing air through the fire apartment, a second stairwell was opened and the mounted fans were able to keep that second stairwell free of smoke as well. Other successful ways to keep the stairwells free of smoke without providing oxygen to the fire apartment were to add volume by opening additional floors below the fire floor or to decrease the speed of the fan.

The portable fans were also effective at ventilating the 16-story stairwell and keeping it free of smoke while pressurizing. In most cases the single portable fan at the base of the stairwell improved conditions in the stairwell. The increased pressures greatly reduced the amount of smoke that was able to flow into the stairwell under natural ventilation conditions. When a second fan was added two floors below the fire floor smoke was kept completely out of the stairwell, even with the fire floor door open or with an additional door open.

The creation of a simulated wind driven fire demonstrated how quickly conditions can change and how a room and contents fire can become a “blow torch” out into the public hallway and into the stairwells. Fire fighters need to appreciate this potential, especially in high-rise buildings because the time to seek an area of refuge is on the order of seconds before conditions become untenable. Alternative techniques to prevent a wind driven condition or minimize its impact such as PPV and fire blankets, showed excellent potential in these experiments. Further experiments and research are needed to confirm this for other configurations.

Positive pressure ventilation fans utilized correctly can increase the effectiveness of fire fighters and survivability of occupants in high-rise buildings. In a high-rise building it is possible to increase the pressure of a stairwell to prevent the infiltration of smoke, if fire crews configure the fans properly. When configured properly PPV fans can meet or exceed previously established performance guidelines for fixed smoke control systems. Proper configuration requires the user to consider a range of variables, including, fan size, set back, and angle, fan position inside or outside of the building, and number and alignment of multiple fans.

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Appendix A. Dimensioned Drawings

