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## Protecting the Stair Enclosure in Tall Buildings Impacted by Stack Effect

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### Biography

Michael Ferreira is a senior fire protection engineer and project manager at Hughes Associates, a fire science and engineering consulting company. He has been responsible for the majority of the firm's smoke management system design projects for the past 10 years, including the design of high-rise stair pressurization systems, zoned smoke control systems, and atrium exhaust systems, and has been responsible for performing commissioning testing to certify the proper operation of these systems. He has published several articles on the innovative use of computer models for smoke management system design, using the use of the CONTAM building air flow and contaminant dispersal model to evaluate the performance of pressurization systems and the use of the Fire Dynamics Simulator CFD model to evaluate smoke tenability conditions.

Michael is a professional engineer and holds a Bachelor of Science degree in Mechanical Engineering and a Master of Science degree in Fire Protection Engineering from Worcester Polytechnic Institute, in Massachusetts. He is a member of ASHRAE, NFPA, and SFPE and serves as a member of the NFPA's Committee on Smoke Management Systems, responsible for authoring NFPA 92A and NFPA 92B.

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## Abstract

Stair pressurization systems are the most commonly utilized means for protecting exit stairwells in high-rise buildings from smoke in the event of fire. Stair pressurization systems are difficult to design for tall buildings due to the impact of stack effect on maintaining uniform pressures over the building's height, and creation of excessive door overpressures that may impact exiting is a concern. The effectiveness of a stair pressurization system is also dependent on maintaining the doors predominately closed to maintain the required pressure differential to keep smoke from entering the stair, a situation that may not be possible during the event of a full building evacuation or where catastrophic damage has occurred to the stair.

This paper evaluates an alternate means for protecting high-rise stairwell enclosures using a high throughput dilution venting system. An analysis was performed using the Fire Dynamics Simulator (FDS) model that showed that a dilution venting system can be an effective method for protecting the stairwell enclosure. The optimal rate for ventilating the stair requires further evaluation, and would require optimization of the airflow rate based on postulated fire scenarios for the building and the desired performance with respect to tenability conditions within the stair.

**Keywords:** Stairwell, smoke, pressurization, dilution, fire, smoke control

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## Introduction

During a fire event in a high-rise building, the environment inside the stair enclosure is an important determining factor for the ability of the building occupants to safely egress the building. In a high-rise building, the stairs typically represent the sole means of egress during a fire. Given recent events that have shifted the mindset toward total building evacuation in the event of a high-rise fire or other emergency event, delays due to occupant queuing in the stairwell can result in occupants being exposed to the environment of the stair for long periods of time during egress from the building. It is therefore imperative for the exit stairs to be free of smoke to the greatest extent possible and to incorporate design features (e.g., lighting) that improve the speed of occupant egress via the stairs.

The current design standard for protecting stairwells in high-rise buildings is to provide a "smokeproof" enclosure, using stair pressurization systems or other design alternatives to prohibit smoke entry into the stairwell. The International Building Code [IBC] (ICC, 2006), currently enforced throughout much of the United States, recognizes three specific means for providing smokeproof enclosures: naturally ventilated stair balconies, mechanical ventilation of a stair and vestibule, or stair pressurization. Due to the relative cost of the associated mechanical systems, and architectural space issues related to providing exterior balconies and stair vestibules, provision of a stair

pressurization system is the most widely selected design option recognized by the IBC.

In tall buildings, specifically those exceeding 25–30 stories in height, stair pressurization systems are difficult to design due to the impact of stack effect on maintaining uniform pressures over the building's height. In addition, the effectiveness of a stair pressurization system is dependent on maintaining the doors predominately closed to maintain the required pressure differential to keep smoke from entering the stair. Openings in the stair created by doors held open during occupant egress, a particular problem during a full building evacuation, or due to structural damage to the stair would severely compromise the performance of the system. This paper examines the design issues associated with stair pressurization systems and evaluates a potentially viable alternate approach involving supplying and exhausting the stair at a high rate of airflow to provide clean air into the stair and remove/dilute any smoke that may be present.

