MEASURING SMOKE & TOXIC GAS PATHWAYS IN TALL BUILDINGS

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Abstract

Smoke moves through tall buildings via the unintentional holes that are found in all fire rated walls. Designers assume these holes are small. They are not! Fifteen years of quantitative testing in gaseous extinguishing system enclosures per NFPA2001 has shown that before they are tested, they are extremely leaky. The more they are tested the tighter the contractors build them. Visual location and sealing of holes does not work. The purpose of this paper is to show that these holes are easily measured, located and repaired.

The principles for measuring the size of these holes in stairwells, elevator shafts, floor slabs and entire floors will be presented. The surprises we uncover when testing buildings will teach us more about how to reduce smoke movement. Past experience shows that improvements can be made for little or no increase in cost and that mid-term savings can be huge.

Keywords: door-fan, Specific Leakage Area, Enclosure Integrity, smoke movement

1. Introduction

Toxic airborne substances of interest are smoke, biological forms, chemical agents, radioactive dust and any other toxic substance that will be transported in an air-stream. For brevity, the term "smoke" will be used in many parts of this paper to refer to all of these airborne substances.

1.1 Surprise Surprise!

Fifteen years of testing clean agent protected rooms in compliance with NFPA12A and NFPA 2001 inside tall buildings has produced a wide range of surprises. Let's take a moment to examine the range of surprises that have been uncovered.

1.1.1 Enclosures designed with expensive gaseous extinguishing systems often have NO protection from smoke events because the upper half of the enclosure is left open.

1.1.2 Gaseous suppression systems often discharge unnecessarily because of smoke from outside the room or the building.

1.1.3 An IMAX theater installed an elaborate air filtration system to remove diesel smoke that came into the room from the cruise ship terminal next door. What they got, was an imbalance from the leaky return on the air cleaner. When the projector's exhaust fan was shut off the flow would then reverse, pulling diesel smoke into the heart of the projector.

1.1.4 Elevator pressurization systems have had to be shut off because the elevator doors jammed when it was operating. New doors had to be installed.

1.1.5 Huge holes appear in fire/smoke rated walls with great regularity when new electrical or plumbing or other services are run.

1.1.6 Buildings often leak so badly that their positive pressurization systems create 1 or 2 Pa instead of the intended 25 or 50 Pa.

1.1.7 Zones and shafts typically leak 10 times more than designers imagine.

1.1.8 When owners complained of poor temperature regulation, wood planks were found rammed through dampers and controls cut so the operator could get "manual" control of the air-handlers.

1.1.9 Large ducts entering vaults that would allow anyone with a screwdriver to walk in unobstructed.

1.2 To Measure Leakage is to Know Smoke Movement

The preceding examples should give the flavor of well intentioned designs that simply do NOT work as planned when tested. Air leakage paths that will allow for the transport of toxic gases are not being comprehensively measured, but from the wide range of surprises that have already been experienced, expect a vast array of shocking surprises. The issue of this paper is how to start testing for toxic gas pathways in tall buildings. The good news is that most of these problems are easy and inexpensive to fix; the bad news is that the same features that don't work in one building get repeated over and over. Once we gain experience, the incorrect assumptions that lead to the initial problems can be corrected.

The Aggarwal 2002 article invites the entering of actual leakage figures for a more accurate CONTAMW simulation. Surely there will be surprises here where actual leakages could vary an entire order of magnitude what from would normally be entered from tabulated values. Many experts agree that there is little data on the leakage of exterior walls, floor slabs and shafts in tall buildings. We are somewhat blind in this area. The pressures are more readily understood than leakage areas because pressures can often be calculated and are easy to measure with a gauge. Refer to Yuill (2001).

There is interest in hospital setting to be able to measure the leakage of fire/smoke barriers that would divide a floor into two or three compartments allowing staff to move patients horizontally during a smoke event. Many of these patients cannot be moved quickly.

2. Leakage Path Measurement Procedures

2.1 Dangerous Contaminants

This paper is concerned with how dangerous contaminants such as toxic gases, hot smoke, cold smoke, biological agents, chemical agents, radioactive agents and airborne dust move through tall buildings. For the purpose of this paper, the term "smoke" will be used to refer to the complete range listed above since they are affected by the same forces.

