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CHARACTERIZATION OF STACK EFFECT IN HIGH-RISE BUILDINGS UNDER WINTER CONDITIONS

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1.0 INTRODUCTION

Hughes Associates, Inc (HAI) has been contracted to perform stack effect testing under winter conditions to characterize the potential of floor-to-floor smoke spread under stack effect conditions. The ICC's Code Technology Committee (CTC) has proposed that elevator lobbies should be omitted from the code based on their assertion that stack effect is minimal in building up to 420 ft. The purpose of the testing was to characterize the magnitude of the stack effect for a variety of buildings, both in type (office, hotel) and height.

To characterize the magnitude of stack effect, HAI conducted measurements in fifteen (15) high-rise buildings in four (4) different cities (Cleveland, Baltimore, Minneapolis, and Philadelphia) during the winter months of January – March, 2013. The impact of stair pressurization system activation on the stack effect via the elevator shafts was obtained in three (3) of the fifteen test buildings. The following letter report describes the buildings visited and measurements taken at each building.

2.0 BUILDING DESCRIPTION

HAI took pressure differential measurements in fifteen (15) high-rise buildings in four (4) different cities (Cleveland, Baltimore, Minneapolis, and Philadelphia) during the winter months of January – March, 2013. Table 1 describes the buildings visited for this study, including: city location, building height, number of floors, occupancy type, exterior wall construction, number of stairs, number of elevator hoistways, stair door undercut gap, elevator door width, and the approximate elevator door leakage area. Building names have been omitted from this report to protect the interests of the property owners.

As shown in Table 1, the test buildings in this study ranged in height from 143 – 492 ft. In some cases the building height could not be obtained. In Table 1, building height values shown in *italics (with asterisks)* are estimated, assuming a floor elevation of 13 feet, based on the elevation heights of the other test buildings. Most test building's floor elevations ranged between 11 – 14 feet. Building 3 had unusually tall floor elevations, near 19.5 feet on average. Outside temperatures ranged from 10 – 59 F.

The type of buildings tested in this study included high-rise residential hotels and business occupancies. The majority of the test buildings (12 of 15) consisted of high-rise residential hotels, due to their ease of access. High-rise business occupancies were difficult to access due to increased security. Generally speaking, most of the buildings visited consisted of a central corridor connecting stairwells and an elevator bank with rooms (or offices) located around the corridor's perimeter.

TABLE 1: Summary of Buildings Tested

Building	City, State	Height (ft)	Floors	Occupancy Type	Exterior Wall Construction	Number of Stairs	Number of Elevator Hoistways	Stair Door Undercut Gap	Elevator Door Width (ft)	Elevator Door Leakage (ft^2)
1	Cleveland, OH	320	25	Residential Hotel	Masonry and Fixed Glass Windows (Non-Operable)	2	4	tight	3.5	0.60
2		419	31	Business		2	3	1/8"	4	0.58
3		430	22			2	8	1/8" to 1"	4	0.58
4		272	22			2	6	1/8" to 1"	4	0.74
5	Baltimore, MD	399	32	Residential Hotel		2	3	1/16" to 3/4"	3.5	0.51
6		_221*_	17		Glass Curtain Wall, Mostly Non-Operable Windows (Operable in limited rooms)	2	6	1/16" to 1/2"	4	0.59
7	Minneapolis, MN	381	31		Masonry and Fixed Glass Windows (Non-Operable)	2	5	1/4" to 1"	4	0.58
8		_221*_	17			2	N/A	1/16" to 1/2"	4	0.52
9		227	19		Glass Curtain Wall (Non-Operable Windows)	2	N/A	1/16" to 3/4"	4	0.52
10		_143*_	11		Masonry and Fixed Glass Windows (Non-Operable)	2	N/A	1/4" to 1/2"	4	0.74
11	Philadelphia, PA	492	33			2	6	tight to 1"	3.5	0.59
12		_364*_	28		Masonry and Sliding Glass Doors to Exterior Balconies (Operable)	2	3	1/4" to 1/2"	3.25	0.49
13		394	32		Masonry and Fixed Glass Windows (Non-Operable)	2	6	1/4" to 3/8"	3.5	0.48
14		_299*_	23			4	10	1/4" to 3/8"	3.5	0.63
15		_195*_	15			2	6	1/4" to 3/8"	3.25	0.65

* Estimated Height assuming 13 feet per Floor

The majority of the test building's exterior walls consisted of glass curtain wall or masonry construction with non-operable windows. Building 12 in Philadelphia (see Table 1), provides a contrasting data point, where each hotel room contained exterior balconies with sliding glass doors.

