Modeling of Stack Effect in High-Rise Buildings under Winter Conditions–Evaluating the Validity of Field Observations

Abstract. To characterize the magnitude of stack effect in existing buildings, differential pressures measurements were taken in fifteen high-rise buildings during the winter months of 2013. A number of interesting observations were made: (1) unless conservative leakage values are used, typical hand calculations may under-predict the shaft-to-building differential pressures, (2) introduction of cold air into pressurized stairwells cooled the stair, but temperatures remained significantly higher than ambient (3) introduction of cold air into pressurized stairwells caused significant pressure and increased door opening forces required at the bottom of the stairs, and (4) pressurization of the stairwells increased the pressure and stack effect flows via the elevator shafts.

Using FDS modelling it was verified that when pressurizing a stairwell with untreated cold outside air, the temperature in the stair cools, but stabilizes at a temperature that is between the outside air temperature and the initial building temperature. Introduction of cold air increases the pressures at the bottom of the stairwell. The CONTAM modelling verified that the cooling of the stair increases pressures at the bottom of the stairwell to the extent that excessive door opening forces are likely. Cooling of the stair also increases the stack effect flow via the elevator shaft over time. The modelling also showed that elevator lobbies reduced the flow to upper floors by approximately 50% for all building types and that elevator hoistway vents had only a modest impact on reducing the flow to upper floors of the building.

Keywords: CONTAM; Elevator Lobby; Elevator Pressurization; FDS, Smoke Control; Stack Effect; Stairwell Pressurization.

1.0 Introduction

Pressure differential testing was conducted during the months of January–March, 2013 [1] to characterize vertical movement of air in buildings under winter conditions. The purpose of the testing was to characterize the magnitude of the stack effect within stairwells and elevator shafts for a variety of buildings of different type (office, hotel) and height. To characterize the magnitude of stack effect, differential pressures measurements were taken in fifteen (15) high-rise buildings, ranging in height from 44–150 m (143–492 ft). During these tests, a number of interesting observations were made that warranted further investigation:

(1) Unless conservative leakage values are used, typical hand calculations may under-predict the shaft-to-building differential pressures;
(2) Introduction of cold air into pressurized stairwells cooled the stair but temperatures remained significantly higher than ambient even after 20–30 minutes;
(3) Introduction of cold air into pressurized stairwells caused significant pressure and increased the door opening forces required at the bottom of the stairs; and
(4) Pressurization of the stairwells increased the pressure (and resulting stack effect flows) via the elevator shafts.

The observations made in 2013 are significant because they seemed to conflict with a number of widely held assumptions, namely that:

- Significant stack effects are only a concern in northern climate cities where extreme cold temperatures exist, as newer construction is tighter than that of older buildings, primarily due to the use of low leakage curtain-wall construction;
- High door opening forces are alleviated due to the introduction of cold air in the stair, which causes the stair temperature to approach that of the exterior, thereby reducing the stack effect;
- Elevator lobbies, hoistway vents and other passive fire protection features may not be warranted due to the fact that stack effect flows are minimal.

To validate the field observations made in 2013, and to examine the validity of the widely held assumptions, modelling was performed to examine the variables impacting the stack effect for a variety of building configurations, including different building types (open office, office with central corridor, hotel/residential), building heights (30 or 60 stories), and building leakage rates (loose/tight). The impact of elevator lobbies and hoistway vents were also evaluated. The modelling included use of Fire Dynamics Simulator (FDS) to look at the cooling of a stairwell when pressurized by untreated ambient air and the use of the CONTAM building airflow model to evaluate stack effect pressures and flows under the changing building conditions.

2.0 FDS Modelling of a Stair Enclosure

A simple stairwell that captured all the relevant parameters was constructed in the FDS model, but excluded the rest of the building to reduce the size of the model domain and thus the computational time required. The important parameters for the simulation were the air injection system and the leakage out of the stair. The purpose of the FDS modelling was to examine the temperature profile within the stairwell as a function of the quantity of stair pressurization air, while adequately accounting for the heat transfer within the stair enclosure.

2.1. Background

Previous evaluations of stairwell and elevator shaft pressurization accounting for varying shaft temperatures using numerical modeling includes the work performed by Miller and Beasley [2] and Bowers et al. [3]. Miller and Beasley [2] studied elevator and stairwell shaft pressurization systems as a means to prevent smoke migration in tall buildings using the CONTAM simulation software developed by the National Institute of Standards and Technology (NIST). The study evaluated a 30 story building with exterior leakages calibrated to experimental data for both a residential and commercial building. Each floor of the building included stairwells at opposite corners of the building and two open (i.e., not enclosed in an elevator lobby) elevator shafts having four sets of elevators. Simulations in CONTAM were conducted to evaluate the effects of the elevator and exterior building doors, ambient temperature, fan location, and shaft venting on the pressurization system performance. Of particular relevance to the work presented in this paper, Miller and Beasley recognized that air supplied to the building shafts by the pressurization system is at a different temperature than the building such that a variable temperature profile exists within the shaft.

To assess the impact of a different temperature in the pressurized shafts, Miller and Beasley modeled an average temperature within both the stairwell and elevator shafts as inputs to the CONTAM model. The average temperature modeled in each simulation was calculated based on a shaft heat transfer model developed by the authors based on correlations for duct flow with axially varying bulk fluid temperature. In essence, the model assumes unconditioned exterior air injected at the top of the shaft is heated by the walls of the shaft which results in a temperature profile that varies axially as a function of the distance from the injection point. Using this approach, the authors calculated the average shaft temperature as the integral of the shaft temperature profile over the height of the shaft. Limitations to Miller and Beasley's approach include the inability to account for buoyancy (i.e., their model assumes the coldest temperatures are at the top of the stair whereas buoyancy would dictate that cold air would settle at the bottom of the stair), the inability to model transient temperature profiles (their model assumes a constant wall temperature), and the inability to account for systems with multiple injection points. Nonetheless, the authors present data based on their model that supports the results presented in this analysis. First, the authors showed that there was a minimal impact on the pressure profile in shafts modeled in CONTAM when a single average shaft temperature was used as opposed to the actual spatially varying shaft temperature. Secondly, the average shaft temperature falls between the exterior temperature and the interior temperature of the building. Finally, the average temperature within a shaft is a function of the flowrate of air introduced to the shaft. Higher flow rates result in a shaft temperature closer to the exterior temperature while lower flow rates result in a shaft temperature closer to the interior temperature. As will be discussed, Miller and Beasley's findings relating to shaft temperature are generally consistent to the findings presented in this paper.

Similar to the work performed by Miller and Beasley, Bowers et al. [3] accounted for the impact of shaft temperature as part of their assessment of stairwell and elevator shaft pressurization systems for 40 and 69 story buildings using CONTAM. As part of the study, Bowers et al. expanded the model presented by Miller and Beasley to account for variable heat transfer coefficients. The authors posited that the average temperature in a shaft could be more accurately determined if changes to the convective heat transfer coefficient were adjusted as a function of the axial distance from the injection point to better capture increases in turbulence. Additionally, the authors expanded the heat transfer model to account for stairwells by developing a geometry correction factor to account for additional surface area of the stairs. As with the model developed by Miller and Beasley, the model presented by Bowers et al. accounts for a single injection point at the top of the shaft and assumes a constant wall temperature so the limitations discussed above are still inherent in the model. The results presented by Bowers et al. also indicate that the average shaft temperatures fall between the exterior temperature and interior building temperature. However, with the modifications made to the heat transfer model, the data for "cold day" conditions (exterior temperature of -12°C) suggests that average elevator and shaft temperatures are closer to the exterior temperature than the interior temperature. This finding is also a function of the flow rate required to achieve the desired differential pressure in the shafts as a higher flow rate in both models corresponded to lower shaft temperatures on a cold day. Bowers et al. do not present empirical data to validate their model but their results appear to be in general agreement with the work presented by Miller and Beasley [2] and the findings presented herein. Ultimately, Bowers et al. concluded that effects of changes to the ambient temperature were found to be relatively minor for elevator pressurization but more substantial for stairwell pressurization systems. In either case, the results showed that different ambient temperatures resulted in different flow rates required to achieve a set differential pressure.

