EVALUATION OF FIRE SERVICE POSITIVE PRESSURE VENTILATION TACTICS ON HIGH-RISE BUILDINGS

Stephen Kerber
Building and Fire Research Laboratory
National Institute of Standards and Technology Gaithersburg, MD, USA 20899-8661

ABSTRACT

Positive Pressure Ventilation (PPV) is a ventilation technique used by the fire service to remove smoke, heat and other combustion products from a structure. This allows the fire service to perform tasks in a more tenable environment. PPV fans are commonly powered with an electric or gasoline engine and range in diameter from 0.30 m to 0.91 m (12 in to 36 in). More recently fans up to 2.1 m (84 in) have been manufactured and mounted on trucks and trailers. 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. 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 air to escape due to the difference between the inside and outside air pressure. The smoke, heat and other combustion products are pushed out of the structure and replaced with ambient air.

Another use of PPV is to increase the pressure in a portion of a structure by not providing a vent location. This increase in pressure, if adequate, will prevent smoke flow to a "protected" area. This is most useful in larger structures such as schools, hospitals and 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 the fans are properly configured. Two sets of experiments were conducted in high-rise buildings to analyze the impact of fire service PPV tactics.

INTRODUCTION

According to the National Fire Protection Association (NFPA) Life Safety Code, a high-rise building is "a building greater than 23 m (75 ft) in height measured from the lowest level of fire department vehicle access to the floor of highest occupiable story"[1]. In 1910, the New York City Fire Department Chief, Edward Croker informed the New York State Assembly that the fire department could not successfully combat a fire in a building greater than 7 stories tall. Three months later a fire in the Triangle Shirtwaist Company, which occupied the top three floors of a ten story building in New York City, resulted in the deaths of 146 people[2]. As a result of that fire, many improvements were made in the life safety of buildings.

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[3*]. Smoke is a major problem in high-rise fires as it travels to building locations remote from the fire and causes a serious life hazard. Stairwells may fill with smoke, hindering evacuation and enabling the spread of smoke to other floors of the building.

Fires in high-rise buildings can produce severe challenges for fire departments. Operations that are normally considered routine, such as fire attack, evacuating occupants and ventilation can become very difficult in high-rises. Smoke and hot gases in the stairwells and the corridors of high-rise buildings complicate rescue and firefighting operations. Between 1977 and 2005, 20 fire fighters died from traumatic injuries suffered in high-rise fires in the United States[4]*.

* Not including the World Trade Center losses of September 11, 2001.

Fire fighters often rely upon built-in fire protection systems to help control a high-rise fire and protect building occupants. In many cases the buildings do not have the necessary systems or the systems fail to operate properly. This has created situations where even the most experienced and best equipped fire departments could not readily control the fire[5-8]. A number of high-rise incidents have resulted in fire fighter fatalities due to disorientation, running out of air, or changes in wind conditions[7, 9-10].

Attempting to control the smoke movement is difficult because fire fighting operations often require opening potential smoke barriers between the source of water and the fire. Buoyancy forces of hot gases and stack effect due to temperature differences between the inside and outside of the building cause smoke travel in high-rise buildings. This smoke travel enters vertical shafts in the building such as stairwells and blocks evacuation of occupants and hinders fire fighting operations.

It is common for the fire service to encounter smoke filled stairwells prior to their arrival. If the stairwells are not contaminated they soon become contaminated once fire department operations begin. Dividing the stairwells in a high-rise building into attack and evacuation stairwells is a good practice but many times it is not possible to keep the evacuation stairwell free of smoke by not opening the stairwell door on the fire floor. Stairwell door assemblies leak and it is possible to have contaminated stairwells without ever opening a stairwell door at all.

Under normal operating conditions the attack stairwell door to the fire floor gets opened and the stairwell becomes completely smoke filled above the fire floor. The thought process then becomes to open the bulkhead door or vent at the top of the stairwell. This does not always accomplish the desired effect as it allows smoke to exit the structure but does not eliminate the fact that the stairwell is now the chimney for the fire gases. 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 will most likely 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.