## Stair Pressurization Systems

Stair pressurization systems typically utilize a single fan with a ducted shaft to multiple injection points or multiple fans distributed over the height of the stair. It is desirable to provide supply inlets every 3–5 floors to evenly distribute air throughout the stair, although stairs serving up to a maximum of 10 stories are capable of being pressurized via a single injection point.

The design requirements for stair pressurization systems included in the various codes and standards, including the IBC and NFPA 92A, *Standard for Smoke Control Systems Utilizing Barriers and Pressure Differences* (NFPA, 2006), specify a minimum and maximum pressure differential. The minimum pressure differential differs between 12.5–37.5 Pa [0.05–0.15 in. H<sub>2</sub>O], and is meant to counteract the anticipated buoyancy force resulting from a compartment fire adjacent to the stair, incorporating appropriate safety factors. The maximum pressure differential specified ranges between 90–100 Pa [0.36 – 0.4 in. H<sub>2</sub>O], and is derived from the maximum allowable door opening force allowed for doors entering the stairs, which is typically specified to be 133 N [30 lbf]. The door opening force must be low enough to allow the majority of building occupants to be capable of opening the door to the stairwell in an emergency event. Excessive force against the door could prevent occupants from entering the stairwell, which could be a dangerous condition even in the event of a small fire in a high-rise building.

### Impact of Stack Effect

Vertical air movement through a building caused by the temperature differential between the conditioned building air and the ambient outside air is known as the “stack effect.” During cold weather conditions, the stack effect causes air to move vertically upward in buildings. During very hot weather conditions, the stack effect causes air to move vertically downward in buildings. Stack effect can have a significant impact on the design of a stair pressurization system and must be considered in its design.

To illustrate the impact of stack effect on a stair pressurization system, an analysis was performed for a stairwell located in a building in New York City, where cold winter temperatures are possible. The analysis assumed that the stair pressurization system was designed to provide the IBC specified minimum pressure differential of 47.5 Pa [0.15 in. H<sub>2</sub>O], at all stair doors using a single-speed fan and a balanced system using multiple injection points. Stack effect was assessed under the recommended winter design temperature of -14 °C [6 °F] recommended for New York by the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook (ASHRAE, 2005), and the milder -4 °C [24 °F] winter design temperature recommended by the National Oceanographic and Atmospheric Association (NOAA). The analysis utilized the CONTAM building airflow model (Walton and Dols, 2005), developed by the National Institute of Standards and Technology (NIST), for a representative high-rise building having a prototypical residential floor plan with residential units situated around a central corridor and elevator lobby. The prototype building contained two stairwells at either end of the central corridor.

Table 1 shows the results of the analysis. As seen in Table 1, for even moderately tall buildings

(>15 stories), the minimum pressure at any given floor served by the stairway drops off substantially from the design pressure and, depending on the assumed outside air temperature, is lower than the minimum 37.5 Pa [0.15 in. H<sub>2</sub>O] recommended by NFPA 92A for a 20–25 story building. At the 25–30 story threshold, air actually enters the stair, as evidenced by the negative pressure differentials shown in Table 1, and the maximum door opening force may be exceeded at the upper portion of the stair. Table 1 also shows the impact of opening a single door into the stair, which results in a substantial overall decrease in the pressure in the stair. Even at ambient temperatures, there is a 50% reduction for the 15-story building and a 30% reduction for the 30-story building.

Table 1 – Impact of Stack Effect

No. of Stories	Amb. Temp (°C)	Min. Stair ΔP (Pa)	Max. Stair ΔP (Pa)	One Door Open	
				Min. Stair ΔP	Max. Stair ΔP
15	20	37.5	37.5	17.5	20
	-4	20	57.5	5	40
	-14	12.5	67.5	0	50
20	20	37.5	37.5	20	22.5
	-4	15	65	2.5	50
	-14	5	77.5	-2.5	65
25	20	37.5	37.5	22.5	25
	-4	7.5	72.5	0	60
	-14	0	90	-5	80
30	20	37.5	37.5	25	27.5
	-4	5	80	-2.5	70
	-14	-2.5	102.5	-10	92.5

- Pressures below minimum 12.5 Pa [0.05 in. H<sub>2</sub>O] for smoke control systems.
- Negative pressure indicates flow into the stair.
- Door opening forces exceed maximum allowable 90 Pa [0.36 in. H<sub>2</sub>O] design pressure.
- Opening one door drastically reduces stair pressures, even with no stack effect.