2.2 Why Gases Move

Gases move when there is a pressure applied across a hole. Double the hole; double the flow. Quadruple the pressure and double the flow. The pressures are easily measured or can be predicted, the holes are harder to measure. Our test procedure consists of simply applying a positive then a negative pressure of the same magnitude across a potential pathway. Measuring the flows required, averaging them and calculating the hole size. Various zones have pre-existing pressures of typically 3 to 25 Pa across them due to HVAC, wind and stack. Testing at 50 Pa in both directions does a good job in overcoming the pre-existing pressures.

2.3 Isolating and Measuring the Leakage of Individual Components

Individual floor slabs were measured by pressurizing the entire floor to 50 Pa with a portable fan mounted in a removable door sealing panel called a door-fan (see Fig1). The door-fan was used to measure the flow and the pressure created over the doorway. While maintaining the same test pressure, the floor above would then be pressurized to the same pressure with a second door-fan and the reduction in flow from the first door-fan noted. This reduction was assumed to be due to the leaks in the common horizontal slab leakage being neutralized. The process was repeated in the other test direction. This takes about a half hour per floor. Fig. 2 shows floor slab neutralized with door-fan #1 & #2.

Using similar techniques, leaks across partition walls, into elevator shafts and other areas can be measured. Leaks from one floor to outdoors can be obtained by subtracting the upper and lower slab leaks and/or leaks into other areas such as elevators.

Figure 1 shows a door-fan set up to measure the leakage of an elevator lobby. Figure 2 shows schematically how two door-fans would be set up to first measure the leakage of the entire floor. Then door-fan #2 would be turned on to neutralize what is in this case the lower slab of the 5th floor. The difference in the flow rate required by door-fan #1 would be caused by the reduction in flow across the lower slab of the 5th floor, giving us the data needed to calculate its' leakage area.

Fig.1 Door-Fan set up

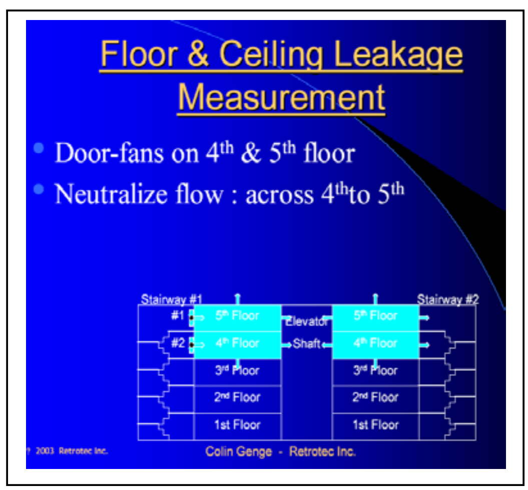

Fig. 2 Set up for floor slab testing

At this stage, the testing technique can be tailored to any specific job. Leakage through almost any component can be measure given enough time and equipment although the most important ones can be measured quite quickly. Leakage areas too small to measure may also be insignificant and have no effect. The testing technician will require an overall knowledge of the buildings HVAC and smoke management systems to get meaningful results.

Figure 3 shows a side view schematic of a room being tested, then in figure 4 a second door-fan is shown neutralizing the pressure across the common wall. The change in flow allows for the calculation of the leakage of the fire/smoke barrier wall on its' own.