Given 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 any occupants that may have attempted to escape but were overcome by smoke on the way out. A difficulty arises in that fire fighters may not have enough air in their 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.

Smarter 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. The NFPA code requires that stairwells in existing high-rise apartment buildings be smokeproof. 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 design 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. While these systems have demonstrated effectiveness and have been installed in many buildings there are still a majority of high-rise buildings without these systems to protect stairwells.

In 1986, the NFPA began to provide guidance for smoke management systems. NFPA 92A[11] was developed to address smoke control utilizing barriers, airflows and pressure differences so as to confine the smoke of a fire to the zone of fire origin and thus maintain a tenable environment in other zones.

Guidance for minimum pressures that are able to inhibit the flow of smoke into the stairwell is provided in Table 1. The values in the table for nonsprinklered buildings are minimum design pressures developed for gas temperatures of 927 ºC (1700 ºF) next to the smoke barrier with a 7.5 Pa (0.03 in. water) safety factor added. These criteria for fixed stairwell pressurization systems provide a metric to assess the ability of fire department positive pressure ventilation (PPV) fans to provide a smoke-free escape route for occupants and a smoke-free staging area for fire fighters.

Table 1. NFPA 92A Minimum Design Pressure Differences Across Smoke Barriers

Building Type	Ceiling Height m (ft)	Design Pressure Difference Pa (in. water)
Sprinklered	Any	12.5 (0.05)
Nonsprinklered	2.7 (9)	24.9 (0.1)
Nonsprinklered	4.6 (15)	34.9 (0.14)
Nonsprinklered	6.4 (21)	44.8 (0.18)

NFPA 92A also states that a smoke control system should be designed to maintain the minimum design pressure differences under likely conditions of stack effect and wind. Pressure differences produced by smoke-control systems tend to fluctuate due to the wind, fan pulsations, door opening, doors closing, and other factors. Short-term deviations from the suggested minimum design pressure difference might not have serious effect on the protection provided by a smoke-control system. There is no clear-cut allowable value of this deviation. It depends on the tightness of doors, tightness of construction, airflow rates, and the volumes of spaces. Intermittent deviations up to 50 % of the suggested minimum design pressure difference are considered tolerable in most cases[11].

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/hr (500 cfm) to as high as 169 900 m^3/hr (100,000 cfm) in some systems.

POSITIVE PRESSURE IN THE FIRE SERVICE

Technology in the fire service has increased greatly in the past 20 years, especially with regards to positive pressure ventilation fans. Fans have been engineered and manufactured to provide flow capacities comparable to those specified for fixed stairwell pressurizations systems. The only difference being that the fire departments fans cannot be fixed in the wall of the stairwell.

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. 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 air to escape due to the difference between the inside and outside air pressure. The 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 of ventilating and examining the fans ability to pressurize. 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 in stairwells to ventilate the 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 continually until there is no more smoke and hot gases being supplied by the fire. 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 but there is still smoke and hot gases 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 dilutes the toxicity of the smoke and cools the hot gases but does not eliminate the problem of a contaminated stairwell.

PPV fans utilized without a vent are able to create an elevated static pressure. The static pressure can be used against the increased pressure created by the fire. The fire wants to naturally ventilate 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 no smoke will flow into the stairwell.

HIGH-RISE PRESSURE EXPERIMENTS

A series of experiments was conducted in a thirty-story vacant office building in Toledo, Ohio. The objective was to evaluate the ability of fire department positive pressure ventilation fans to pressurize a stairwell in a high-rise structure to the performance metrics established for fixed stairwell pressurization systems[12]. One hundred and sixty configurations were examined and variables such as fan size, fan angle, setback distance, number of fans, orientation of fans, number of doors open and location of vents open were altered to examine capability and optimization of each. Fan size varied from 0.4 m (16 in) to 1.2 m (46 in). The face of the fan was angled between 90 degrees and 80 degrees relative to the horizontal. The setback distance went from 0.6 m (2 ft) to 3.6 m (12 ft). Between one and nine fans were used and fans were located at three different exterior locations and three different interior locations. Fans were oriented in both series and in parallel. Doors throughout the building were opened and closed to evaluate the effects. Finally a door to the roof and a roof hatch were used as vent points to evaluate the effects. The measurements taken during the experiments included differential pressure, air temperature, carbon monoxide, metrological data and sound levels. The results obtained provide the fire service guidance on how to place their fans to achieve optimal performance and the limitations the fans have in high-rise operations.