In large cities such as New York, buildings exceeding 30 stories are commonplace. In addition, the cold winter temperatures magnify the impact of stack effect on these buildings and make it very difficult to protect stair enclosures using pressurization smoke control systems. In other locales, such as Dubai in the United Arab Emirates (UAE) and some Asian cities, hot summer design temperatures may actually create the greatest stack effect. Stair pressurization systems in the

super-tall high-rises (having 90 or more stories) in these locales may be severely impacted by stack effect, even for moderate outside air temperature differentials. For these buildings, other design considerations must be made to properly design a stair pressurization system, such as providing intermediate doors or transfer corridors to break up long stair runs, or otherwise designing to account for the impact of stack effect

### Design of Modulating Systems

In order to deal with the impact of stack effect on the design of stair pressurization systems in tall buildings, design engineers often propose to provide modulating stair pressurization systems that adjust the air flow into the stair based on measured pressure differentials between the stair and floors served by the stair. Components of a modulating system are typically a powered or barometric relief damper at the top of the stair, a stair pressurization fan equipped with a variable frequency drive (VFD) and pressure sensors at multiple locations in the stairwell.

Modulating stair systems are difficult to test and commission, difficult to maintain, and have the potential to create un-safe conditions in the stair if not designed properly. For example, a common mistake is to modulate the stair fan to always maintain pressures above the design minimum pressure differential in the stair, using the lowest measured pressure differential from the various sensors installed at various heights throughout the stairwell. In a stack effect condition, modulating the fan based on a pressure sensor near the bottom of a stair would potentially cause unacceptably high door opening forces high in the stair. The fan may also ramp up due to an open door, creating pressures that would cause the door to slam shut when released, causing the potential for occupant injury. A proper design needs to specify a maximum fan setting to avoid over-pressurizing the stair enclosure.

### Design of an Alternate Stair Protection System

The performance of a stair pressurization system may be significantly impacted by stack effect and the presence of openings into the stair due to structural damage during an event or due to open doors. During a full-building evacuation, the opening of multiple doors into the stair for prolonged periods of time may seriously diminish the effectiveness of a stair pressurization system. Attempts to account for the stack effect using modulating stair pressurization fans have the potential to over pressurize stairwell doors if the system is not designed/balanced properly, and can result in occupants not being able to access the stairwell in event of a fire.

An alternate approach was examined where both supply and exhaust is provided for a stair to provide a high throughput dilution system to protect the stair. This system provides a net neutral pressure differential in the stairwell with respect to the floor served, and has the benefit of removing smoke from the stair in the event of a fire. This system would also allow longer continuous

stairwell runs in super tall high-rise buildings and limit overpressures due to stack effect. Stack effect pressures could be relieved at the top of the stairwell using barometric relief dampers, without the active protection system adding to the overpressure that would need to be relieved.

### Evaluation Using CFD Modeling

The performance of the proposed stair dilution system would be difficult to evaluate via testing under live fire conditions in a high-rise building. System performance was therefore evaluated using the computational fluid dynamics model Fire Dynamics Simulator (FDS), developed by the National Institute of Technology (NIST) in the United States (McGrattan, 2005). FDS has been under development at NIST's Building Fire Research Laboratory (BFRL) for over a decade. The model is public domain software available from the NIST website, making it a frequently used design tool by fire protection engineers. FDS is specifically designed with fire scenarios in mind and can be readily applied to fire protection engineering applications. The model is intended to handle isolated and spreading fires in human habitable spaces in the presence of obstacles such as furniture, overhead ceiling obstructions, and other structural members. The model can handle both passive and forced vents (e.g., smoke exhaust, stair pressurization). Fuel properties and burning rates of a fire are user-defined. The model is well validated for these applications, as described in the fire protection literature (McGrattan, 2007).