2.2. FDS Model Construction

The Fire Dynamics Simulator (FDS) version 6.1 was used for this analysis. FDS is a computational fluid dynamics model of thermally driven fluid flow and related phenomenon, developed by a multi-national team lead by the National Institute of Standards and Technology (NIST) [4]

The walls of the stairwell were assumed to be constructed of 13 mm thick gypsum wallboard. The stairs were assumed to be steel. To evaluate any potential effects of the heat capacity and heat transfer through the surrounding walls on the results, a sensitivity run was performed using material parameters of concrete for the walls and stairs. The important parameters for the materials used in the model are shown in Table 1 [5].

Table 1
Thermal Properties of Material Used in FDS Model

Material	Thermal Conductivity, *k*, [J/s-m-°C]	Heat Capacity, c_p, [J/kg-°C]	Density, ρ, [kg/m³]	Surface Emissivity, ε, (–)
Normal Weight Concrete	1.4	880	2,300	0.9
Steel	63.9	434	7,832	0.9
Gypsum Wall-board	0.17	1,100	800	0.9

The stairwell included a landing on each level with a door to the rest of the floor, and a stair to the floor above with a landing halfway up. The full stair as it appears in the FDS model, and a close-up of the lower section is shown in Figure 1.

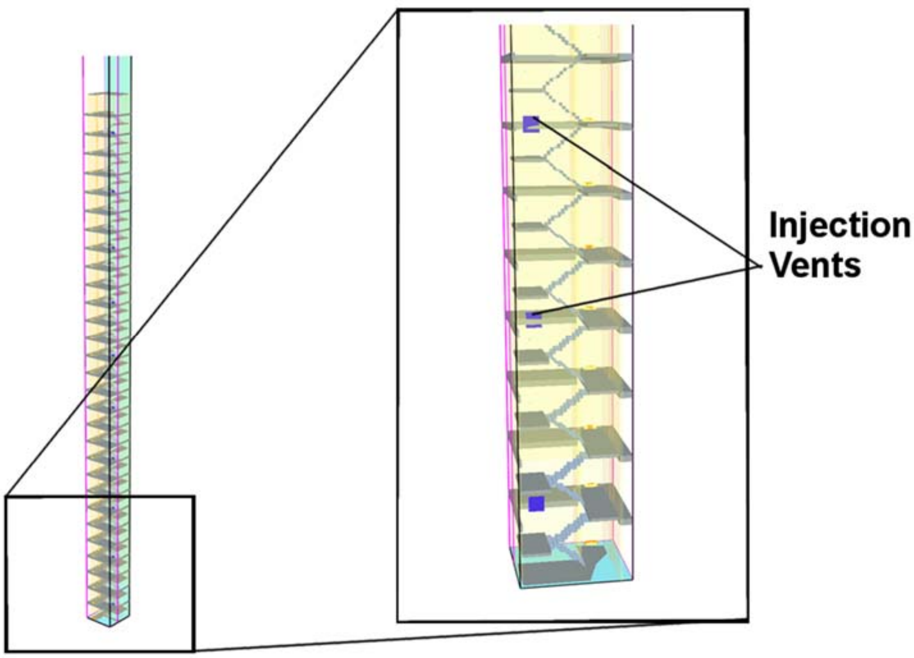

Figure 1. Overview of the 30 story stair and close-up view. Injection points shown as blue squares

2.3. Stair Pressurization System

The pressurization system consisted of injection vents placed at every third floor, starting on the 2nd floor. The vents were approximately 1 m^2 and placed above the landing on the stair wall. In the FDS model, the vents were modeled as supply vents providing air at a prescribed mass flow rate and air temperature.

To simulate a stair pressurization system operating in a building located in a cold environment, two below-freezing temperatures were chosen; -3.3°C (26°F) and -16.7°C (2°F). These were based on a survey of average and minimum winter temperatures in major metropolitan areas in North America. Data was analyzed from the fundamentals handbook of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [6] and National Oceanic and Atmospheric Administration (NOAA). The ASHRAE data used was the 99.6 DB value, which is the temperature that was exceeded less than 35 hours in a year, based on weather data from 1986–2010. From NOAA weather data, the minimum and average winter temperatures were evaluated.

These represent mild and severe winter conditions respectively, which frequently occur in a large number of densely populated cities. The minimum average winter temperatures from some major cold-weather cities is shown in Table 2. It should be noted that while extreme cold stack effect conditions are typically considered a problem only for northern cities, extreme weather conditions in recent years have shown this to be an incorrect assumptions. The widely reported “Polar Vortex” in the winter of 2014 resulted in extended periods of cold temperatures across the southern parts of the U.S. Temperatures below the ASHRAE design temperature for New York listed in Table 2 were experienced in cities such as Charlotte, NC and Atlanta, GA. Relatively low temperatures were measured as far south as Texas and Florida.

Table 2
Average and Minimum Winter Temperatures for Select Locations

Location	ASHRAE 99.6% DB [°C (°F)]	Normal Minimum Temperature [°C (°F)]	Normal Average Temperature [°C (°F)]
New York, NY	-10.1 (13.8)	-3.2 (26.3)	0.4 (32.7)
Boston, MA	-13.3 (8.1)	-5.4 (22.2)	-1.7 (29)
Chicago, IL	-18.6 (-1.5)	-8.6 (16.5)	-4.6 (23.8)
Denver, CO	-18.6 (-1.4)	-8.5 (16.7)	-1.1 (30)
Minneapolis, MN	-24 (-11.2)	-13.6 (7.5)	-9.1 (15.6)
Average	**-16.9 (1.6)**	**-7.9 (17.8)**	**-3.2 (26.2)**

The flow rate for the pressurization system was calculated using the CONTAM model assuming an ambient temperature of 20°C. The system was designed to produce a pressure of 12.5 pa above ambient. Three inputs were used to arrive at the required flow rate from the vents; loose, average and tight leakage through building components. This produced three different flow rates, shown in Table 3. The total flow from the pressurization system was injected through 10 vents in the 30 story building.

Table 3
Assumed Wall Leakage Rates and Resulting Flow Rate for the Pressurization System

Construction	Door Leak [m^2]	Total Leakage Area [m^2]	Total Flow Rate [m^3/s]
Tight	0.007	0.37	1.27
Average	0.023	0.39	4.39
Loose	0.043	0.41	10.24

The leakage into or out of the stair was simulated in the FDS model using the HVAC submodel. This allows FDS to calculate the forced flow through small openings, such as those around a door, without having to model these openings explicitly, as they are much smaller than the numerical grid used. Instead, the leakage opening is represented as a larger vent in FDS with the actual surface area of the opening prescribed as a parameter and used for the calculation. The local pressure on either end of the HVAC system, and the resistance in the duct is used to calculate the flow rate and the direction. In the FDS model of the stair system one vent was placed on the bottom of each door on every floor, representing leakage around the doors leading into the stair. The leakage from all the surrounding walls was lumped together into one HVAC vent going floor to ceiling on one wall on each floor.

2.4. FDS Run Matrix

The three different pressurization system flow rates were modeled with the two temperature scenarios, to give a total of six primary FDS simulations. In addition, three sensitivity cases were modeled to evaluate if changing these parameters would significantly affect the results. One with different material properties, one with an open door on the bottom floor, and a case with a 60 story building rather than 30.