Structure

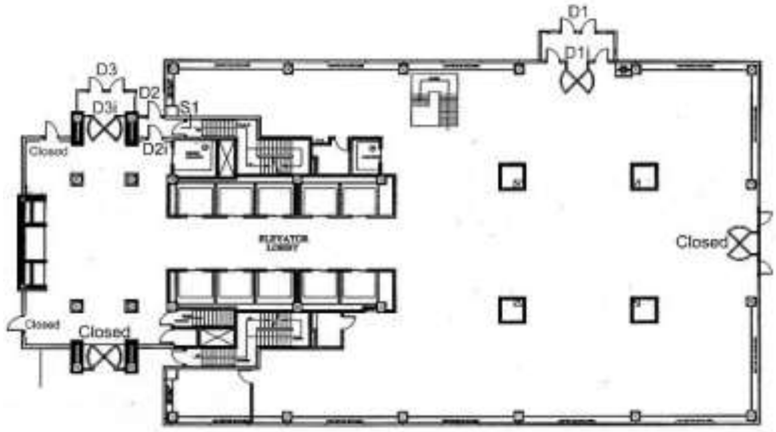
The building was constructed in 1969 with an overall height of 121.9 m (400 ft) and an overall floor area of 40,645 m^2 (437,500 ft^2). Each floor was approximately 48.8 m (160 ft) wide by 25.9 m (85 ft) deep with a ceiling height of 3.6 m (11.7 ft). The ground floor was taller and had a ceiling height of 6.3 m (20.7 ft). Two mechanical floors are located between floors 13 and 14 (figure 1).

Three exterior doors were utilized during the experiments, the single door directly into the stairwell (D2), the double door on the right side of the front of the building (D1), and the double door on the left side of the front of the building (D3). The rotary doors inside of D1 and D3 were open for the duration of the experiments. All other doors to the ground floor were closed at all times. The door to the stairwell (S1) remained open during all of the experiments and led to the stairwell that was used for the experiments (figure 2).

The stairwell used for the experiments had a half story of steps that led to a landing that transitioned into the actual stair shaft. The stair shaft measured 2.44 m (8.0 ft) wide and 5.14 m (16.9 ft) long. There was a 0.1 m opening between the stair flights. The stairwell ended at the 29th floor with no access to the exterior of the building. The second stairwell in the building provided access to the roof and roof hatch but opened only to the exterior of the building at the ground floor without room to place a PPV fan.

Figure 1. Exterior of Building

Figure 2. Ground Floor Plan



Instrumentation

The measurements taken during the experiments included differential pressure, air temperature, carbon monoxide, meteorological data and sound levels. A differential pressure transducer and thermocouple were located on the stairwell door knob of every other floor. A plastic tube was run under the door to the opposite door knob to reference the pressure readings to the floor side. Carbon monoxide was measured in the stairwell on floors 1, 14 and 28. Measurements were made using a chemical cell monitor with built-in sample pump. Weather was monitored and recorded during each of the experiments using two portable weather stations. Temperature, relative humidity, average wind speed, average wind direction and barometric pressure were recorded continuously.

Experimental Procedure

Prior to each of the experiments the setup was configured according to the experimental variables. Background measurements were recorded and the fan(s) were started and throttled to full speed. The duration of each experiment was three minutes. At the completion of each experiment the fan was turned off, readings were allowed to return to ambient and the procedure was repeated.

Figure 3. Fan Placements: Portable fan outside, trailer mounted fan and portable fan inside.