### Stairwell Model Domain

In order to examine the impact of a stair pressurization system versus a dilution venting system, a model domain was constructed representative of a 20-story stairwell (see Figure 1). Although a 20-story stairwell is a relatively short stair run for high-rise buildings, this resulted in a model domain that allowed reasonable computational times (15 cm grid, 250,000 total cells). The relative performance of the scenarios evaluated would also be expected to apply directly to stairwells in taller buildings.

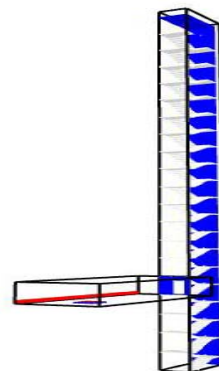


Figure 1. FDS model domain for 20-story stairwell with fire compartment adjacent to the 5<sup>th</sup> floor of the stair.



On the fifth “floor” of the stairwell, a separate 93 m<sup>2</sup> [1000 ft<sup>2</sup>] enclosure was attached, containing the fire. This size enclosure is representative of the total volume of a corridor in a residential building, a large office lobby space, or other moderately sized space directly adjacent to the stairwell. For all of the model scenarios, vertical air movement through the stair was induced by connecting the stair to an ambient (outside air) zone set to a colder temperature. The simulation temperatures correspond to the -14 °C [15 °F] ASHRAE winter design temperature for New York City previously discussed. The internal stair temperature was set to 20 °C [68 °F].

A single basic fire scenario was evaluated by the model simulations. The non-sprinklered fire scenario simulates a more severe fire in a building not equipped with automatic sprinklers, or where the sprinkler system has become disabled due to a catastrophic event. The maximum fire size for this scenario is 2,000 kW. Because sprinklers are not included in the FDS model for this fire scenario, smoke enters the stair with a significant buoyancy force.

### FDS Model Scenarios

A range of model scenarios was simulated in FDS using the 20-story stairwell model domain, varying the openings present in the stair. Three basic stairwell ventilation configurations were evaluated:

- a *baseline* case where no ventilation is present to evaluate the smoke conditions that would develop in the stair in the absence of stairwell protection;
- a supply only *stair pressurization* system where 10,000 cfm sufficient to pressurize the stair to 0.15 in. H<sub>2</sub>O with doors closed, is provided via 4 distributed injection points; and
- a supply/exhaust *dilution* case where 10,000 cfm supply and an equal amount of exhaust are provided to and from the stair.

Simulations varied whether the door to the fire compartment was open or closed to the stairwell and varied the extent to which doors on other floors of the stairwell were held open, simulating occupants queuing to enter the stair in a full-building evacuation scenario. When doors were assumed to be closed, the total leakage of the door was approximated by an area of 0.02 m<sup>2</sup> [.25 ft<sup>2</sup>]. The open fire compartment door had an area of 1.95 m<sup>2</sup> [21 ft<sup>2</sup>]. When doors on the upper floors of the stair were assumed held partially open due to a full building evacuation condition, doors on alternate floors were modeled with an opening of 0.37 m<sup>2</sup> [4 ft<sup>2</sup>].

### FDS Model Results

For the fire scenario evaluated, the non-sprinklered condition results in hot smoke conditions within the fire compartment that exert a buoyancy force across the openings to the stair enclosure. As shown in Figure 2,

the upper layer of the fire compartment reaches steady-state temperatures of 325 – 400 °C [620 – 750 °F]. This buoyancy force, coupled with the draw into the stair created by the imposed stack effect conditions, are the drivers for smoke spread into the stair from the fire compartment.

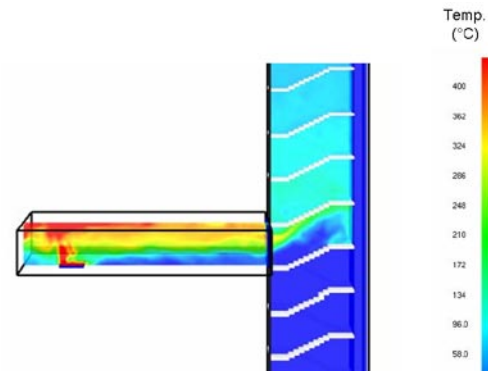


Figure 2. Fire compartment temperatures with all doors to the stairwell assumed closed.