Most test buildings contained two stairwells (Building 14 had four stairs). Stair door leakages ranged considerably, with undercut gaps ranging between 0 (gasketed) – 1 inch. The number of elevator hoistways in each building ranged from 3 – 10. Measured elevator door leakage ranged from 0.48 – 0.74 ft^2/door, which is consistent with values reported in *Design of Smoke Management Systems* by Klote and Milke [2002].

3.0 BUILDING MEASUREMENTS TAKEN

For each building tested, HAI measured the following (when possible):

- Differential pressure (dP) between stair and building.
    - On 1-2 upper levels (near top of building).
    - On 1-2 lower levels (ground floor).
- Differential pressure (dP) between elevator hoistway and building.
    - On 1-2 upper levels (near top of building).
    - On 1-2 lower levels (ground floor).
- Differential pressure (dP) between exterior and building at ground floor doors.
- Outside temperature at the time of testing.
- Building temperature at the time of testing.
- Number of stairwells and elevator hoistways present
- Stairwell door undercut gaps.
- Approximation of total leakage at each elevator door.

A calibrated hand-held differential pressure gauge (TSI model 8702) was used to take all differential pressure measurements. For many measurement locations, a range of differential pressures were observed. This was especially true for elevator hoistway measurements, where elevator cars were in motion (as measurements were taken during normal building activity). Best efforts were made to take average differential pressure measurements when all elevator doors were closed and elevator cars stationary. Likewise, best efforts were made to take stairwell measurements when all stair doors were closed.

In an attempt to isolate the impact of outside air temperature on shaft-to-building differential pressures, repeat measurements were conducted on the same building during different outside temperatures. Repeat measurements were conducted on Buildings 1, 2, 3, and 11.

When possible, data on the impact of stair pressurization system activation on vertical airflow movement via the elevator shafts was recorded. This was done by taking initial differential pressures in the elevator shafts (with respect to the building) at the top of each shaft when the stair pressurization system was off, and repeating the measurements while the system was turned on.

4.0 MEASURMENT CONSIDERATIONS

The driving forces of air movement in a building include naturally occurring stack effect, wind effects, fan-powered ventilation systems, and elevator piston effect. It is important to note that shaft-to-building differential pressures recorded during this study likely included all of these driving forces, at least to some degree. Although stack effect is expected to be one of the primary contributors, the magnitude of the other driving forces is unknown and should be considered when analyzing the pressure differential data. Nevertheless, the differential pressures stated in this report are actual values, under normal building activity, regardless of the driving force (or combination of driving forces) producing the result.

Most testing was conducted while the building was under a normal HVAC mode. It is important to note that stair and elevator shaft differential pressures during a fire alarm event may be considerably different due to changes in fan-powered ventilation systems, including smoke management systems (ex. stair pressurization). Proper fire protection design should consider both ventilation conditions (i.e. normal and fire mode) when predicting vertical airflow movement in a building. HAI was able to take elevator shaft differential pressure measurements from three (3) different buildings (Building 3, 5, and 7) with the stair pressurization system both on and off.

5.0 RESULTS

Table 2 provides a summary of the measurements taken at each building including: outside temperature, inside temperature, temperature delta, exterior-to-building differential pressure at ground level, stair-to-building differential pressure on lower/upper levels, and elevator-to building differential pressure on lower/upper levels. Positive differential pressure values indicate flow from the shaft (or exterior) into the building. Negative differential pressure values indicate flow from the building into the shaft (stair or elevator).