Table 4
Primary FDS Runs

Run Num.	Construction	Injected Air Temperature [˚C]	Total Flow Rate [m3/s]
1	Tight	-16.7	1.27
2	Average	-16.7	4.39
3	Loose	-16.7	10.24
4	Tight	-3.3	1.27
5	Average	-3.3	4.39
6	Loose	-3.3	10.24

Table 5
Sensitivity Runs, Variations of Run Number 3

Run Num.	Construction	Injected Air Temperature [˚C]	Total Flow Rate [m3/s]	Sensitivity Parameter
7	Loose	-16.7	10.24	Concrete Walls and Stairs
8	Loose	-16.7	10.24	Door open
9	Loose	-16.7	10.24	60 stories

2.5. FDS Model Results

The FDS model output was used to provide a temperature gradient over time in the stair shaft as input to the CONTAM model, but the results were also analyzed to further evaluate the effect the injection of cold outside air has on the air temperature in the stairwell. Two main points of interest were the time required to reach a minimum steady state temperature inside the stairwell, and how close this was to the temperature of the outside.

The temperature was measured at each of the 30 floors in the building during the simulation. The measured temperature varied based on the distance from the measuring device and the cold air injection point, which were placed every 3rd floor. As cold air moved down, much lower temperatures were measured at the lowest floor, compared to a device just above an injection point. The temperature in the stair shaft at some points in time for simulation 3 is shown in Figure 2.

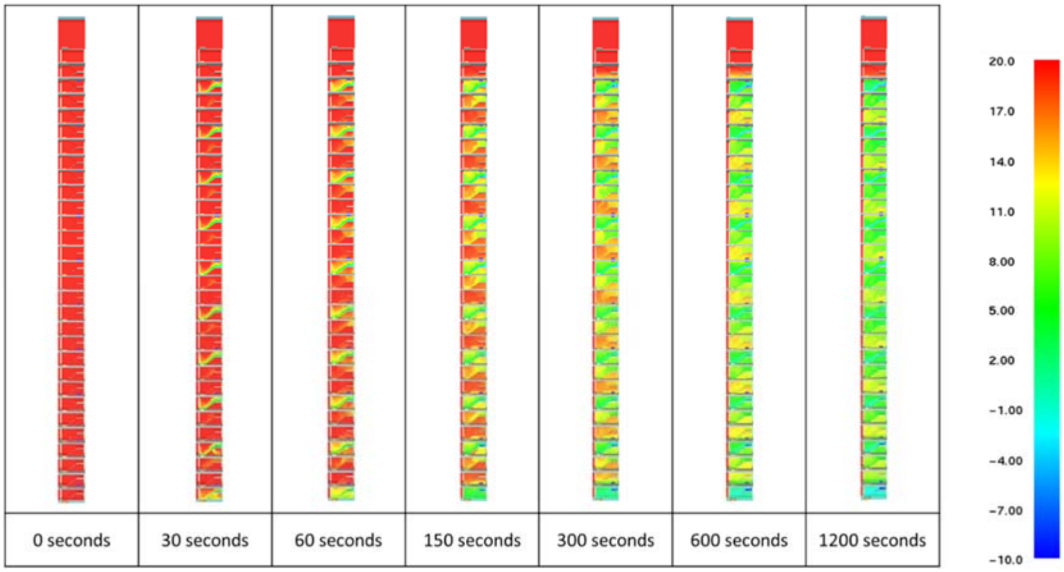

Figure 2. Vertical slice of temperature at points in time for simulation 3

A repeating pattern developed every three floors as the cold air being injected would fall down and gradually mix with the warmer air in the shaft and absorb heat from the surrounding building elements; the walls and the stair structure. A closer view of five floors were the repeating pattern is visible at 60 seconds and 600 seconds is shown in Figure 3. At 60 second the floor directly above the injection point maintains about 20˚C, while the floor below has a temperature around 5˚C. After 10 minutes the average temperature in the stair has dropped close to the minimum value and the difference between the floors is less pronounced.

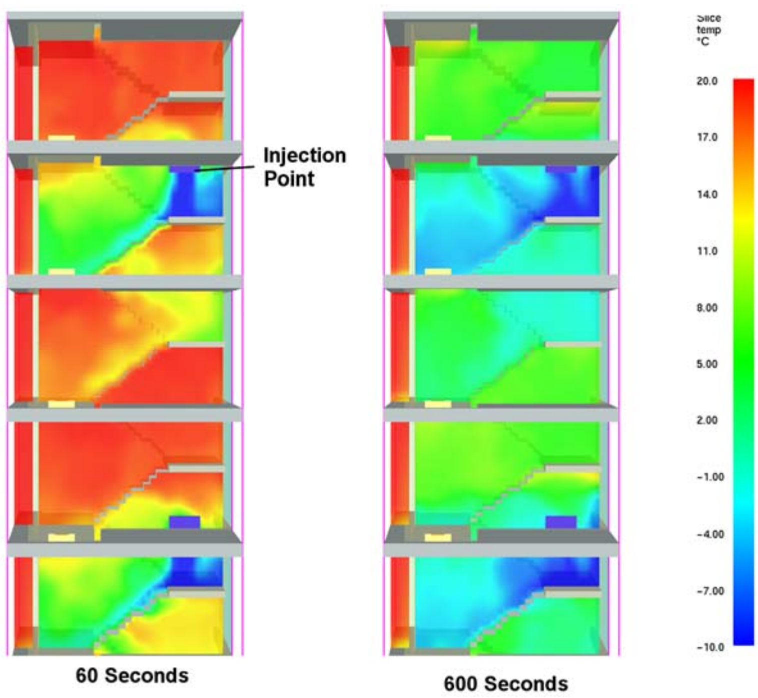

Figure 3. Temperature distribution over five floors in the stair shaft after 60 seconds and 600 seconds

The average temperature compared to the measurement from each of the 30 floors is shown in Figure 4 for the simulation with -16.6˚C external temperature and average leakage (run 3)

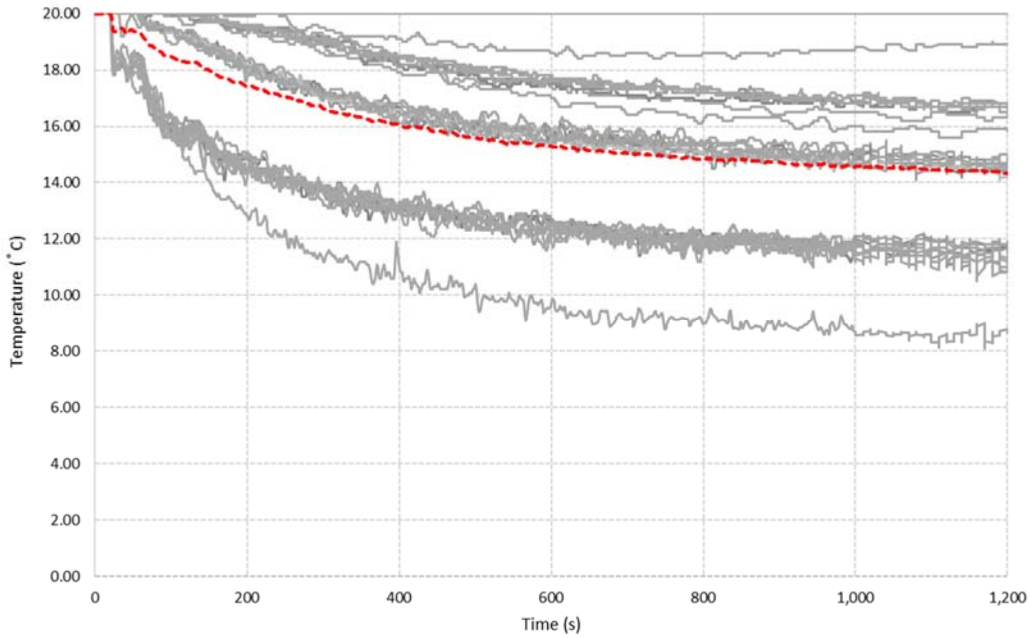

Figure 4. Average and individual floor temperature measurement

The figures shown that there is great variation between individual measurement points, but all the curves follow the same curve shape. To simplify comparison, the average temperature was used for all cases.