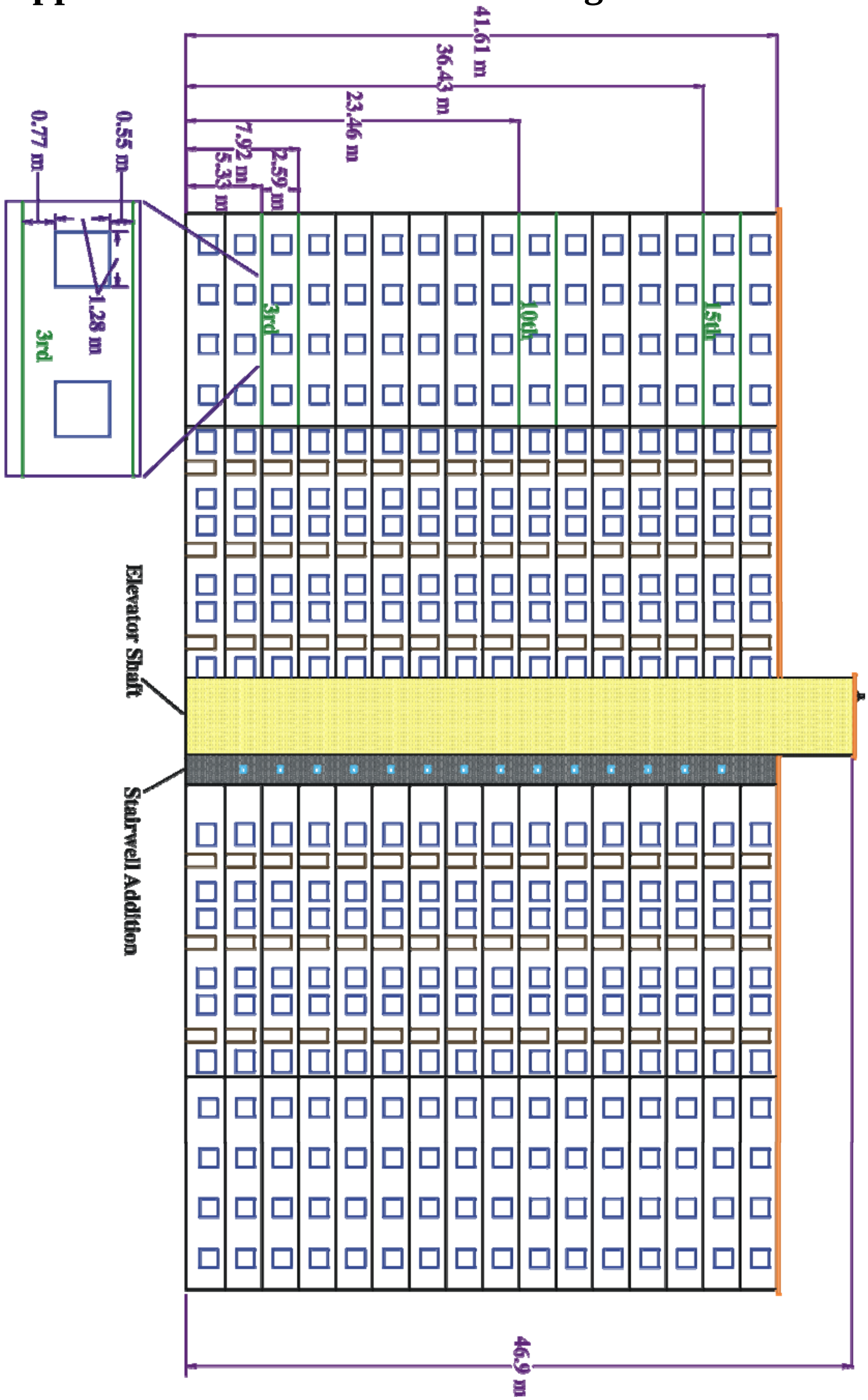

Figure 1. Front elevation

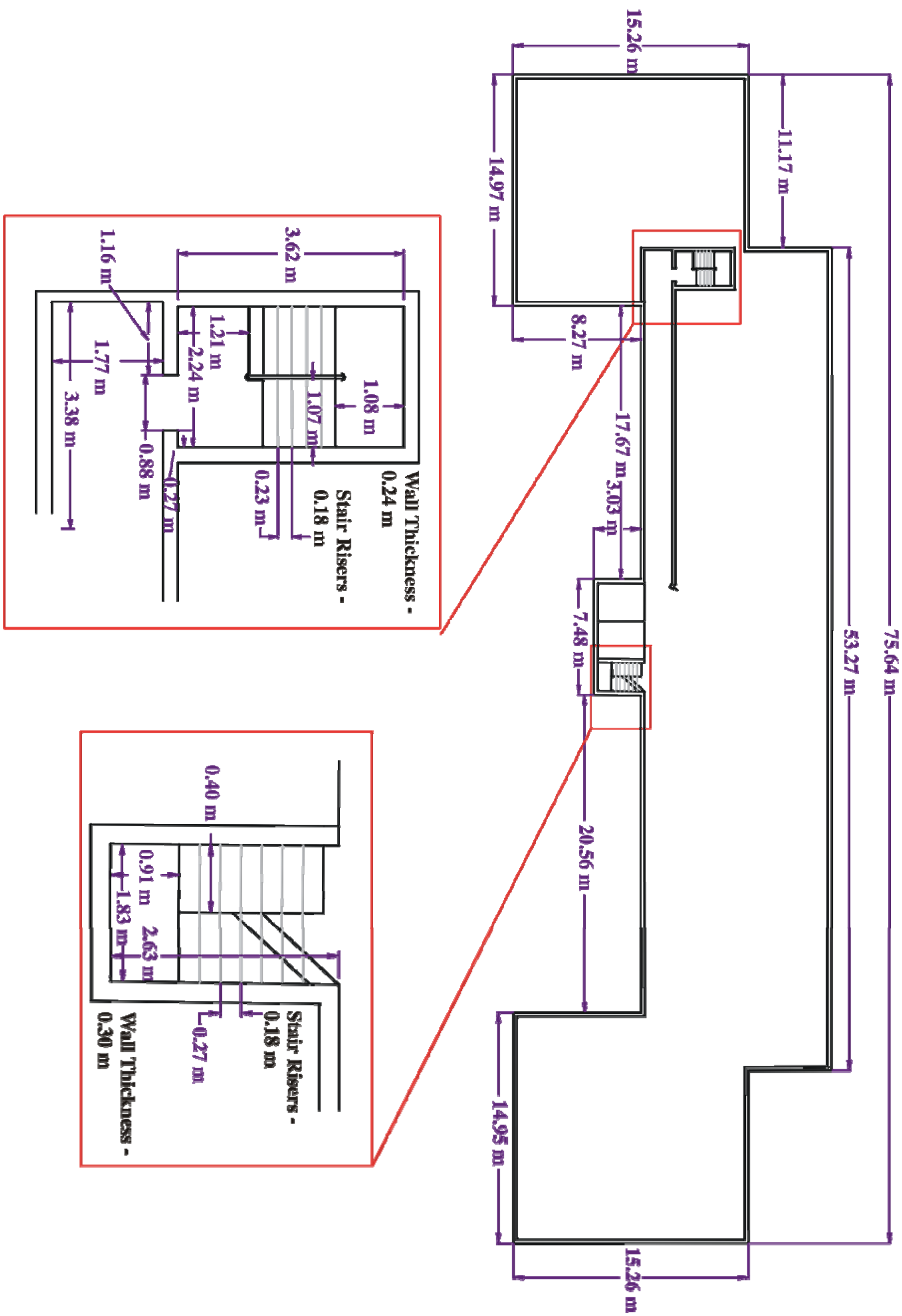

Figure 2. Overall dimensions with stair detail

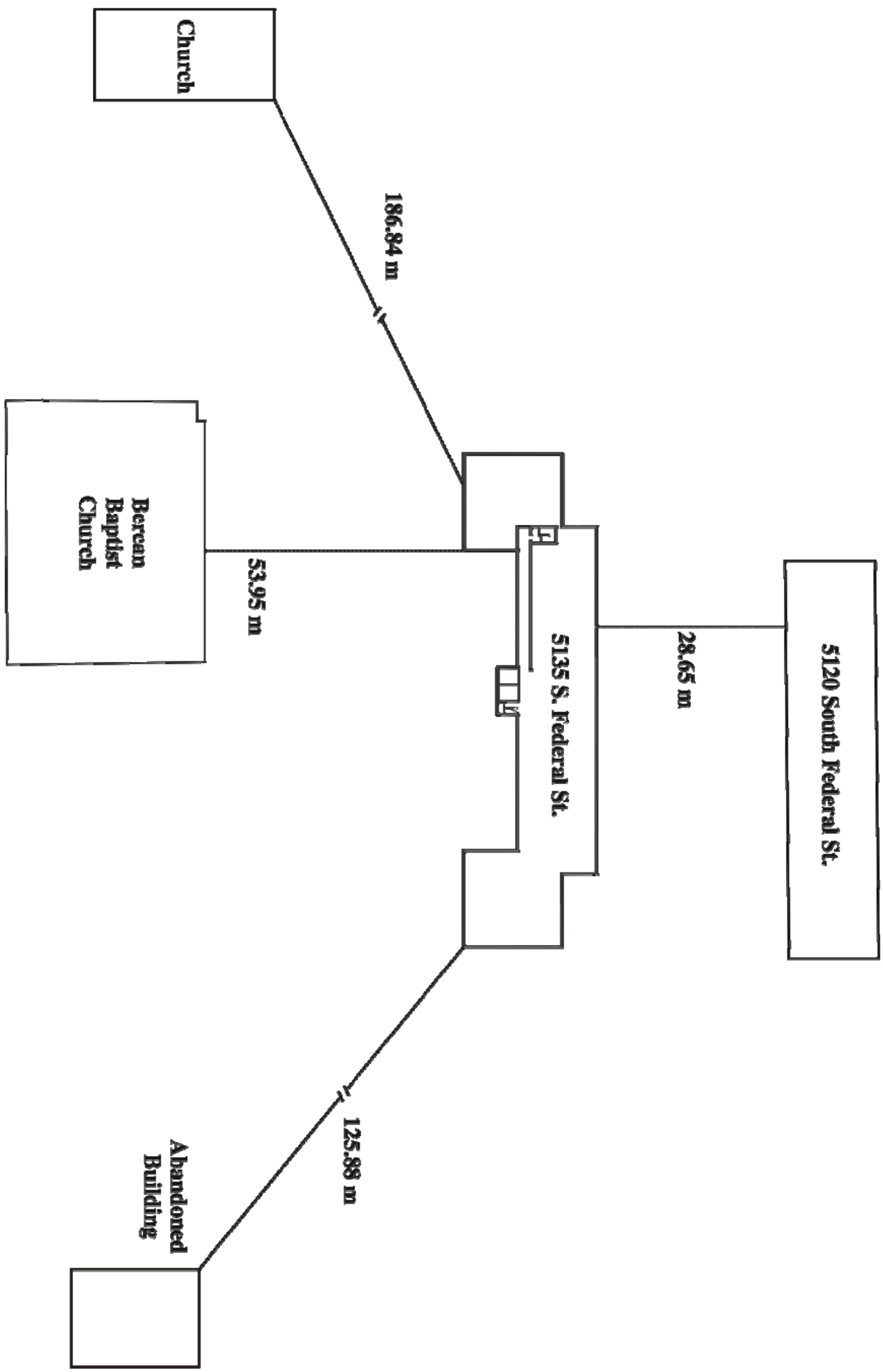

Figure 3. Structure location and exposures

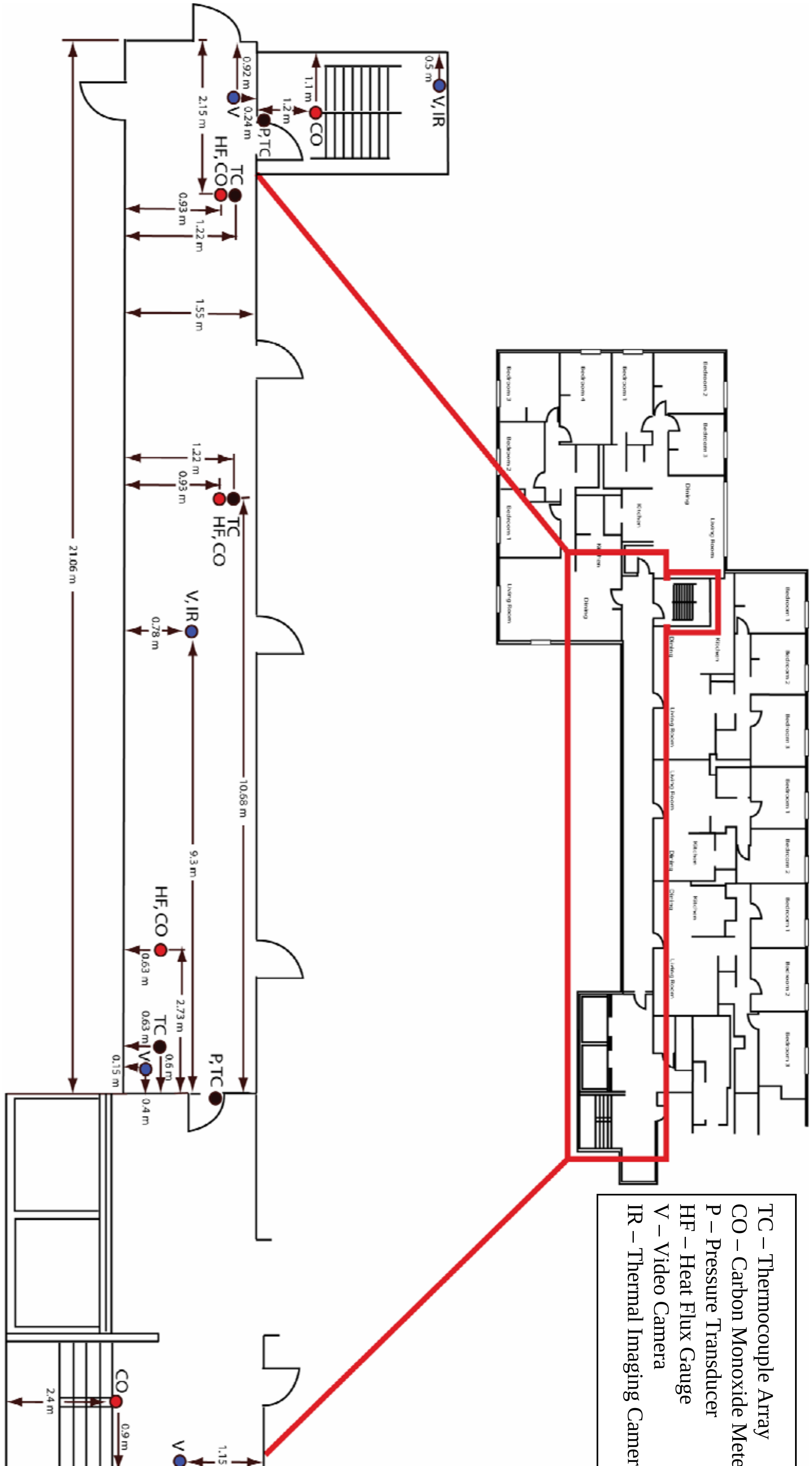

Figure 4. Hallway and stair instrument locations

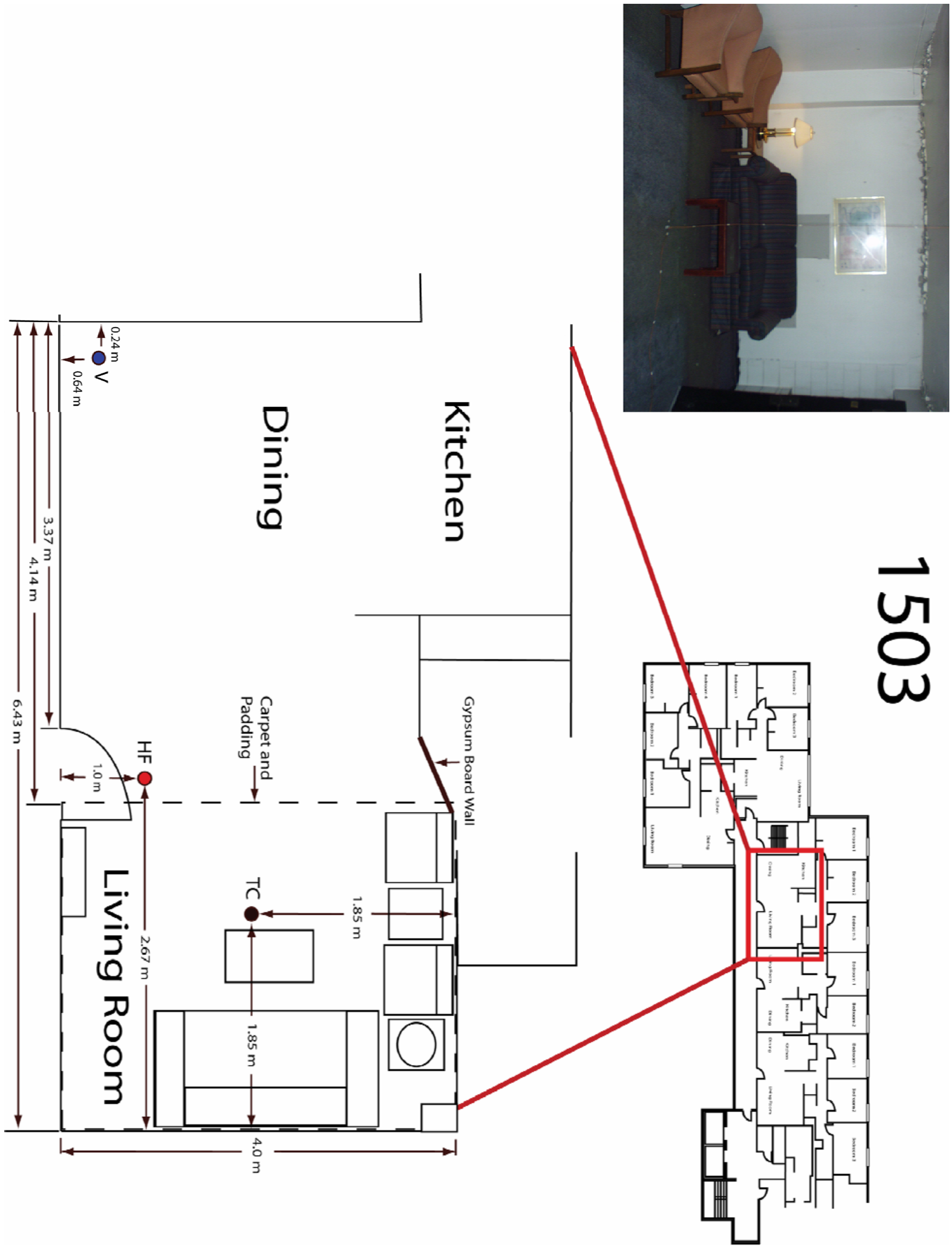

Figure 5. Apartment 1503 dimensions and instrument locations

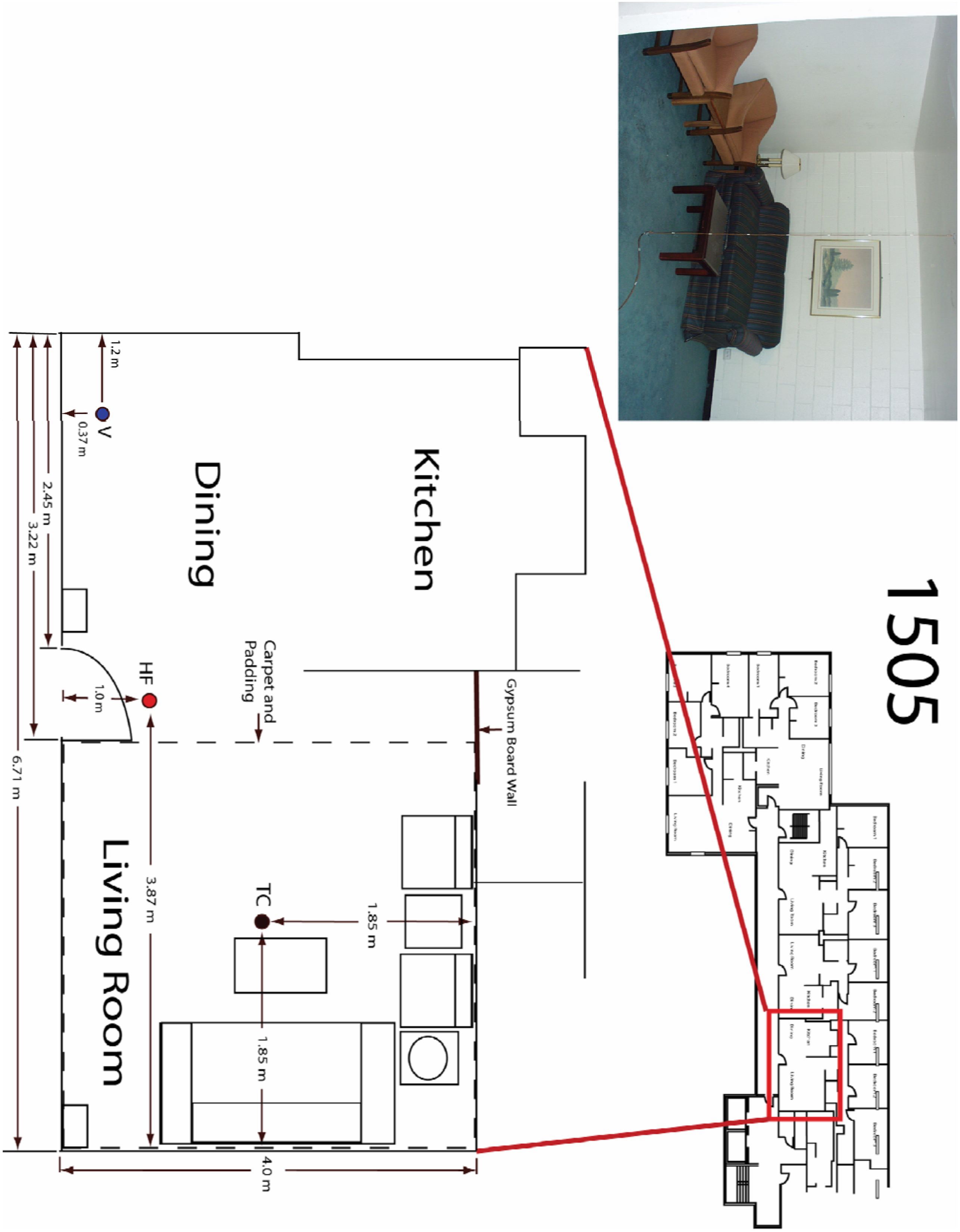

Figure 6. Apartment 1505 dimensions and instrument locations

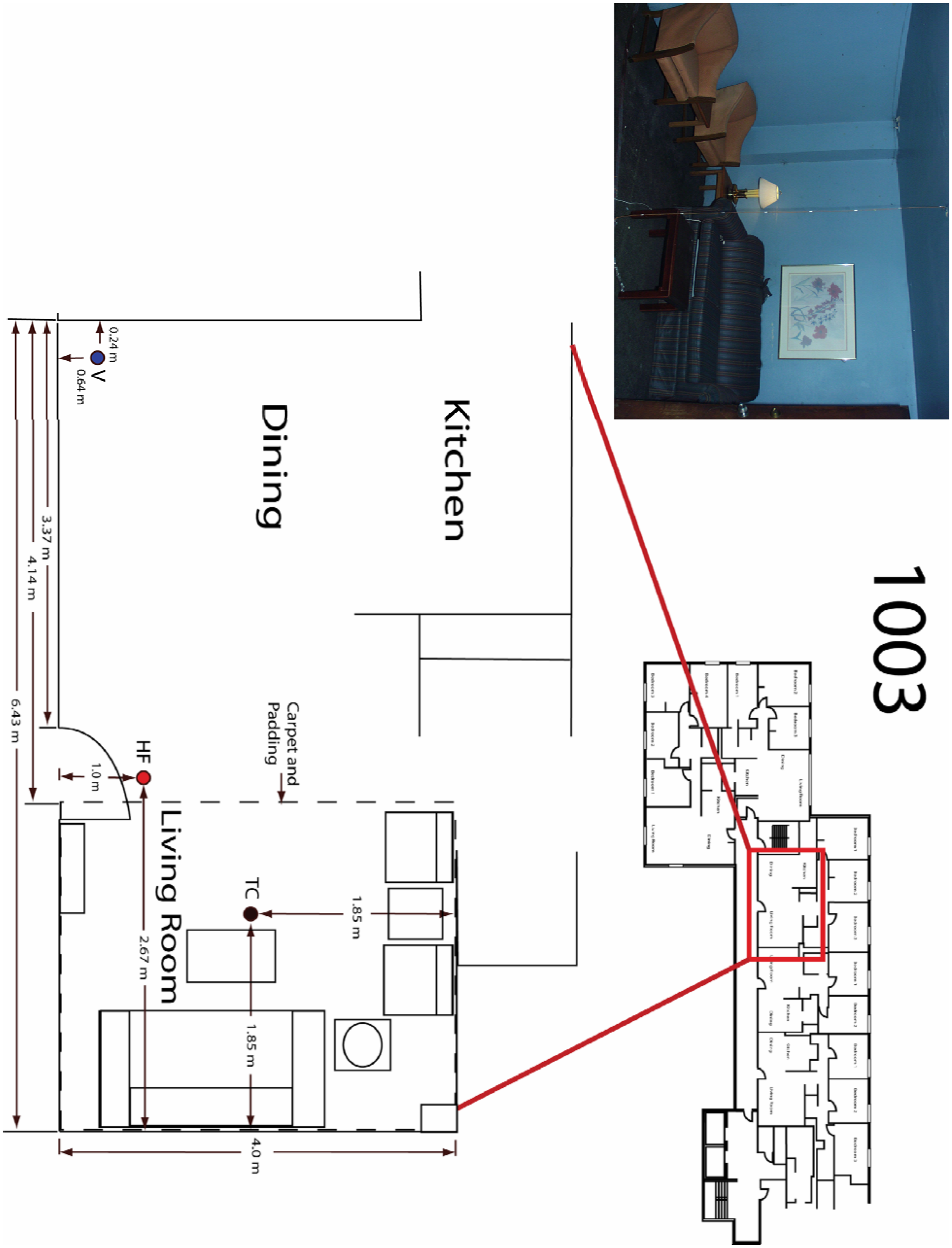

Figure 7. Apartment 1003 dimensions and instrument locations

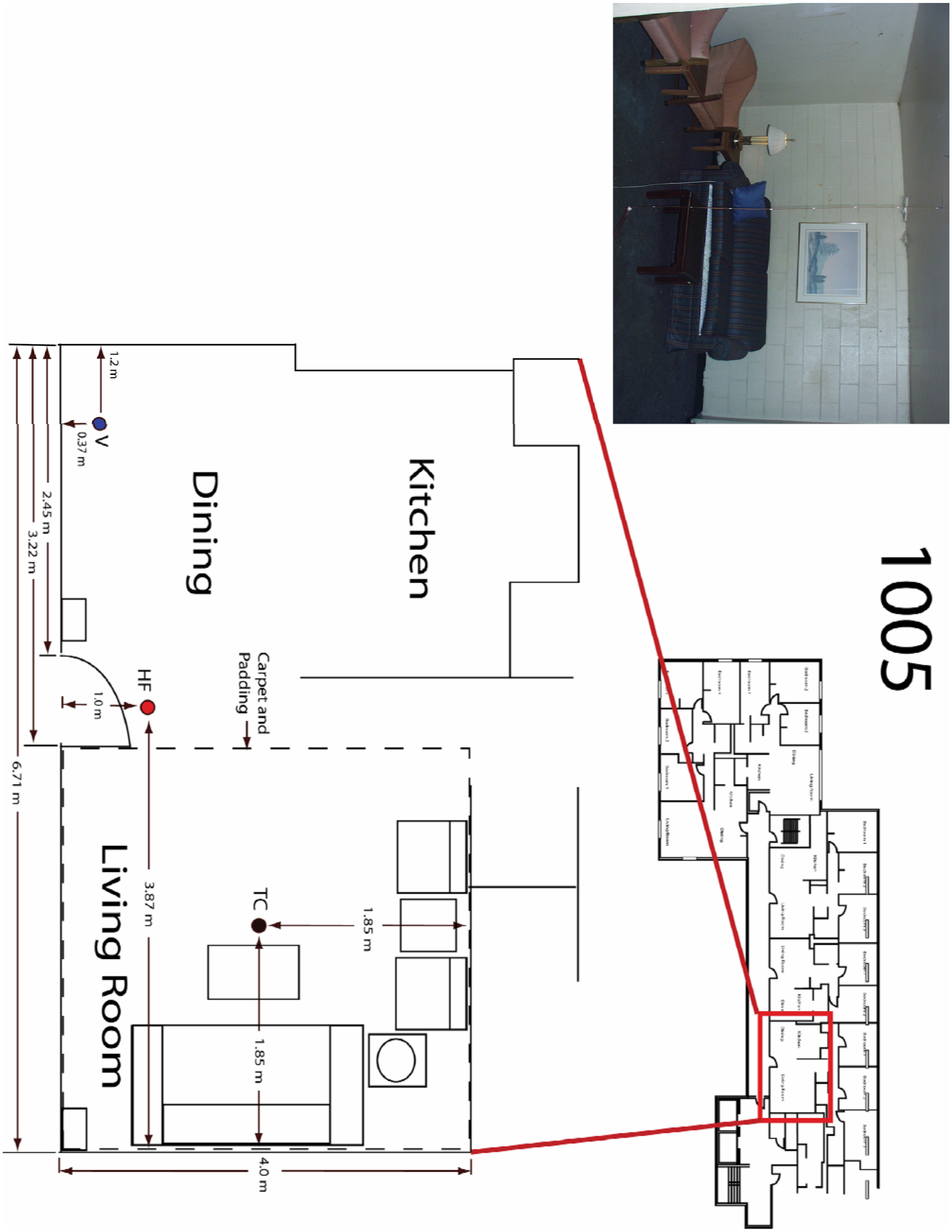

Figure 8. Apartment 1005 dimensions and instrument locations

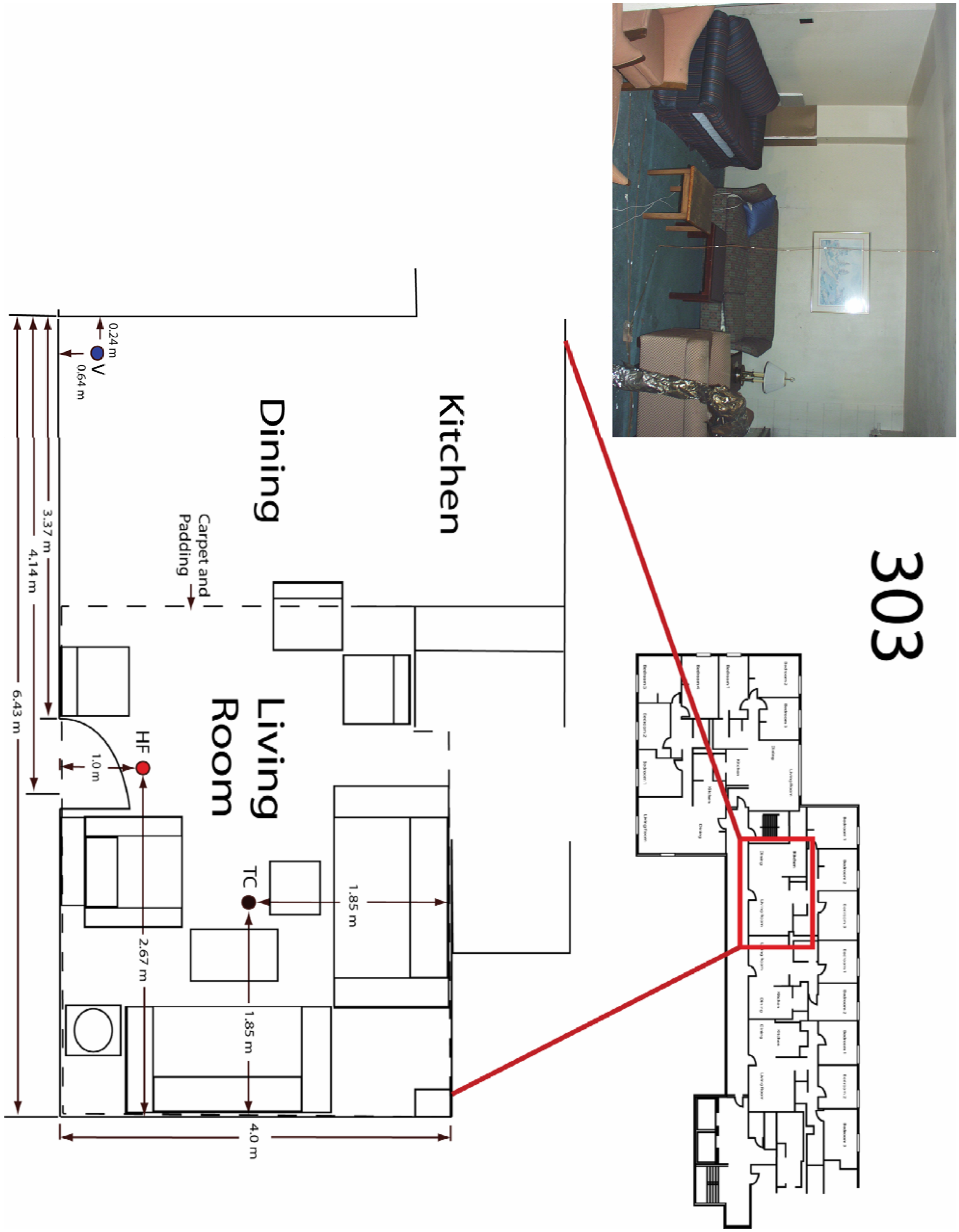

Figure 9. Apartment 303 dimensions and instrument locations

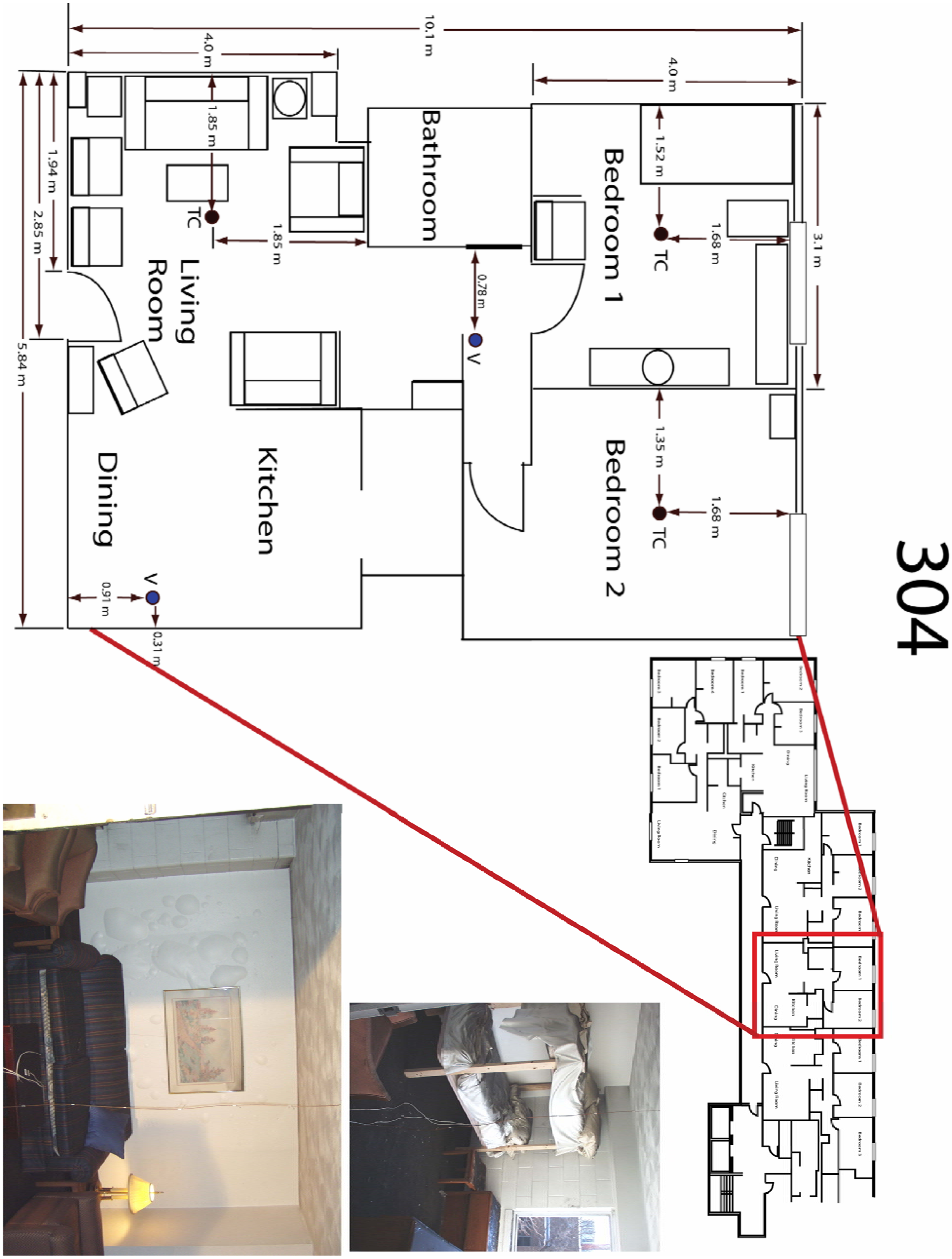

Figure 10. Apartment 304 dimensions and instrument locations

Appendix B. Detailed Data for Apartment 1503

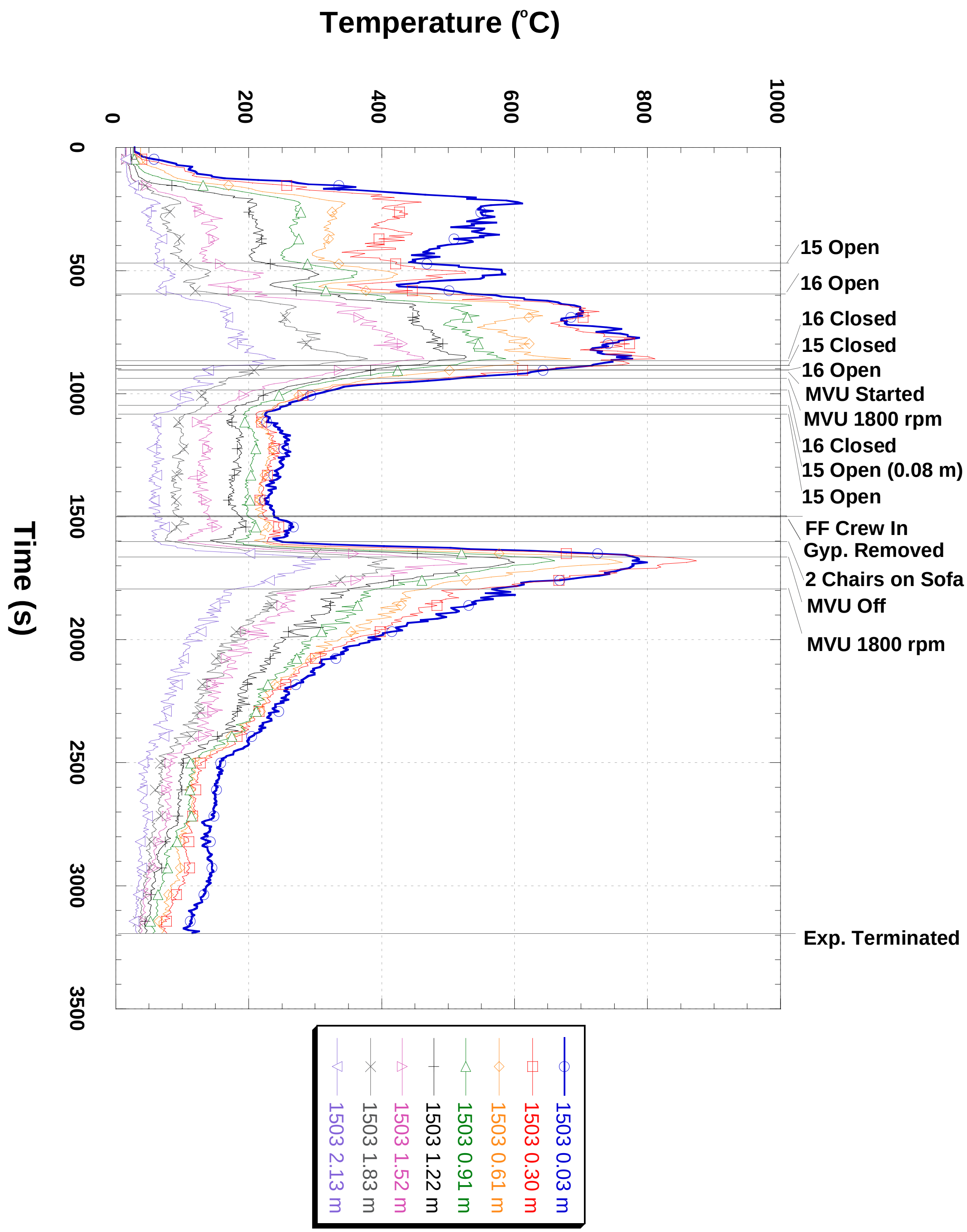

Figure 1. Detailed temperature vs. time for 1503 living room

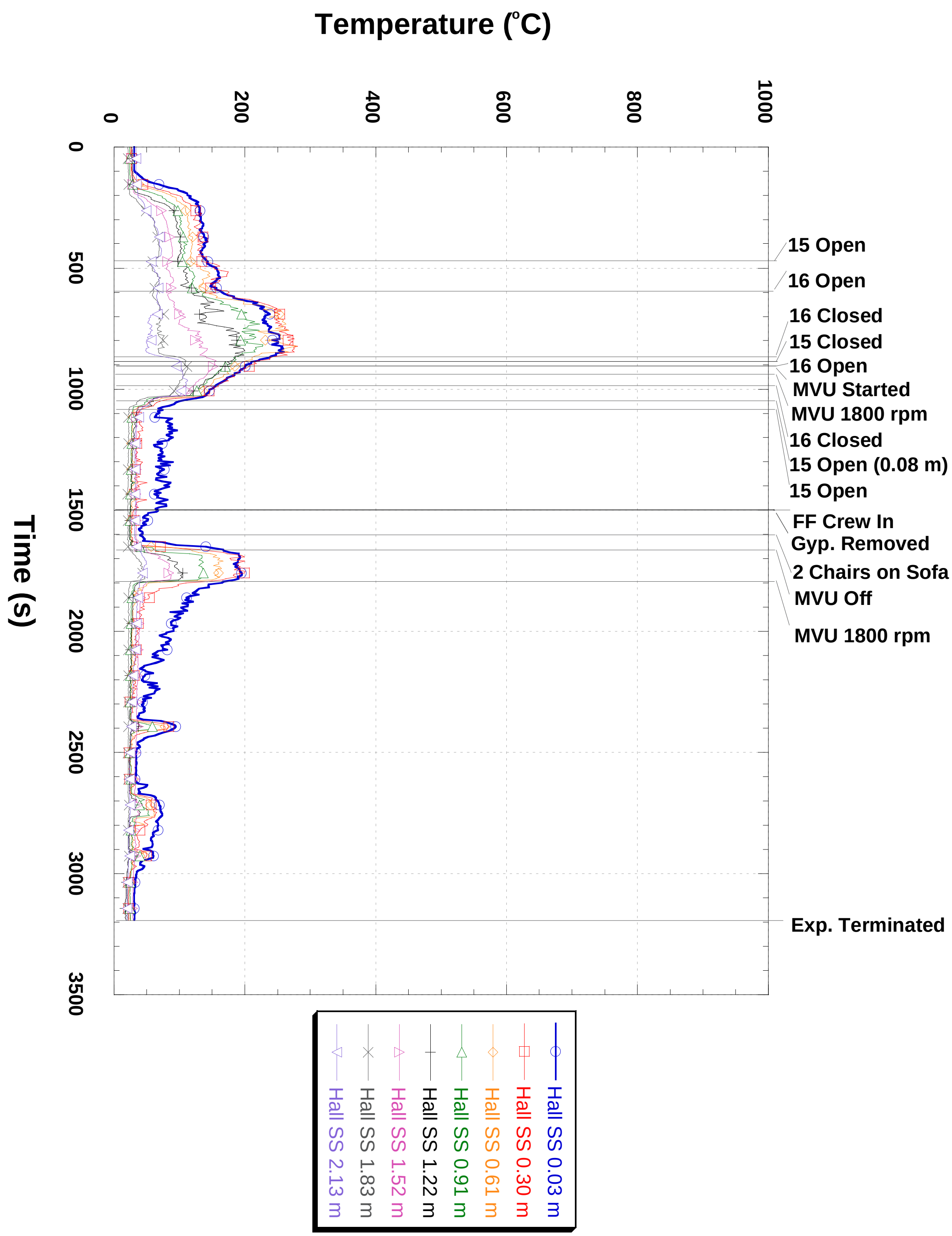

Figure 2. Detailed temperature vs. time for 1503 hallway adjacent to the south stair

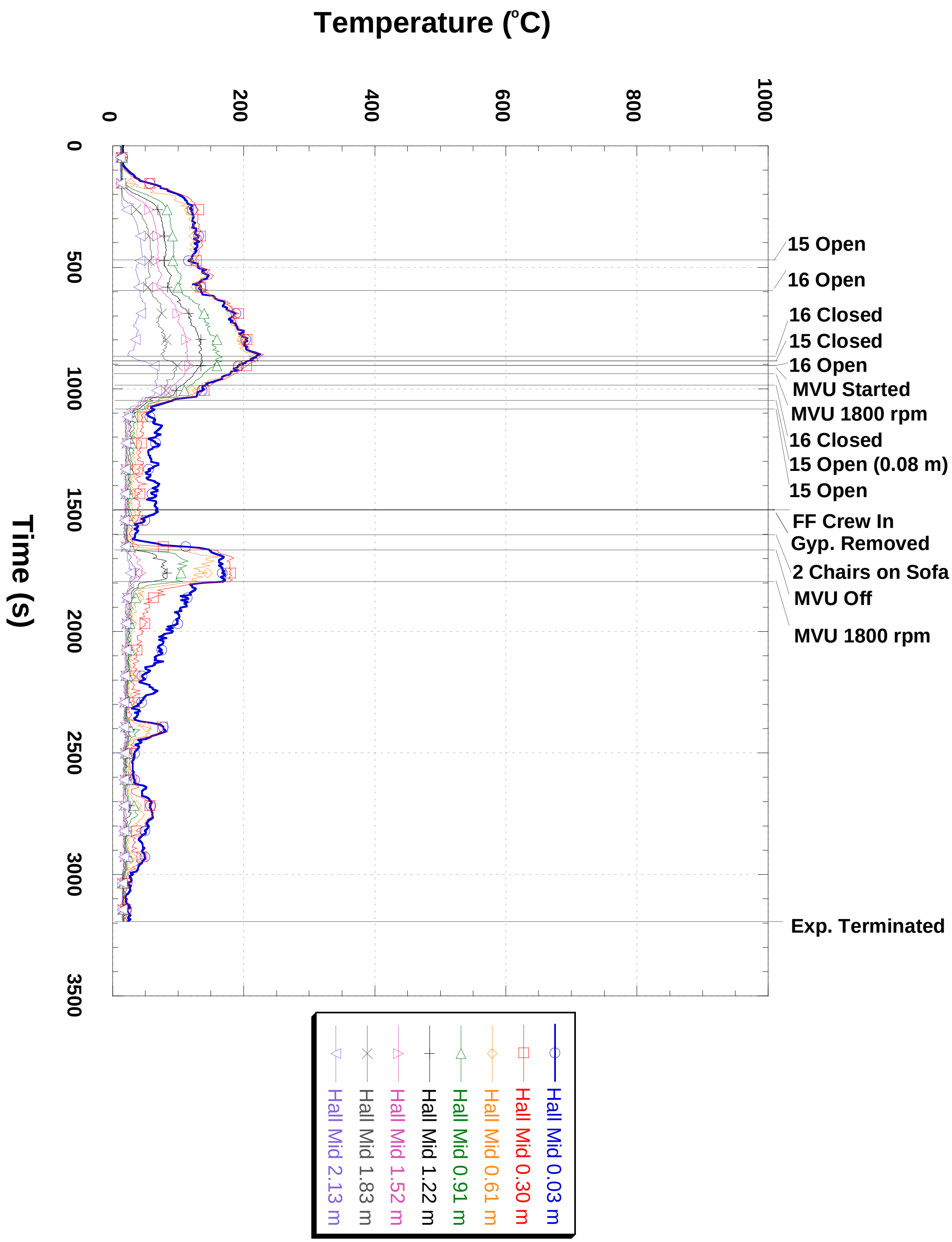

Figure 3. Detailed temperature vs. time for 1503 middle hallway

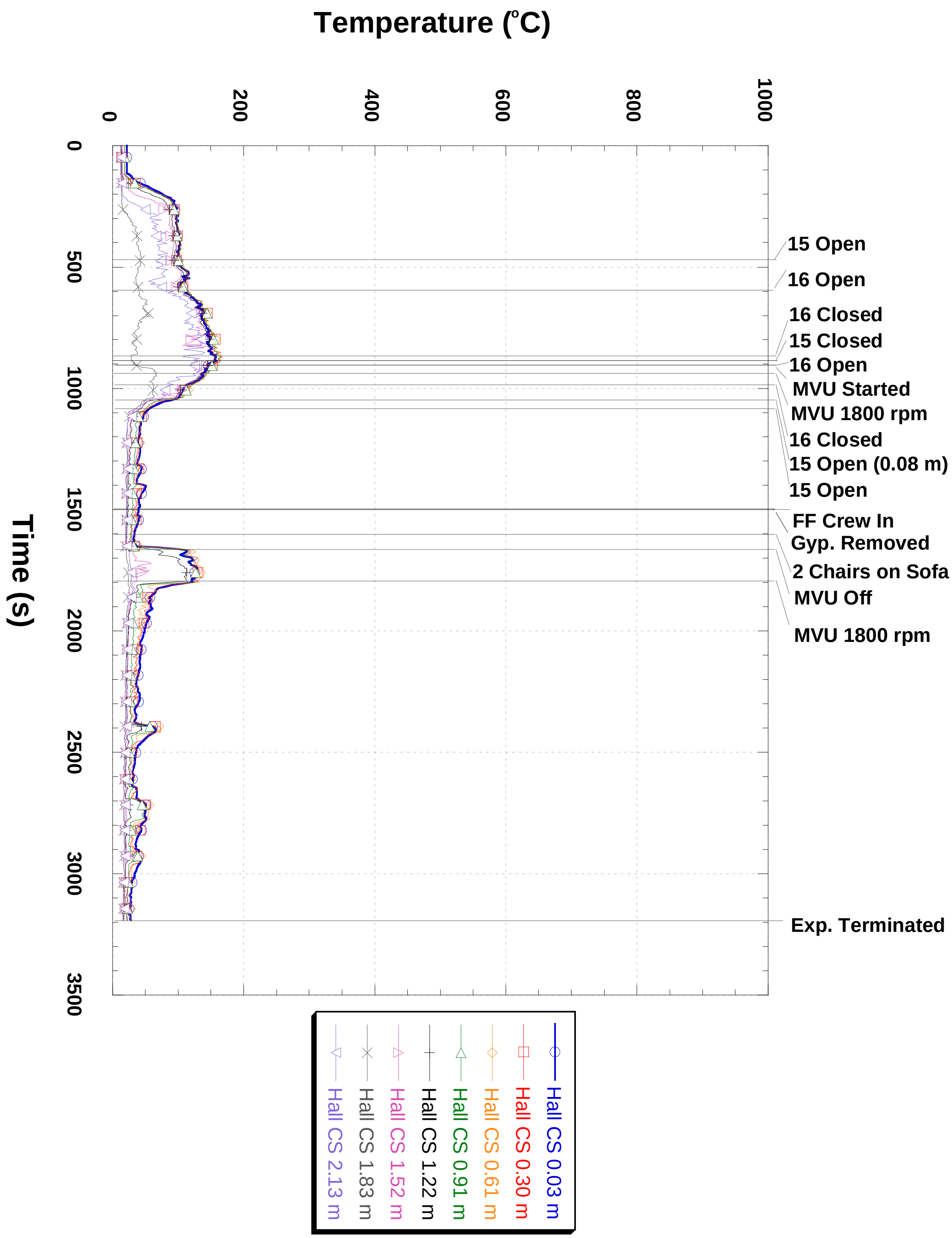

Figure 4. Detailed temperature vs. time for 1503 hallway adjacent to the center stair