As shown in Table 2, there was ***evidence of winter stack present in all buildings tested based on the differential pressures measured***. In all buildings, air was observed flowing from the building into the stairwells and elevator hoistways on the lower levels. Pressure differential magnitudes on the lower levels for the stairwells ranged from -0.011 to -0.093 in. W.G. (-0.044 in. W.G. average). Pressure differential magnitudes on the lower levels for the elevator hoistways ranged between -0.012 to -0.100 in. W.G. (-0.052 in. W.G. average).

Similarly, in most buildings (except Building 6 and 7) air was observed flowing from the stair and elevator hoistways into the building on the upper levels. Pressure differential magnitudes on the upper levels for the stairwells ranged from -0.006 to 0.135 in. W.G. (0.041 in.

W.G. average). Pressure differential magnitudes on the upper levels for the elevator hoistways ranged from -0.008 to 0.140 in. W.G. (0.039 in. W.G average). In Building 6 and 7, it is likely that pressurized corridors caused air to flow into the stair and elevator hoistways on the upper levels of the building. A more detailed study was conducted on Building 7, were stair-to-building pressure differentials were measured on every floor. Air was measured flowing out of the stairs into the building on Floors 7 – 18 (middle levels) at differential pressures as high as 0.012 in. W.G. Air was also measured flowing out of the stairs, to ambient, through roof access doors at differential pressures between 0.509 – 0.607 in. W.G.

TABLE 1: Summary of Building Differential Pressure Measurements

						Lower Levels, dP (in. W.G.)			Upper Levels, dP (in. W.G.)	
Building	**City, State**	**Height (ft)**	**Outside Temp. (F)**	**Building Temp. (F)**	**Temp. Delta (F)**	**Exterior-to-Building (Ground Level)**	**Stair-to-Building**	**Elevator-to-Building**	**Stair-to-Building**	**Elevator-to-Building**
1	Cleveland, OH	320	12	74	62	0.380	-0.025	-0.021	0.022	0.027
		320	*28*	*74*	*46*	*0.280*	*-0.040*	*-0.016*	*0.028*	*0.034*
2		419	12	73	61	0.300	-0.059	-0.070	0.135	0.140
		419	*28*	*73*	*45*	*0.370*	*-0.050*	*-0.088*	*0.078*	*0.053*
3		430	28	71	43	0.130	-0.050	-0.100	0.080	0.085 (0.170)
		430	*59*	*71*	*12*	*0.080*	*-0.031*	*N/A*	*0.037*	*N/A*
4		272	16	73	57	0.190	-0.093	-0.093	0.074	0.085
5	Baltimore, MD	399	30	69	39	0.130	-0.038	-0.090 (-0.100)	0.055	0.030 (0.045)
6		*221*	34	72	38	0.051	-0.011	-0.012	-0.006	-0.008
7	Minneapolis, MN	381	10	77	67	0.140	-0.046	-0.055	-0.002	-0.002 (0.005)
8		*221*	18	72	54	0.120	-0.031	-0.075	0.038	0.030
9		227	18	74	56	0.100	-0.028	-0.048	0.032	0.035
10		*143*	18	74	56	0.125	-0.014	-0.032	0.010	0.025
11	Philadelphia, PA	492	48	75	27	0.077	-0.085	-0.068	0.035	0.021
		492	*39*	*75*	*36*	*0.083*	*-0.078*	*-0.084*	*0.040*	*0.027*
12		*364*	52	75	23	0.077	-0.051	-0.048	0.067	0.080
13		394	51	74	23	0.065	-0.055	-0.033	0.047	0.031
14		*299*	48	75	27	-0.025	-0.018	-0.025	0.002	0.004
15		*195*	49	74	25	0.052	-0.040	-0.023	0.015	0.004

Minimum	143	10	69	12	-0.025	-0.093	-0.100	-0.006	-0.008
Maximum	492	59	77	67	0.380	-0.011	-0.012	0.135	0.140
Average	339	31	73	42	0.143	-0.044	-0.052	0.041	0.039

Positive dP values indicate Flow Into Building
Negative dP values Indicate Flow Into Shaft
Repeat measurements for different outside temperature
dP values in ( ) indicate stair pressurization active

All exterior-to-building differential pressure measurements (except Building 14) indicate a winter stack force was present as air flowed from the exterior into the building on the lower levels. Excluding Building 14, exterior-to-building pressure differential magnitudes on the ground floor ranged from 0.051 to 0.380 (0.153 average). In Building 14, it is likely that an over-pressurized lobby and/or wind effect caused air to flow out of the building on the ground level under winter conditions.