The average temperature over time was plotted for the three leakage rates (tight, average, and loose) with an exterior temperature of -16.6˚C and the three with -3˚C and are shown in Figure 5 and Figure 6 respectively. The outside temperature is indicated by the red line at the bottom of the plot.

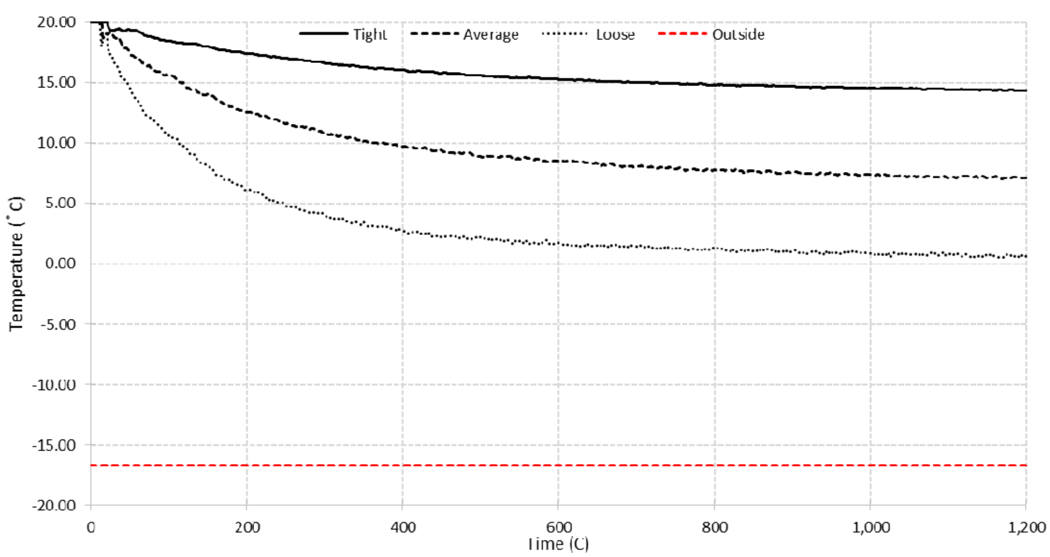

Figure 5. Average stair temperatures for the three runs with -16.6˚C outside temperature

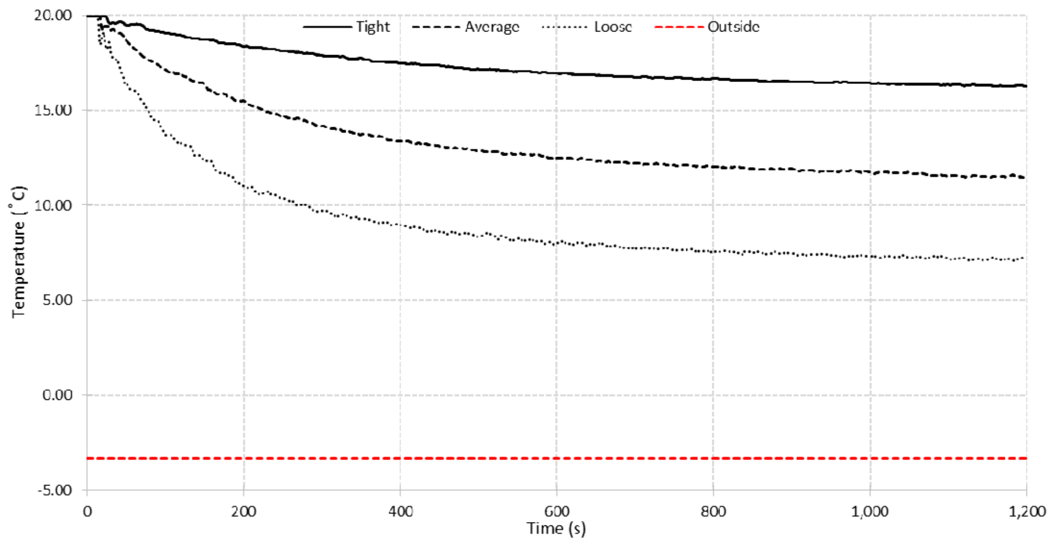

Figure 6. Average stair temperatures for the three runs with -3˚C outside temperature

The two plots show that after the largest drop in temperature occurs before 400–600 seconds. After this time the temperatures in the stair shaft show only a minor decline. The temperature drop after 3 min represents between 40–65% of the total decline in temperature.

Temperature data for Run 3 compared to the three sensitivity runs is plotted in Figure 7. All three sensitivity runs show higher temperatures in the stairwell than seen in the baseline run. The concrete wall is thicker and has a higher thermal conductivity than the gypsum wallboard and thus release more heat into the stair shaft, slowing the cooling. With an open door on the lowest floor, additional air flows out at the bottom of the stair, mainly from the air injection point at that level. Thus, this also results in higher temperatures on average. The 60-story stair shaft was given an equivalent increased air injection volume, but still results in higher temperatures. This shows that the baseline run results in lower temperatures in the stair shaft, a conservative result in the context of this analysis.

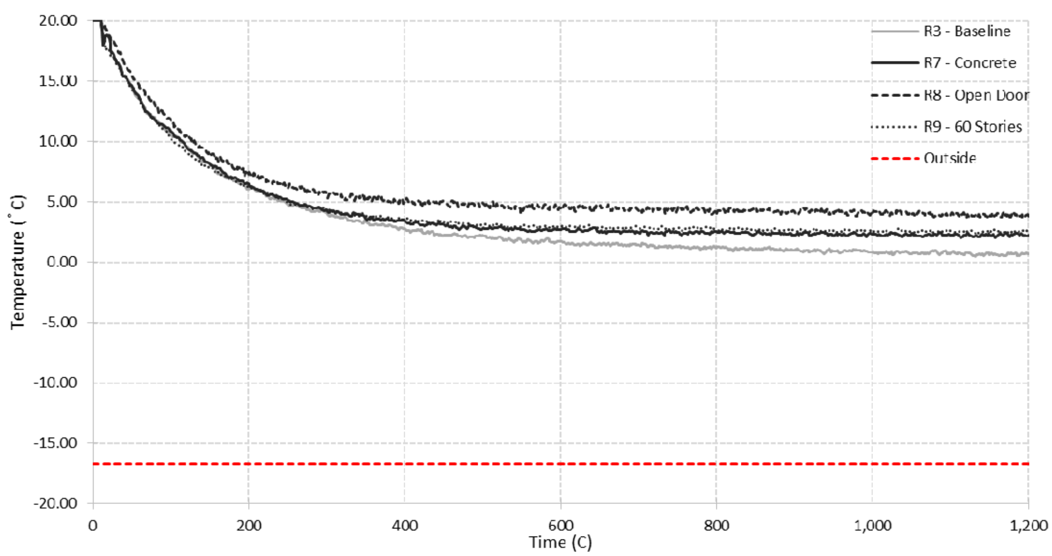

Figure 7. Average stair temperatures for the three sensitivity runs and the baseline run.

Minimum temperature reached in the star shaft at steady state and the total temperature drop is show in Table 6, and for the sensitivity runs in Table 7. The temperature drop from ambient as a percentage of the drop required to reach the outside temperature (i.e., the max possible decline in temperature) is also shown.