Discussion

For this limited series of experiments, the fan setback distance and angle needed to be optimized in order to maximize the impact of the fan. The fans used in these experiments had optimal configurations of 1.2 m (4 ft) and 85 degrees for the 0.4 m (16 in) fan, 1.8 m (6 ft) and 85 degrees for the 0.5 m (21 in) fan, and 1.2 m (4 ft) and 80 degrees for the 0.7 m (27 in fan) (figure 4). The setback distances suggest that PPV fans rely on the air that is entrained around the shroud from air being pulled through the shroud to achieve the cone of air to seal the doorway. The fans positioned right in front of the doorway, which had limited air entrainment, were not able to raise the pressures in the stairwell as well as the fans set back from the doorway.

This set of full-scale experiments indicates that when possible the PPV fan should be placed at the stairwell doorway and not at another ground floor entrance. Adding the volume of the first floor makes any number of fans at the ground floor entrances less effective, especially above the 10th floor. This may not hold for buildings with smaller lobbies or with first floors that can be sectioned off to limit the volume, but typically high-rise buildings have large open lobbies.

During these ambient temperature experiments, placing PPV fans in series was less effective than placing the fans in a V-shape. When the fans were in a V-shape it did not seem to make a large difference if the fans were at the same angle or if one was angled at the top and the other at the bottom of the doorway. If building geometry prevents the fans from being placed in a V-shape, adding a second fan in series only increases the pressure by about 25 % and a third fan an additional 10 %.

Similar to fixed smoke control systems, opening stairwell doors has a large impact on stairwell pressures. Opening a stairwell door reduces the pressure on floors above the open door to approximately ambient, eliminating the desired impact of the PPV fan. A significant increase in pressure could be achieved by closing the doorway to the width of a hoseline. If the fire crew closes the doorway on their hoseline instead of keeping the door completely open, the amount of smoke that infiltrates into the stairwell will be greatly reduced. This will be of significant benefit to the people exiting through this stairwell and fire crews operating above the fire floor.

Placing portable fans in the building was the only way to effectively pressurize the entire stairwell. In a 30-story stairwell a 0.7 m (27 in) fan placed at the ground floor and one 0.7 m (27 in) fan set back from the 12th floor stairwell doorway greatly increased the pressure in the entire stairwell (figure 5). There was no make-up air provided to the fans set back in the building. This is not necessary as the fan recirculates the same air to the stairwell doorway maintaining the pressure on a continuous basis.

The fans positioned in the building were more effective when configured using the same optimal setback and angle described previously for fans at the ground floor stairwell doorway. Placing the fans in the doorway was ineffective because there was no cone of air to seal the doorway. Also, moving the fans back to 2.4 m (8 ft) was less effective. Fans should not be placed within the stairwell; this resulted in lower pressure differentials and generated CO readings in excess of 300 ppm in the stairwell.

The results of placing the fan on the 12th floor and the fan on the 22nd floor suggested it may be most effective to place a 0.7 m (27 in) fan at the stairwell doorway 2 floors below the fire to get the desired pressures and reduce the impact of doors opening on any of the floors. This configuration also allows for ventilation in addition to pressurization. The smoke that has already infiltrated the stairwell could be vented out of the top of the stairwell while the localized pressure will prevent any additional smoke from entering the stairwell. The data suggest that this will work on sprinklered buildings even with the top and bottom of the stairwell open and the pressures are borderline to work on an unsprinklered building based on the threshold pressures specified in Table 1.

When venting the top of the stairwell and pressurizing the stairwell, a smaller vent such as a roof hatch should be considered rather than a bulkhead or roof door in order to maximize the potential pressure differential. A roof hatch is usually large enough to vent sufficient smoke while small enough to increase the pressure in the stairwell.

Fixed stairwell pressurization systems usually have at least one fan that is built into a wall or the top of the stairwell. The pressure loss due to the fire department fan being set back as opposed to sealed in the doorway yielded an 80 % efficiency based on the comparison of pressure differences. This setback allows access and egress from the fan inlet doorway which is essential for most fire department operations. The 20 % loss has little impact on the overall ability of the fans to pressurize the stairwell. The large trailermounted fan was able to pressurize the stairwell to the NFPA 92A unsprinklered threshold in the entire stairwell when utilized on the stairwell doorway (figure 6). It was also able to pressurize the stairwell to the unsprinklered threshold at the other ground floor entrance when it had to pressurize the entire first floor and basement in addition to the stairwell. Attention needs to be given to the maximum allowable pressure with these large fans in order to ensure that the pressure does not prevent the opening of doors into the stairwell. This value is specified in national codes such as NFPA 101 or in local codes and is a function of stairwell door size, handle location and door closer force. This value is often approximately 80 Pa to100 Pa which the large fans are capable of creating in the lower portions of the stairwell.