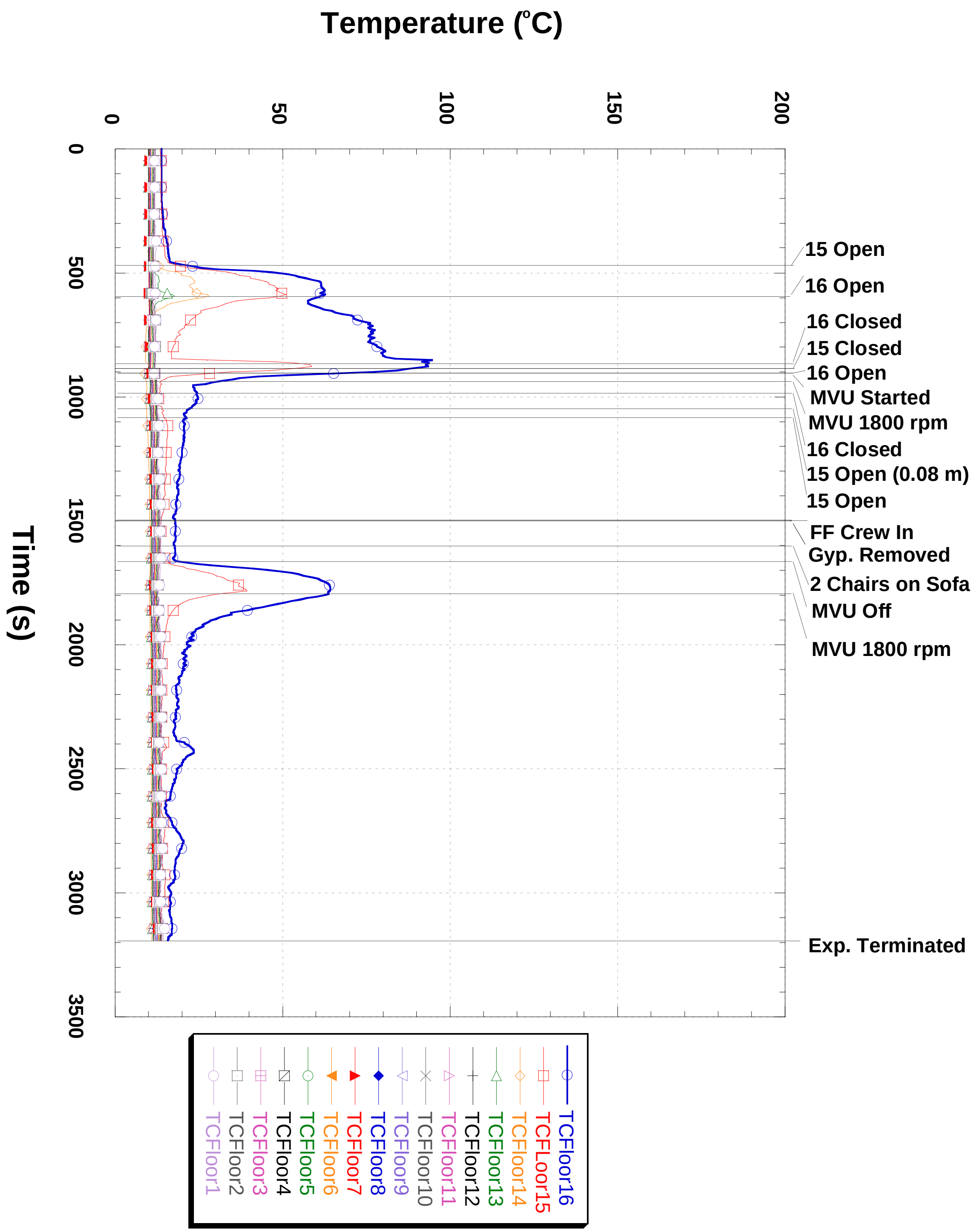

Figure 5. Detailed temperature vs. time for 1503 south stair

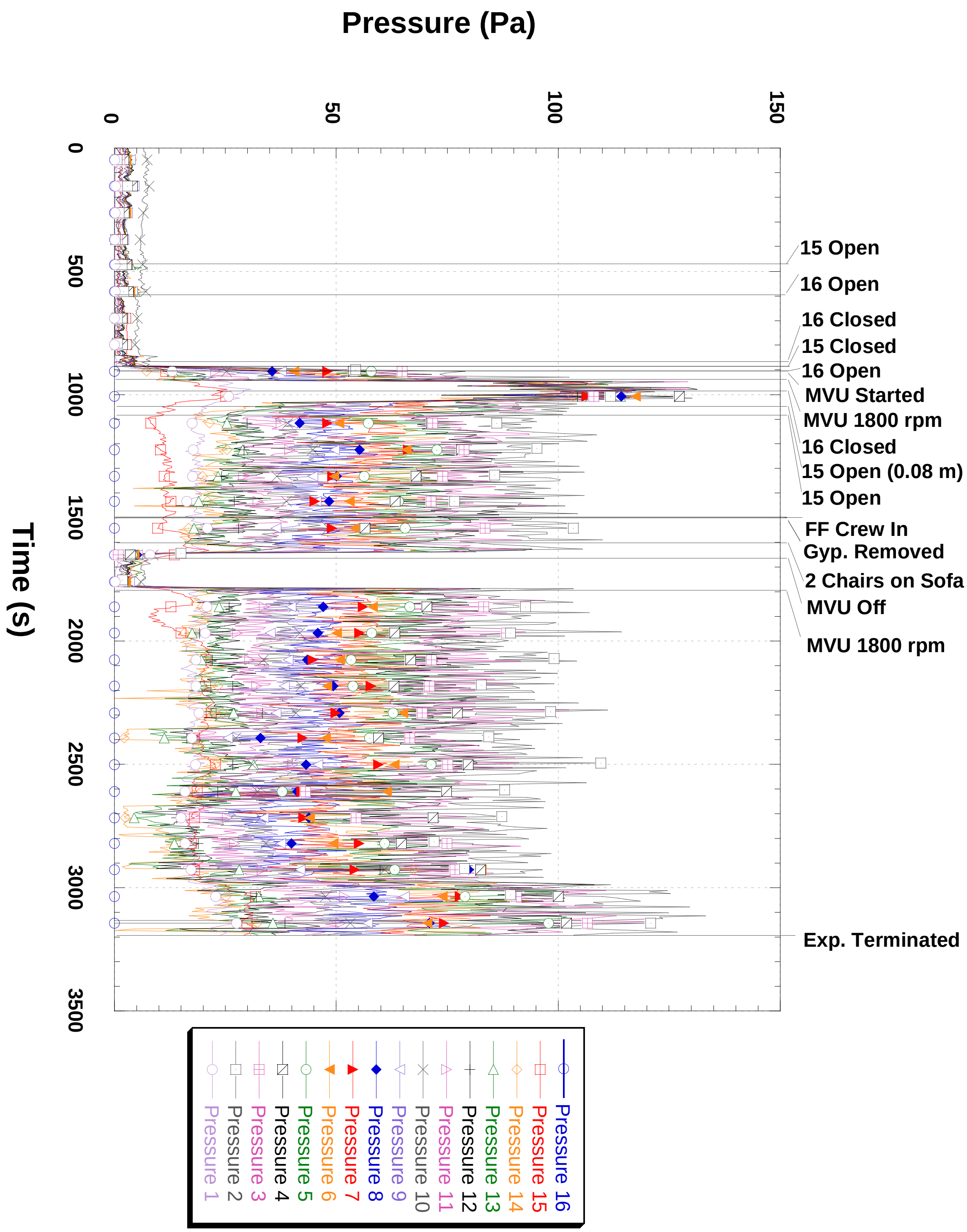

Figure 6. Detailed pressure vs. time for 1503 south stair

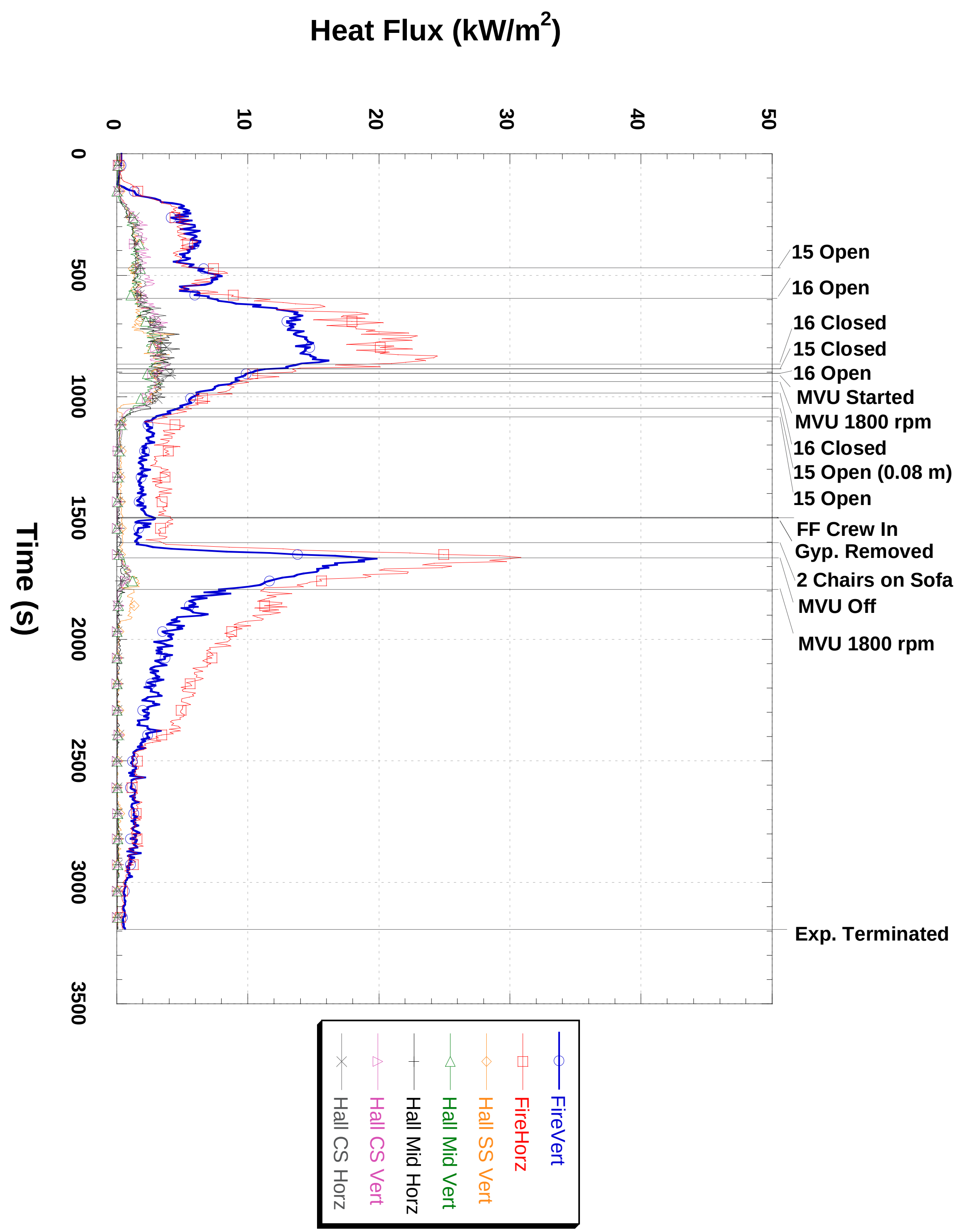

Figure 7. Detailed heat flux vs. time for 1503

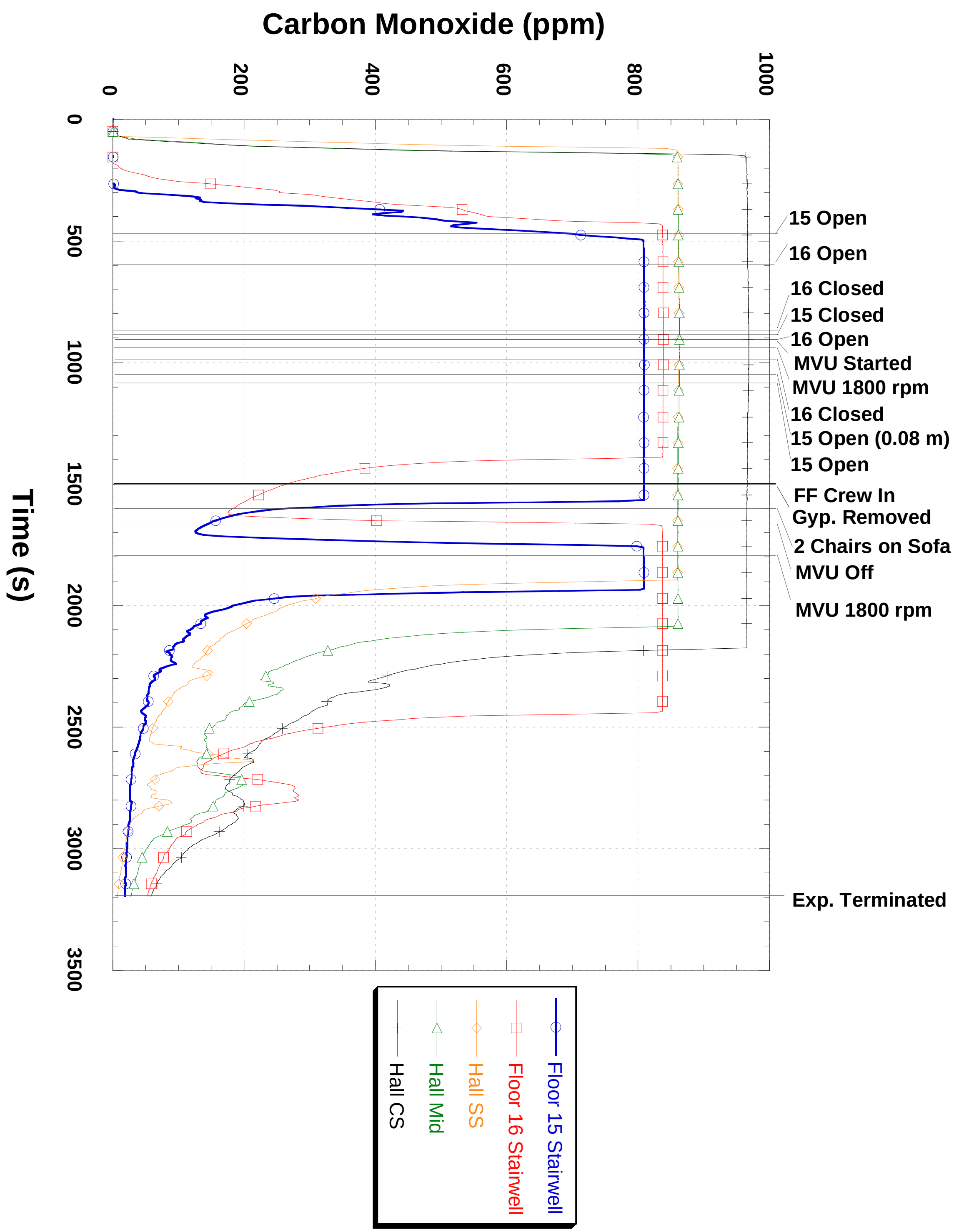

Figure 8. Detailed carbon monoxide vs. time for 1503

Appendix C. Detailed Data for Apartment 1505

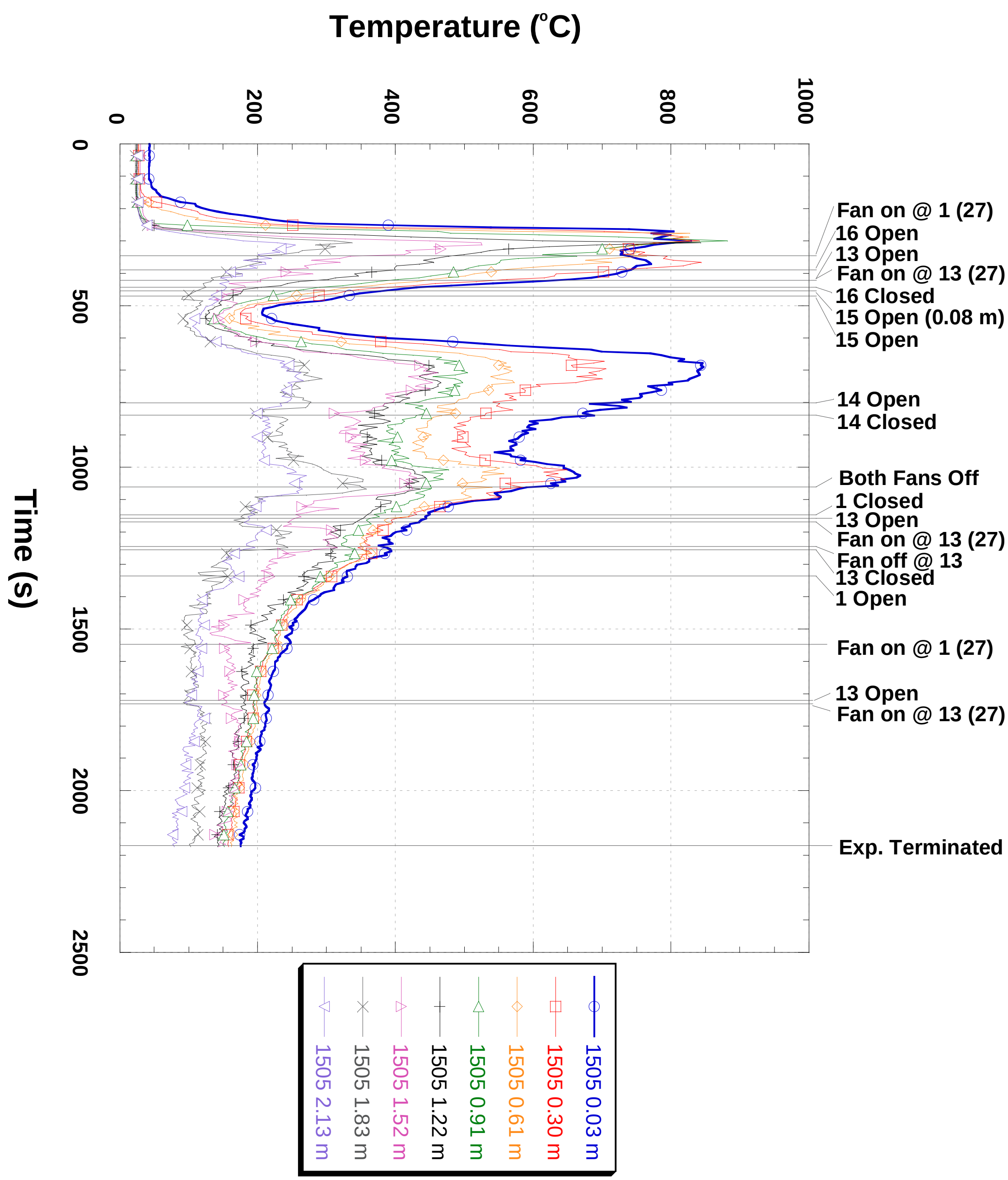

Figure 1. Detailed temperature vs. time for 1505 living room

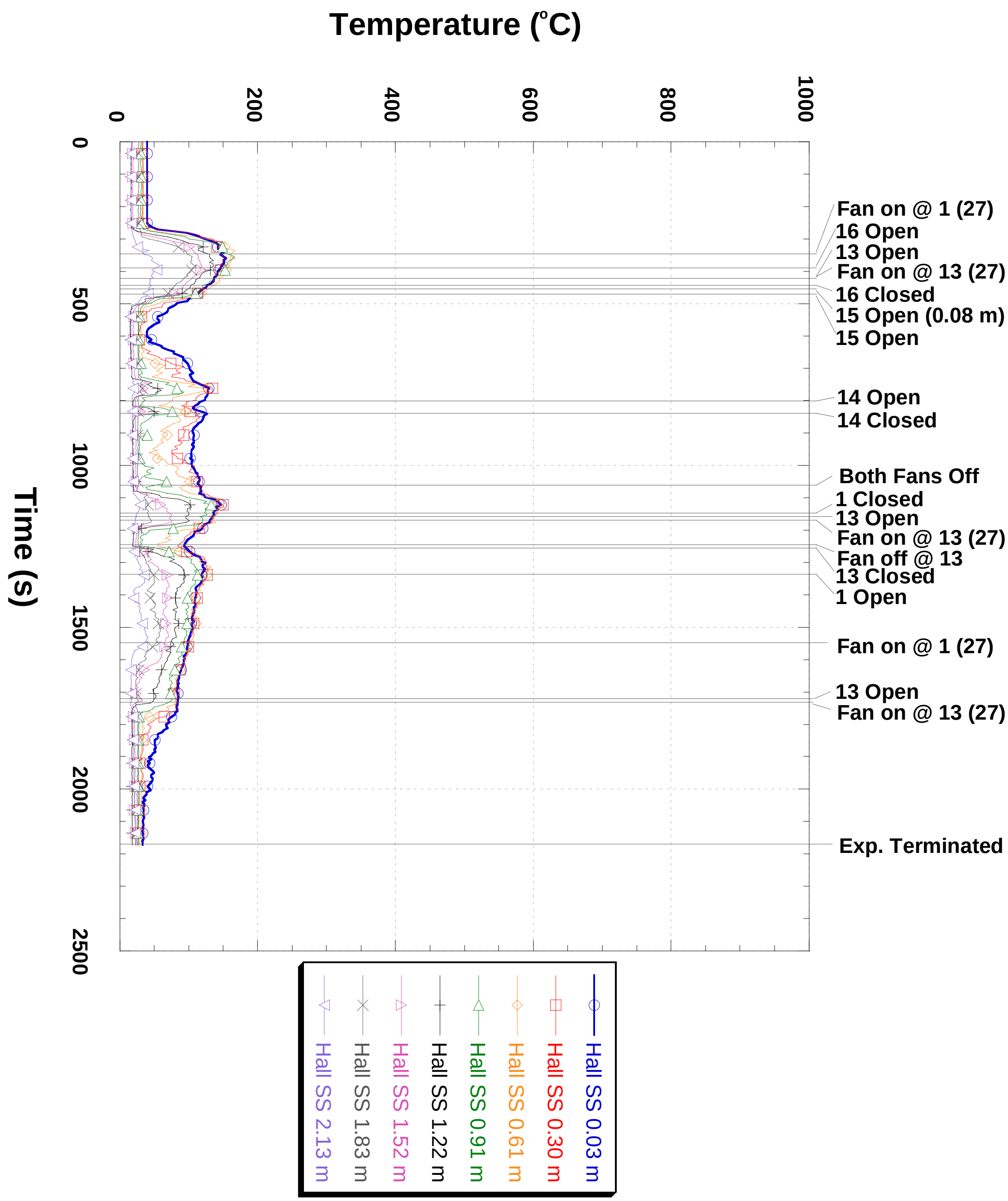

Figure 2. Detailed temperature vs. time for 1505 hallway adjacent to the south stair

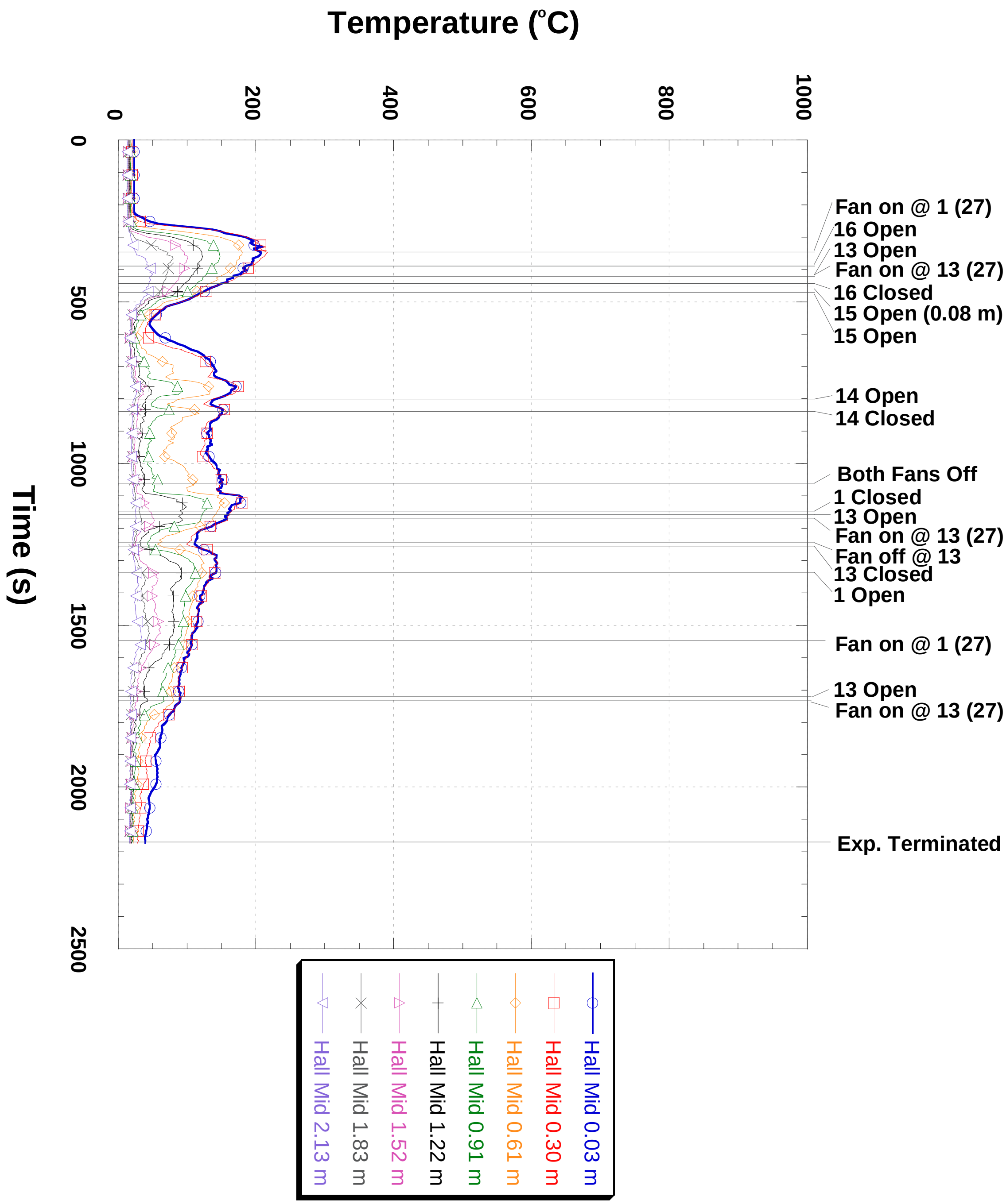

Figure 3. Detailed temperature vs. time for 1505 middle hallway

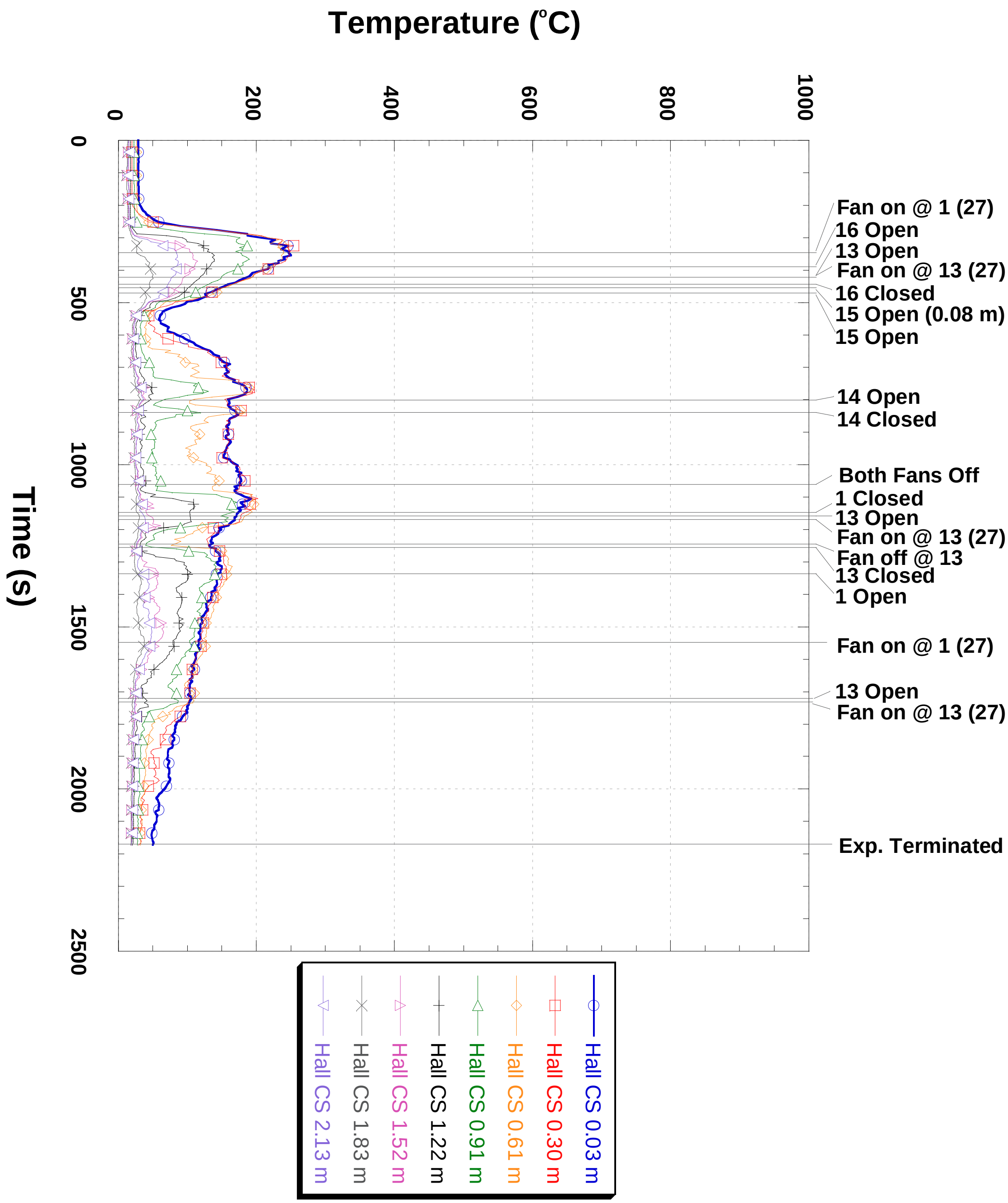

Figure 4. Detailed temperature vs. time for 1505 hallway adjacent to the center stair