Table 6
Temperature Drop Data for the Six Runs

Run	Construction	Outside Temperature	Min Stair Temperature [˚C]	Temperature Drop [˚C]	% of drop to Outside
1	Tight	-16.7	14.3	5.7	15%
2	Average	-16.7	7.1	12.9	35%
3	Loose	-16.7	0.5	19.5	53%
4	Tight	-3.3	16.2	3.8	16%
5	Average	-3.3	11.5	8.5	37%
6	Loose	-3.3	7.1	12.9	55%

Table 7
Temperature Drop Data for the Baseline and Sensitivity Runs

Run	Outside Temperature	Min Stair Temperature [˚C]	Temperature Drop [˚C]	% of drop to Outside
3 (Baseline)	-16.7	0.5	19.5	53%
7 (Concrete)	-16.7	2.0	18.0	49%
8 (Open)	-16.7	3.7	16.3	44%
9 (60 Stories)	-16.7	2.4	17.6	48%

The temperature drop as a percent of the max possible is similar for the two different outside temperature configurations with a given leakage rate. This indicates that for a given supply rate, the temperature inside the stair shaft stabilizes once it has dropped a percentage of the total required to reach the outside conditions. Additional simulations must be performed to determine if this relationship holds true for other temperature and supply rate configurations.

3.0 CONTAM Modelling of Simplified Buildings

The CONTAM building airflow model [7] was used to evaluate the impact on building airflows within stairwells and elevator hoistways caused by stairwell cooling due to the injection of cold, outside air by the pressurization system. This software program is recognized by NFPA 92A [8] as being appropriate for the design of pressurization smoke control systems. Three different architectural layouts were considered for the CONTAM modelling analysis: (1) Office with Corridor, (2) Open Office, and (3) Hotel.

3.1. Model Construction

Figure 8 shows the typical floor, as modeled, for the three different layouts. For a given model, the typical floors are located on all levels above the ground level (Floor 1). The "Open Office" model is identical to the "Office with Corridor" model, except the central corridor has been removed. All models contain two (2) pressurized stairwells. On the ground level (Floor 1) one stairwell discharges directly to ambient, while the other stairwell discharges to the interior lobby. The "Office" and "Hotel" models consist of 8 and 2 elevator hoistways, respectively. An elevator hoistway vent is located at the top of each shaft. The CONTAM models assume all elevators recall to Floor 1 and remain open. Elevator lobbies are not present on Floor 1.

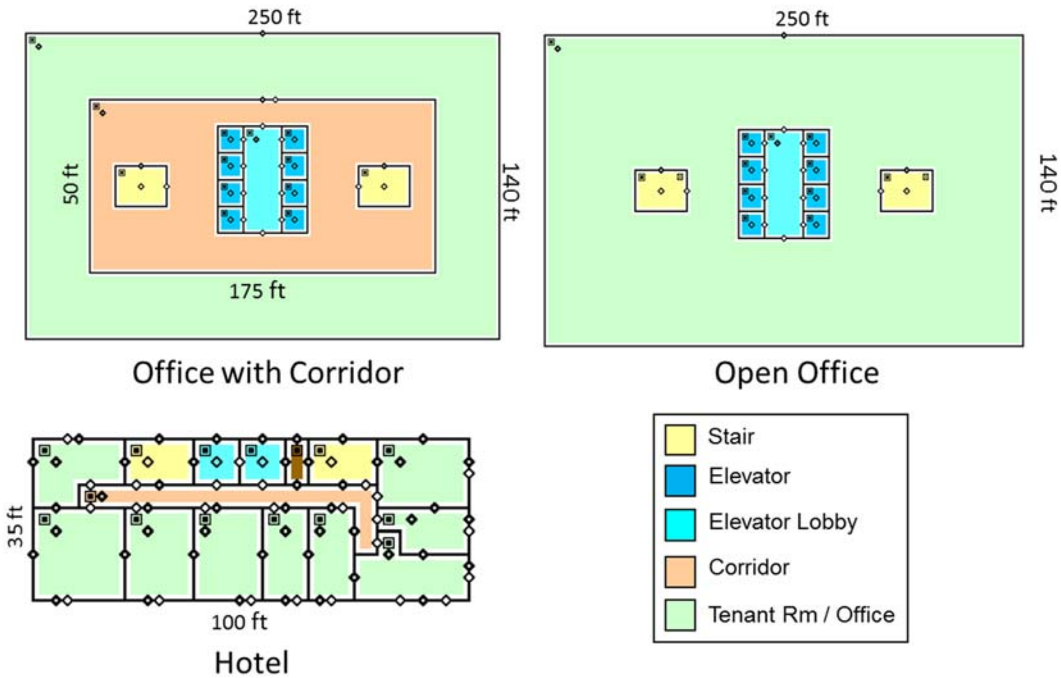

Figure 8. CONTAM model typical floor layouts

To help bound the impact of architectural building leakage on the CONTAM modeling results, two (2) building leakage groups were developed, "looser" and "tighter". Table 8 shows the leakage areas used for the various building components. Door and wall leakages are based on values reported in the *Handbook of Smoke Control Engineering* [9]. A leakage area of 0.56 m^2 (6 ft^2) was used for the open, recalled elevator doors on Floor 1 [10].

Table 8
Leakage Properties of Building Components

Airflow Path Type	Looser Building [m^2 (ft^2)]	Tighter Building [m^2 (ft^2)]
Stair Door	0.04 (0.46)	0.023 (0.25)
Elevator Door–Closed (Floors 2 and Up)	0.06 (0.66)	0.046 (0.50)
Elevator Door–Recalled (Floor 1)	0.56 (6.00)	0.557 (6.00)
Elevator Lobby Door	0.03 (0.32)	0.023 (0.25)
Corridor Door	0.03 (0.32)	0.023 (0.25)
Stairwell Wall [m^2/m^2 (ft^2/ft^2)]	0.00011	0.00011
Exterior Wall [m^2/m^2 (ft^2/ft^2)]	0.00035	0.00017
Hoistway Vent	0.28 (3.00)	0.28 (3.00)
Supply Capacity Per Stair [m3/s (cfm)]	10.24 (21,700)	4.39 (9,300)

Commercial buildings are often assumed to be fairly airtight and that envelope air leakage does not have a significant impact on stack effect or other building airflows. Furthermore, it is assumed that more recently constructed buildings are tighter than older buildings. A review of commercial and institutional building airtightness data, performed by the National Institute of Standards and Technology (NIST) on the leakage of glass curtain wall construction found significant levels of air leakage and debunked the myth of airtight commercial buildings [11, 12]. Findings of this study suggest an average envelope leakage area ratio of 3.25×10^{-4} which is close to the "loose" exterior wall leakage area ratio of 3.5×10^{-4} reported in in the ASHRAE publication *Handbook of Smoke Control Engineering* [9]

Similarly, a recent study was conducted to characterize stack effect in high-rise buildings (up to 150 m) under winter conditions [1]. In this study, shaft-to-building differential pressures (for stairwell and elevator shafts) were measured and compared with hand calculations. For hand calculations, the leakage area between the shaft and building (A_{si}) and leakage area between the building and outside (A_{io}) are estimated. As discussed in the Handbook of Smoke Control Engineering, in general, the ratio A_{si}/A_{io} varies from about 1.7 to 7 [9]. A ratio value of 7 would depict a very "tight" building envelope and a value of 1.7 would depict a very "loose" building envelope. The field measured and hand calculated shaft-to-building differential pressures at the top of the shaft results in the best match when using a A_{si}/A_{io} ratio value of 2, as shown in Figure 9. This study suggests the average commercial building envelope is more on the "loose" side than "tight", and supports the findings of the NIST study performed by Emmerich and Persily [12]. Therefore, for this analysis, the FDS and CONTAM models assume an envelope tightness of "loose" to "average" [9].