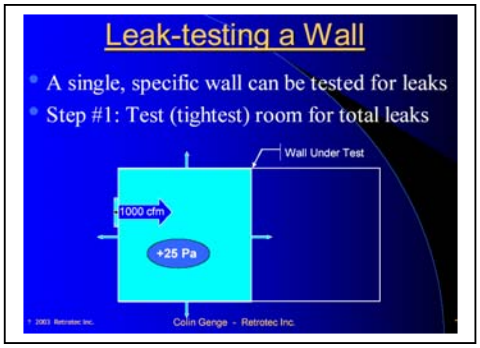

Fig. 3 Leak test part of a floor

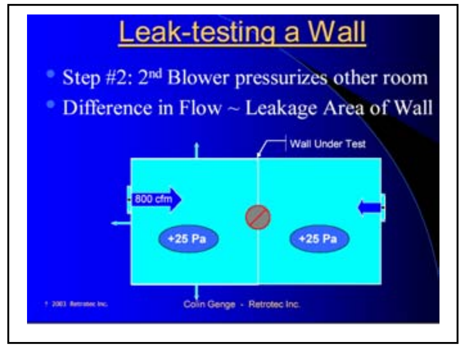

Fig. 4 Neutralize the common wall

3. Pressures are the Driving Forces

3.1 Pressures that affect Leakage Area Measurements

Stack pressures, wind and HVAC pressure must be compensated for by testing in both directions when measuring leakage. Stack pressures can be easily calculated using the formula:

$$Ps = 9.81 \times H \times ((273+Tin)/(273+Tout)-1) *1.205 \qquad \text{Eq.1}$$

Ps = stack pressure in Pascals
9.81 = acceleration of gravity constant
H= height in meters
Tin= indoor temperature in C
Tout= outdoor temperature in C
1.025= density of air at 20C

Ps is typically 2 to 25 Pa and need to be overcome to make effective measurements. This pressure is also the driving force in a stairwell. This pressure will cause all airborne agents to move. The buoyancy of hot smoke will add to this pressure. Where the outdoor temperature is -10 C, the stack will be 108 Pa overall. Where upper leaks have the same area as lower leaks, this will get split: -54 Pa at the bottom and +54 Pa at the top. Refer to Lovatt (1994). Wind pressures are typically 1 to 5 Pa but can reach 50 Pa or higher in tall buildings under windy conditions. HVAC pressures are typically 5 to 25 Pa. They are caused by fresh air introduction to the building. All these pressure are overcome in testing by making measurements in different directions at the same absolute pressure. The flows are averaged to negate a wide range of errors that would otherwise give unrepeatable results.

3.2 Driving Forces that will Distribute Toxic Agents

These same pressures may also be the driving forces for smoke and other non buoyant toxic gases. Hot smoke has the added driving force of its' own buoyancy. Explosions may create their own pressure wave that may act as a driving force and of course the explosions may creates its' own holes. The piston effect of elevators moving in their shafts is a powerful, short duration force that can push them pull agents here and there.

Calculations were performed for stairwells, elevator shafts, entire floors to outdoors, floor-to-floor slab leakage and enclosure leakage. Leakage areas were calculated from the 50 Pa test pressures unless the maximum driving force is assumed to be higher than that for tall stairwells. In the case where higher than 50 Pa stack pressures were expected, the leakage area calculations were extrapolated to that higher pressure. Some readings were taken at 10 Pa where the leakage area was 10 to 30% lower than those taken at 50 Pa but were not used because they are less repeatable. The extra leakage at the higher pressures is an added safety factor. The exact method of these calculations and the procedure would take about 20 pages to describe so have been left out of this paper.

To arrive at a maximum worst case egress time for any zone, a calculation was made based upon:
G. Tamura's figure of 1% smoke concentration for an atmosphere to become untenable. This formula is admittedly crude so should be used for comparative purposes only.

Min. Egress Time= V x c x 1.271 / Pa^0.5 / ELA /F

V= Volume in m^3

c = 1% smoke concentration in our example

1.271 = constant from NFPA2001 Appendix C, for flow formula

Pa= driving force in Pa

ELA= measured leakage area with 0.61 discharge coefficient

F= decimal fraction of portion of leaks subjected to smoke

4. Observations

4.1 Stairwells

Stairwells often have half inch gaps under door ways. Other gaps appear in the walls as buildings move and concrete cracks with time. As new, most stairwells have such small volumes that they will fill with smoke rapidly.

An active line of defense is to provide pressurization fans. If they have a small enough flow to ensure the pressure is low enough to allow the doors to be opened, this flow rate will often be totally insufficient to maintain pressurization when all doors are opened to evacuate the floors in an emergency. Variable speed fans or pressure regulating damper may be a solution. Refer to Yuill, (1994).

Measuring pressures under different scenarios requires only a pressure gauge. Finding leaks can be done efficiently with air current testers while the pressurization system is running. Temporary fans can be installed in door ways to test non-pressurized stairwells. Flow rates required to pressurize existing stairwells in different scenarios can be easily measured with door fan flow measuring equipment.