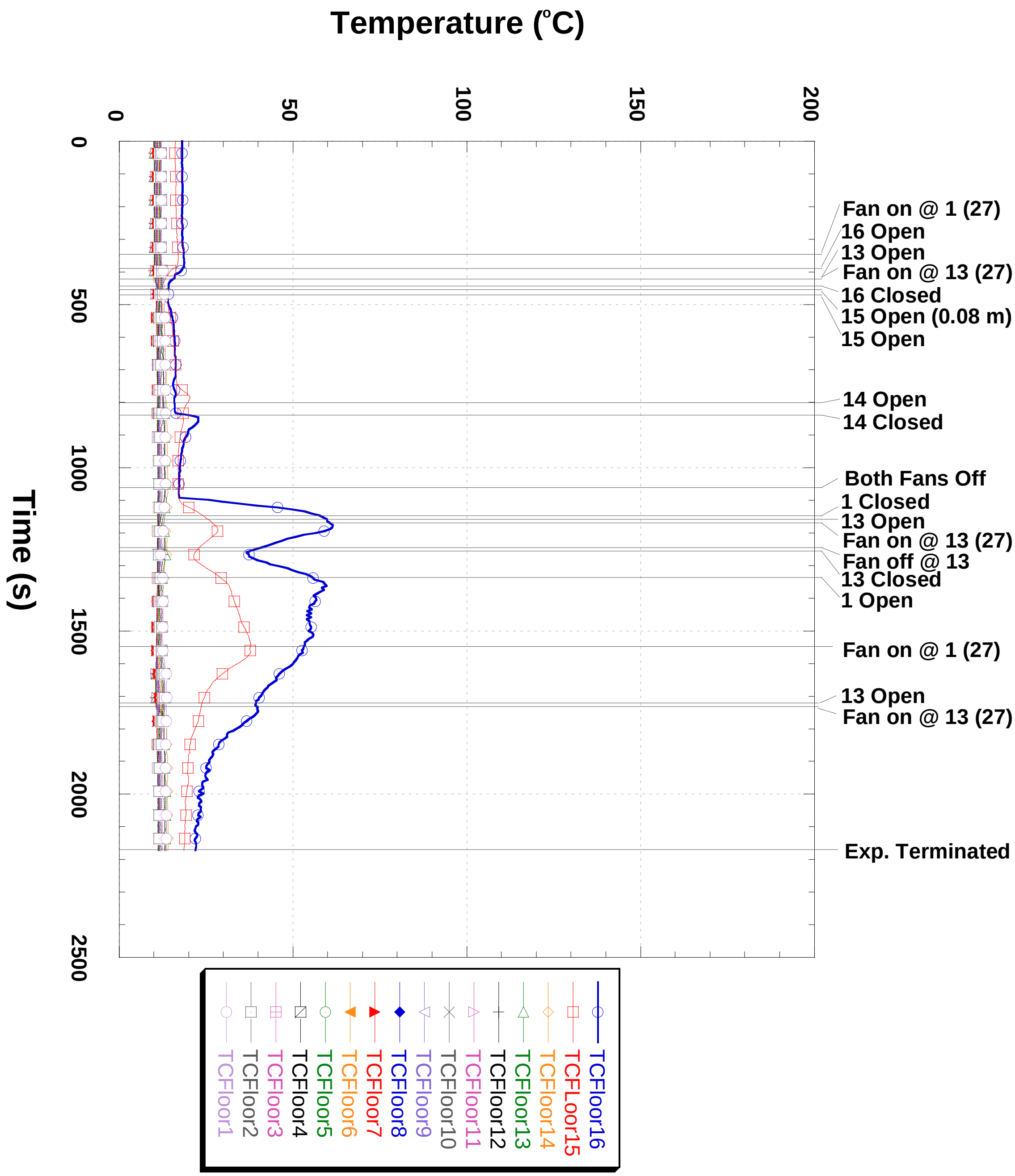

Figure 5. Detailed temperature vs. time for 1505 south stair

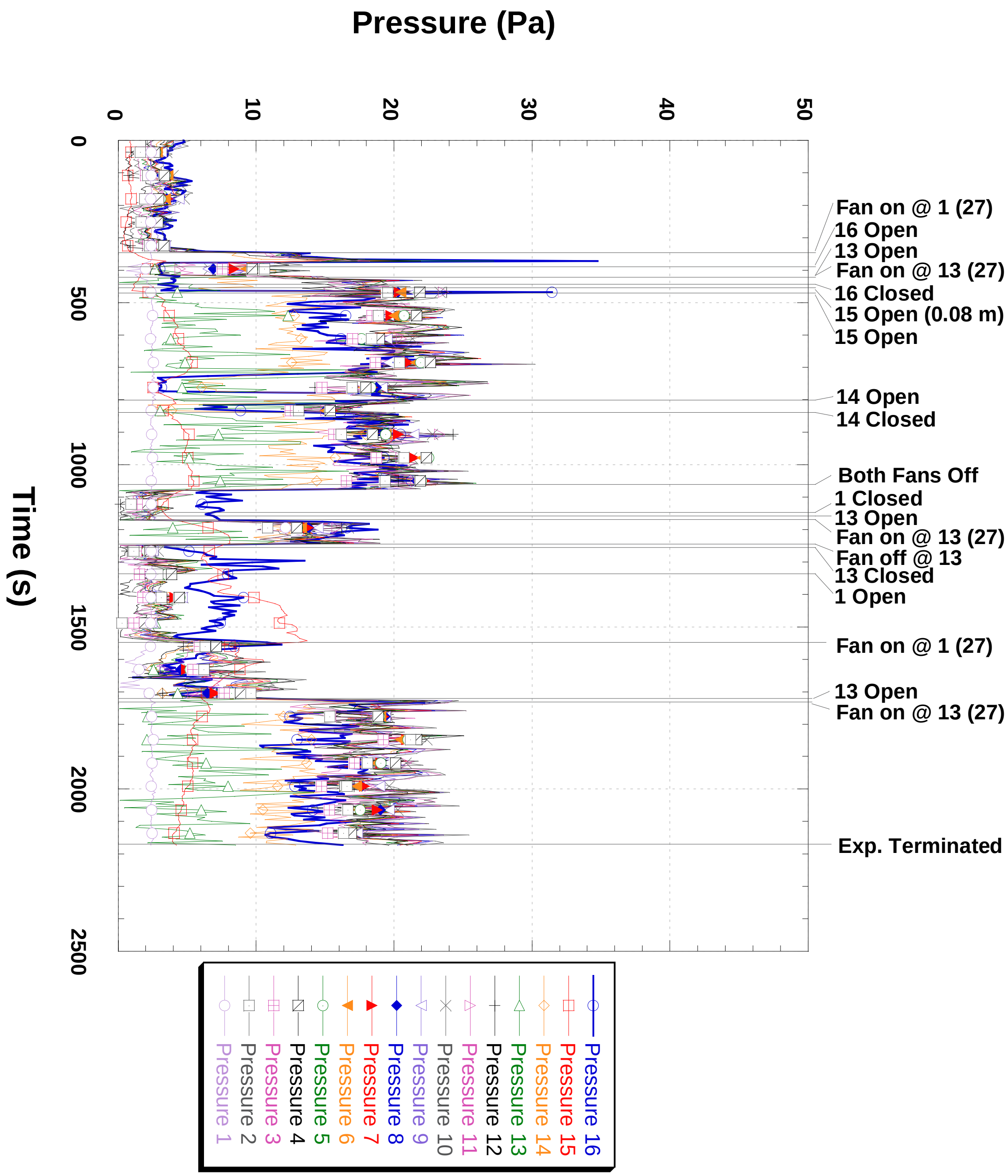

Figure 6. Detailed pressure vs. time for 1505 south stair

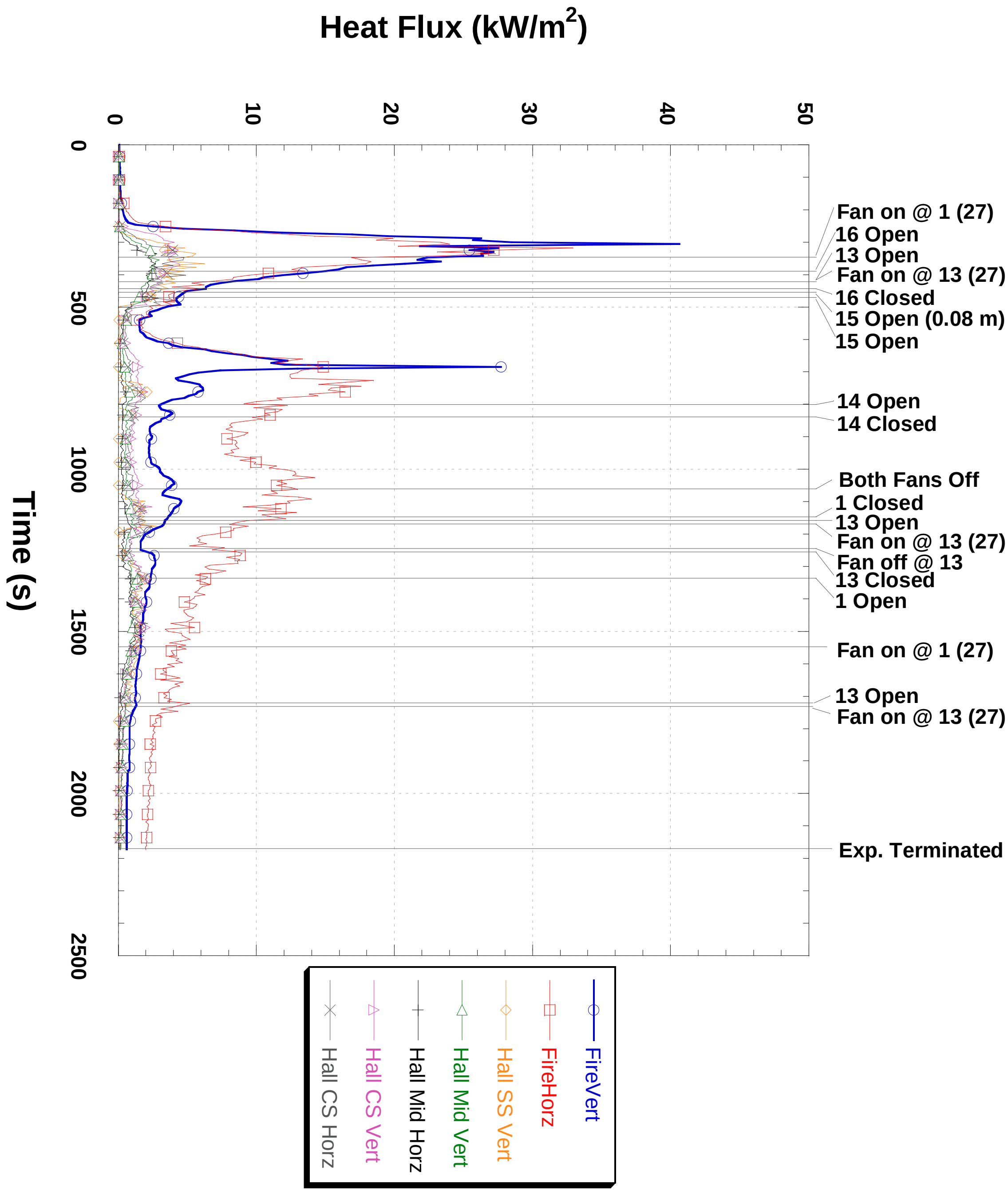

Figure 7. Detailed heat flux vs. time for 1505

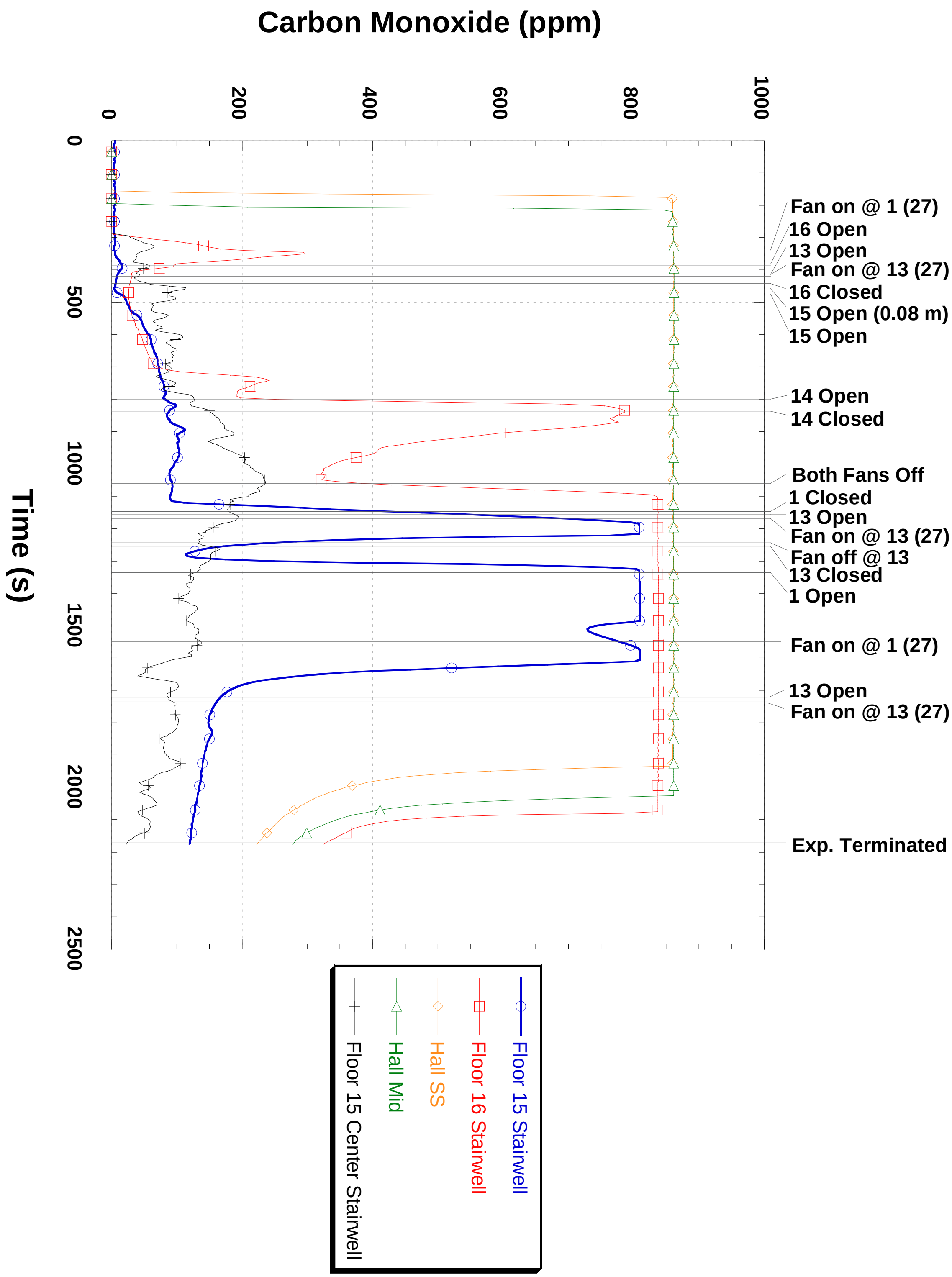

Figure 8. Detailed carbon monoxide vs. time for 1505

Appendix D. Detailed Data for Apartment 1003

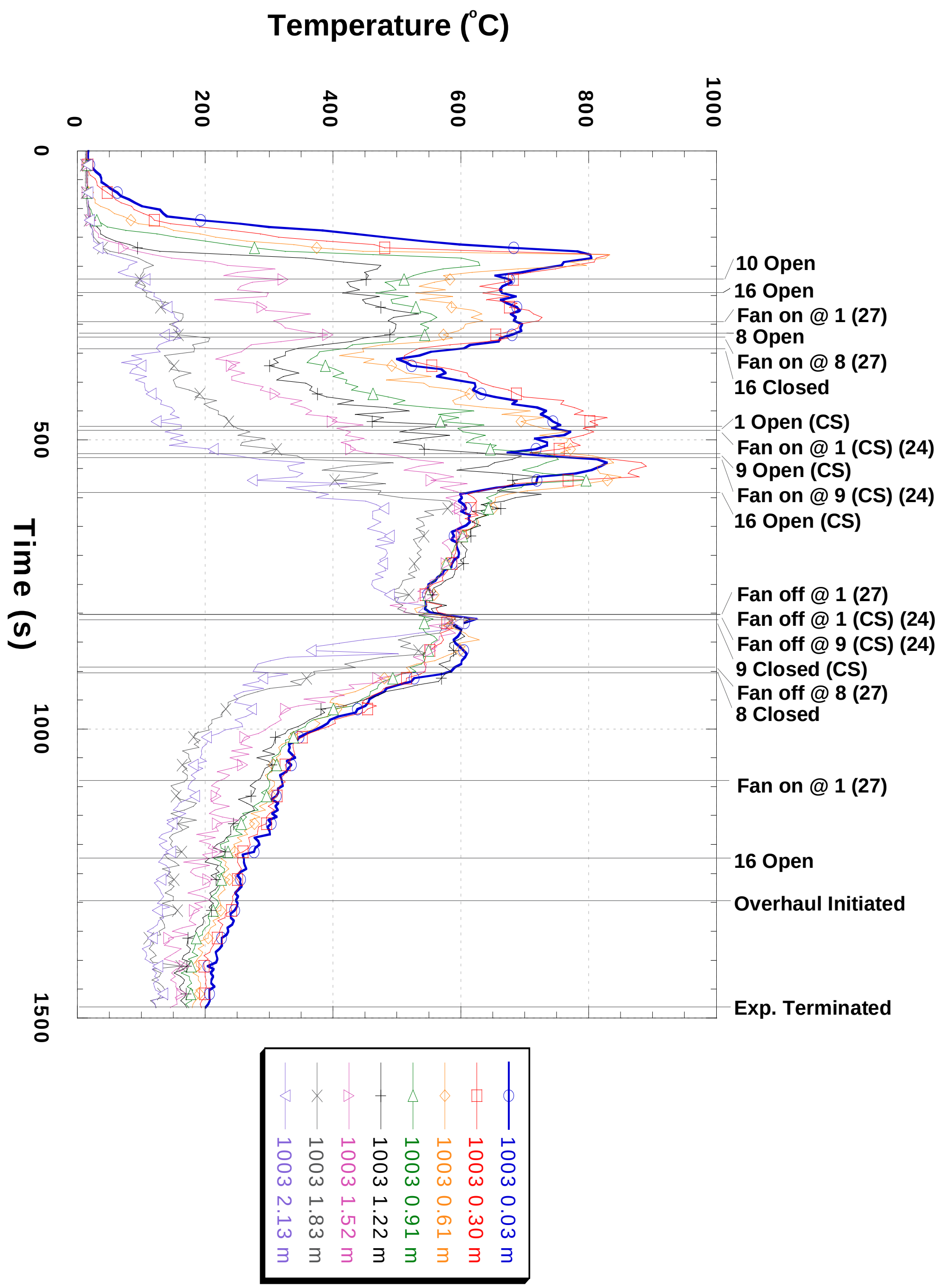

Figure 1. Detailed temperature vs. time for 1003 living room

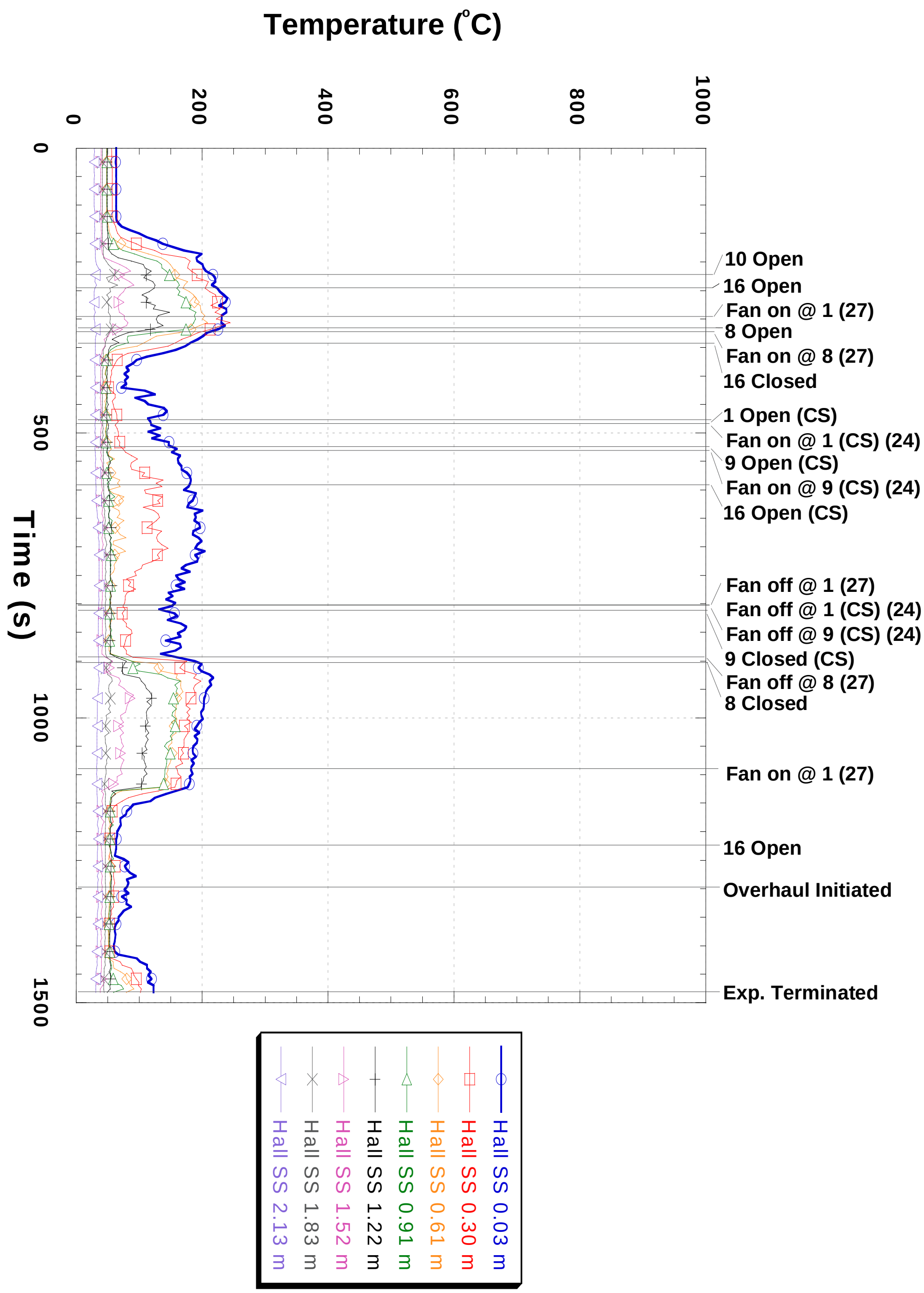

Figure 2. Detailed temperature vs. time for 1003 hallway adjacent to the south stair

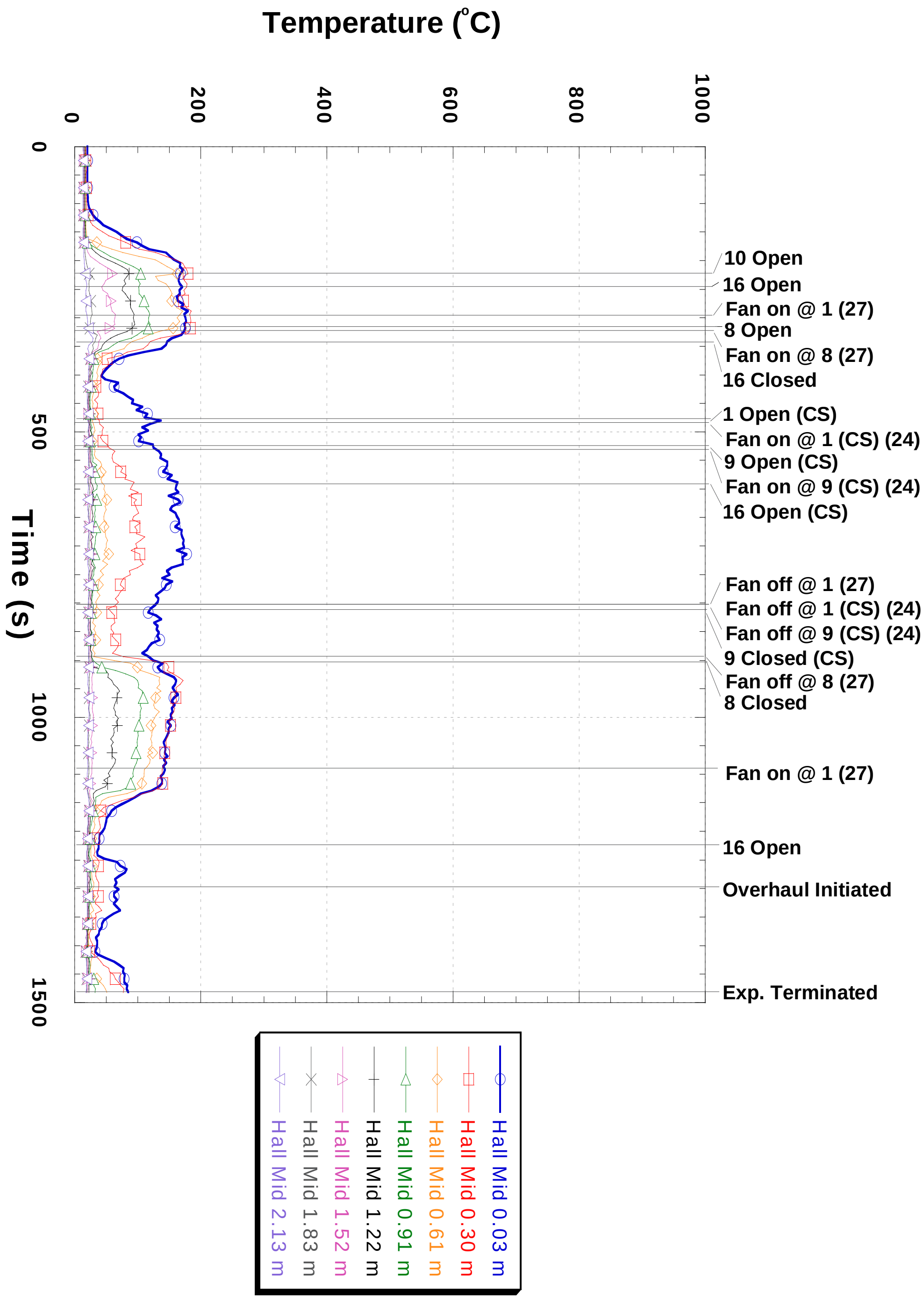

Figure 3. Detailed temperature vs. time for 1003 middle hallway

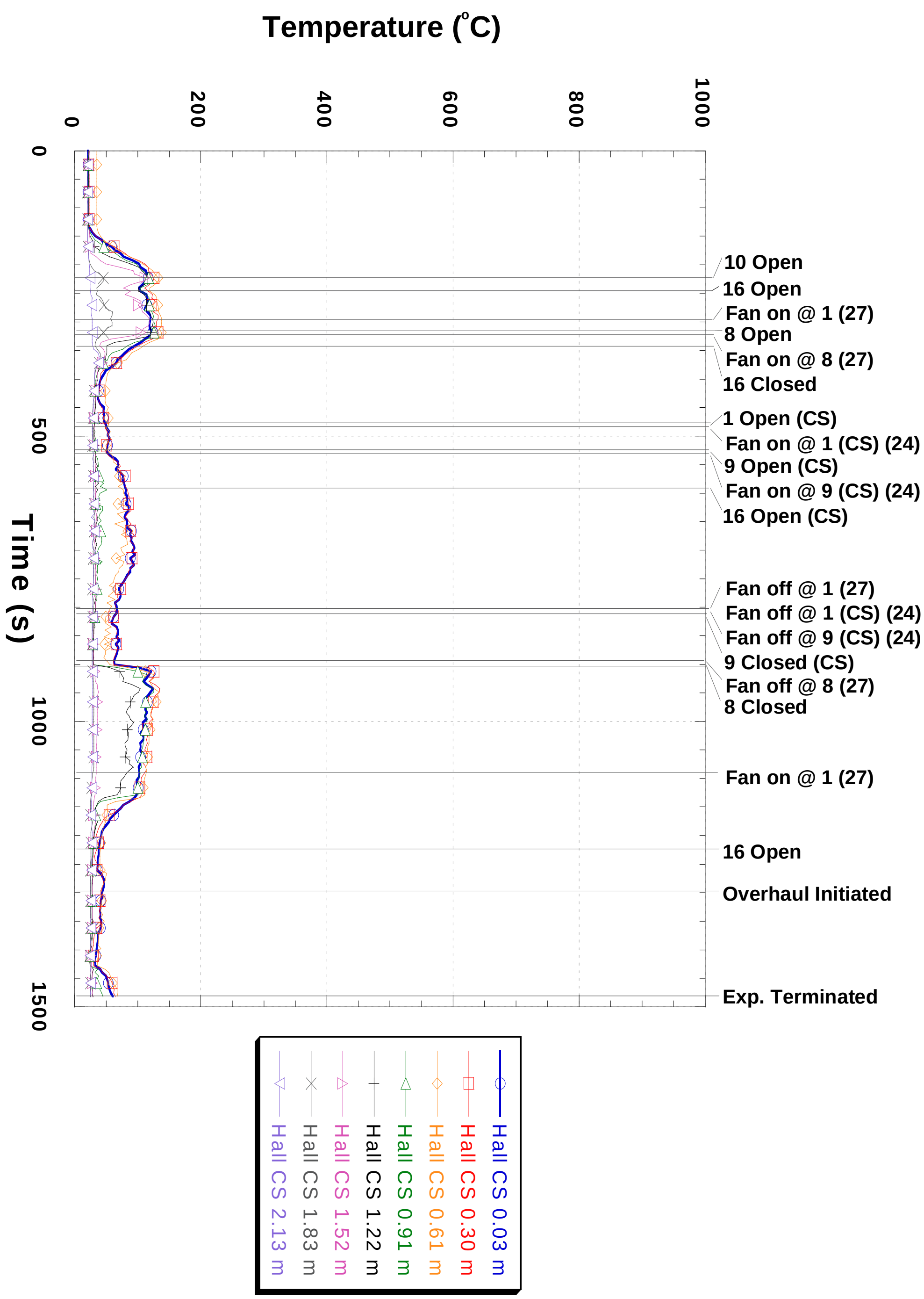

Figure 4. Detailed temperature vs. time for 1003 hallway adjacent to the center stair