There are multiple fan manufacturers and each of them has differences whether it is blade type, shroud size, engine power rating, etc. Not all PPV fans behave the same and it is important to utilize them optimally to get the desired performance. These results provide guidance to the important variables but may not be relevant to all fan types. As technology improves so will the ability of the fans to move air. The fans used in these experiments represent the best current technology available and the size and power rating of the fans may not be representative of older fans that may currently be on fire apparatus.

The CO produced by the PPV fans was at least one order of magnitude less than that created by a fire. As long as the PPV fans were not placed in the stairwell with the door shut, the National Institute of Occupational Safety and Health (NIOSH) ceiling exposure of 200 ppm was not exceeded. However, CO readings less than 50 ppm are unlikely with a gasoline powered PPV fan (figure 7). Electric PPV fans or natural ventilation should be considered if CO readings less than 50 ppm are desired.

The noise levels created by the fans reached as high as 110 dB next to the fan at full throttle. This is comparable to a chainsaw and can have an impact on communications on the fire ground. Attempting a conversation or radio transmission near the PPV fan was difficult both for the sender and receiver. Attention should be given to the location of the command post and potential for PPV fan usage locations.

Figure 4. Pressures created by a 0.7 m fan at the base of the stairwell.

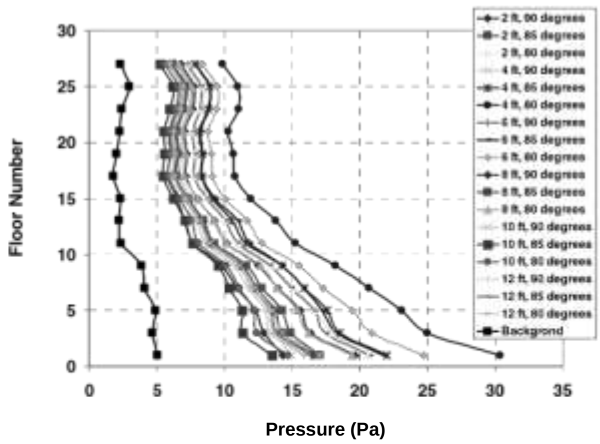


Figure 5. Pressures created by 0.7 m fans in the building.

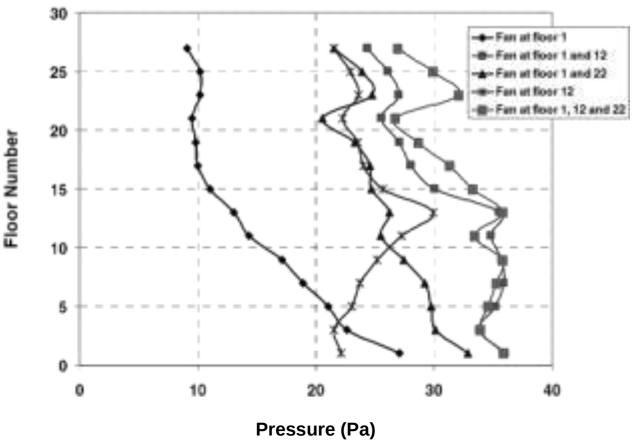
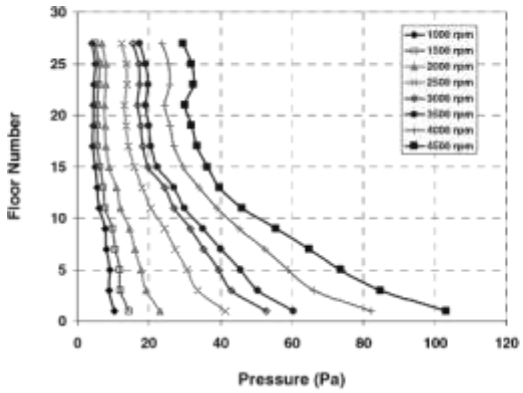
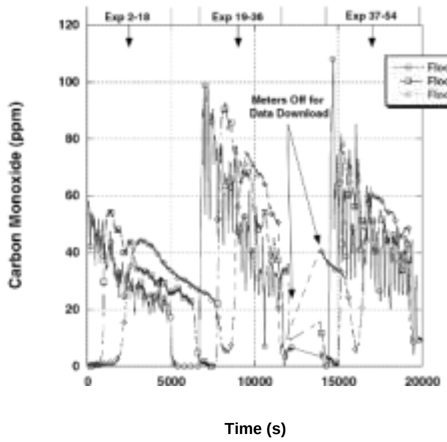