In Table 2, values in parentheses [()] indicates a differential pressure recorded while the stair pressurization system was active. As shown in Table 2, for all three buildings when the stair pressurization system was activated, elevator-to-building differential pressures on the upper floors increased. This increase in differential pressures is due to additional air entering the elevator shafts via "bleed" air from the pressurized stairwells. The magnitude increase was more evident in Building 3 compared to Buildings 5 and 7. This may be due to the differences in the architectural layout of the central corridors and lobby areas on the lower levels. The ground level of Building 3 consists of relatively small/tight elevator lobbies with one set of exterior doors, whereas in Buildings 5 and 7 the lower levels consist of large, open areas (with multiple floors open to each other) and with multiple exterior doors.

6.0 DISCUSSION

There is a relatively strong correlation between measured exterior-to-building differential pressures (at the ground level) and a building's height and outside temperature. However this exterior force on the building does not always translate proportionally for shaft-to-building differential pressures. The architectural layout of a building plays a critical role in determining how the exterior stack force on the building is translated to the interior vertical shafts of the building. Take the repeat measurements of Building 2 for example. Notice as the temperature dropped from 28 F to 12 F, the exterior-to-building force actually dropped from 0.370 to 0.300, which is counterintuitive. Elevator-to-building differential pressures on the upper floors did increase with a drop in outside temperature (as expected) from 0.053 to 0.140 in. W.G. However, the primary reason for this substantial pressure increase, between the two scenarios, is due to a change in the configuration of a set of corridor double doors on the upper floor (which open to a large open floor layout). In the lower pressure scenario the corridor doors are closed and in the higher pressure scenario the corridor doors are open. Opening the corridor doors (which open to a large open floor layout) reduced the flow resistance on that level, resulting in higher elevator-to-building differential pressures (and vertical airflow movement). This is analogous to removal of an elevator lobby. A CONTAM model [Walton, 2005] of Building 2 was constructed by HAI (from past projects) and validates this dynamic. This is just one example of how the architectural layout (and corridor door positions) of a building can play a critical role in shaft-to-building differential pressure measurements.

The building data set is somewhat limited in that all of the buildings tested contained a central corridor connecting the stairs and elevator shafts. Although this is a common building layout, other common building layouts such as an open floor layout (ex. cubicles) were not studied. As previously mentioned, CONTAM modeling shows these centralized corridors provide airflow resistance (or back-pressure) decreasing shaft-to-building differential pressures. In comparison, open floor layouts may be more susceptible to stack force as there is less resistance to airflow.

A building's envelope leakage also plays a critical role on shaft-to-building differential pressures. This dynamic is well documented in literature [Klote and Milke, 2002] and is also supported by the data set. For example, Building 12 had one of the highest measured elevator-to-building differential pressures on the upper floors, even though the building height was average for the data set (364 ft) and the outside temperature was relatively warm at 52 F. The likely reason for relatively high differential pressures in Building 12 is due to the relatively loose envelope of the building (as each hotel room has exterior balconies with sliding glass doors).

Based on past modeling studies, other important architectural variables that impact shaft-to-building differential pressures include stair and elevator hoistways connections to ambient. These include, discharge doors, roof access doors, barometric relief dampers and elevator hoistway vents. The impact of these architectural components was not included in this study.

A building's ventilation systems also play a critical role on shaft-to-building differential pressures. The impact of ventilation systems was not included in this study.

Based on measured elevator-to-building differential pressure measurements and elevator door leakages, the total quantity of air (or smoke in a fire event) flowing onto the uppermost building level from the elevators due to winter stack was calculated (using the orifice equation) for average and "worst-case" conditions (assuming the stair pressurization system is active). Results are provided in Table 3. As shown in Table 3, ***winter stack effect could cause significant smoke migration to the upper floors of the building via the elevator shafts*** (approximately 1,500 cfm based on average values from the data set). Activation of the stair pressurization system may substantially increase airflow and smoke migration via the elevator shafts (approximately 8,000 cfm based on worst-case values for the data set) unless methods are implemented to prevent this increased airflow.