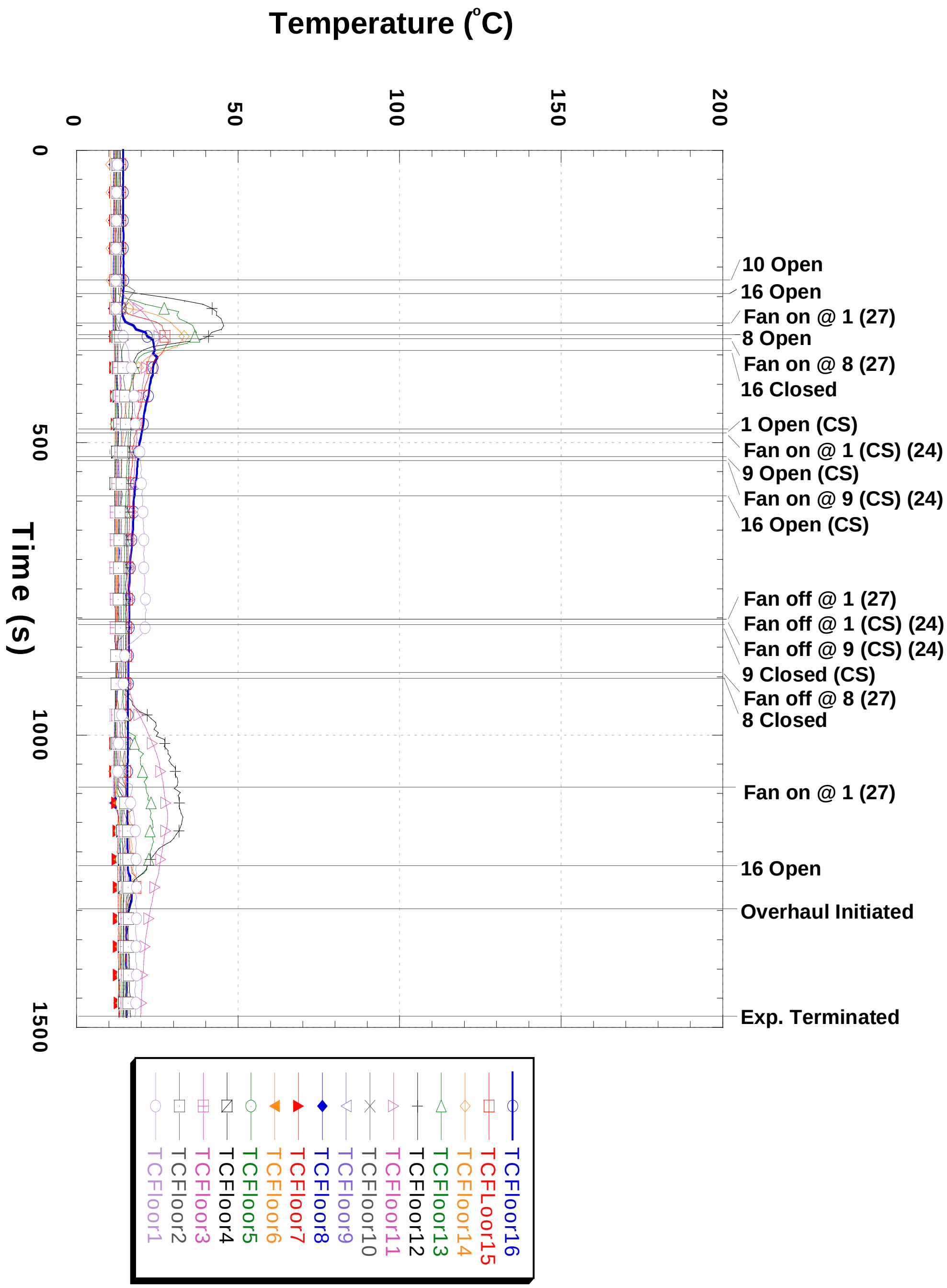

Figure 5. Detailed temperature vs. time for 1003 south stair

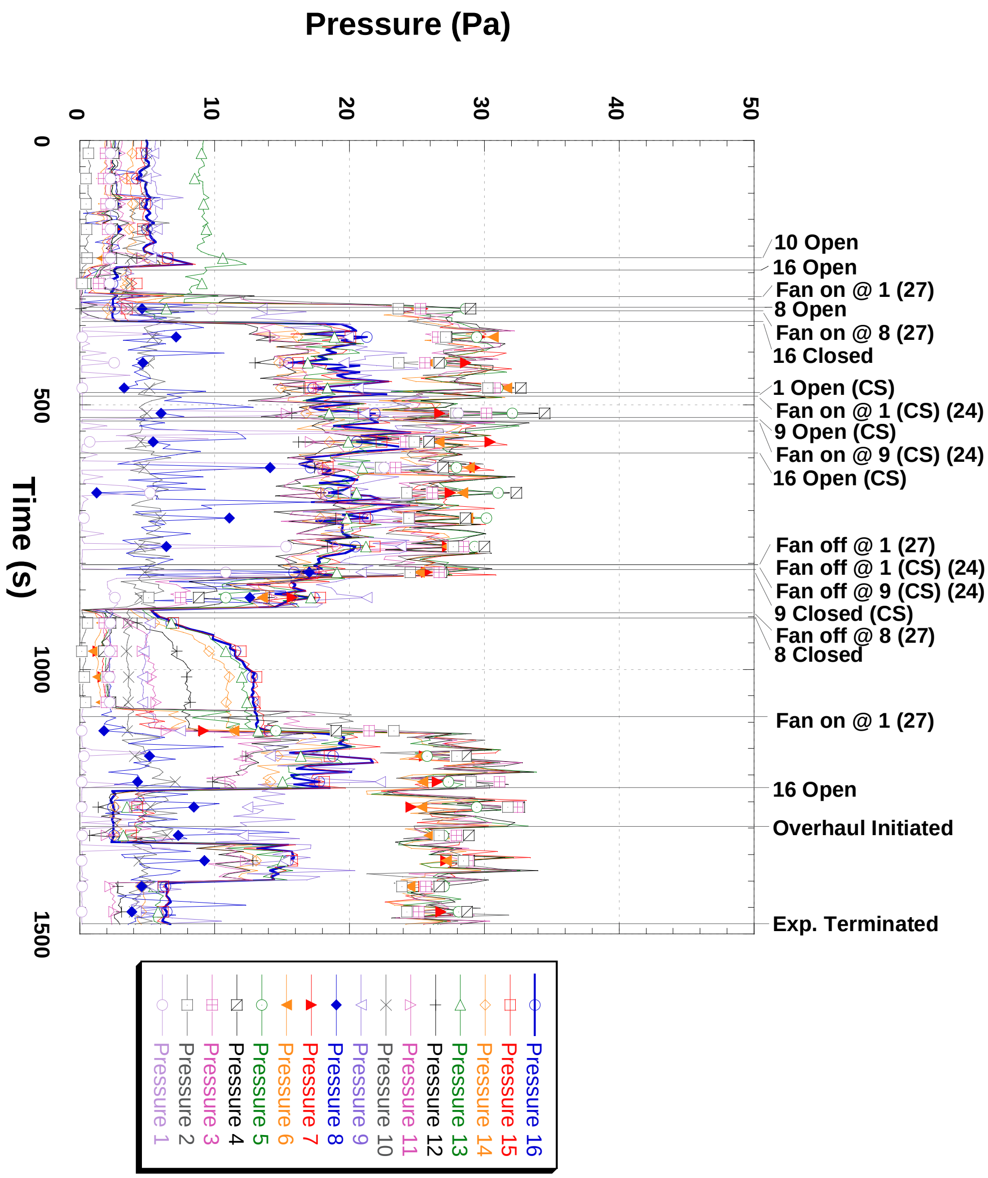

Figure 6. Detailed pressure vs. time for 1003 south stair

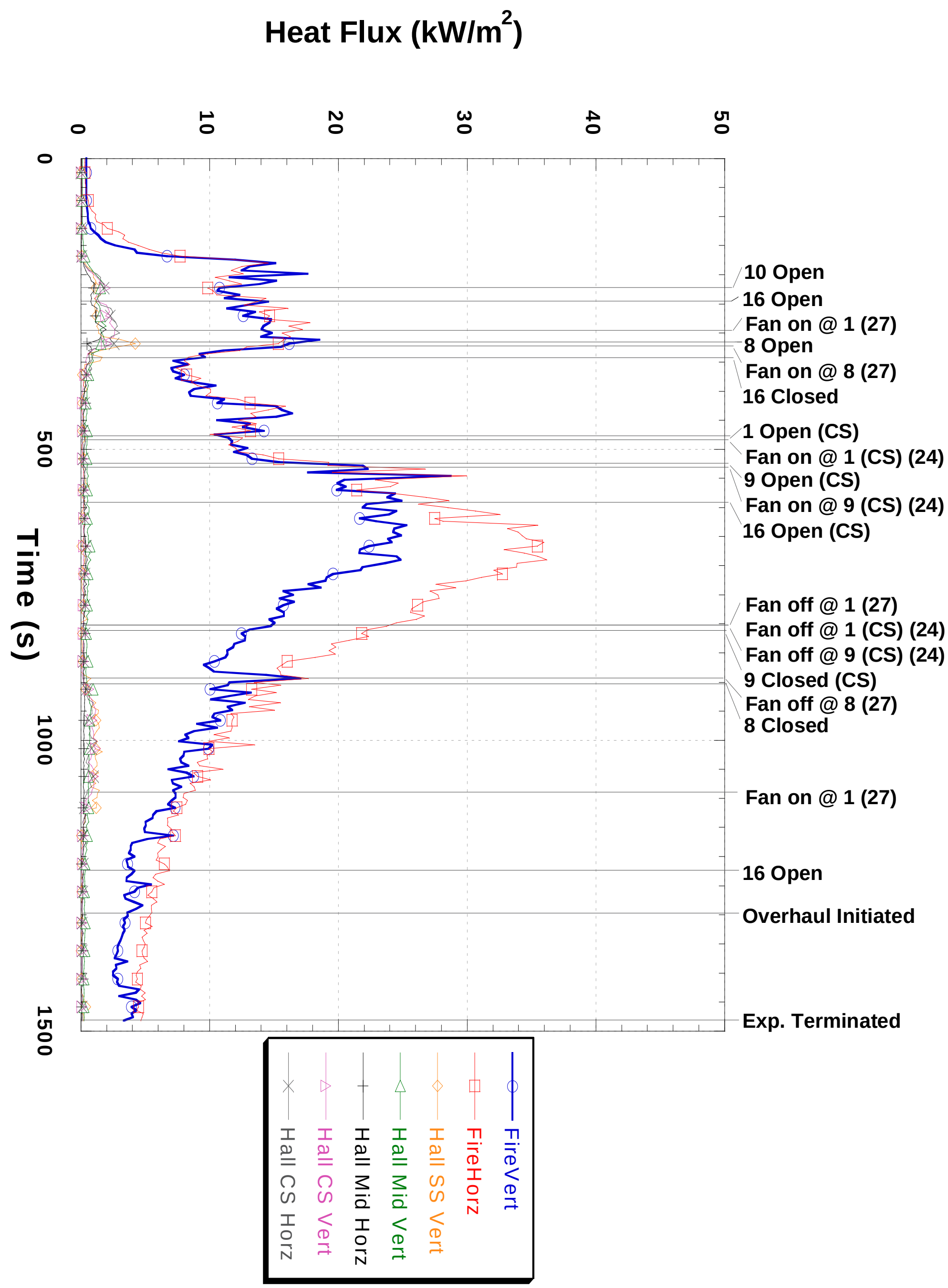

Figure 7. Detailed heat flux vs. time for 1003

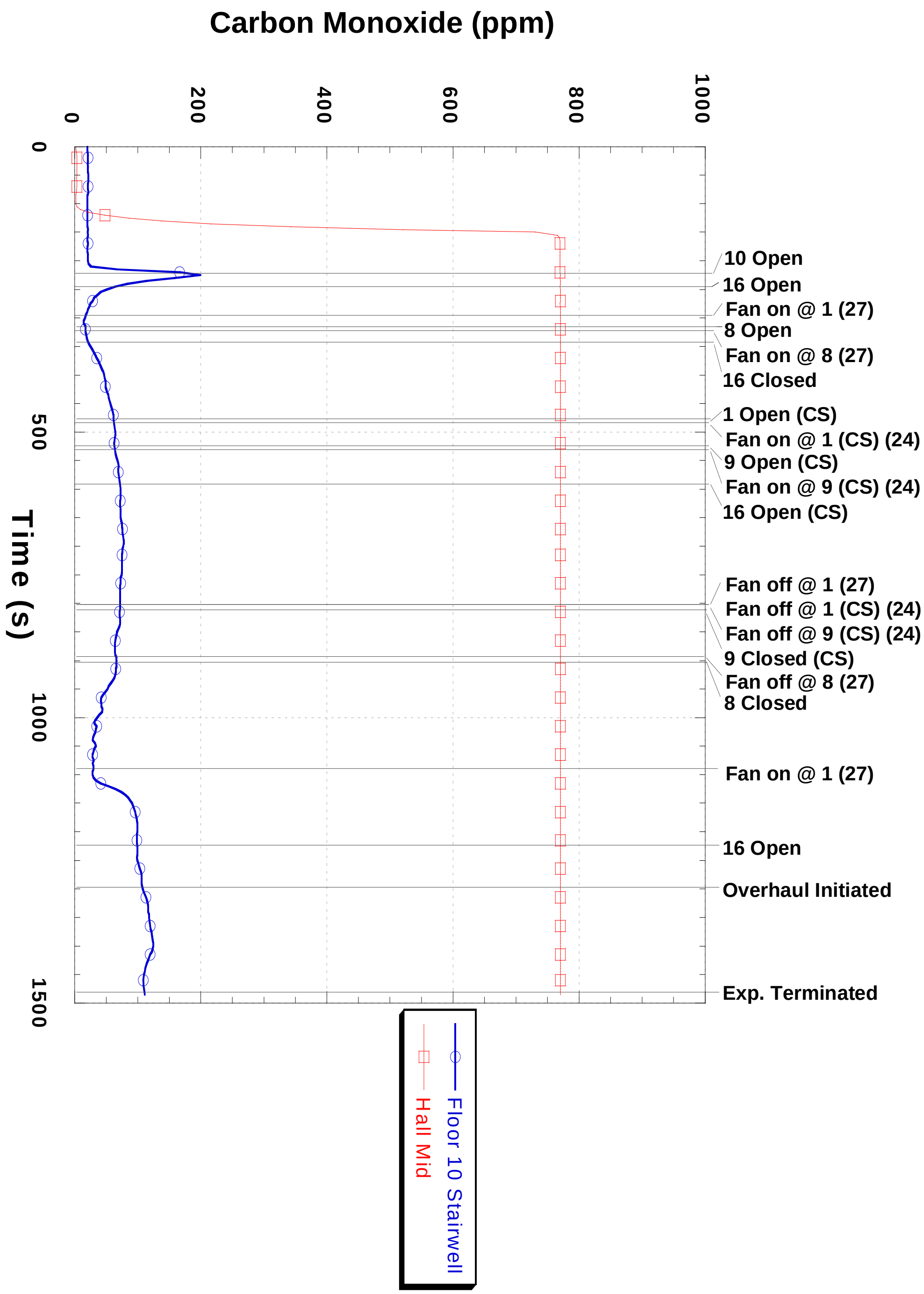

Figure 8. Detailed carbon monoxide vs. time for 1003

Appendix E. Detailed Data for Apartment 1005

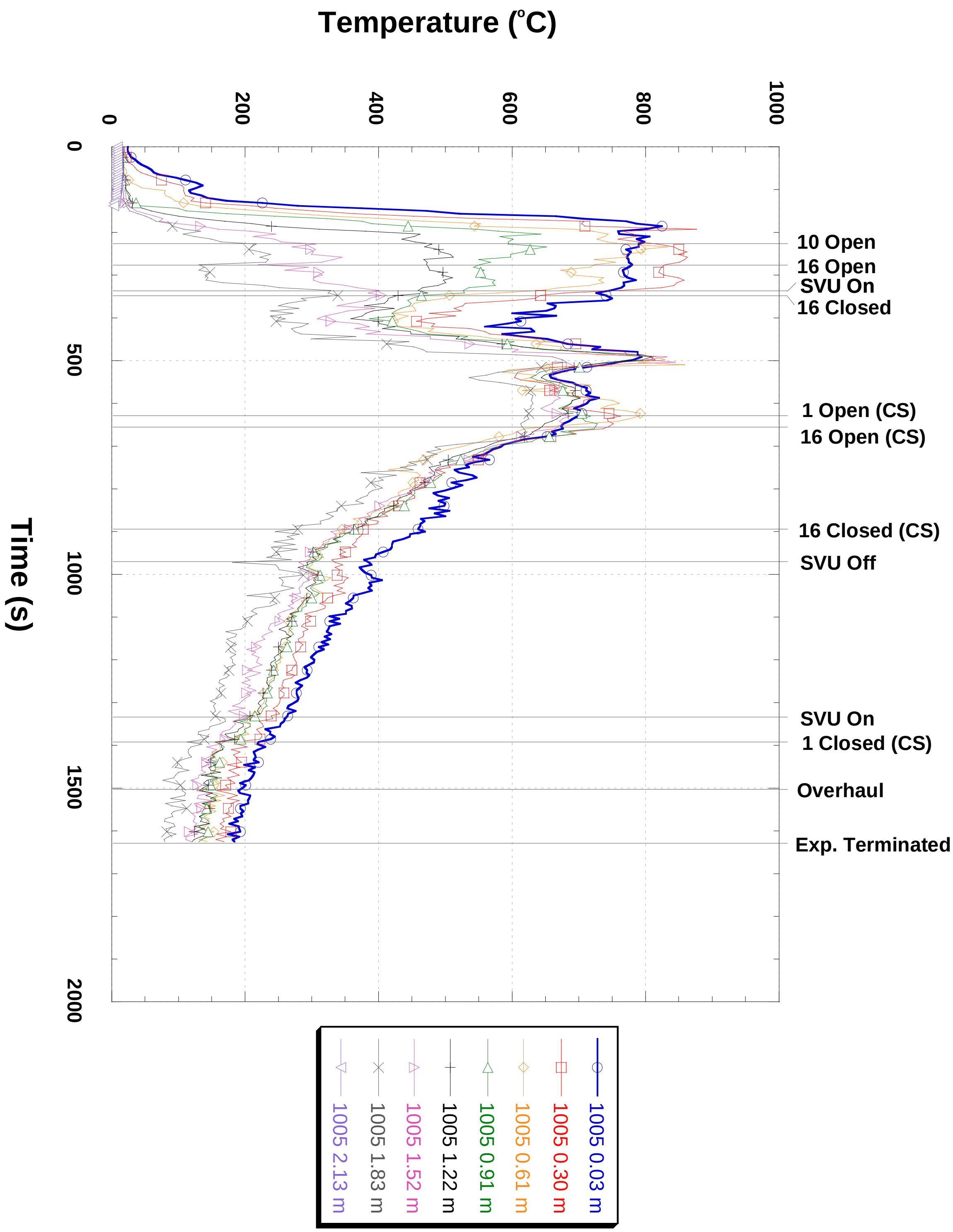

Figure 1. Detailed temperature vs. time for 1005 living room

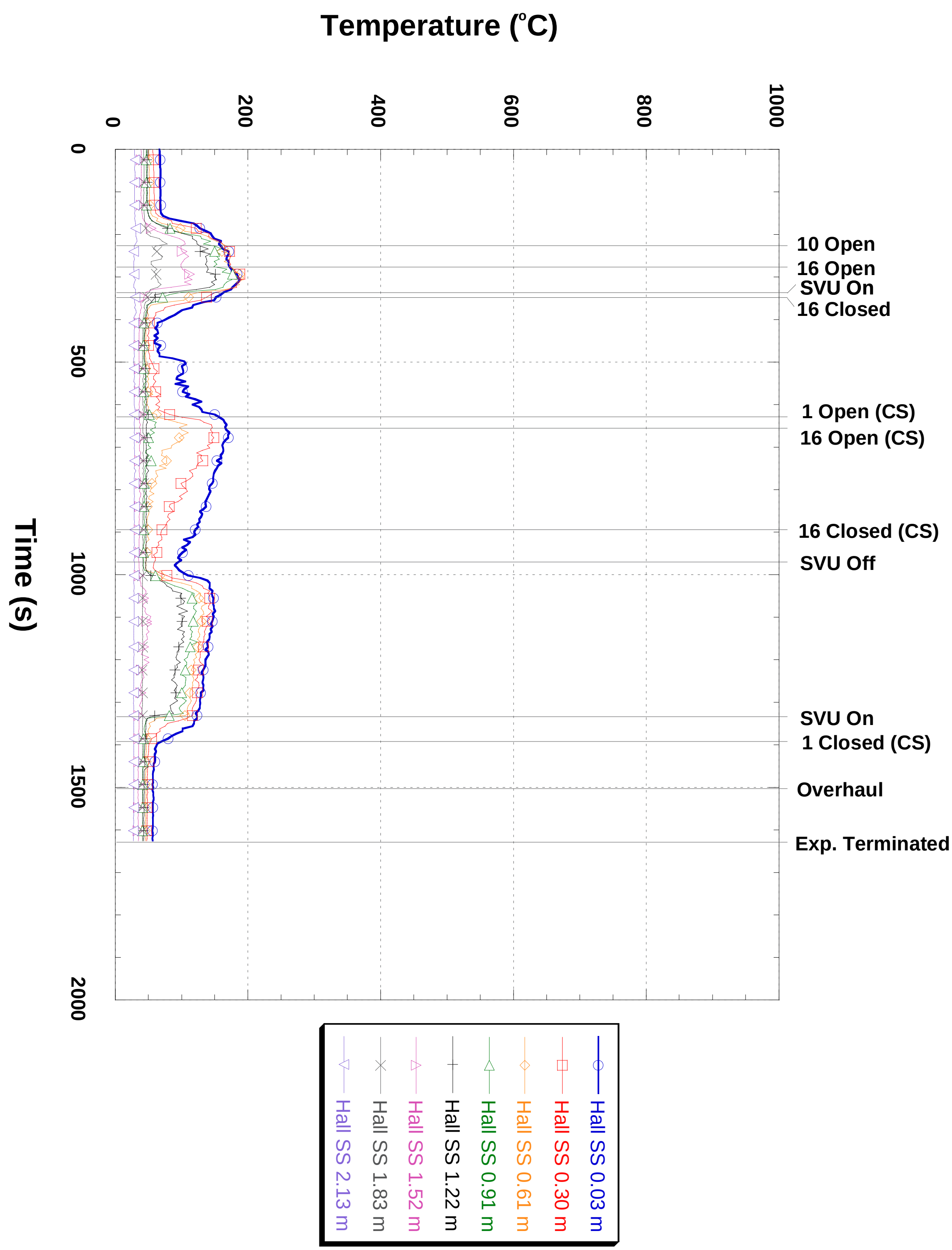

Figure 2. Detailed temperature vs. time for 1005 hallway adjacent to the south stair

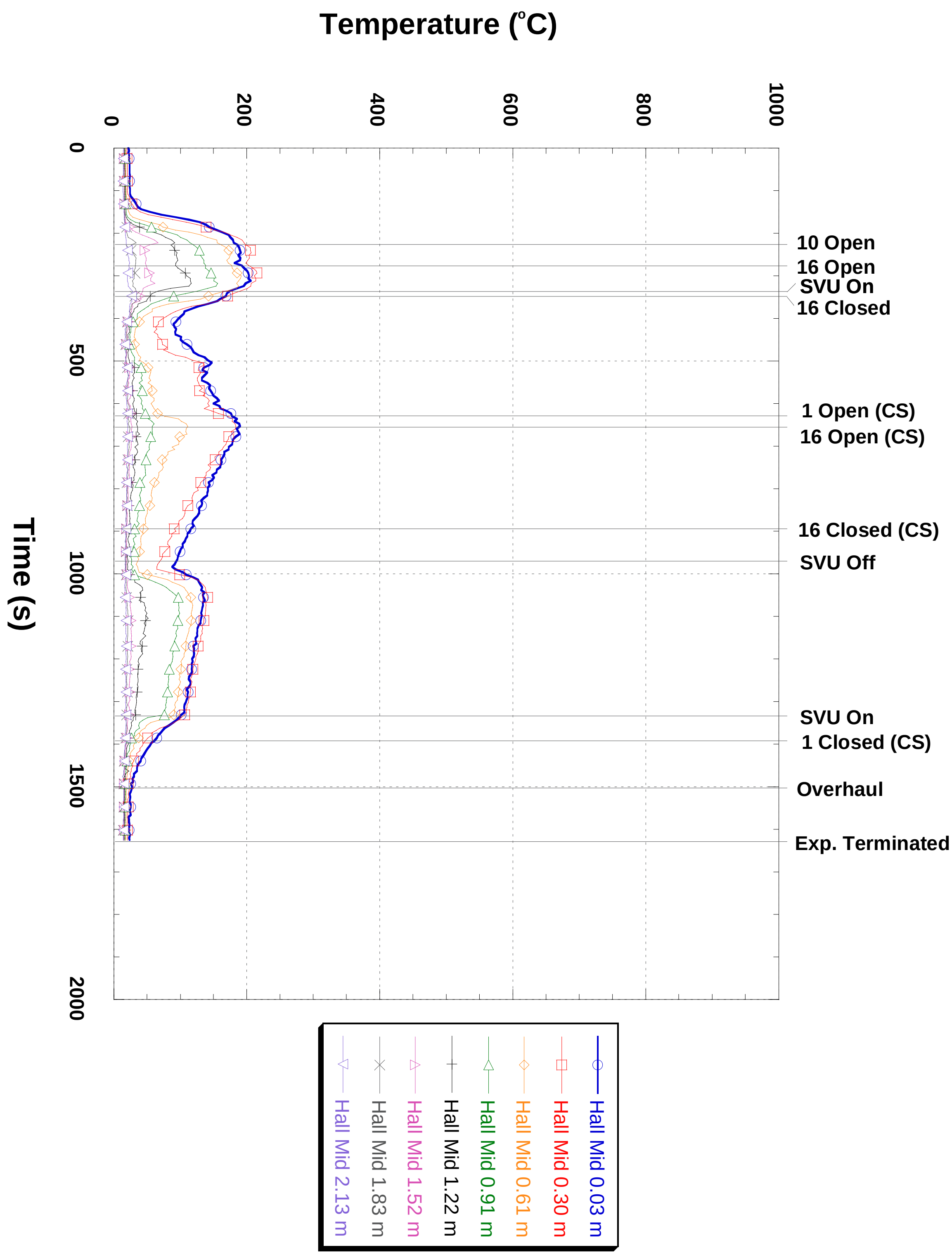

Figure 3. Detailed temperature vs. time for 1005 middle hallway

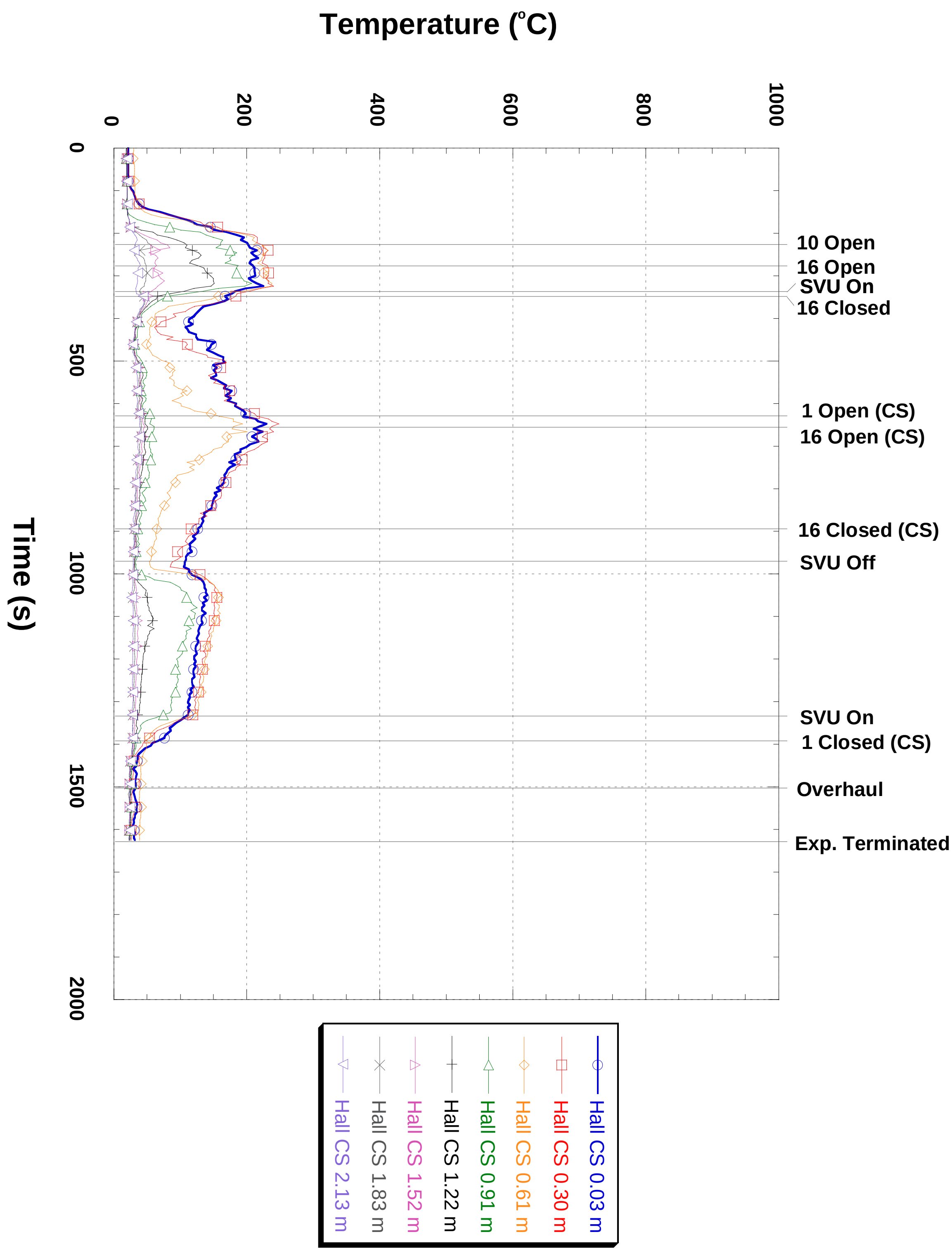

Figure 4. Detailed temperature vs. time for 1005 hallway adjacent to the center stair