Figure 6. Pressures created by a 1.2 m (46 in) fan at the the stairwell entrance.

Figure 7. Carbon monoxide levels created by the portable fans at the stairwell entrance.





Results

The data collected during this limited set of full-scale experiments in a 30-story office building demonstrated that in order to maximize the capability of PPV fans the following guidelines should be followed:

- Regardless of size, portable PPV fans should be placed 1.2 m (4 ft) to 1.8 m (6ft) set back from the doorway and angled back from vertical at least 5 degrees. This maximizes the flow through the fan shroud and air entrainment around the fan shroud as it reaches the doorway.
- Placing fans in a V-shape is more effective than placing them in series.
- When attempting to pressurize a tall stairwell, portable fans at the base of the stairwell or at a ground floor entrance alone will not be effective.
- Placing portable fans inside the building below the fire floor is a way to generate pressure differentials that exceed the NFPA 92A minimum requirements. For example, if the fire is on the 20th floor, placing at least one fan at the base of the stairwell and at least one near the 18th floor blowing air into the stairwell could meet the NFPA 92A minimum requirements.
- Placing a large trailer mounted type fan at the base of the stairwell is another means of generating pressure differentials that exceed the NFPA 92A minimum requirements.
- Fans used inside the building should be set back from the stairwell doorway and angled just as if it were positioned at an outside doorway.

The experiments also document that PPV fans can be loud enough to negatively impact fire ground and command post communications. Gasoline powered fans generate carbon monoxide but the magnitude has to be compared to that of the hazard created by the fire in the building. Overall, when properly setup and correctly operated, positive pressure ventilation is a tool which the fire service can use to improve the safety and effectiveness of fire ground operations.

HIGH-RISE FIRE EXPERIMENTS

A second series of experiments took place in a 16-story high-rise in Chicago, IL, in cooperation with the Chicago Fire Department (CFD) and the Chicago Housing Authority. The purpose of the experiments was to build on the previous results from Toledo with live fire experiments. NIST technical staff members worked side by side with more than 70 CFD staff in preparing and instrumenting the building for the experiments. Several rooms were furnished and burned on the 15th, 10th and 3rd floors. The pressure and temperature on each floor was monitored. Temperature and heat flux measurements were made on the fire floors to characterize the thermal environment that firefighters work in. Results demonstrate the positive impact that the fans can have in improving stairwell conditions to allow for occupant egress and safer fire fighting operations.

Experimental Configuration

The experiments were conducted in a 16-story high-rise apartment building (figure 8). The building construction consisted of poured concrete floor and ceiling deck with concrete block corridor walls and gypsum board interior walls. The overall building dimensions were 75.6 m (248.0 ft) wide by 20.8 m (68.2 ft) deep by 46.9 m (153.9 ft) tall. The left side 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 corridors from the second to sixteenth floors were open air, only covered with an expanded metal. This is not representative of the 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. 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 six apartment fires with the 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 (figure 9). Floor 3 utilized a furnished living room in apartment 3 and a furnished bedroom and living room in apartment 4.

Figure 8. Front Elevation of the building.

Figure 9. Floor plan.

Furnishings

The fuel load for the experiments was designed to simulate a common living room configuration with a modest fuel load. The purpose of the fuel load was to create high heat and dense smoke conditions in the apartment of origin and the common corridor. 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 upholstered chairs, two end tables, a coffee table and a lamp.