Figure 3 shows the comparative model results for the condition where all doors to the stairs are closed (leakage area = 0.02 m<sup>2</sup> [.25 ft<sup>2</sup>]), with the stair subject to the stack effect created by a -14 °C [15 °F] outside air temperature. As expected, the pressurization system keeps smoke out of the stair via the pressure differential created across the closed door. While the dilution system allows some smoke to be drawn into the stair due to the stack effect induced negative pressure into the stair enclosure, the dilution system is effective in dramatically improving the stair environment with respect to the baseline “no ventilation” case, and visibility distances are maintained above 10 m throughout the stair, except for the two floors nearest the fire, for which visibility is maintained at roughly 3 m.

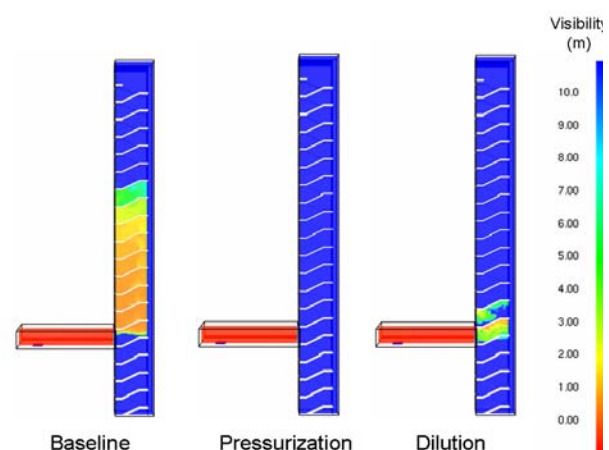


Figure 3. – Results for three ventilation conditions with all doors to the stairwell assumed closed.

During a full building evacuation, conditions would change substantially, as the presence of partially open doors into the stair enclosure would increase the

draw of smoke into the stair due to stack effect, and decrease the overpressure in the stair created by the stair pressurization system substantially. As shown in Figure 3, the dilution system performs better than the pressurization system in this case, although both active ventilation systems greatly improve the stair environment with respect to the baseline case.

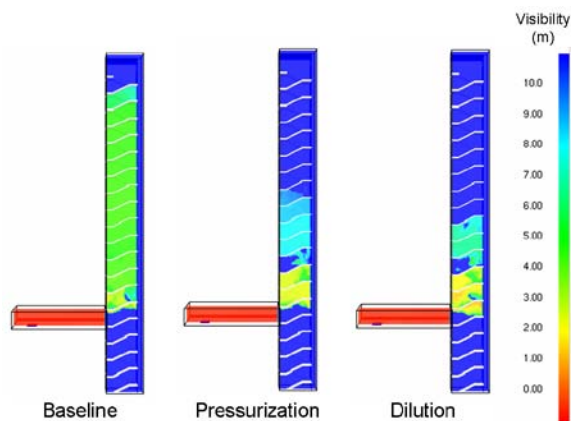


Figure 4. – Results for three ventilation conditions with the fire compartment door closed and doors on other floors of the stairwell partially open, increasing the impact of stack effect.

Figure 5 shows the results for the three ventilation conditions evaluated when the fire compartment door is open, for the full building evacuation condition where doors in the stairwell are assumed partially open. While it is unlikely that the door to the stairwell on the fire floor would remain open during a fire event, this scenario is indicative of a catastrophic situation where a large opening exists between the fire floor and the stair. Figure 4 shows that for the fire scenario modeled, both active ventilation options improve the environment within the stair enclosure; however, the dilution ventilation option performs best and improves visibility within the stairwell by a factor of two (1 m versus 0.5 m visibility) throughout most of the stair with respect to the baseline case.