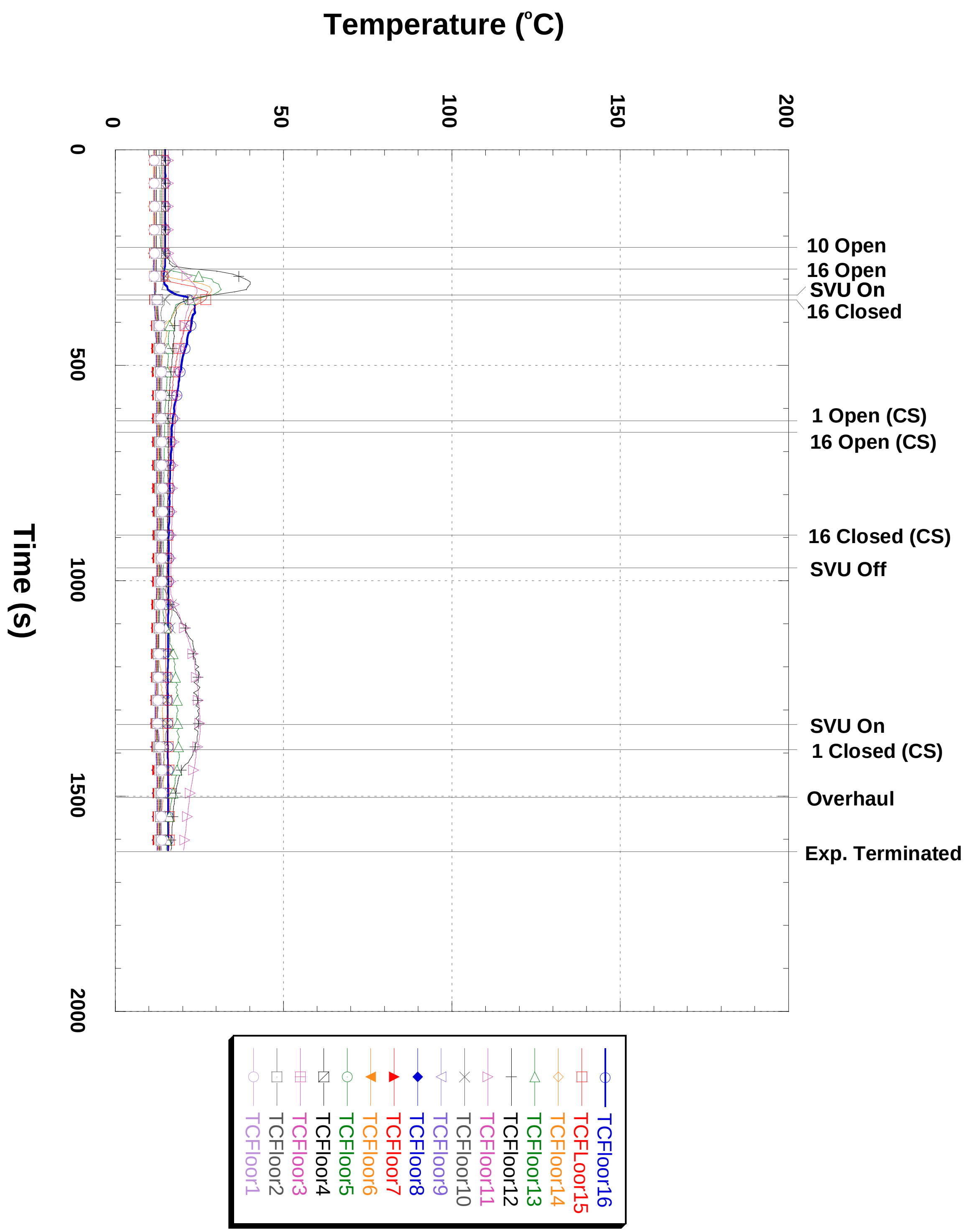

Figure 5. Detailed temperature vs. time for 1005 south stair

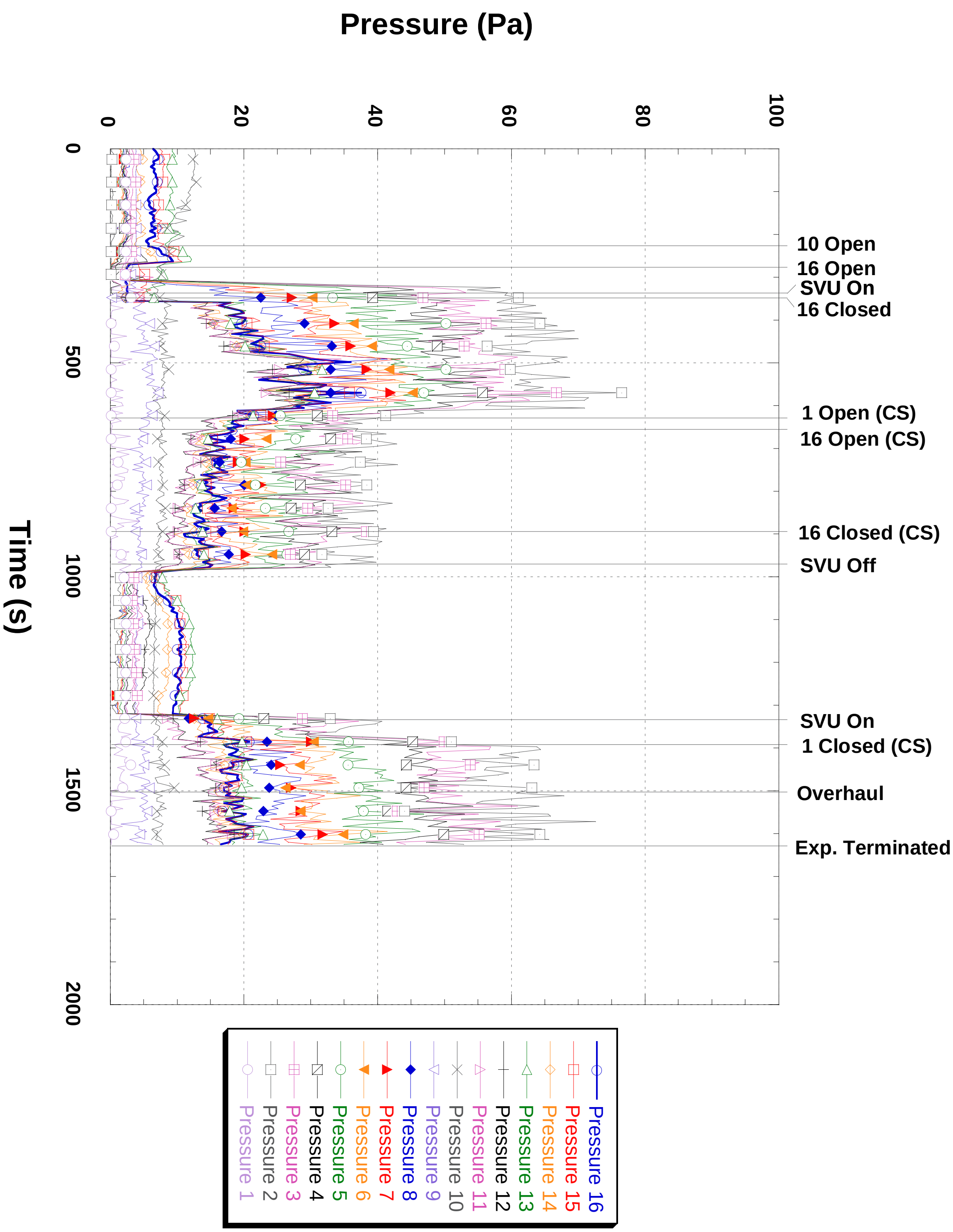

Figure 6. Detailed pressure vs. time for 1005 south stair

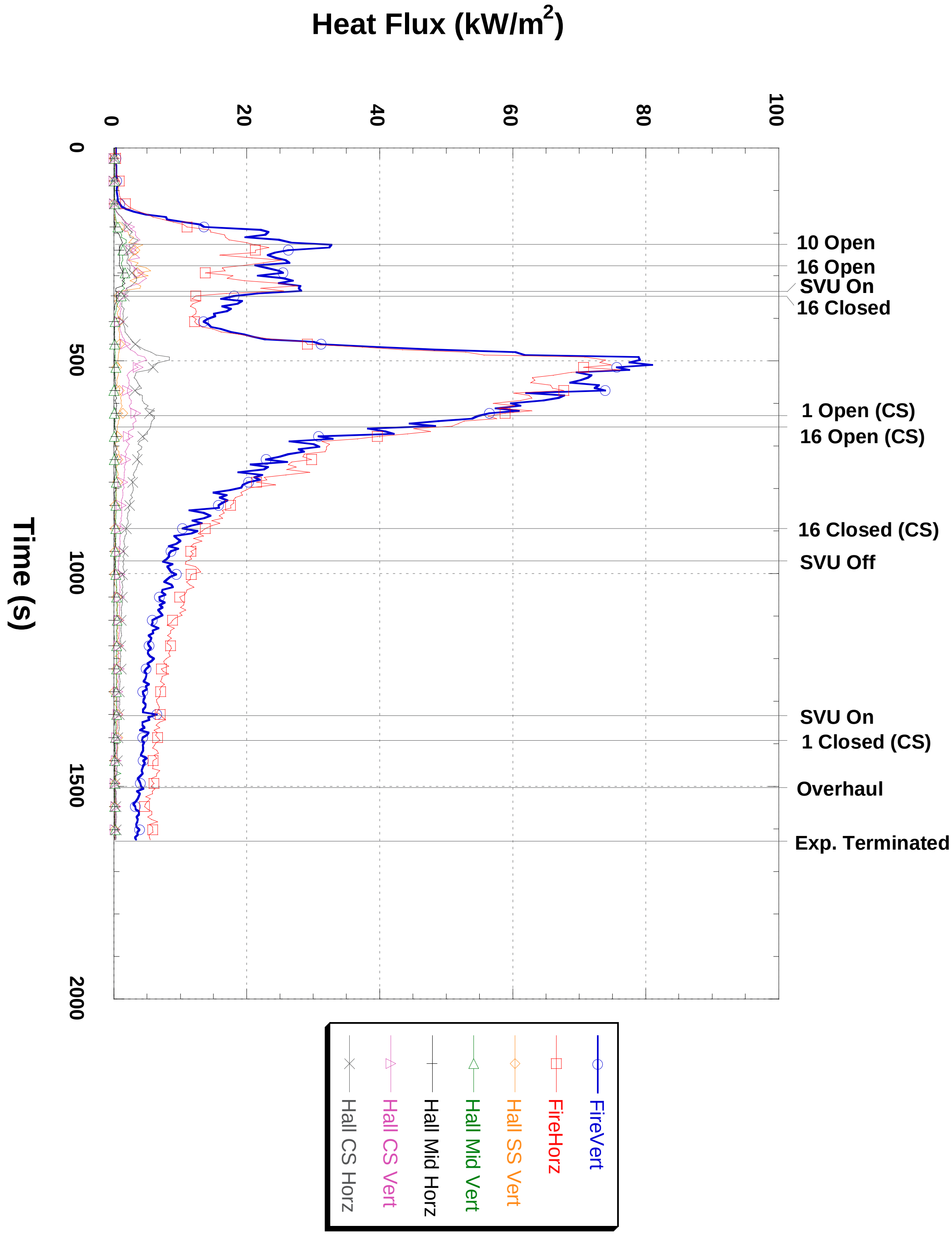

Figure 7. Detailed heat flux vs. time for 1005

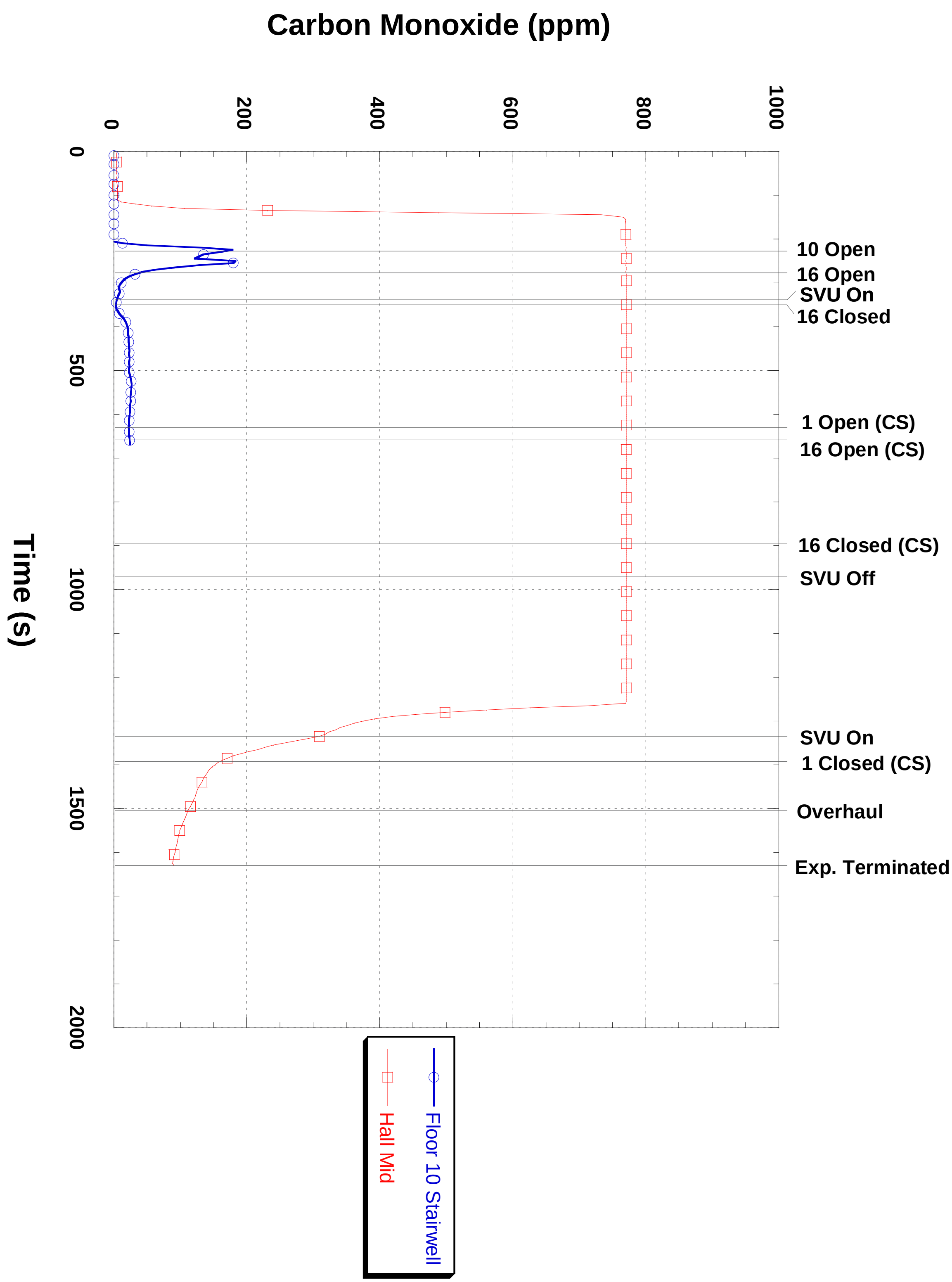

Figure 8. Detailed carbon monoxide vs. time for 1005

Appendix F. Detailed Data for Apartment 303

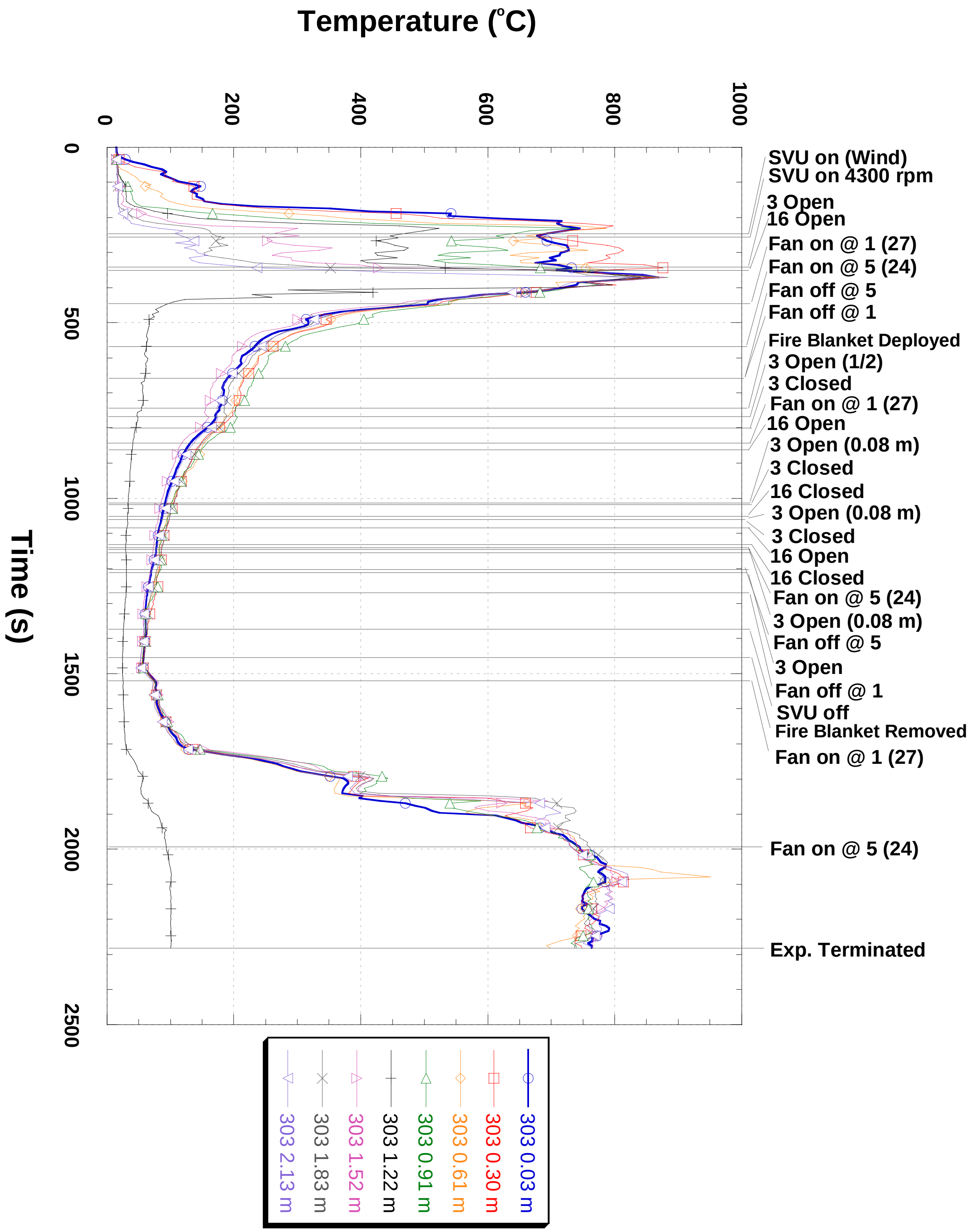

Figure 1. Detailed temperature vs. time for 303 living room

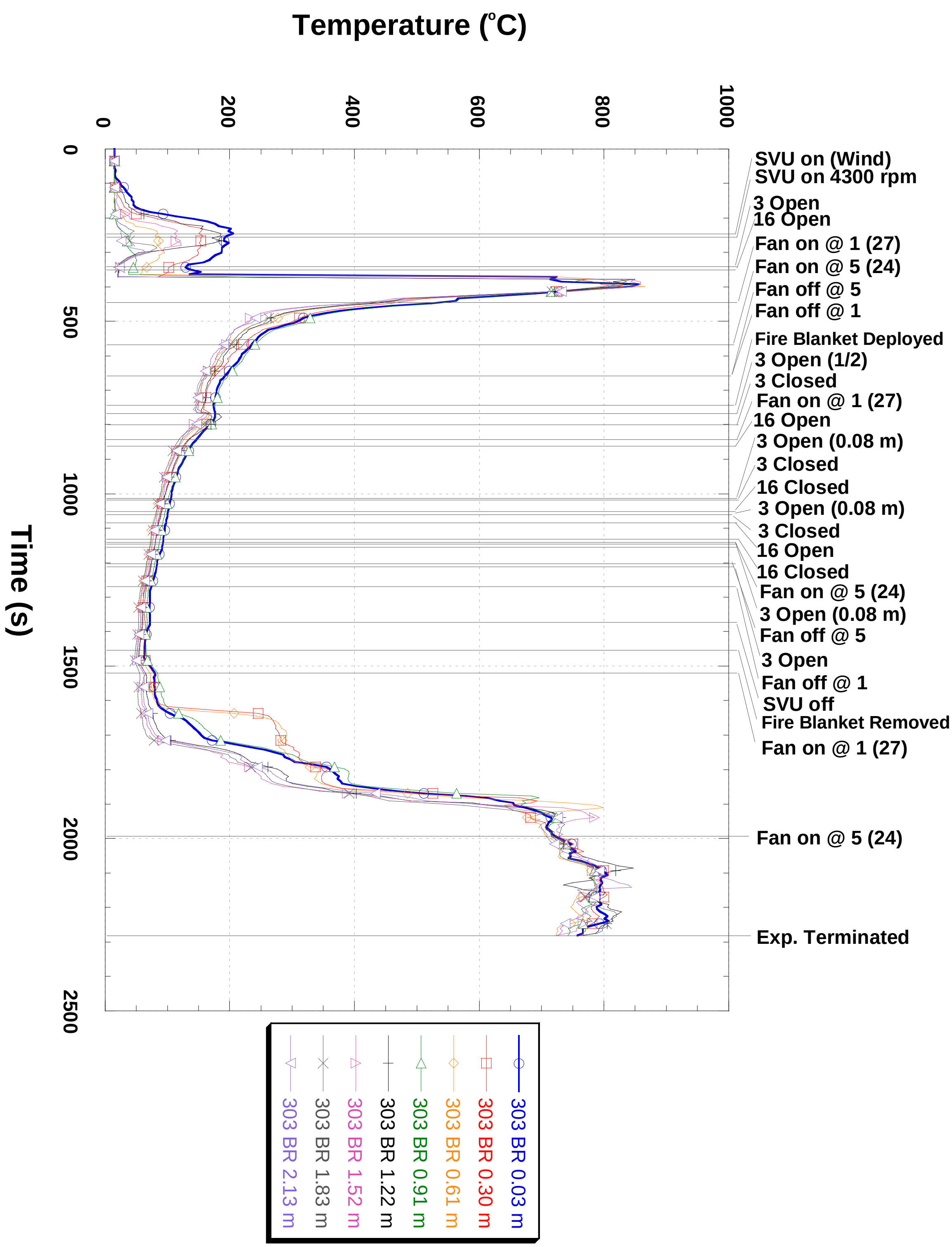

Figure 2. Detailed temperature vs. time for 303 hallway adjacent to the south stair

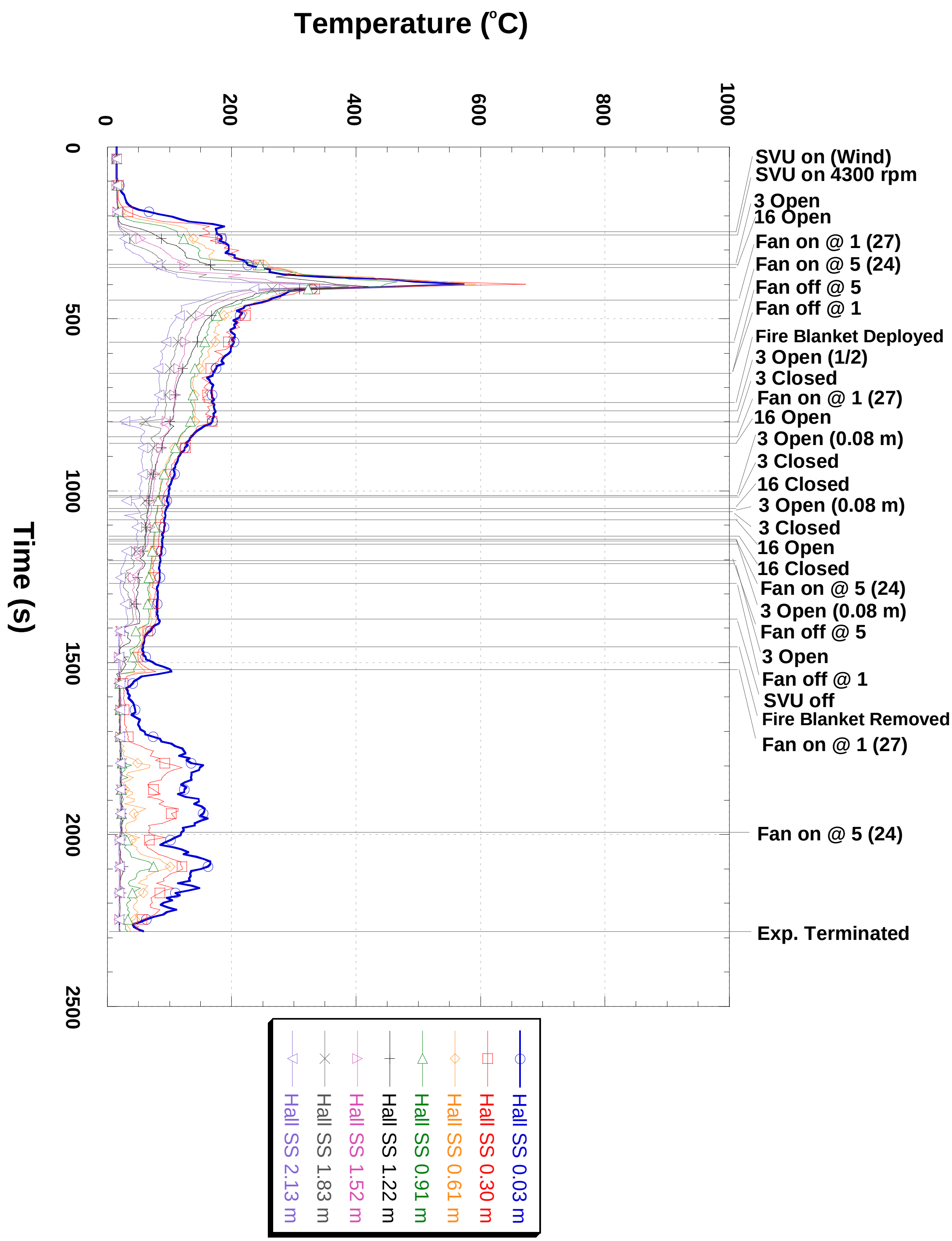

Figure 3. Detailed temperature vs. time for 303 hallway adjacent to the south stair