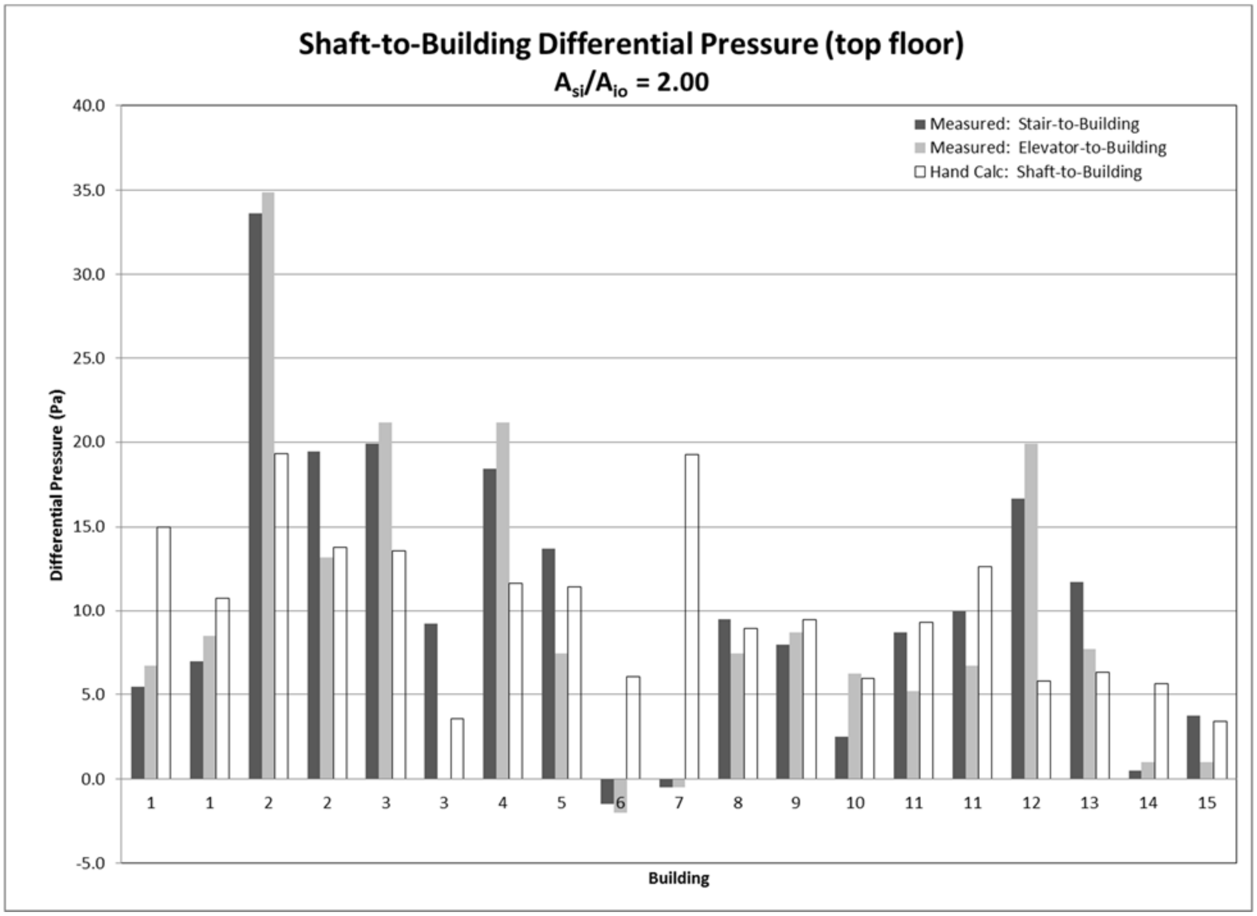

Figure 9. Maximum shaft-to-building differential pressures–measured vs. Hand calculations (Eq. 2), Asi/Aio = 2.00 [1]

3.2. Stairwell Pressurization

Stairwell pressurization is the only active mechanical system present in the CONTAM models. Fan pressurization capacities used for this study were bound by considering a range of stair door leakages and target stair-to-building differential pressures. The 30-story "Office with Corridor" CONTAM model (with hoistway vents and no elevator lobbies) was used for sizing the stairwell pressurization fans. Stair door and other architectural leakages are based on values reported in literature [9]. CONTAM modeling results for sizing the stairwell pressurization fans are provided in Table 9.

Table 9
Stairwell Pressurization Fan Capacities

Flowrate Category	Target Differential Pressure [Pa (in. W.G.)]	Stair Door Leakage Area [m^2 (ft^2)]	Fan Capacity [m^3/s (cfm)]	Air Changes Per Hour
Low	(0.05)	0.0073 (0.079)	1.27 (2,700)	1.4
Average	(0.15)	0.0227 (0.244)	4.39 (9,300)	5.0
High	(0.30)	0.0428 (0.461)	10.24 (21,700)	11.6

Stairwell temperatures predicted by the FDS models were used for the CONTAM modeling analysis using temperature schedules [7]. As previously discussed, the FDS model predicted temperatures varying from floor to floor within the stairwell, dependent on the placement relative to the air injection point. A comparison study in CONTAM revealed that using a single average temperature profile in the stairwell resulted in similar results (stair and elevator differential pressures and airflows) as when using a unique temperature profile in the stairwell for each floor. Therefore, a uniform, average temperature profile schedule was used for the CONTAM modeling analysis. The stairwell temperature schedule used for the "looser" and "tighter" CONTAM models are listed in Table 10. A trapezoidal temperature schedule was used to allow CONTAM to linearly interpolate between temperature values.

Table 10
Stairwell Temperature Schedule

Time (sec)	Looser Building Stairwell Temperature (°C)	Tighter Building Stairwell Temperature (°C)
0	20	20
30	16.7	18.8
60	13.5	17.1
150	8.2	14.1
300	4.1	10.8
600	1.7	8.5
1200	0.7	7.1

3.3. CONTAM Model Scenarios

Table 11 shows the CONTAM simulation matrix used for this analysis. The analysis considered the impact of altering:

1. Building layout
2. Building height
3. Building leakage
4. Stair pressurization fan capacity
5. Presence of elevator lobbies
6. Presence of elevator hoistway vents.

All runs assume elevators are recalled to Floor 1 and the outside air temperature is -16.7˚C (2˚F). The analysis considers both a 30- and 60-story building. Each story has an elevation of 3.96 m (13.0 ft), resulting in a total building height of 119 m (390 ft) and 238 m (780 ft), respectively.

Table 11
CONTAM Scenarios

<table>
<tr><th>Run</th><th>Building Layout</th><th>Building Height (Stories)</th><th>Hoistway Vent (Y/N)</th><th>Elevator Lobby (Y/N)</th><th>Building Leakage</th><th>Stair Fan Capacity [m³/s (cfm)]</th></tr>
<tr><td>1</td><td rowspan="4">Office with Corridor</td><td rowspan="4">30</td><td rowspan="4">Y</td><td rowspan="2">Y</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>2</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>3</td><td rowspan="2">N</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>4</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>5</td><td rowspan="4">Open Office</td><td rowspan="4">30</td><td rowspan="4">Y</td><td rowspan="2">Y</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>6</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>7</td><td rowspan="2">N</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>8</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>9</td><td rowspan="4">Hotel</td><td rowspan="4">30</td><td rowspan="4">Y</td><td rowspan="2">Y</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>10</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>11</td><td rowspan="2">N</td><td>Looser</td><td>10.24 (21,700)</td></tr>
<tr><td>12</td><td>Tighter</td><td>4.39 (9,300)</td></tr>
<tr><td>13</td><td rowspan="3">Office with Corridor</td><td>30</td><td>N</td><td rowspan="3">N</td><td rowspan="3">Looser</td><td rowspan="3">10.24 (21,700)</td></tr>
<tr><td>14</td><td>60</td><td>Y</td></tr>
<tr><td>15</td><td>60</td><td>N</td></tr>
<tr><td>16</td><td rowspan="3">Open Office</td><td>30</td><td>N</td><td rowspan="3">N</td><td rowspan="3">Looser</td><td rowspan="3">10.24 (21,700)</td></tr>
<tr><td>17</td><td>60</td><td>Y</td></tr>
<tr><td>18</td><td>60</td><td>N</td></tr>
<tr><td>19</td><td rowspan="3">Hotel</td><td>30</td><td>N</td><td rowspan="3">N</td><td rowspan="3">Looser</td><td rowspan="3">10.24 (21,700)</td></tr>
<tr><td>20</td><td>60</td><td>Y</td></tr>
<tr><td>21</td><td>60</td><td>N</td></tr>
</table>

3.4. Results and Discussion

The impact of stair cooling due to pressurization on elevator-to-building airflows was studied. Table 12 provides results for Scenarios 1-12 which considers a 30-story building with elevator hoistway vents for each of the three architectural layouts considered. Table 12 provides elevator-to-building differential pressures (Pa) and airflows (m^3/s) located on the bottommost (Floor 1) and topmost floor (Floor 30) of the building for both when the stair is warm (after initial pressurization) and when the stair is cool and relatively steady-state (after 10 minutes of pressurization). Airflows reported in Table 12 are the sum of all elevators shafts (i.e., Office = 8 shafts; Hotel = 2 shafts).