Instrumentation

The measurements taken during the experiments included differential pressure, gas temperature, heat flux, carbon monoxide, meteorological data, video recording, thermal imaging and sound levels. A differential pressure transducer and thermocouple were located on the door knob of every floor in the south stairwell. A 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 analyze the effects of ventilation. 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) off of the floor. Each location was comprised of two gauges, one mounted horizontally facing the fire and one mounted vertically facing the ceiling. Carbon monoxide (CO) was measured in both stairwells as well as in the corridor. Measurements were made using a fire department chemical cell monitor with built-in sample pump.

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. 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.

Experimental Procedure

Prior to ignition in each experiment, a 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.

After ignition the fire was allowed to grow until the living room reached flashover conditions and visibility became limited in both the apartment and corridor. As smoke began to leak into the stairwell different ventilation tactics were utilized. Ventilation tactics included the use of compartment sized fans and larger mounted fans (MVU, SVU) (figure 10). 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 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.

Discussion

For this limited series of experiments, the fans and their locations were determined by the previous series of pressure experiments. One experiment on each of the fire floors utilized portable fans and the other utilized a large truck or trailer mounted 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 recorded. The minimum design pressures of NFPA 92A were used as baselines to compare to the actual pressures measured (figures 11-12).

This building was unsprinklered therefore every experiment attempted to obtain a minimum pressure of 25 Pa in the stairwell, in the area of the fire floor. Numerous events were examined by changing fan placement and the location and number of open doors (Table 2). The events 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 of the events that were successful in prohibiting smoke infiltration into the stairwell had pressures significantly below 25 Pa. The lowest fire floor pressure 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 °C and 300 °C. Utilizing the 100 °C and 300 °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. These limited data from this practical set of configurations suggests that this correlation is effective in estimating the pressure required to stop smoke spread.

Table 2. 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]**			
Experiment Number 1503 – 15th Floor Apartment 3, 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					

Temperatures in the fire apartments peaked at approximately 800 °C (figure 13). The temperature in the entire hallway peaked between 100 °C and 300 °C at the ceiling level and 100 °C and 150 °C at 0.91 m from 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 maximum on the fire department gas monitors. Stairwell CO levels dropped below 200 ppm during ventilation. The average temperatures remained fairly constant during all of the experiments. Temperatures ranged between 11 °C (52 °F) and 17 °C (63 °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 was mainly out of the south 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.

Figure 10. Portable and truck mounted fans during experiment.

Figure 11. Stairwell pressures created by a truck mounted fan during experiment in apartment 1503.

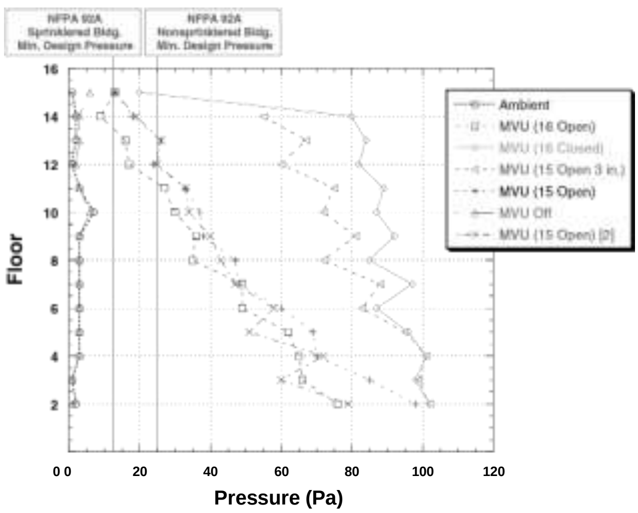
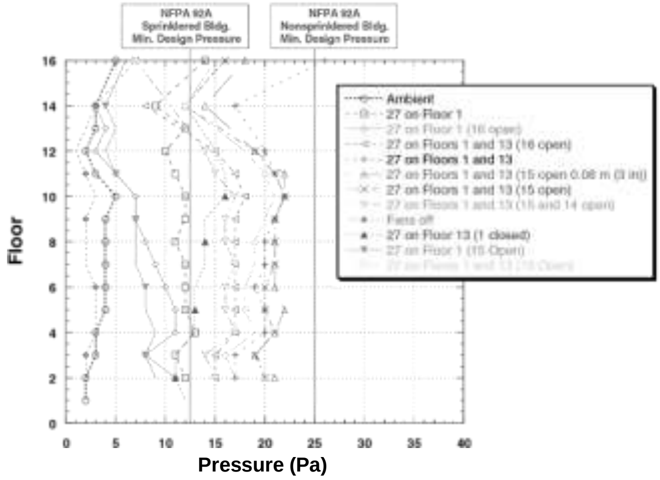