TABLE 3: Estimated Airflow Rate from Elevator Shafts to Upper Floor of Building Due to Winter Stack and Stair Pressurization

	Average	Worst-Case
Elevator-to-Building dP (in. W.G.)	0.039	0.17
Number of Elevators	5	10
Area per Elevator Door (ft^2)	0.59	0.74
Total Area (ft^2)	2.95	7.4
Flow rate (cfm)	**1,521**	**7,963**

Inherent stack effect holds true if the stairwells (and other vertical shafts) remain at building temperature. But when the stairwell pressurization systems are activated, unconditioned outside air is supplied to the stairwells and the temperature within the stairwell begins to transition toward the temperature of the outside air. As the stair shaft temperature changes over time, the pressure profile in the stair can invert changing normal winter stack effect to a reverse stack effect. The opposite is possible under summer conditions as well. This condition (such as the more typical cold outside, cool stair, warm building) creates competing stack forces. It should be noted that in all three buildings for this study where the stair pressurization system was activated, the stairwell temperatures remained relatively warm (>55 F) during pressurization because the supply air was conditioned (per design) and/or because there were heaters located in the stairs. Therefore, the impact of cooling the stairwells during pressurization on elevator-to-building airflow movement could not be characterized in this study. CONTAM modeling (from past HAI studies) shows that cooling the stairs may produce increased stack within the elevator hoistways.

7.0 CONCLUSIONS

To characterize the magnitude of stack effect, HAI conducted measurements in fifteen (15) high-rise buildings in four (4) different cities (Cleveland, Baltimore, Minneapolis, and Philadelphia) during the winter months of January – March, 2013. Test buildings in this study ranged in height from 143 – 492 ft. Outside temperature ranged from 10 – 59 F.

There was evidence of winter stack present in all buildings tested based on the differential pressures measured. In all buildings, air was observed flowing from the building into the stairwells and elevator hoistways on the lower levels. Pressure differential magnitudes on the lower levels for the stairwells and elevators ranged between -0.011 to -0.100 in. W.G. (-0.048 in. W.G. average).

Similarly, in most buildings (except Building 6 and 7) air was observed flowing from the stair and elevator hoistways into the building on the upper levels. Pressure differential magnitudes on the upper levels for the stairwells and elevators ranged from -0.006 to 0.140 in.

(0.040 in. W.G. average). In Building 6 and 7, it is likely that pressurized corridors caused air to flow into the stair and elevator hoistways on the upper levels of the building. In Building 7, were stair-to-building pressure differentials were measured on every floor, air was measured flowing out of the stairs into the building on Floors 7 – 18 (middle levels) at differential pressures as high as 0.012 in. W.G.

The shaft-to-building pressure differentials measured in this study translate to potentially large quantities of smoke migration via the elevator shafts. Therefore, HAI supports protection of the elevator shafts either by passive means (i.e. elevator lobbies, zero-clearance-doors, etc) or active means (i.e. hoistway pressurization), as stated in the 2012 International Building Code (IBC).

The exterior stack force on the building under winter conditions does not always translate proportionally for shaft-to-building differential pressures. Although a building's height and climate (outside temperature) play important roles in determining vertical airflow movement within a building, other variables such as architectural layout, architectural leakage, wind effects, and ventilation systems should all be considered. Therefore, exempting certain protective measures such as elevator lobbies or pressurization systems based purely on some arbitrary building height (420 feet in this case), is an oversimplified (and potentially dangerous) approach that is not supported by the test data. A rational and comprehensive analysis considering a building's architecture, mechanical systems, and climate exposure should be performed before exempting any passive or active smoke mitigation systems.

Future studies should look to expand on this data set. Interesting data points would include warm climates, buildings with operable openings, buildings with open floor layouts, and the impact of stairwell pressurization systems (especially for systems that provide unconditioned air to the stairwells).

8.0 REFERENCES

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