4.2 Elevator Shafts

Elevator Shafts are considered the main vertical smoke transport path by many. The visible door leak can be a major contributor but in some cases the shaft itself can have 90% of the total leaks. How can this be? Look first at the massive leaks at the top of the shaft in the motor room.

A solution then may be to intentionally pressurize them in a fire event. A limitation in pressurizing elevator shafts comes from the doors themselves. Often they jam when the pressure is applied. This inability to operate at the typical pressure ranges required to eliminate them as a transport path has defeated some installations. New doors had to be fitted at an unexpected cost. Beware!

4.3 Elevator Lobbies

Elevator lobbies are a great opportunity to isolate the shafts. The shafts themselves may be encased in concrete but the doors still open into lobbies that have huge leakage paths into the rest of the building. Isolating the elevator lobbies with slab to slab concrete walls may not be possible on ground floors but on many floors, a reception area can be found in the area adjacent to the elevator doors. An airtight fire barrier built around this lobby could effectively break the floor into three main zones plus two stairwells. This gives 5 areas of refuge on each floor.

4.4 Ducting

Ducting must be dampered with smoke rated dampers that will close on alarm. Dampers with thermal links are often found in these applications where they will not be effective in protection against cool smoke. The Ducts themselves often get damaged such that seams open up, access hatches get removed and are sometimes cut into for various reasons.

4.5 Floor Slabs

Floor Slabs can be surprisingly tight. Ducting, cabling, garbage and plumbing will come down through fire rated shafts that we have seen become quickly degraded after construction as every new wire or pipe is put in by a trade that may not know they are cutting through a fire barrier. Periodic measurement of the leakage area of these shafts will identify breaches that can be easily repaired. Grilles and panels fitted to these shafts are often inadequate. Surprisingly, they can also be very leaky. Floor slabs are difficult to test after the building is occupied. If measurements were made, tenants could be advised about what to expect in catastrophic circumstances.

4.6 Shafts

Shafts must be sealed with the correct materials that will maintain their elasticity with time. Movement destroys and degrades the smoke sealing with time. Consider access panels that may also be used to test the service shafts. Numerous penetrations have been noticed in the fire rated walls around vertical service shafts.

4.7 Exterior Walls

Exterior Walls usually leak around detailing that is difficult to control during construction. Airsealing experience has shown that what gets measured gets fixed. Houses became 10 to 20 times tighter once the leakage was measured. Exterior leaks make the building vulnerable to smoke from adjacent buildings. They also add to the energy load, rain penetration problems and noise. Exterior walls usually leak badly but the fresh supply system keeps the building pressure positive so the walls act like exhaust ports.

4.8 Partition Walls

Partition Walls have been tested in hundreds of thousands of clean agent equipment enclosures. These walls invariably leak where they connect to the horizontal slabs, through cable runs and ductwork that passes through the walls. Initial tests will usually be about ten times leakier than allowable by NFPA 2001. By contrast, properly executed designs with flexible wall to slab sealants, correct cable penetration seals and dedicated air-handlers will easily pass the NFPA procedure.

4.9 Air inlets

Air inlets are often positioned where they pull in exhaust fumes from garages since air flow patterns can have these gases clinging to the walls Spiderman fashion till they get sucked in by the fresh air supply system. Air inlets may be positioned where they will draw in smoke from neighboring building fires or dumpster fires.

4.10 Dampers

It may be incorrectly assumed that dampers will seal one area from another. This is false. Almost all dampers tested have a lot of leakage between the damper frame and the duct; the blades are seldom stroked properly; debris is often found between the blades, many simply do not operate at all. Often thermal link dampers are installed in area where smoke control is vital in spite of the inability of smoke to cause the damper to close. Fire rated dampers that DO close may not have a smoke rating.

5. Test Results

Test data was taken on a variety of enclosures to differentiate between different types of zones. Just prior to the test, pressure measurements were taken. They ranged from -16 to +16 Pa. Some were as low as 0.7 Pa but none were zero. Floors typically had positive pressures due to fresh air being drawn into the building.