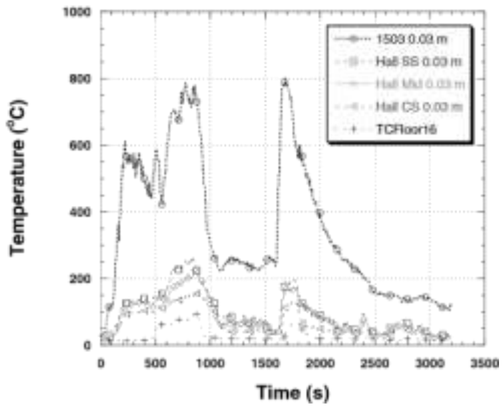
Figure 12. Stairwell pressures created by 0.7 m fans

Figure 13. Ceiling temperatures during

during experiment in apartment 1505.



experiment in apartment 1503.



Results

The data collected during this limited set of full-scale experiments in a 16-story apartment building demonstrated that PPV fans can effectively vent the smoke out of the stairwell and keep the smoke out of the stairwell during realistic apartment fire conditions. Differential pressures as low as 9 Pa were able to keep the stairwell free of smoke even with the fire floor door open. Two portable fans were required to generate sufficient pressures and the mounted fans were able to generate pressures that were able to keep smoke out of both stairwells. When the pressures were not high enough to completely prevent smoke infiltration into the stairwells, they slowed down the smoke flow significantly. Overall, the fans increased visibility, decreased temperatures and decreased CO levels in the stairwell.

CONCLUSIONS

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 metrics 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.

REFERENCES

[1] NFPA 101, Life Safety Code. National Fire Protection Association, Quincy, MA., 2006.

[2] Grant, Casey,C., Triangle Fire Stirs Outrage and Reform, NFPA Journal, May/June 1993, pp73-82.

[3] Hall Jr., John. High-rise Building Fires. NFPA, Quincy, MA. August 2005.

[4] Traumatic Firefighter Fatalities in High-rise Office Buildings in the United States 1977-Present, NFPA Database Search. National Fire Protection Association, Quincy, MA. January 2007.

[5] Isner, Michael, S., Fire Investigation Report: High-Rise Office Building Fire, Alexis Nihon Plaza, Montreal, Canada, October 26, 1986. National Fire Protection Association, Quincy, MA.

[6]

Nelson, Harold, E., An Engineering View of the Fire of May 4, 1988 in the First Interstate Bank Building, Los Angeles, California. NISTIR 89-4061. National Institute of Standards and Technology, Gaithersburg, MD. March 1989.

[7] Klem, Thomas J., Fire Investigation Report: One Meridian Plaza, Philadelphia, PA, February 23, 1991. National Fire Protection Association, Quincy, MA.

[8] Madrzykowski, D., and Walton, W.D., Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations, NIST Special Publication, SP-1021. National Institute of Standards and Technology, Gaithersburg, MD. July 2004.

[9] NIOSH ALERT:Preventing Injuries and Deaths of Fire Fighters. National Institute for Occupational Safety and Health (NIOSH), Morgantown, WV. September 1994.

[10] Three Fire Fighters Die in a 10-Story High-Rise Apartment Building – New York. Fire Fighter Fatality Investigation Report F99-01. National Institute for Occupational Safety and Health (NIOSH), Morgantown, WV. August 1999.

[11] NFPA 92A. Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences. National Fire Protection Association, Quincy, MA. 2006 Edition.

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