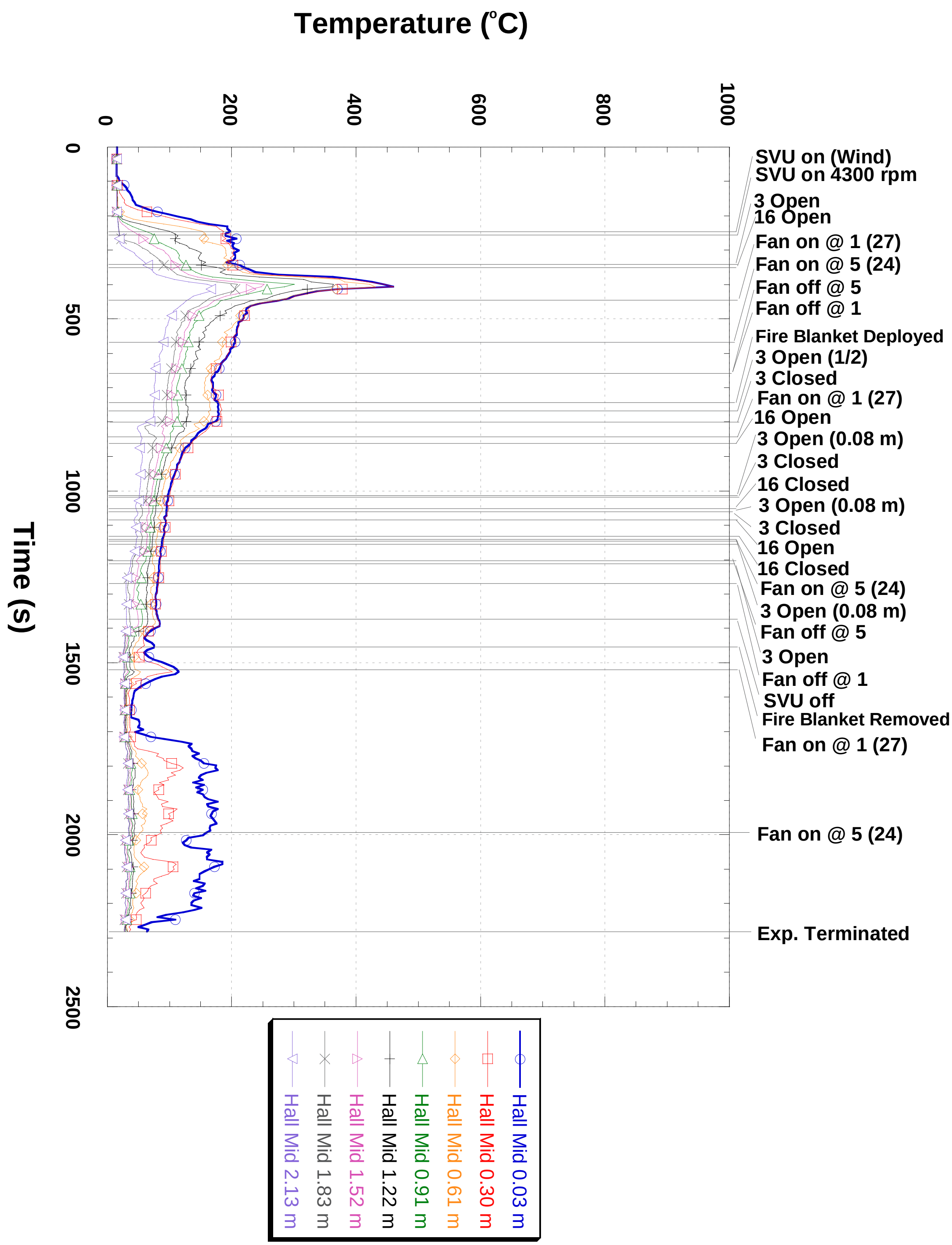

Figure 4. Detailed temperature vs. time for 303 middle hallway

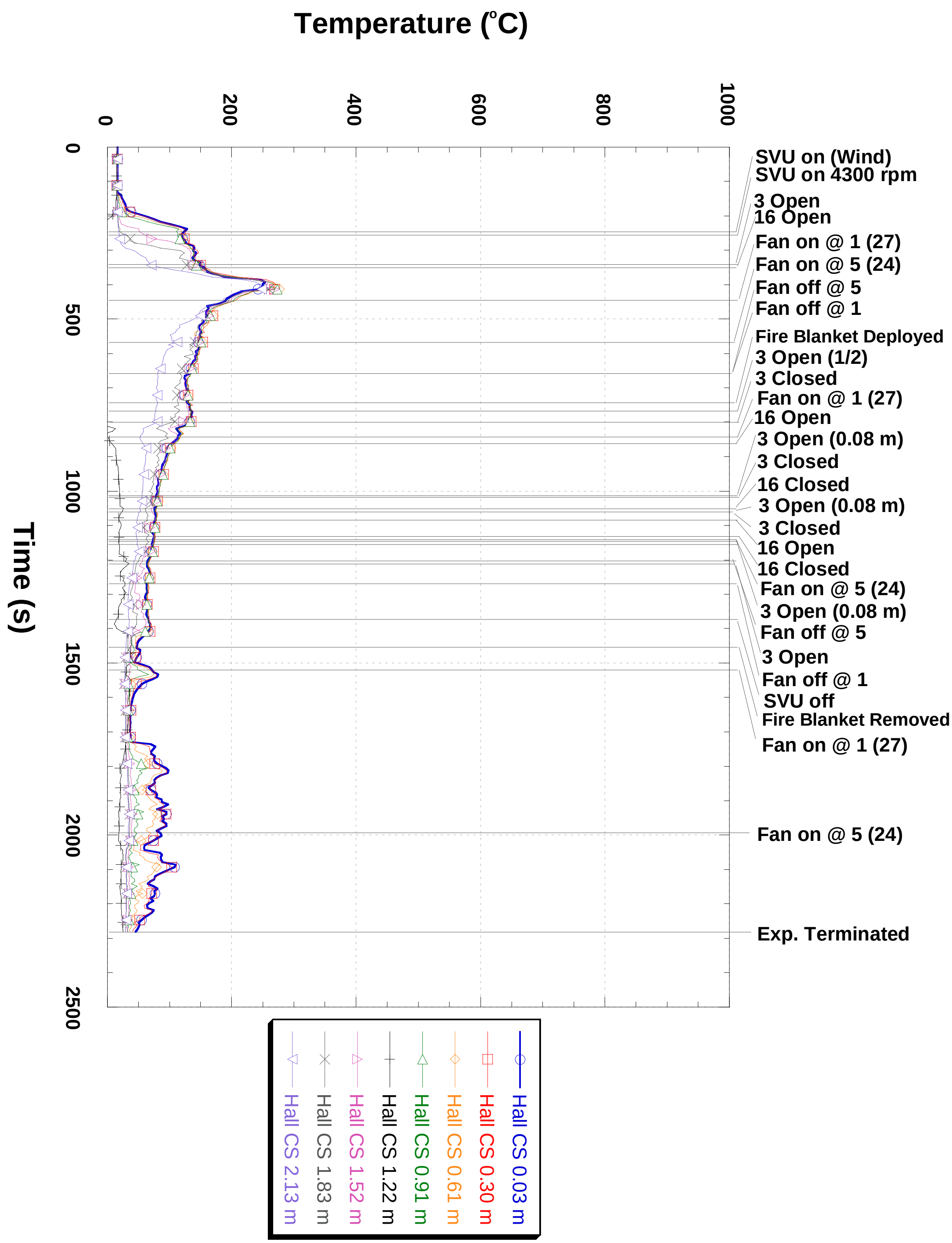

Figure 5. Detailed temperature vs. time for 303 hallway adjacent to the center stair

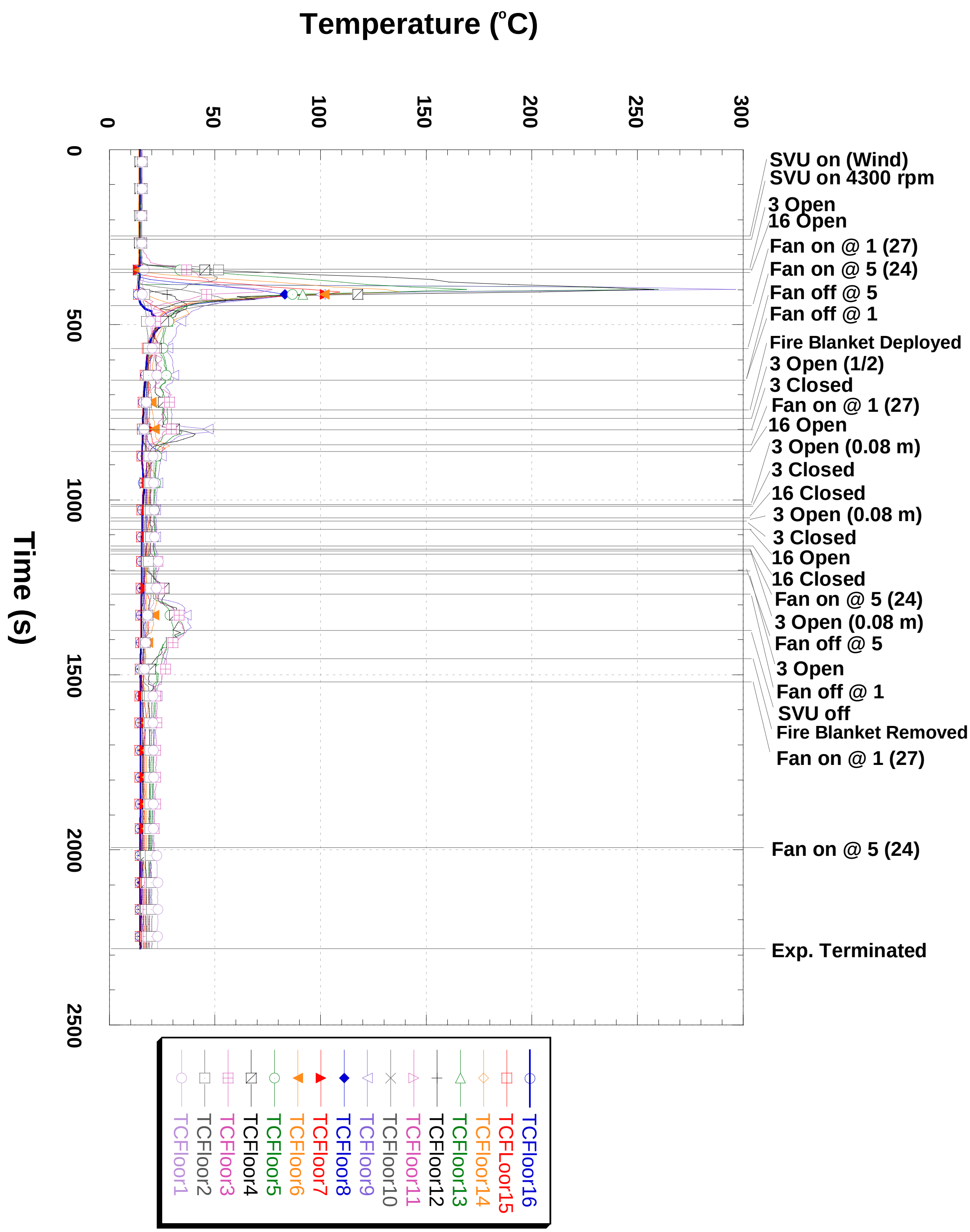

Figure 6. Detailed temperature vs. time for 303 south stair

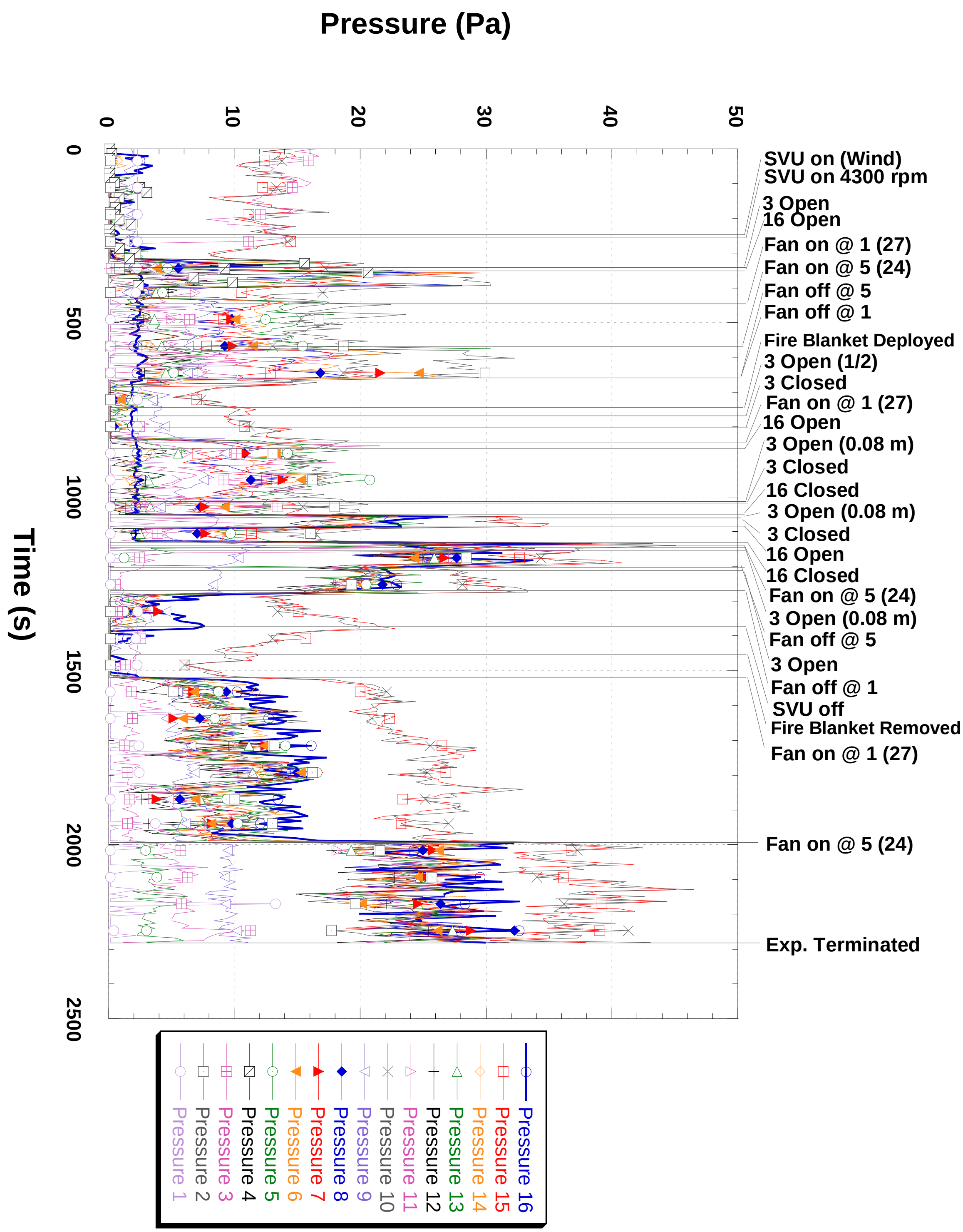

Figure 7. Detailed pressure vs. time for 303 south stair

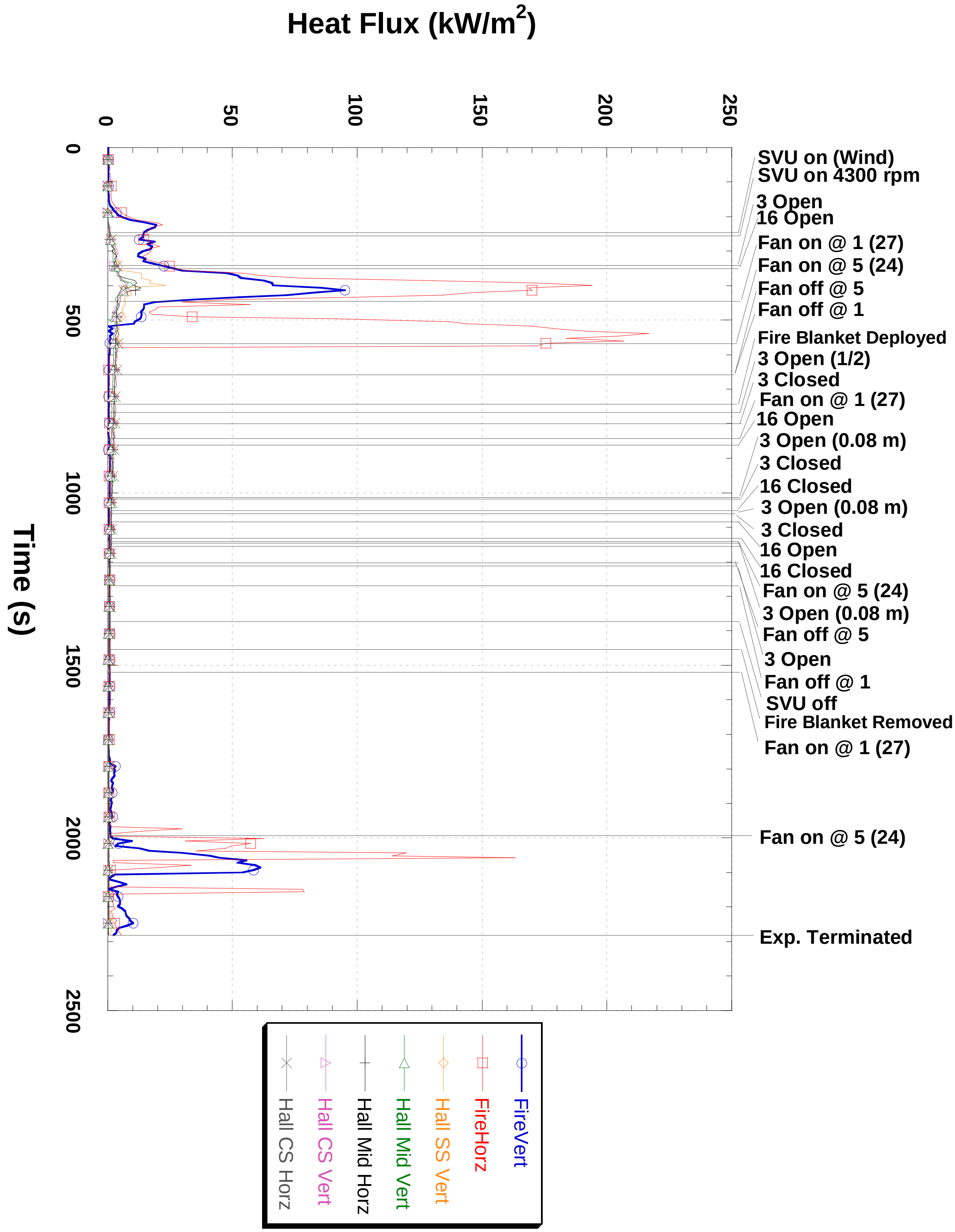

Figure 8. Detailed heat flux vs. time for 303

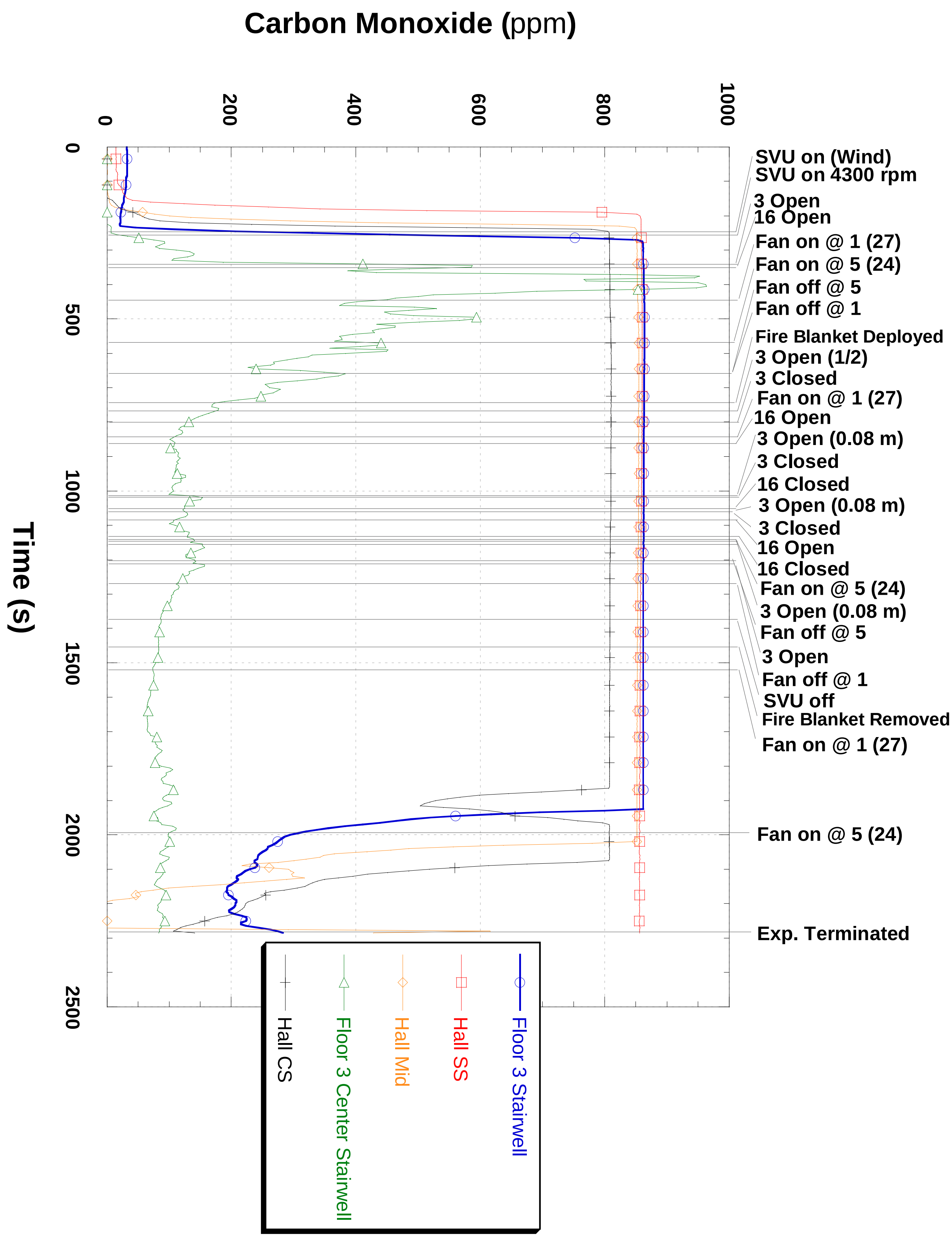

Figure 9. Detailed carbon monoxide vs. time for 303

Appendix G. Detailed Data for Apartment 304

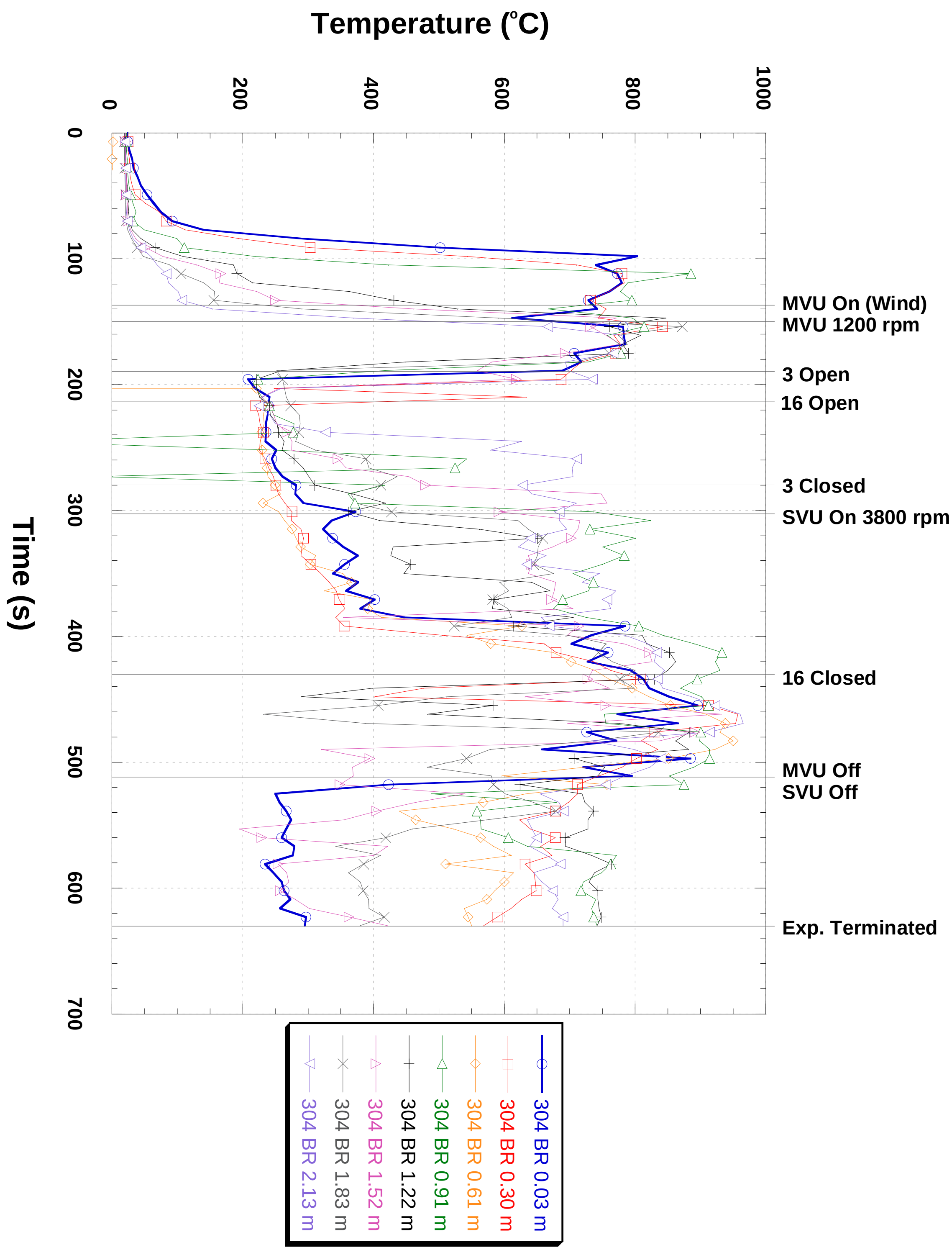

Figure 1. Detailed temperature vs. time for 304 bedroom

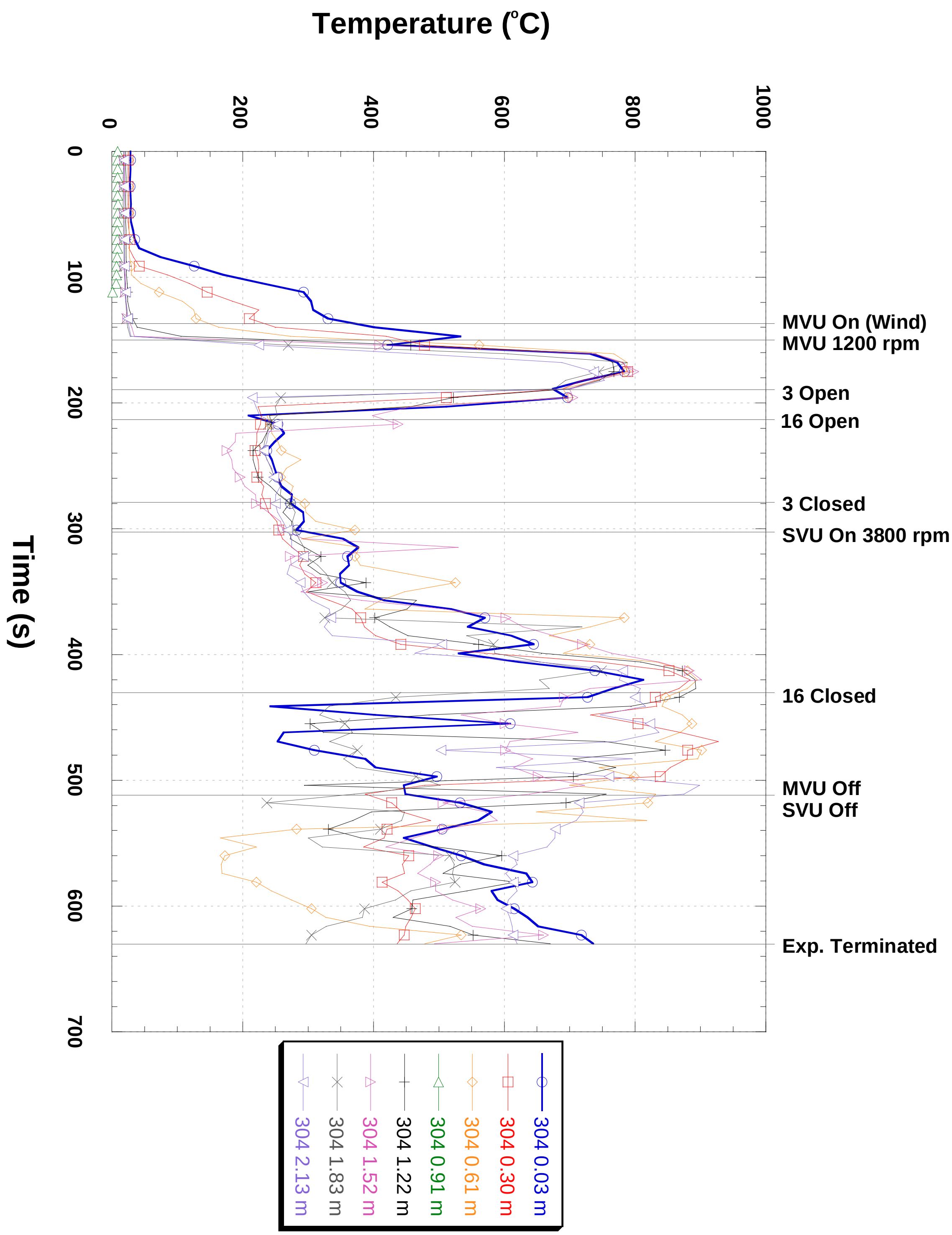

Figure 2. Detailed temperature vs. time for 304 living room

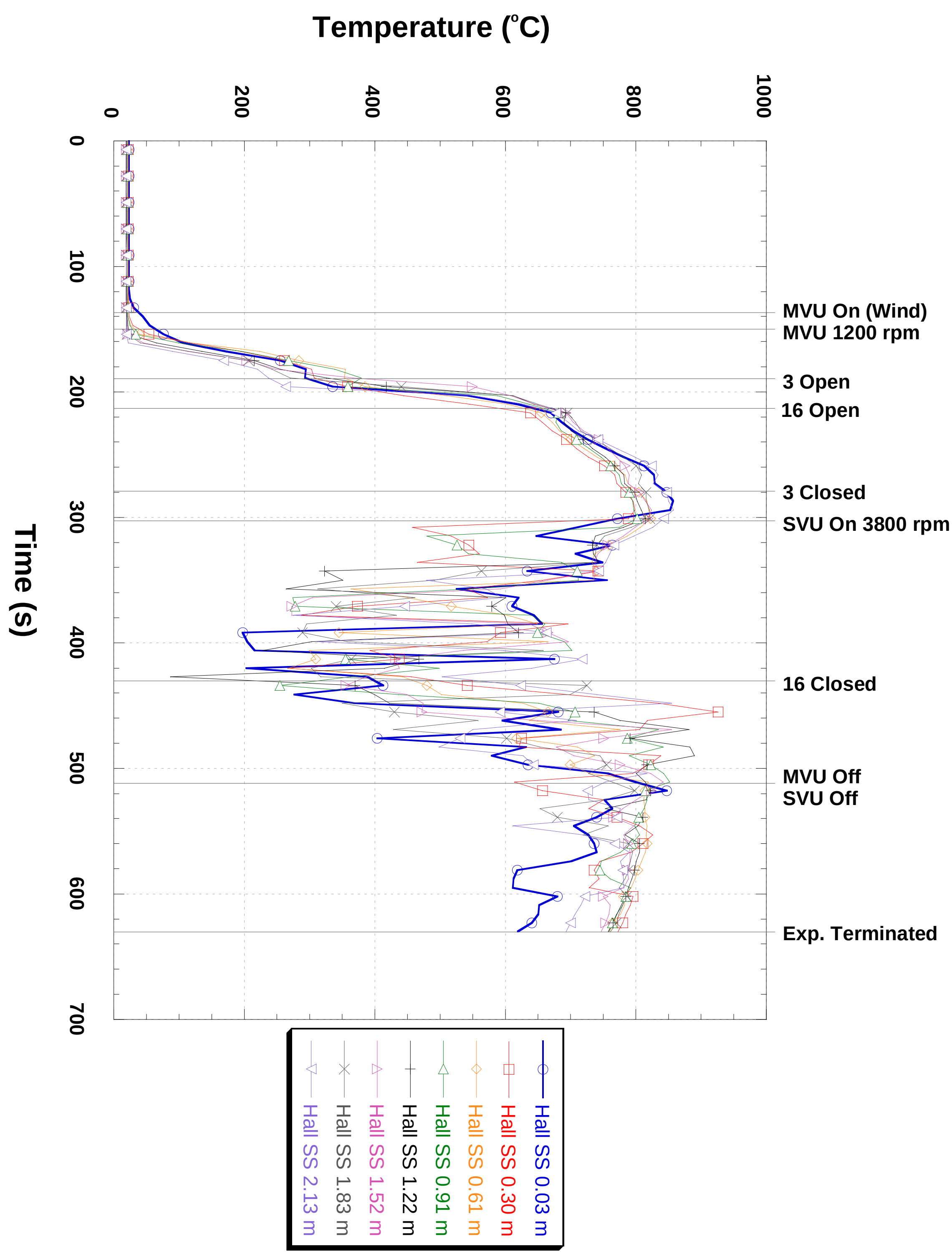

Figure 3. Detailed temperature vs. time for 304 hallway adjacent to the south stair