"*Type*" varies from enclosures measured in dams to office towers. Examples of existing tall building standards show a building that just passes is still very leaky for smoke control purposes.
"*Ht.*" is used to calculate maximum stack for the Driving Force value used in the Minimum Egress Time calculation.
"Envelope area" is used to calculate the "leakage per area"
"*Vol*" is the volume is used in the "Minimum Egress Time" calculation.
"*Leakage Area*" is measured using a calibrated door fan designed specifically to test tall buildings.
SLA is the Specific Leakage Area, or leakage area in cm^2 per m^2 of surface area, and is used to compare the relative tightness of one enclosure or surface versus another. Clearly the SLA of 36 for one elevator door is high but the Elevator shaft at 12 stands out as exceptionally leaky.
"*Driving Force*" is an estimated maximum pressure that would drive smoke through the leaks.
"*Min. Egress Time*" Minimum Egress Time is calculated by taking 1% of the volume divided by the flow rate through one half the leaks at the Driving Force pressure shown.

			Envel-				*Driv-*	*Min.*
			ope		*Leakage*	*SLA*	*ing*	*Egress*
Type	Description	*Ht.*	*area*	*Vol.*	*Area*		*Force*	*Time*
	-all concrete	m	m2	m3	cm2	cm2/ m2	Pa	min
Hydro Dam	Elevator shaft	80	1210	1000	5483	4.53	100	0.08
Hydro Dam	stairwell	80	1015	800	3113	3.07	100	0.11
Hydro Dam	stairwell	80	915	800	2361	2.58	100	0.14
Hydro Dam	stairwell	80	1412	800	5270	3.73	100	0.06
Hydro Dam	stairwell	80	1015	800	2509	2.47	100	0.14
Hydro Dam	Elevator shaft	60	1003	800	12110	12.07	75	0.03
Hydro Dam	stairwell	60	1015	800	3597	3.54	75	0.11
Hydro Dam	stairwell	60	1015	800	1738	1.71	75	0.23
Office Tower	2nd floor	4	4600	7200	4664	1.01	10	2.07
Office Tower	2nd floor, lower slab	4	1800	7200	152	0.08	10	63.46
Office Tower	elevator lobby,2nd flr	4	480	576	4305	8.97	10	0.18
Office Tower	elevator doors, 2nd flr	30	4	180	145	36.25	25	1.05
TM23 UK stnd	Good practice	4	2500	4000	6250	2.50	10	0.86
TM23 UK stnd	Best practice	4	2500	4000	3125	1.25	10	1.71
UBC 905 stnd	walls	4	2500	4000	25000	10.00	10	0.21
UBC 905 stnd	exit enclosures	4	2500	4000	8750	3.50	10	0.61
UBC 905 stnd	other shafts	4	2500	4000	37500	15.00	10	0.14
UBC 905 stnd	floors and roofs	4	2500	4000	12500	5.00	10	0.43
NFPA2001	fm200 protected	4	2500	4000	10000	4.00	10	0.54
Computer flr	lower slab and walls	5	7000	11000	4164	0.59	15	2.89
House	R-2000 maximum	3	725	900	225	0.31	10	5.10
PFEER stnd	Oil Platform	3	350	560	14	0.04	10	55.60
Apartment	8+9th floor, lower slab	6	1656	3024	1300	0.79	8.1	2.2
Apartment	6+7th floor, lower slab	6	1656	3024	1600	0.97	8.1	1.8
Apartment	4+5th floor, lower slab	6	1656	3024	1100	0.66	8.1	2.6
Apartment	2+3th floor, lower slab	6	1656	3024	1000	0.60	8.1	2.9

6. Discussion

6.1 Comparative Results

These test results are meant to give the reader an overview of different types of Tall building features to discover what the limits are. First notice the SLA range from 0.04for all welded steel construction, to 0.31 or better for all wood houses, to 0.08 for continuous concrete slabs to 12.07 for elevator shafts. Those with more dynamic openings such as doors and cable shafts tend to leak more but flat walls can leak badly too if no attention is paid to detailing of the joints and repair of cracks and unintentional wiring and plumbing openings.

Beware; most concrete slabs are much leakier than the 2nd floor, lower slab of the Office Tower which shows a minimum egress time of 63 minutes. The building shown had no ductwork running from floor-to- floor. Buildings that do have ducting, cable runs and chases between floors can have 10 to 100 times the leakage shown. By way of comparison, the Apartment has average egress times of around 2 minutes.