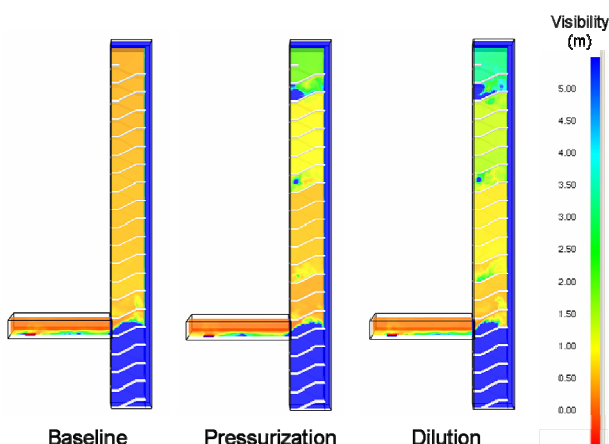


Figure 5. Results for three ventilation conditions with the fire compartment door open and doors on other floors of the stairwell partially open, increasing the impact of stack effect.

## Modeling Summary

The simulations performed using FDS showed that a high throughput dilution venting system has the potential of providing equivalent protection to a typical stair pressurization system, without the associated problems due to door overpressure exacerbated by stack effect. In addition, while the amount of pressurization air that can be delivered to the stair is limited by the potential overpressures created, a balanced dilution system does not have this limitation. Therefore, the performance of the dilution system evaluated for the purposes of this paper may be enhanced by increasing the ventilation rates. The optimal rate for ventilating the stair bears further evaluation, and is likely only limited by ventilation shaft space constraints and system cost issues. Actual use of a dilution venting system would require optimization of the airflow rate based on postulated fire scenarios for the building and the desired performance with respect to tenability conditions within the stair.

## Other Stairwell Design Options

In addition to providing a ventilation system capable of improving the tenability conditions within the stair, other aspects can be incorporated into the stair design that will improve the speed of occupant egress via the stair, and thus limit the time of exposure to any potentially hazardous environment within the stair. Provision of adequate stair lighting, photoluminescent stair/path lighting (see Figure 6), and adequate door/stair widths may greatly increase the speed of occupant travel within the stair in a smoky environment, in combination with a stairwell dilution system or other ventilation option.



Figure 6. – Photoluminescent stair/path lighting (source: irc.nrc-cnrc.gc.ca)

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## Conclusion

The predominant means for improving the environment in high-rise stair enclosures is to protect the stairs using stair pressurization systems. Stair pressurization systems must be properly designed to avoid creating adverse conditions to exiting such as unacceptably high door opening forces due to stack effect. The effectiveness of these systems may also be impacted by openings created in the stairs.

Design alternatives such as the “dilution” venting system evaluated in this paper may be viable solutions for protecting stairs in tall buildings. These alternatives may be less impacted by stack effect, damage to stairwells caused by a localized event in the building, or prolonged opening of doors in a full building evacuation. Performance based fire protection engineering analysis provides a means for evaluating alternative designs that may be more appropriate for protecting tall high-rise buildings.

## References

- ASHRAE (2005), 2005 *ASHRAE Handbook – Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, USA, 2005.
- IBC (2006), *International Building Code*. International Code Council, Washington, D.C., USA, 2006.
- MCGRATTAN, K. (2005). *Fire Dynamics Simulator (Version 4) Technical Reference Guide*. NIST SP 1018, National Institute of Standards and Technology, Gaithersburg, MD, USA, 2005.
- MCGRATTAN, K. (2007). *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*. Volume 7: Fire Dynamics Simulator. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD, and Electric Power Research Institute (EPRI), Palo Alto, CA, USA. NUREG-1824 and EPRI 1011999, 2007.
- NFPA 92A (2006), *Standard for Smoke Control Systems Utilizing Barriers and Pressure Differences*. National Fire Protection Association, Quincy, MA, USA, 2006.
- WALTON, G.N. and DOLS, W.S. (2005). *CONTAM 2.4 User Guide and Program Documentation*. NISTIR 7251, National Institute of Standards and Technology, Gaithersburg, MD, USA, 2005.