Table 12
Elevator-to-Building Airflows for 30-Story Building with Elevator Hoistway Vents (Scenarios 1-12)

			Office Building–Corridor (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Elevators				Elevators			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
1	Y	Looser	-72.24	-2.71	0.84	0.35	-2.24	-5.16	1.00	0.38
2		Tighter	-45.21	-2.13	0.72	0.24	-0.94	-3.34	0.94	0.28
3	N	Looser	-59.48	-2.44	5.18	0.86	-1.59	-4.35	5.48	0.89
4		Tighter	-33.88	-1.84	3.04	0.50	-0.69	-2.86	3.64	0.55

			Office Building–No Corridor (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Elevators				Elevators			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
5	Y	Looser	-73.98	-2.72	1.82	0.51	-2.36	-5.30	2.13	0.55
6		Tighter	-43.84	-2.09	1.25	0.32	-0.94	-3.34	1.52	0.35
7	N	Looser	-42.92	-2.07	15.57	1.50	-1.61	-4.38	16.94	1.56
8		Tighter	-22.32	-1.49	5.70	0.69	-0.61	-2.70	6.57	0.74

			Hotel (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Elevators				Elevators			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
9	Y	Looser	-56.54	-0.59	11.46	0.16	-4.58	-1.84	18.33	0.20
10		Tighter	-53.55	-0.58	2.94	0.06	-3.26	-1.56	9.39	0.11
11	N	Looser	-63.77	-0.63	8.59	0.28	-3.91	-1.71	13.40	0.35
12		Tighter	-48.82	-0.55	2.74	0.12	-2.74	-1.45	8.22	0.21

As shown in Table 12, for each of the three architectural layouts considered, the “looser” model with no elevator lobbies resulted in the highest elevator-to-building airflows on the top floor of the building (Scenarios 3, 7, and 11).

The next set of runs (Scenarios 13–21), looked at varying building height and the presences of elevator hoistway vents, using the “worst-case” runs from the previous set (i.e., “looser” building with no elevator lobbies) as a baseline. Elevator-to-building differential pressure and airflow results for Scenarios 13–21 is provided in Table 13.

Table 13
Elevator-to-Building Airflows for 30-Story Building with Elevator Hoistway Vents (Scenarios 13-21)

					Office Building–Corridor							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Elevators				Elevators			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	**Stories**	**Vent**	**Lobby (Y/N)**	**Leak**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**
3	30	Y	Y	Looser	-59.48	-2.44	5.18	0.86	-1.59	-4.35	5.48	0.89
13	30	N		Tighter	-43.02	-2.07	9.02	1.14	-0.94	-3.34	9.65	1.18
14	60	Y	N	Looser	108.15	-3.29	14.62	1.45	-2.91	-5.89	20.38	1.71
15	60	N		Tighter	-90.49	-3.01	19.12	1.66	-2.28	-5.20	25.96	1.93

					Office Building–No Corridor							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Elevators				Elevators			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	**Stories**	**Vent**	**Lobby (Y/N)**	**Leak**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**
7	30	Y	Y	Looser	-42.92	-2.07	15.57	1.50	-1.49	-4.23	14.03	1.42
16	30	N		Tighter	-33.68	-1.83	21.92	1.78	-1.13	-3.66	20.35	1.71
17	60	Y	N	Looser	-78.96	-2.81	39.11	2.37	-2.67	-5.63	37.14	2.31
18	60	N		Tighter	-69.72	-2.64	46.58	2.59	-2.31	-5.24	44.51	2.53

					Hotel							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Elevators				Elevators			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	**Stories**	**Vent**	**Lobby (Y/N)**	**Leak**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**
11	30	Y	Y	Looser	-63.77	-0.63	8.59	0.28	-4.98	-1.93	1.49	0.12
19	30	N		Tighter	-51.06	-0.57	13.20	0.35	-1.49	-1.07	4.91	0.21
20	60	Y	N	Looser	-123.47	-0.88	28.65	0.51	-10.21	-2.76	12.70	0.34
21	60	N		Tighter	-109.60	-0.83	34.52	0.56	-7.85	-2.41	17.44	0.40

As shown in Table 13, elevator-to-building airflows on the top floor increased within building height, as would be expected due to increase stack effect. The data also indicates the presence of elevator hoistway vents is beneficial in reducing elevator-to-building airflow on the upper levels of the building.

Using the "Hotel" architectural layout as an example, elevator-to-building differential pressures as a function of time, under stairwell pressurization, on the top floor of the building (i.e., while the stair is cooling) is provided in Figure 10. As shown in the figure, for all scenarios the elevator-to-building pressure difference on the top floor of the building drops when the stairwell pressurization fans are first initiated. This is because air coming from the two pressurized stairwells enters the guestroom corridors, increasing the corridor pressure, and thus decreasing the elevator-to-corridor differential pressure. As the stair begins to cool, the pressure profile within the stair changes and eventually flips. The colder, higher density air within the stair, relative to the surrounding building temperature, causes a reverse stack effect within the stair. This is counter-intuitive for stairwell pressure profiles under an extreme winter condition. As the stair cools, more air flows out of the bottom of the stair and less out the top. This dynamic results in increased elevator-to-building differential pressures at the top of the building as the stairwell cools for two main reasons; (1) the guestroom corridor pressure on the top floor decreases as less air enters the corridor from the pressured stairwells, and (2) more air enters the lobby on the bottom level from the pressurized stairwells and flows into the elevator shaft via the open, recalled elevator doors.

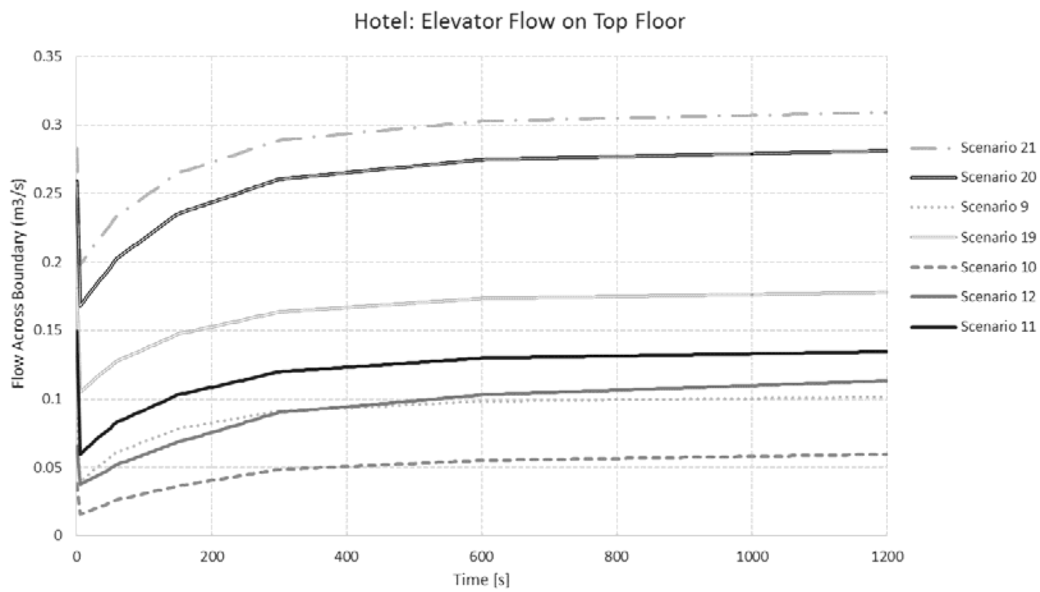

Figure 10. Elevator-to-building flow on top floor of hotel

The impact of stair cooling due to pressurization on stair-to-building airflows was studied. Table 14 provides stair-to-building differential pressures (Pa) and airflows (cfm) located on the bottommost (Floor 1) and topmost floor (Floor 30) of the building for both when the stair is warm (after initial pressurization) and when the stair is cool and relatively steady-state (after 10 minutes of pressurization). Airflows reported in Table 14 are for a single stairwell that discharges into the interior of the building (i.e., lobby).