6.2 Driving Forces

Driving forces can vary a lot although the difference between 100 Pa and 10 Pa is only about 3:1 when the square root relationship between pressure and flow is taken into account. Leakage areas in contrast leak in direct proportion to their size. Double the hole size and double to flow rate is generally true.

6.3 Minimum Egress Times

Most of the Minimum Egress Times calculated are extremely low. The formulae can be reconsidered for different area where an area of refuge may require 30 minutes and a stairwell 15 minutes since the stairwell would not typically be a place to take cover for long periods. A closer look could be taken at the assumption that fully half the leaks would be supplied with smoker whereas in a stairwell perhaps only one door in 16 may have smoke trying to get in. This 1 door in 16 would increase the stairwell Times by a factor of 4; even at that the Times are still too short with none of them allowing a one minute exposure.

6.4 Stairwells

Given short Minimum Egress Times for stairwells, pressurization seems the obvious answer. It can be expected that most stairwell doors will be open in an emergency to evacuate all floors requiring massive airflow. Since smoke that does get into the shaft will find its' way to the top, would a vent at the top help? Could this vent be a pressure regulating type that would allow excess pressure to be bled off until doors were opened to relieve it? Would it be practical to bring an air inlet duct to a lower portion of the so that smoke would efflux more efficiently?

6.5 Computer Simulations

Computer simulations such as those referenced by Aggarwal et. al. (2002) typically use figures for compartment leakage gleaned from tables. Results would change dramatically if the real tested values were entered.

6.6 Leak Location

Holes are easily located once they are measured. If it is known that there is 5 m^2 of holes, the enclosure is pressurized to 25 Pa and neutral buoyancy smoke is used in small 1 cc puffs to track down the culprits. In the hands of an experienced technician, 90% of the leaks can be located on a 2000 m^2 floor in about one to two hours, depending on accessibility.

7. Conclusions

7.1 Comparative Results

The floor slab with the 63 minute time and the energy efficient wood frame house with the 5 minute time show that envelopes can be made very smoke tight. The former because of the construction style and the latter because of the testing and training the builders undergo. The figures on these two give us a clue as to how we may get better smoke control in tall building.

1. eliminate leaky construction features, and
2. test all floor, stairwells, areas of refuge and elevator shafts

Oil platforms performing to the PFEER standard show up in the table at 55 minutes showing us what can be done with relatively small enclosures. Larger poured slabs should be easy to get tight but shafts require special attention. Specialized sealing techniques such as fire rated spray rubber can be used on all suspect areas, top quality door-seals should be applied and regular testing should take place to ensure the shafts have not been compromised.

7.2 Valuable Surprise Findings

The most interesting feature of testing tall buildings is the surprise element. Most systems do not work as designed. That is why we test drive everything except the leakage paths in tall buildings. The reason they don't get tested is because no one really expects a fire. Or, designs that don't work can survive because there is a small chance they will be tested by catastrophe. Surprise! Elevator shaft pressurization will probably be limited by the pressure at which the elevator doors jam. Surprise! Leakage increases with time, cracking, aging and movement. Surprise! Routine testing upon commissioning new buildings will show up unexpected and sometimes totally unacceptable faults. Surprise! Stairwells offer little protection unless they can be pressurized with enough air to keep out smoke which is a difficult design problem. Unexpected benefits of testing would be, safer buildings, fewer water leaks, reduced maintenance and reduced tenant complaints due to exhaust and garbage odor movement.

7.3 The Next Step

The first step is to become more familiar with problem areas and to document them so the same mistakes are not made by each group separately. Next, is to establish guidelines for successful strategies and new design details that will maximize protection both in new designs and to retrofit old ones. Eventually guidelines could be established for various components, standard sealing methods can be developed that take time, wear and tear and movement into account. It is important to understand the impact of the surprises we will find when we test tall buildings and to be wary of a quick fix. This type of testing must be done by thoroughly trained technicians who have benefited from the experience of others and can apply basic principles in a thoughtful analytical way in finding what is wrong with any particular building.

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