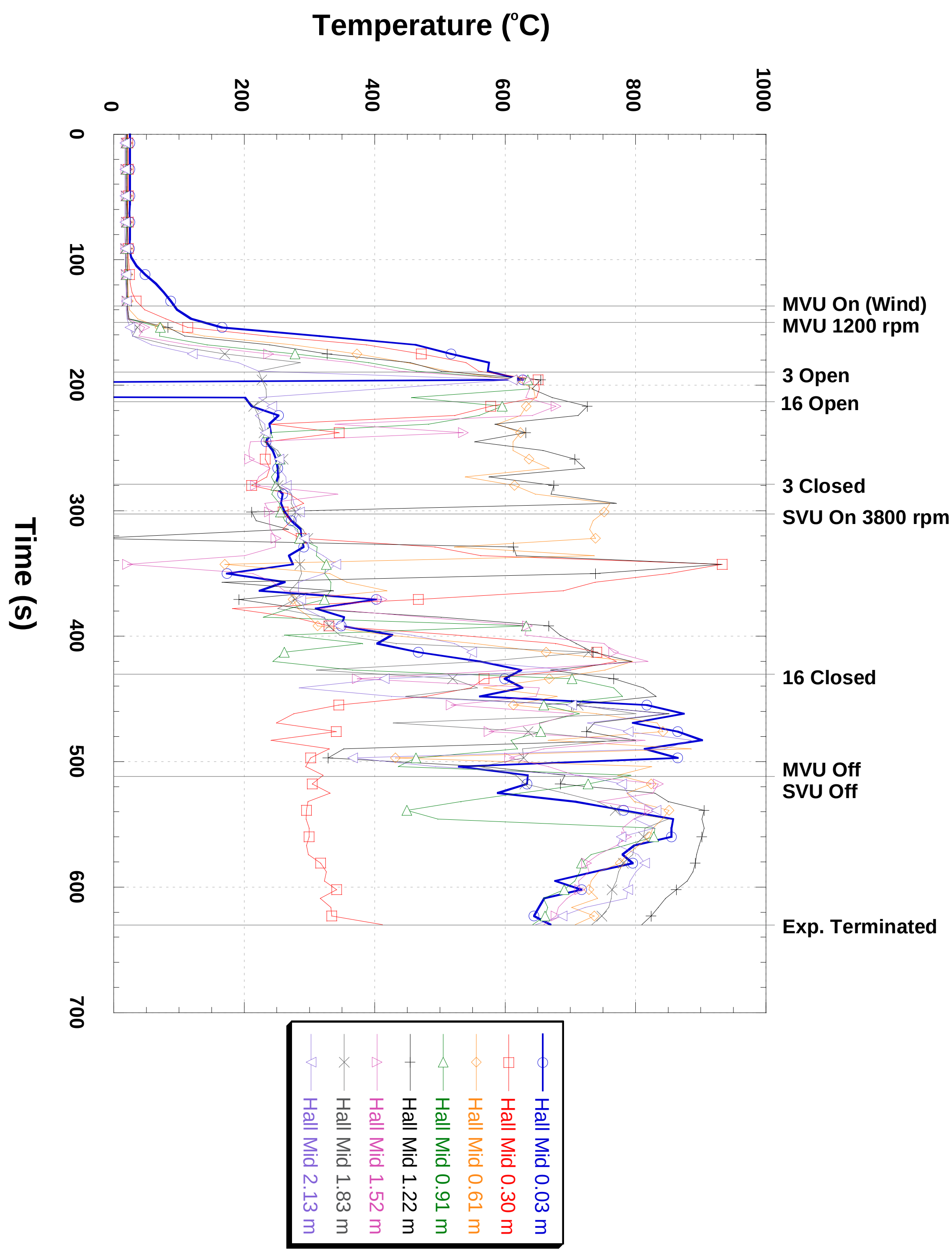

Figure 4. Detailed temperature vs. time for 304 middle hallway

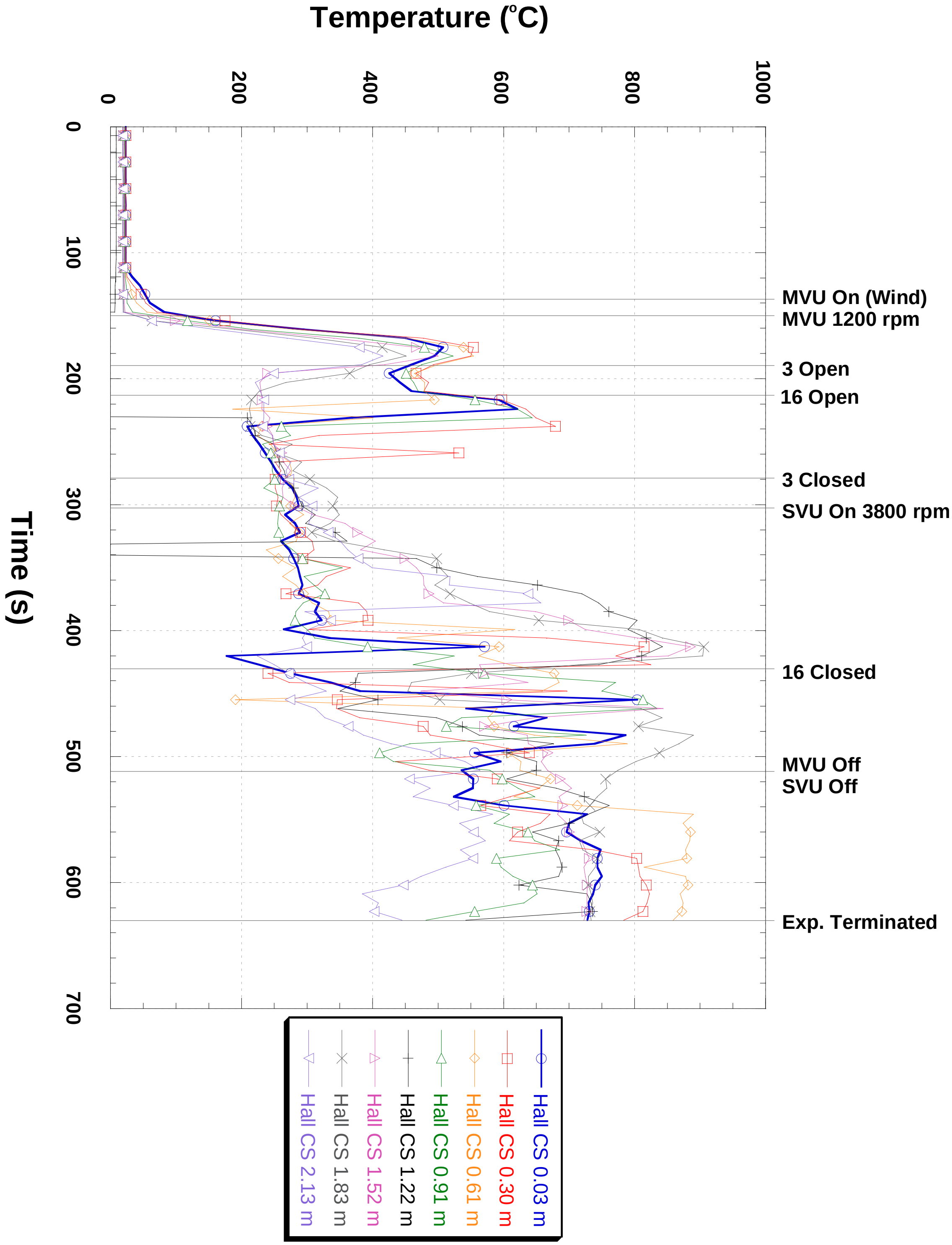

Figure 5. Detailed temperature vs. time for 304 hallway adjacent to the center stair

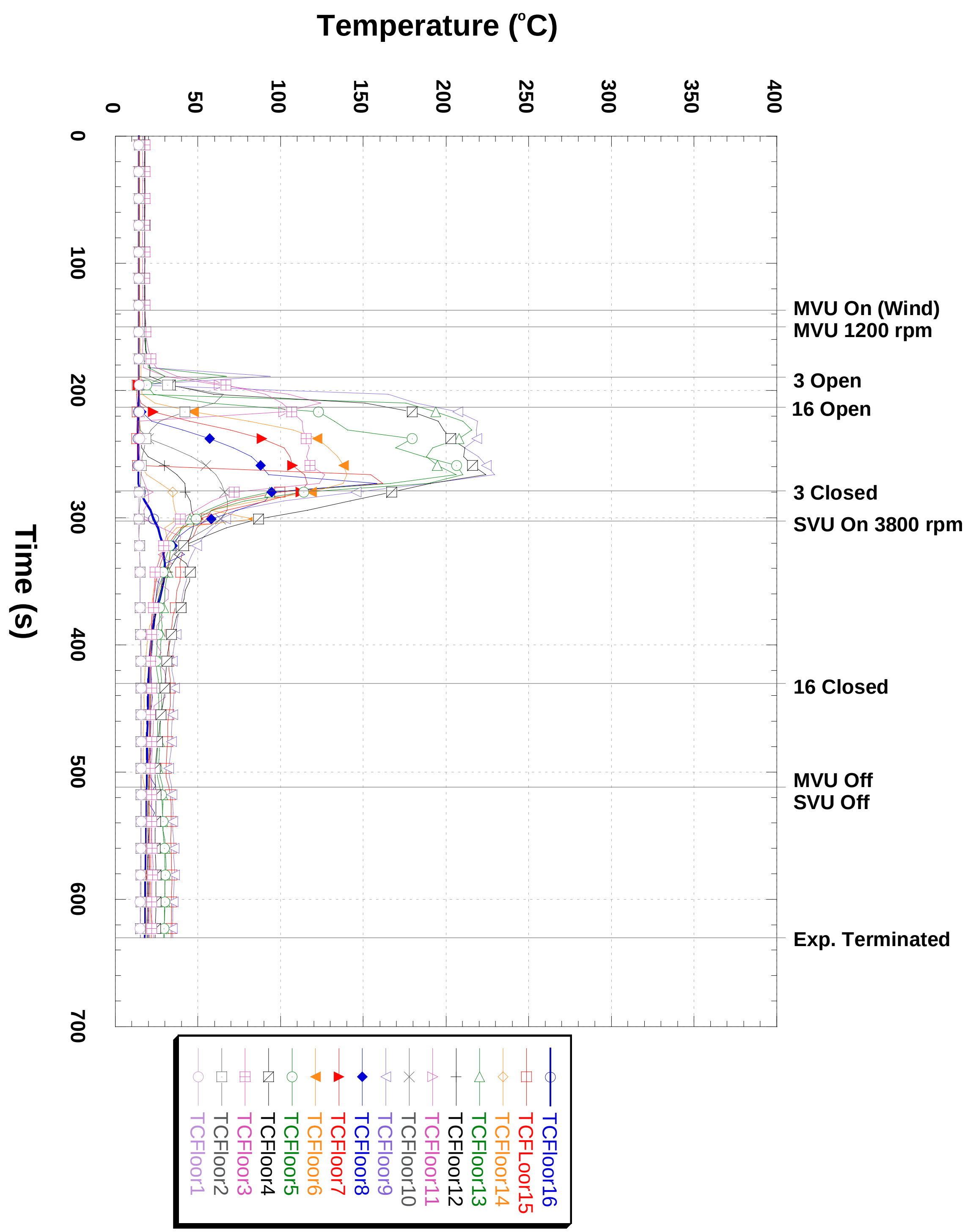

Figure 6. Detailed temperature vs. time for 304 south stair

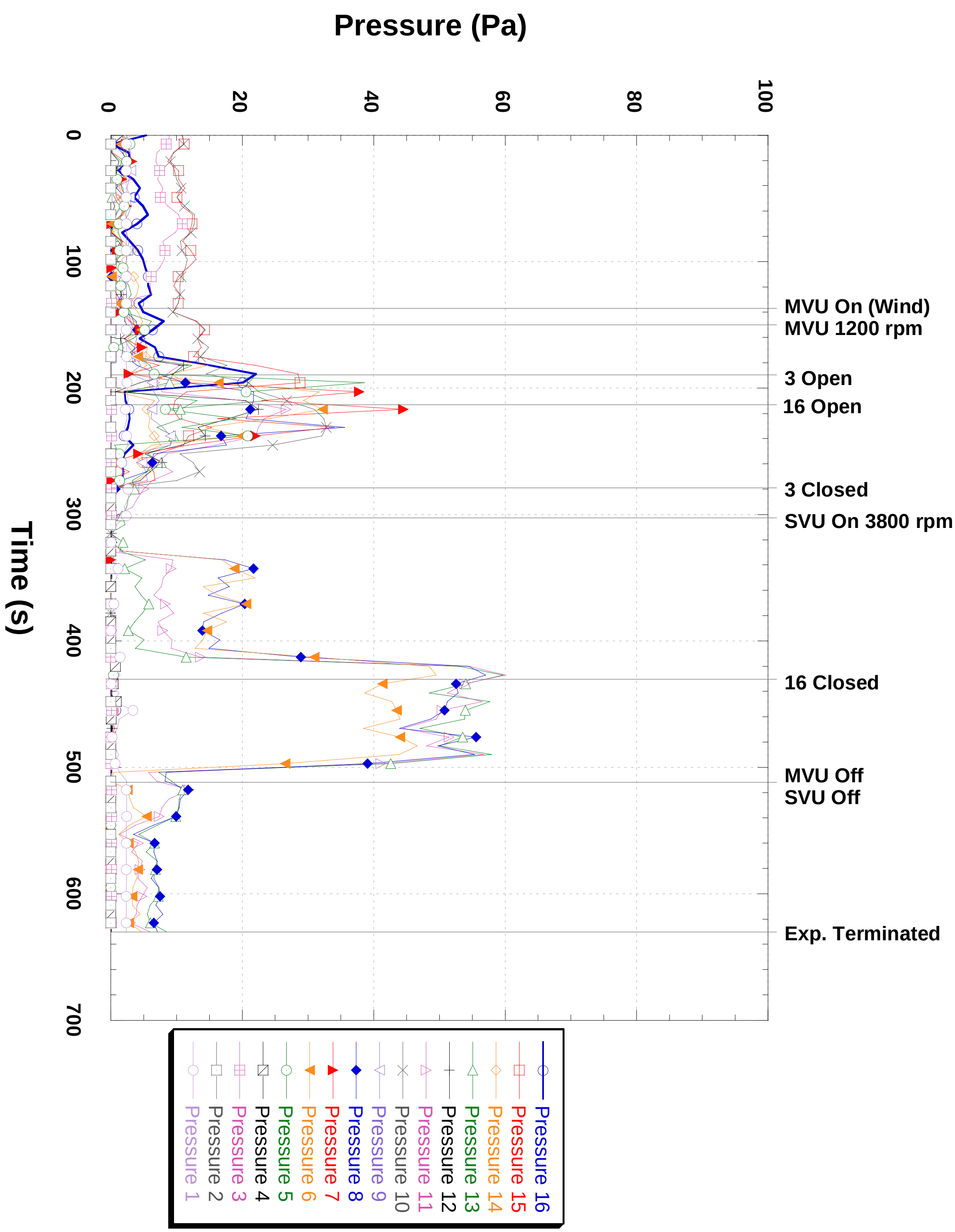

Figure 7. Detailed pressure vs. time for 304 south stair

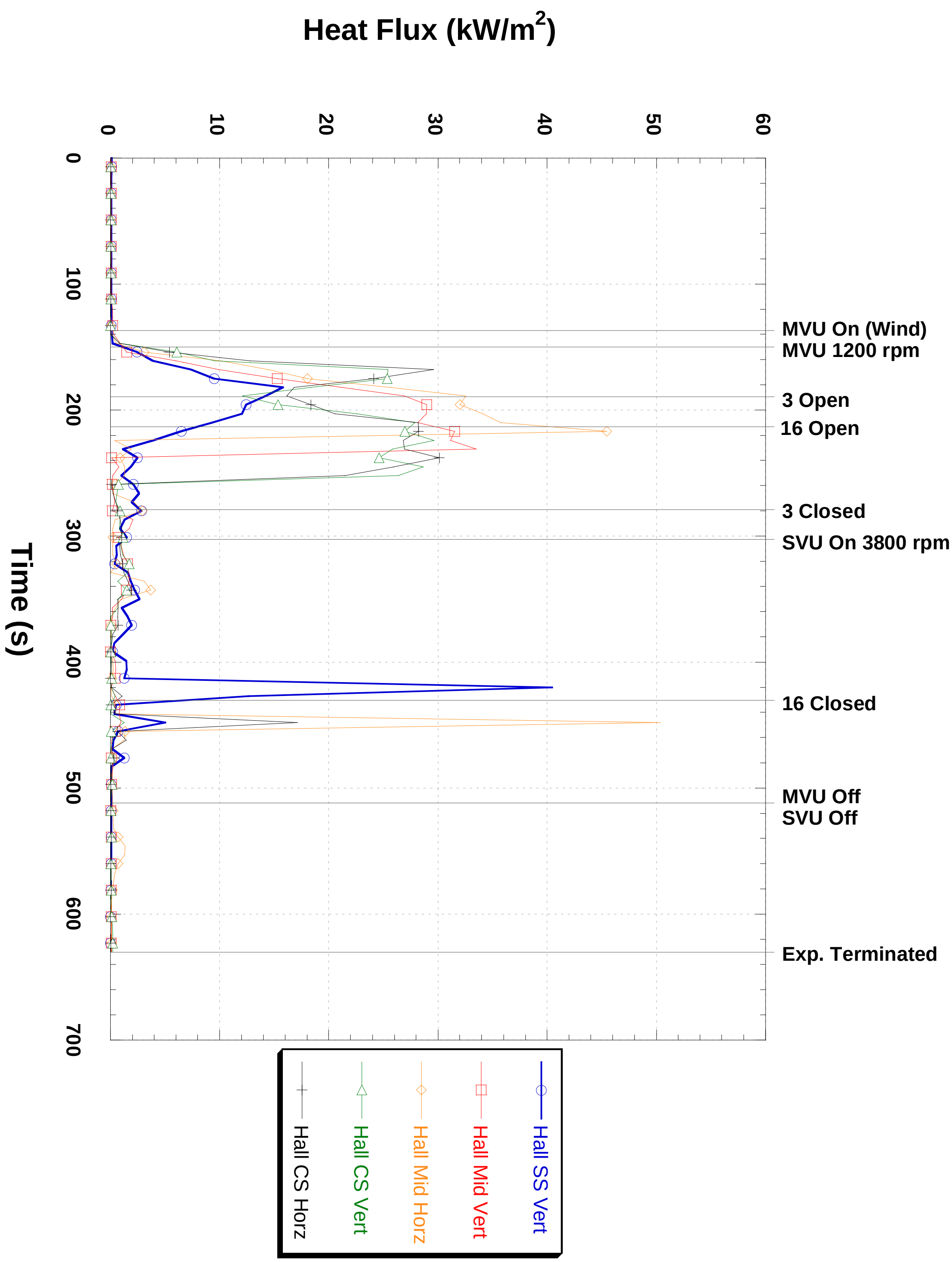

Figure 8. Detailed heat flux vs. time for 304

Appendix H. Unit Conversions and Reference Scales For Fire Fighters

Unit Conversions

Property	To convert from	to	Multiply by
Length	Foot (ft)	Meter (m)	0.3048
Mass	Pound (lb)	Kilogram (kg)	0.4536
Time	Second (s)	Second (s)	1.0
Area	Square foot (ft^2)	Square meter (m^2)	0.0929
Volume	Cubic foot (ft^3)	Cubic meter (m^3)	0.0283
Energy, work, quantity of heat	British Thermal Unit (Btu)	Joule (J)	1055.0
Power, heat release rate	British Thermal Unit per minute (Btu/min)	Watt (W) = J/s	17.573
Heat Flux	British Thermal unit per square foot minute (Btu/ (ft^2 min))	Watts per square meter (W/m^2)	189.15
Pressure	Pascal (Pa)	Pound per square inch (lb/in^2)	0.000145
Carbon Monoxide	Parts per million (ppm)	Percentage (%)	0.0001

With the exception of the kilogram (kg), the conversions given above are to base units such as a Joule (J) or a Watt (W). In the scope of a fire within a building these units are small, so the values would be reported as kilo-Joules (kJ) or kilo-Watt (kW). The kilo prefix means multiply the base unit by 1000. Another prefix that may be used is Mega This prefix means multiply the base unit by 100,000.

Temperature Conversions:

Degree Fahrenheit (°F) = (Degree Celsius (°C) X 1.8) + 32
Kelvin (K) = Degree Celsius (°C) + 273.15

Reference: NIST Special Publication 811, Guide for the Use of the International System of Units (SI), National Institute of Standards and Technology, Gaithersburg, MD, April 1995.

Reference Scales for Fire Fighters

Temperature

This table provides a set of temperatures commonly experienced during firefighting operations and information on the human and equipment response.

Temperature	Response
37 °C (98.6 °F)	Normal human oral/body temperature [1]
44 °C (111 °F)	Human skin begins to feel pain [2]
48 °C (118 °F)	Human skin receives a first degree burn injury [2]
55 °C (131 °F)	Human skin receives a second degree burn injury [2]
62 °C (140 °F)	A phase where burned human tissue becomes numb [2]
72 °C (162 °F)	Human skin is instantly destroyed [2]
100 °C (212 °F)	Water boils and produces steam [3]
140 °C (284 °F)	Glass transition temperature of polycarbonate [4]
230 °C (446 °F)	Melting temperature of polycarbonate [5]
250 °C (482 °F)	Charring of natural cotton begins [6]
>300 °C (>572 °F)	Charring of modern protective clothing fabrics begins [6]
>600 °C (1112 °F)	Temperatures inside a post-flashover room fire[7, 8]

References:

1. Klinghoffer, Max, M.D., "Triage Emergency Care Handbook," Technomic Publishing Company, Inc., Lancaster, PA, 1985.
2. American Society for Testing and Materials, ASTM C1055, Standard Guide for Heated Systems Surface Conditions That Produce Contact Burn Injuries, 4:6, ASTM West Conshohocken, PA, 1997.
3. Shugar, G.J., Shugar, R.A., Lawrence, B., "Chemical Technicians' Ready Reference Handbook," McGraw-Hill Book Company, New York, 1973.
4. Quintiere, J., "Radiative and Convective Heating of a Clear Plastic Fireman's Face Shield", National Bureau of Standards (currently NIST), Gaithersburg, MD, NBS Report 10-855, March 1972.
5. Askeland, Donald R., "The Science and Engineering of Materials", Wadsworth, Inc., Belmont, CA., 1984.
6. Krasny, John F., Sello, Stephen B., "Fibers and Textiles, Fire Protection Handbook," 16th Edition, 1986. NFPA, pp.5-27.
7. Fang, J.B., and Breese, J.N., "Fire Development in Residential Basement Rooms," National Bureau of Standards (currently NIST), Gaithersburg, MD, NBSIR 80-2120, 1980.
8 Drysdale, D., "An Introduction to Fire Dynamics", 2nd Edition, John Wiley & Sons, New York, 1999.

Heat Flux

This table provides heat (exposure) flux levels commonly experienced during firefighting operations and information on the human response to the heat flux levels or conditions associated with the given heat flux.

Heat Flux	Response
~1.0 kW/m^2	A typical solar flux during the summer [1]
2.5 kW/m^2	Typical fire fighter exposure and working environment [2]
4.5 kW/m^2	Unprotected human skin will receive a second degree burn injury in about 30 seconds [3]
10 kW/m^2	Unprotected human skin will receive a second degree burn injury in about 10 seconds [3]
20 kW/m^2	Heat flux in a room at the floor level at the beginning of flashover [4]
80 kW/m^2	Unprotected human skin will receive an instant second degree burn injury, flashover is established in a room [3]
84 kW/m^2	Heat flux specified in the NFPA 1971 test for Thermal Protective Performance (TPP) to evaluate fire fighter's thermal protective clothing [3] Firefighter in full PPE protected from burn injury for 17 seconds or less at this heat flux [5]
170 kW/m^2	Maximum heat flux level measured by NIST with a post-flashover fire inside a burning room [4]

References:

1. Young, H.D., and Freedman, R.A., "University Physics", 9th Edition. Addison-Wesley, Reading, MA., 1996.
2. Donnelly, M.K., Davis, W.D, Lawson, J.R., Selepak, M.J., "Thermal Environment for Electronic Equipment Used by First Responders, NIST Technical Note 1474, 2006.
3. NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting 2007 Edition, National Fire Protection Association, Quincy, MA 2007
4. Fang, J.B., and Breese, J.N., "Fire Development in Residential Basement Rooms," national Bureau of Standards (currently NIST), NBSIR 80-2120, Gaithersburg, MD, 1980
5. Peacock, R.D., Krasny, J.F., Rockett, J.A., Huang, D., "Protecting Fire Fighters Exposed in Room Fires, Part 2: Performance of Turnout Coat Materials Under Actual Fire Conditions", *Fire Technology*, August 1990.

Carbon Monoxide

This table provides common symptoms from carbon monoxide exposures of a given duration to a particular concentration. There are number of variables that could cause an individual to respond differently.

Concentration	Common Symptoms	Duration of Exposure
35 ppm	None	<= 8 hours
150 ppm	Mild headache	2 – 3 hours
400 ppm	Headache/nausea	1 – 2 hours
800 ppm	Headache/nausea/dizziness Progressing to unconsciousness	45 minutes 2 hours
6400 ppm	Headache/nausea/dizziness	1 – 2 minutes
12800 ppm	Immediately dangerous to life and health (IDLH)	1 – 2 minutes

References:

1. Delagi, Robert, "A CO Emergency: Whose Call Is It, Anyway?", *Fire Engineering Magazine*, October 2007.
2. Henry CR, Satran D, Lindgren B, Adkinson C, Nicholson CI, Henry TD, MD (2006). "Myocardial Injury and Long-term Mortality Following Moderate to Severe Carbon Monoxide Poisoning". *JAMA* **295**: 398-402.
3. Raub JA, Mathieu-Nolf M, Hampson NB, Thom SR. (2000). "Carbon monoxide poisoning-a public health perspective". *Toxicology* **145** (1): 1-14.

Pressure

This table provides a range of pressures used during firefighting operations.

Pressure	Situation
12.5 Pa (0.0018 psi)	Suggested pressure difference to inhibit smoke flow across a doorway in a sprinklered building [1]
25 Pa (0.0036 psi)	Suggested pressure difference to inhibit smoke flow across a doorway in a non-sprinklered building [1]
2990 Pa (0.434 psi)	1 foot of water head [2]
101,000 Pa (14.7 psi)	Atmospheric pressure at sea level [3]
240,000 Pa (35 psi)	Solid stream nozzle operating pressure [2]
690,000 Pa (100 psi)	Fog nozzle operating pressure [2]

References:

1. NFPA 92A. Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences. 2006 Edition.
2. Hall, R. and Adams, B., Eds, Essentials of Fire Fighting, 4th ed., Oklahoma State University, Stillwater, OK, 1998, 716p.
3. U.S. Standard Atmosphere, 1976, U.S. Government Printing Office, Washington, D.C., 1976.

Heat Release Rate

This table provides a list of common items and their associated approximate peak heat release rates.

Approximate Peak Heat Release Rate	Item
5 W [1]	Burning cigarette
80 W [1,2]	Burning match or candle
50 to 300 kW [3]	Small Trash Can, Trash Bag Fires
80 kW to 2.5 MW [4,5]	Burning Upholstered Chair
3,000 kW or 3 MW [6]	Burning Upholstered Sofa
1.6 MW to 5.2 MW [7]	Burning Christmas Tree
5.3 MW [8]	Base Design Fire
Approximately 10 to 40 GW/acre [9]	Forest Fire – Timber w/understory

References:

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