Table 14
Stair-to-Building Airflows for 30-Story Building with Elevator Hoistway Vents (Scenarios 1-21)

			Office Building–Corridor (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Stairs				Stairs			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
1	Y	Looser	-43.84	-0.22	40.33	0.21	143.08	0.41	71.65	0.29
2		Tighter	-20.43	-0.08	31.24	0.10	90.89	0.17	45.81	0.12
3	N	Looser	-54.55	-0.24	9.59	0.10	120.06	0.37	38.11	0.21
4		Tighter	-29.14	-0.10	7.87	0.05	68.00	0.15	17.53	0.08

			Office Building–No Corridor (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Stairs				Stairs			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
5	Y	Looser	-37.36	-0.20	61.52	0.26	144.34	0.41	90.89	0.33
6		Tighter	-14.92	-0.07	40.28	0.11	93.88	0.18	54.35	0.13
7	N	Looser	-34.87	-0.20	22.54	0.16	121.42	0.38	50.94	0.24
8		Tighter	-15.94	-0.07	11.93	0.06	69.00	0.15	21.42	0.08

			Office Building–Corridor (30 stories, Vent)							
			T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
			Stairs				Stairs			
			Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
9	Y	Looser	-34.87	0.20	14.45	0.13	88.10	0.32	22.58	0.16
10		Tighter	-37.06	-0.11	10.69	0.06	52.13	0.13	9.21	0.06
11	N	Looser	-54.05	-0.24	11.21	0.11	81.70	0.31	12.55	0.12
12		Tighter	-39.61	-0.11	5.73	0.04	45.91	0.12	2.04	0.03

					Office Building–Corridor							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Stairs				Stairs			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	Stories	Vent	Lobby (Y/N)	Leak	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)	dP (Pa)	Flow (m^3/s)
3	30	Y	Y	Looser	-54.55	-0.24	9.59	0.10	120.06	0.37	38.11	0.21
13	30	N		Tighter	-42.67	-0.22	8.84	0.10	115.35	0.37	36.32	0.21
14	60	Y	N	Looser	-99.88	-0.33	16.69	0.14	165.57	0.44	14.89	0.13
15	60	N		Tighter	-86.68	-0.31	15.67	0.13	161.16	0.43	13.53	0.13

					Office Building–No Corridor							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Stairs				Stairs			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	**Stories**	**Vent**	**Lobby (Y/N)**	**Leak**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**
7	30	Y	Y	Looser	-34.87	-0.20	22.54	0.16	121.42	0.38	50.94	0.24
16	30	N		Tighter	-32.63	-0.19	21.60	0.15	113.83	0.36	49.31	0.24
17	60	Y	N	Looser	-62.77	-0.26	39.61	0.21	165.20	0.44	39.23	0.21
18	60	N		Tighter	-60.53	-0.26	38.11	0.20	158.10	0.43	37.34	0.21

					Hotel							
					T1 = 0 seconds (Fans Off - Warm Stair)				T1 = 10 minutes (Fans On - Cool Stair)			
					Stairs				Stairs			
					Bottom Floor		Top Floor		Bottom Floor		Top Floor	
Run	**Stories**	**Vent**	**Lobby (Y/N)**	**Leak**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**	**dP (Pa)**	**Flow (m^3/s)**
11	30	Y	Y	Looser	-54.05	-0.24	11.21	0.11	116.82	0.37	43.54	0.23
19	30	N		Tighter	-47.50	-0.23	10.21	0.11	113.09	0.36	42.10	0.22
20	60	Y	N	Looser	-91.17	-0.32	12.45	0.12	153.69	0.42	32.13	0.19
21	60	N		Tighter	-84.69	-0.16	11.73	0.11	146.71	0.41	30.89	0.19

Consideration of stair cooling is commonly overlooked by design engineers and furthermore is not mentioned in the latest *Handbook of Smoke Control Engineering* (2012). As shown in Table 14, under a normal winter stack conditions (i.e., warm stair and cold outside) the model shows higher stairwell differential pressures on the top floor and lower pressures on the bottom floor. This would be the expected result when modeling a stairwell pressurization system under extreme winter temperatures, assuming stair cooling is not accounted for.

The importance of considering stair cooling is noticeable when studying the data in Table 14. As shown in the table, under a warm stair assumption, the difference between the top and bottom stairwell differential pressures is a relatively tight range. When the stairwell cools, this difference increases considerably, which may impact the building's height limit for satisfactory pressurization. Furthermore, the pressure profile in the stair flips as the stair cools. Meaning, the highest differential pressure is now at the bottom of the stairwell, rather than the top.

4.0 Summary and Conclusions

The FDS modelling verified that when pressurizing a stairwell with untreated cold outside air, the temperature in the stair cools but stabilizes at a temperature that is between the outside air temperature and the initial building temperature. The results showed that, even for the models corresponding to loose building construction, the lowest temperature achieved was approximately mid-way between the initial inside temperature of the building and the outside temperature. Tighter building construction, and thus less required pressurization air, resulted in less of a temperature reduction.

While high initial stack effect pressures at the top of the stair are alleviated, introduction of cold air increases the pressures at the bottom of the stairwell, The CONTAM modelling verified that the cooling of the stair increases pressures at the bottom of the stairwell to the extent that excessive door opening forces are likely. Pressures on the top floor of the office building configuration ranging from 87.2–139.5 Pa (0.35–0.56 in.W.G.) are reduced to 37.4–74.7 Pa (0.15–0.30 in. W.G.) The unexpected result, however, is that pressures at the bottom of the stair ranging from 74.7–109.6 Pa (0.30–0.44 in. W.G.). increase to 99.6–161.9 Pa (0.40–0.65 in. W.G.), well above the threshold at which excessive door opening forces are created.

Cooling of the stair also increases the stack effect flow via the elevator shaft over time. The magnitude of the increase is higher for building arrangements such as the hotel/residential building where a corridor creates a direct connection between the stairs and elevators and where the ratio between stair leakage and elevator leakage (due to fewer elevators) is higher. Flow out the top floor of the building has the potential to increase by 15–25 % due to the increased stack effect in the elevator shaft in hotel/residential building configurations.

The modelling also showed that elevator lobbies reduced the flow to upper floors by approximately 50% for all building types and that elevator hoistway vents had only a modest impact on reducing the flow to upper floors of the building. This conclusion was consistent for all building types and leakage assumptions. For an office building with a central corridor arrangement, approximately 3.87 m^3/s (2,500 cfm) enters the upper floor of a 30 story loose building when no elevator lobby is present. This number increases to almost 6.19 m^3/s (4,000 cfm) for a 60 story building. At this airflow rate, any smoke present in the air traveling vertically via the elevators would quickly fill a corridor space, and could impact the ability of building occupants to exit safely via the stairwells.

5.0 References

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